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Research Associate,
RARS, Lam, ANGRAU
Email- sudhasmart.no1@gmail.com

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Effects of phosphorus fertilizer rate and *Rhizobia* inoculation on growth, nodulation and yield of Soybean [*Glycine max* (L.) Merrill] varieties under nitisol of South-Western Ethiopia

Garoma F, **Amsalu N** and **Gedefa S**
Oromia Agricultural Research Institute, Bedele Agricultural Research Center, Ethiopia

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ABSTRACT

Soybean is high quality protein source for resource poor families and oil crop in Ethiopia, but low phosphorus levels and soil acidity limit yields in the BunoBedele area. Therefore, the aim of this study is to investigate the effect of phosphorus fertilizer and different rhizobia strains on soybean performance in terms of growth, nodulation, and yield in Nitisol of southwestern Ethiopia. The experiment was conducted at BunoBedele, Ilkekerero sub site of Bedele Agricultural Research Center in 2023 main cropping season. The experiment included 16 treatment combinations four phosphorus levels (0, 10, 20 and 30 kg P ha^{-1}), with and without inoculation MAR-1495 *rhizobia*, and two soybean varieties (Ketta and Cheri). The experimental design was Randomized Complete Block Design RCBD) in factorial arrangement with three replications. The Analysis of variance showed very high significant ($P<0.0001$) interactions between *rhizobia* inoculation and phosphorus levels, as well as variety ($P<0.0001$) effects on growth, nodulation, and yield. The highest yields were achieved (3.45 ton ha^{-1}) with 30 kg P ha^{-1} and *Rhizobium* inoculation, particularly with the Ketta variety, while the lowest grain yield was observed 0.33 ton ha^{-1} under un-inoculated rhizobia and control plot of P application. The combined application of MAR-1495 *rhizobia* and 30 kg P ha^{-1} significantly improved nodulation and yield. This approach also resulted in the highest net benefits (113231.2 ETB) and marginal rate of return (541.6%), making it a profitable strategy for enhancing soybean production and farmer income in the region. The findings from this research provide several practical recommendations for optimizing soybean cultivation in environments similar to the one studied: Cultivar Selection and Fertilizer Management. By implementing these practical recommendations, farmers in similar environments can optimize their soybean cultivation practices and improve the productivity and profitability of their operations.

KEY WORDS: *Glycine max*; *Inoculation*; *MAR-1495 strain*; *Phosphorus*; *Symbiotic nitrogen fixation*

1. Introduction

Soybean (*Glycine max* (L.) Merrill) is one of the most important pulse crops and it belongs to the family (Leguminosae). Soybean is cultivated all over the world, as a major source of oil (20%) and protein (40%). Soybean is one of the most valuable crops in the world, due to its multiple uses as a source of livestock and aquaculture feed, protein and oil for the human diet (Ali *et al.*, 2020). Beside, producing valuable grain, soybean fixes between 50-300 kg N ha^{-1} which makes a

CONTACT Garoma F ✉ garomafirdidisa21@gmail.com

significant N contribution to inter-cropped and rotated cereal crops (Craswell and Vlek, 2013), estimated the improvement of maize crop following soybean crop at between 0.5 and 3.5 tons ha^{-1} or 30-350% relative to maize-maize sequences. The country's current foremost soybean-growing regions are located in the West and Southwest of the country. More than 44% of the country's soybean production is produced in the Oromia region, especially in the western and eastern areas of Wollega and Illu-ababor (Debela and Wogi, 2020). These regions have vast fertile land and favorable agricultural climate suitable for growing soybeans. In Ethiopia, an area of 75,938.88 hectares of land is planted with soybeans, producing 185,522.23 tons with a yield of 2.44 ton ha^{-1} (CSA, 2021/22), low compared to the world average of 2.74 ton ha^{-1} (USDA, 2021/22). In the Ethiopian region, production and fluctuations in two consecutive years (2021 and 2022) show the area from 83,613.66 ha to 75,938.88 ha, a decrease of 9.18%. Production 208,497.43 tons to 185,522.23 tons, changes 11.02%, and productivity from 2.49 ton ha^{-1} to 2.44 tons ha^{-1}, down 2.04% compared to 2021 production area , output also decreased by 11.02% (CSA, 2021/22).

In Oromia Region an area of 4946.85 hectares of land is planted with soybeans, producing 10941.7 tons with a yield of 2.2 tons ha^{-1} (CSA, 2021/22), low compared to the worldwide and National average of 2.74 and 2.43 ton ha^{-1}. In BunoBedele an area of 1,663 hectares of land is planted with soybeans, producing 3,448.5 tons with a yield of 2.07 tons ha^{-1} (Zone of BunoBedele Agricultural office, 2021/22), still low compared to the worldwide, national and regional average of 2.74, 2.44 and 2.2 ton ha^{-1}.

In spite of the awesome potentials of the crop, soybean production is still insufficient owing to low yields, resulting in a wide gap between what is right now produced and what is needed. As a way of improving production level, one of the major areas to consider is the development of high yielding and improved varieties and development of improved cultural management practices. Soybean yield reduction resulting from soil acidity and other constraints is a significant issue in various regions, particularly in areas with high rainfall and acidic soils (Dabesa and Tana, 2021b). Here are some key points regarding the impact of soil acidity and other constraints on soybean yields: Soil acidity with associated low nutrient availability is a major constraint to soybean production in many regions, including southwestern Ethiopia. Soil pH levels below 5.0 can lead to high Al content, P fixation, and deficiencies in essential nutrients like Mg^{2+}, Ca^{2+}, and K^{+}, which can significantly reduce soybean yields. Lime application can help alleviate these issues by increasing root and shoot yields, but high rates of lime application may not be economically feasible for resource-poor farmers. Other Constraints: Drought and water stress can also significantly impact soybean yields, particularly in areas with limited rainfall. Pests and diseases can further reduce yields if not managed effectively. Limited access to quality inputs, such as improved seeds and fertilizers, can also hinder optimal soybean production. Inadequate post-harvest handling, storage, and marketing infrastructure can lead to losses and reduce farmer income. Many of factors, such as Drought, soil acidity, soil fertility reduction, poor nutrient use, poor agronomic practices, and poor accessibility to quality seed, Pests, diseases and climate change affected soybean production (Koskey *et al*., 2017).

Soil acidity is a prevalent problem in the Ethiopian highlands, affecting soil productivity and crop yields. Acidic soils cover a substantial portion of arable land in Ethiopia, with the western part of the country being particularly affected (Gurmessa, 2021a). Factors contributing to soil acidity in Ethiopia include heavy rainfall, high temperatures, erosion of topsoil, and improper agricultural practices that lead to the degradation of organic matter and leaching of essential nutrients from the soil (Beyene *et al*., 2023). Acidic soils in Ethiopia are inherently infertile and often exhibit aluminum or manganese toxicity, which hinders plant growth and reduces crop productivity. The low pH of acidic soils affects nutrient availability, especially phosphorus and other macronutrients, essential for plant growth. Approximately 43% of the Ethiopian arable land has influenced by soil acidity, of these about 28.1% of soils were dominated by strongly acidic soils (pH 4.1-5.5) (Bekana *et al*., 2022). Correcting soil acidity through liming can improve soybean yields, but high rates of lime application may not be economically feasible for resource-poor farmers. Selecting soybean varieties tolerant to soil acidity and phosphorus deficiency can help mitigate these constraints. Integrated soil management options, such as micro-dosing lime application, can improve soil physical and chemical properties and enhance crop production. Proper agronomic practices, including row planting and timely fertilizer application, can also enhance soybean yields

The establishment of an effective and efficient BNF depends on optimizing all of the components (*i.e.* legume *Rhizobium*, management and environment) together. An understanding of the effects of these management factors on the symbiosis may assist in the selection of P-efficient soybean genotypes that will enhance symbiotic nitrogen fixation and soybean yield. Phosphorus is an essential ingredient for *Rhizobia* bacteria to carry out BNF processes. Insufficient P restricts root development, the process of photosynthesis, translocation of sugars and other such functions, which directly impact N fixation by legume plants. The phosphorus serves as an energy source during the physiological processes taking place in the plant (Karthika *et al*., 2018). Therefore, this study was aims to investigate the effect of phosphorus fertilizer and rhizobia strains on soybean performance in terms of growth, nodulation, and yield in Nitisols of southwestern Ethiopia. The findings of this research was contribute to the development of sustainable agricultural practices, including optimized phosphorus management and the identification of suitable rhizobia strains, to enhance soybean production in Nitisols of southwestern Ethiopia.

2. Material and Methods

2.1 Description of the study area

The experiment was conducted in the Bedele district, of Oromia regional state, Southwestern Ethiopia in the 2023 main cropping season. The district is located between 8°14′30″N and 8°37′53″N latitude and 36°13′17″E to 36°35′05″E longitude (Fig. 1).The area is situated at about 480 km Southwest of Addis Ababa, Ethiopia, and the elevation of the study area ranges from 1013 to 2390 m.a.s.l. The experimental site has a sub-humid climate of 13.1°C and 26.5°C, minimum and maximum annual temperatures, respectively. The area receives an annual rainfall of 2097.6 mm with maximum precipitation from April to October (Bedele National Metrology Station, 2022/2023) (Fig. 2). The area is characterized by a rugged topography dominated by gentle slopes and localized steep slopes ranging from 2 to 45%. The predominant soil types are Nitisols, Luvisols and Cambisols in the plateau and side slopes and Vertisols in low land (Regassa *et al*., 2023). The soil acidity of the study area ranged from slightly acidic to very strongly acidic with pH values of 4.5 to 6.8 and the available P (ppm) content of nearly 80.23% of the soils was in the very low (< 5) and low (5-10) categories (Gedefa *et al*., 2021). Mixed farming is the main agricultural activity carried out in the area. The main livelihood strategies in the district include crop production, livestock rearing, and off-farm activities. The major crops grown in the district includes maize (*Zea-maize*), wheat (*Tritium aestivum*), sorghum (*Sorghum bicolor*), finger millet (*Eleusine coracana*), coffee (*Coffee arabica* L.), and teff (*Eragrotis abyssinica*). Pulse crops such as faba bean (*Vicia faba*) and field peas (*Pisum sativum*) are also grown in selected areas. Generally, the study area covered a total area of 74468.50 hectares of land (Huluka *et al*., 2018).

2.2 Experimental materials

The study has used soybean Varieties named as: Ketta and Cheri obtained from BeARC. Table 1 shows brief description of the varieties.

2.3 Experimental design and procedure

The field experiment was laid out in factorial randomized complete block design (RCBD) with three replications (Table 2). The treatments were consists of two cultivars, four different P rates (0, 10, 20, and 30 kg ha^{-1}) and two levels of *BradyRhizobium* (un-inoculated and inoculated

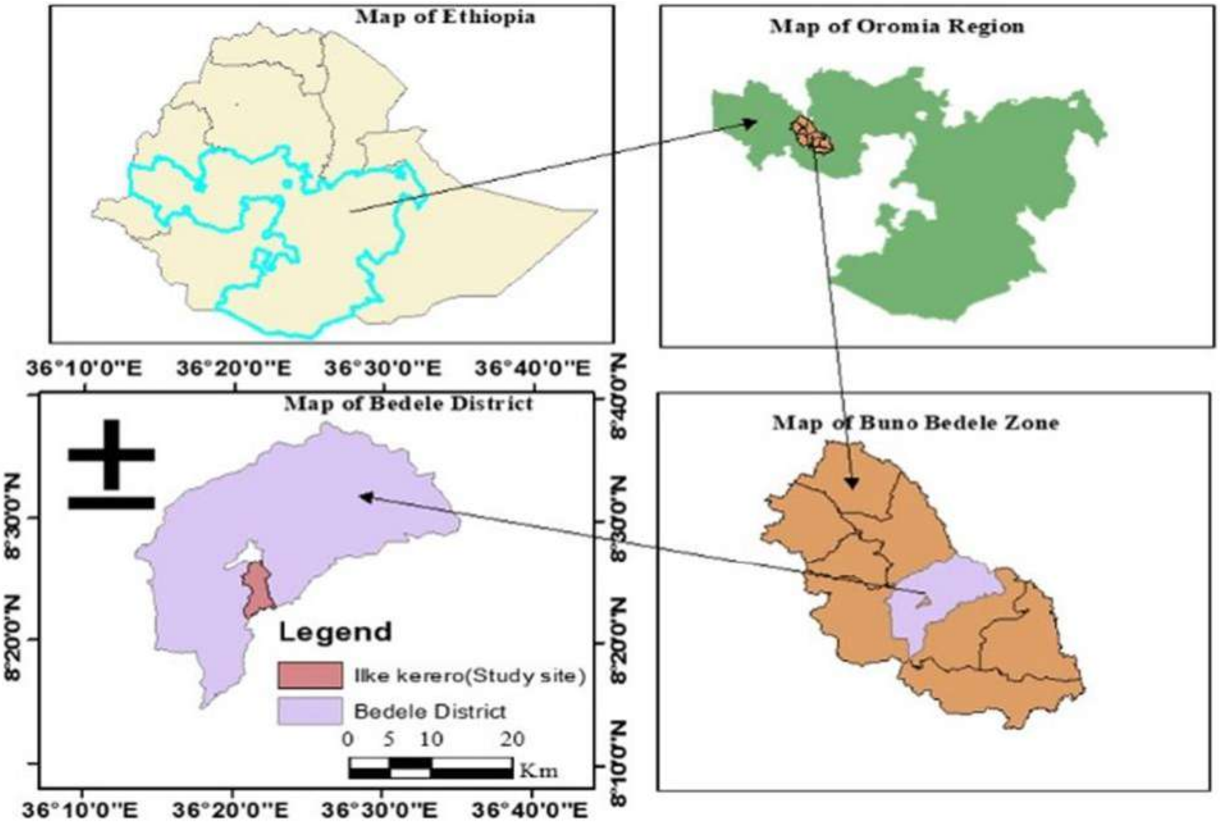

Fig. 1: Location map of the study area

with MAR-149). Therefore, this experiment consists of 16 treatments and replicated 3 times. A total of 48 plots. The size of each experimental plot was 4.2 m × 2 m (8.4 m²), with distances between plants, rows, plots, and blocks of 5 cm, 60 cm, 0.5 m, and 1 m, respectively, for a total area of 576.7 m². The seeds were weighed on an electronic scale and soaked in a sugar solution. *BradyRhizobium* strain (MAR-1495) was applied to the moistened seeds at a rate of 10 g kg^{-1} seeds. The *BradyRhizobium* inoculum was thoroughly mixed with the seeds. Seeds were air-dried in the shade for 30 min to maintain cell viability and then sown within 1 hour at the required rate and spacing.

2.4 Soil sampling and analysis

Before planting, representative soil samples were randomly collected from eight test plots at depths of 0-20 cm using an auger. Finally, composite samples were prepared for analysis to determine the physicochemical properties of the soil experimental site. A 1 kg composite sample was prepared and brought to the soil laboratory of the Bedele Agricultural Research Center in labeled polythene bags. The soil samples were air-dried, ground, and sieved through a 2-mm sieve to analyze soil texture, pH, available phosphorus, and cation exchange capacity (CEC), and the soil samples were ground to a sieve size of 0.5 mm. Soil organic carbon content was determined by the Walkley and Black (1934) as described in the FAO (2006) Laboratory Guide for Plant Nutrient Analysis (Pineiro *et al*., 2008). Soil texture was measured using the hydrometer method (Bouyoucos, 1951).

Soil pH was measured in water using a potentiometric pH meter and a glass electrode

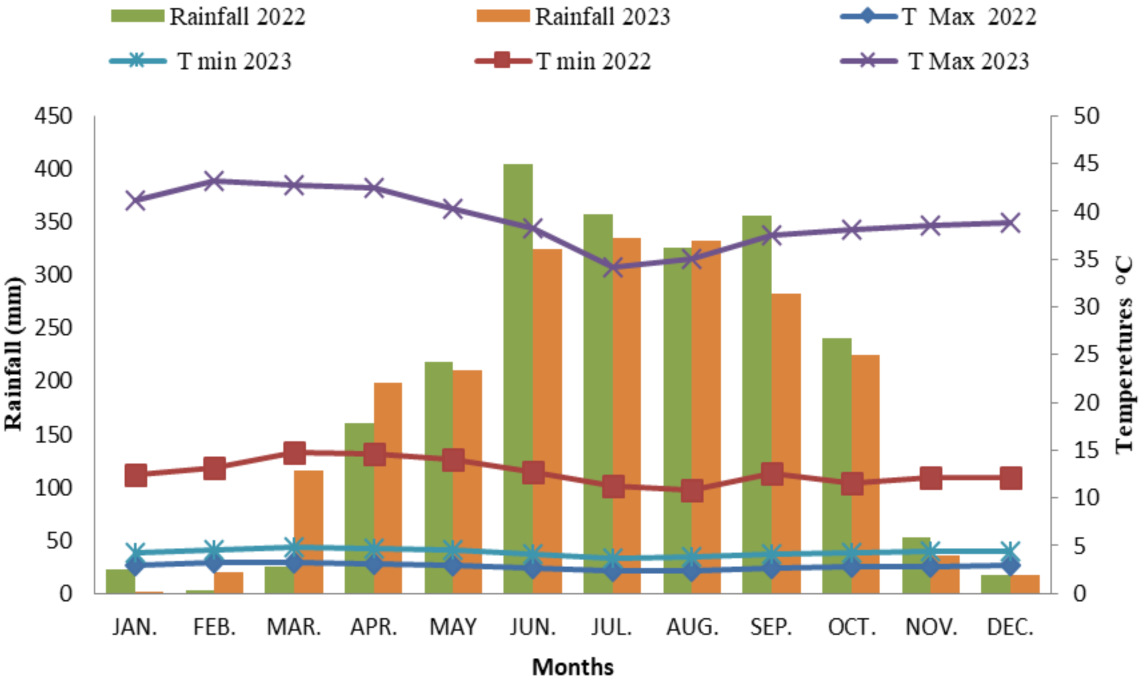

Fig. 2: Monthly rainfall (mm), minimum and maximum temperature (°C)
Source: Ethiopia Agrometeology institute, Bedele metrology first class station in 2022 and 2023

connected to a digital pH meter at a soil-to-water ratio of 1:2.5 (Pineiro *et al*., 2008).Total nitrogen was measured using the Kjeldahl method (Jackson, 1967). Available soil phosphorus was extracted and measured by spectrometer using the Olsen method Holford and Cullis (1985). Cation exchange capacity (CEC) was determined by using ammonium acetate method (Miller and Wolin, 1982). After soybean harvest, representative soil samples were randomly collected in a V-shape at two to three locations in each experimental plot using an auger at a depth of 0 to 20 cm. Finally, plot-based samples were prepared for analysis to determine the effects of treatments on selected soil chemical properties at the experimental sites. The collected soil samples were air-dried, ground, and sieved with a mesh size of 2 mm. Samples were prepared, placed in polyethylene bags, labeled, and sent for analysis of available phosphorus, total nitrogen, organic carbon, and soil pH using the same procedures described above.

2.5 Land preparation and planting

The site was cleared using a tractor in April 2023. A field which was cropped to finger millet in the previous season plowed to a depth of 0-20 cm to create fine seedbeds and leveled by hand before field layout. A fine seedbed is prepared according to the design, the field layout is prepared, and each treatment is randomly assigned to experimental units within a block. The soybean was planted on June 26, 2023; with a 60 cm inter row spacing and a 5 cm between intra row spacing. As a precaution to avoid cross-contamination, the non-inoculated treatment was planted first followed by the inoculated treatment. This experiment was conducted under rain-fed conditions.

2.6 Management of the experiment

The inoculated seeds of each treatment were sown by one individual, Ridges were made to prevent the spread of bacteria due to rainwater on the site and within the city block, weed managements, followed, and data recorded was carried out during the growing season. In the experimental field, weeding was performed during the growing season.

2.7 Data collected

2.7.1 Phenological parameters

Days to 50% flowering: Record the number of days from emergence until 50% of the plants in the plot have at least one flower.

Days to 90% physiological maturity: Number of days from emergence until 95% of plants in each net plot show yellow color and pods turn yellow before senescence is recorded.

Table 1: Varieties characteristics

Varity	Maturity Type	Altitude (m.a.s.l.)	Rainfall (mm)	Breeder/ Maintainer	Year of Release	Oil Content	Protein Content	Yield $t\ ha^{-1}$
Ketta (PR-145-2)	Medium	1200-1900	1000-1200	BARC/OARI	2011	18.82	38.73	1.4-3.2
Cheri (IPB-81-EP7)	Medium	1300-1850	900-1300	BARC/OARI	2003	21.30	35.90	2.2

Source: (Tesfaye et al., 2018)

2.7.2 Nodulation parameters

Total number of nodules: Nodule and root characteristics were measured by carefully uprooting five randomly selected plants from each plot along with the soil during the time of flowering.

Root volume: The root samples of five plants were collected and immersed carefully in 1000 ml capacity plastic cylinder, which is filled up with water to a volume of 100ml. The volume of water displaced by the roots was recorded as root volume per plant.

Tap root length: The tap root length of five randomly selected plants was measured and the average of the root lengths was recorded.

Total Number of effective nodule: Deep dark red, slightly dark red and pink nodules were considered effective for nitrogen fixation. On the other hand, green or white ones may be considered ineffective. The percentage of effective nodules (%) was then calculated.

Nodule fresh weight (g per plant): Root nodules were collected from five plants, and weighed, and the average fresh weight of the nodules was recorded.

Nodule dry weight (gm. per plant): The nodules were dried in an oven at 70 °C for 48 h to constant weight. The dry nodule weight was then measured and the average nodule dry weight was recorded.

2.7.3 Growth parameter

Leaf area: This is measured at physiological maturity in five randomly selected marked plants. Five plants were randomly sampled from each plant to represent the lower, middle, and upper parts. Then measure the length and width with a ruler in centimeters, multiply the width by the length and the correction factor to get the area of each leaf, and applying the equation LA = a × (L × W), where LA is the leaf area (cm^2), L is the leaf length (cm), W is the largest leaf width (cm), and a is the angular coefficient (2.0185) (Turek *et al.*, 2023).

$$\text{Leaf area index} = \frac{\text{Leaf area}}{\text{Ground cover}} \quad \text{-------} \ (1)$$

Leaf Area Index: The leaf area index was calculated using the relation

The plant height: Plant height was measured from the ground to the highest tip of the stem for five

Table 2: Treatments combination arrangement

Varieties	*Rhizobium*	Phosphorus level (kg P ha^{-1})			
		0 kg P ha^{-1}	10 kg ha^{-1}	20 kg ha^{-1}	30 kg ha^{-1}
		P_0	P_1	P_2	P_3
V_1	R_0	$V_1R_0P_0$	$V_1R_0P_1$	$V_1R_0P_2$	$V_1R_0P_3$
	R_1	$V_1R_1P_0$	$V_1R_1P_1$	$V_1R_1P_2$	$V_1R_1P_3$
V_2	R_0	$V_2R_0P_0$	$V_2R_0P_1$	$V_2R_0P_2$	$V_2R_0P_3$
	R_1	$V_2R_1P_0$	$V_2R_1P_1$	$V_2R_1P_2$	$V_2R_1P_3$

V_1= Katta, V_2= Cheri, R_0 = No *Rhizobium*, R_1= Inoculated with *Rhizobium*, P_0 = No P applied, P_1= 10 kg P ha^{-1}, P_2 =20 kg P ha^{-1} and P_3 =30 kg P ha^{-1}

randomly selected plants per plot at physiological maturity before harvest. Average plant height (cm) was calculated for each treatment.

Number of primary branches: This was measured during the sampling period and at physiological maturity when all plants stopped growing. We counted the branches of the five plants sampled from each plot and calculated the average.

2.7.4 Yield and yield components

Number of pods per plant (count): Counts were made from five randomly selected plants from the middle three rows at maturity and expressed as the average for each plant.

Number of seeds per plant (count): Counts were made from five randomly selected plants from the central row at maturity and expressed as the average of the five plants.

Hundred seed weight (g): The harvested seeds per net plot were randomly counted and weighed (g) using an electronic balance at a seed moisture (GT PRO) content of 12.5% standard moisture content for soybean crops.

Grain yield: It was measured by harvesting the crop from the three central rows of the net plot area.

Above ground biomass: The total aboveground biomass of the net plot area in the middle three rows was determined by harvesting at physiological maturity near the soil surface and drying in the sun to constant weight. Finally, the net plant plot area biomass yield was converted to per hectare and expressed in tons ha^{-1}.

Harvest index (%): The harvest index per plot was recorded as the ratio of grain yield to soil biomass yield of or more per plot. Calculated using flow equation:

$$\mathrm{HI}(\%) = \frac{\mathrm{GY}}{\mathrm{BY}} \times 100 - - - - - - - - (2)$$

Where HI = harvest Index, GY = Grain Yield (kg), BY = Biological Yield (kg)

2.7.5 Phosphorus uptake efficiency

Phosphorous is essential to crop production; it stimulates early root formation and growth, gives a rapid and vigorous start to plants, and promotes flower and seed production. Phosphorous is needed in the genetic coding material, which controls cell division. The P content in plants is usually between 0.1 to 0.5% of the dry matter. Total P in plant material can be attained either by wet-digestion procedure or by dry-ashing procedure. Both methods are satisfactory. However, dry-ashing is a simpler, easier, non-hazardous and economical option. Later, P content in the digests or dissolved ash aliquots is measured spectrometer. Dry ashing is appropriate for analyzing P, but only in plant tissues containing low silica contents (like legumes). The procedure is slight modifications (Pratt and Chapman, 1961).

Dry-ashing procedure

1. Weigh 0.5-1.0 g dry and ground plant material in a 30-50 mL porcelain crucibles or Pyrex glass beakers.
2. Place porcelain crucibles into a cool muffle furnace, and increase temperature gradually to 550 °C.
3. Continue ashing for 5 hours after attaining 550 °C.
4. Shut off the muffle furnace and open the door cautiously for rapid cooling.

5. When cool, take out the porcelain crucibles carefully.
6. Dissolve the cooled ash in 5-mL portions 2 N HCl and mix with a plastic rod.
7. After 15-20 minutes, bring to the volume (usually to 50-mL) using DI water.
8. Mix thoroughly, allow standing for about 30 minutes, and use the supernatant or filter
9. Through Whatman No. 42 filter paper, discarding the first portions of the filtrates.
10. Analyze the aliquots for P by spectrometer (by Ammonium Vanadate-Ammonium Molybdate yellow color method).

Phosphorus uptake efficiency (PUE) was calculated using the formula of (Fituma, 2015).

PUE=P concentration× drybiomass yield--------(3)

Agronomic efficiency (AE) is defined as the grain yield per unit of fertilization.

$$\mathrm{AE}\left(\frac{\mathrm{kg}}{\mathrm{kg}}\right)=\frac{\mathrm{Gf}-\mathrm{Gu}}{\mathrm{Na}}-----------(4)$$

Where, Gf is the grain yield (kg) in the fertilized area, and GU is the grain yield in the fertilized area. Unfertilized area (kg), Na is the amount of P applied (kg).

2.8 Partial budget analysis

Economically acceptable treatments were determined through a partial budget analysis that estimated total grain yield using adjusted yield to grain market value and growing season inputs. Only the total variable cost (TCV) was used to calculate costs. The current prices of soybeans, inoculants, and P, as well as the costs of applying inoculation and P, were considered to vary according to their costs. To estimate the economic parameters, soybean yield was valued at an average market price of birr kg^{-1}. To compare soybean yields with the yields farmers receive, the achieved yields have been revised downward by 10%. Both costs and benefits were converted to Ethiopian Birr (ETB) amounts and reported per hectare. Net treatment benefits (NB) and TCV were compared using a two-step superiority analysis described below. The first step was to calculate NB as shown in the following formula suggested by CMMITY Program, (1988).

NB = (GY×P)-TCV, (1) where GY × P is the total field benefit (GFB), GY is adjusted profit. Grain yield per hectare, P is the field price per unit of harvest. Second, beneficial TCVs were listed in ascending order according to dominance analysis. All treatments with NB below the low TCV treatment were marked with the letter “D” for being dominant and excluded from further analysis. Non-dominant treatments were subjected to marginal return (MRR) analysis.

$$\mathrm{MRR}\ (\%)=\frac{\text{Change in }(\mathrm{NBb}-\mathrm{NBa})}{\text{Cahnge in TCV }(\mathrm{TCVB}-\mathrm{TCVa})}\times 100-----(5)$$

Where NBa = NB is the immediately lower TCV, NBb = NB is the next higher TCV, TCVa = immediately lower TCV, TCVb = next TCV highest TCV. MRR of 100% implies a return of one Birr on every Birr of expenditure in the given input. Finally, a treatment having marginal rate of return (MRR) greater than 100% and with the highest net benefit was considered to be economically the best.

2.9 Statistical analysis

All data were examined for normal distribution and analysis of variance (ANOVA) was performed using the statistical analysis system “SAS, 2012”. Software version 9.0, using the Proc- GLM method. Treatment differences were separated using the least significant difference (LSD) method with a probability of 5%. Correlation analysis between parameters was performed to determine the magnitude and extent of their relationships.

3. Results and Discussion

3.1 Soil physico-chemical properties before Soybean planting

The results of the analysis of selected physicochemical properties indicate that the particle size distribution of the soil is dominated by clay (58%) followed by sand (32%), and silt (10%) (Table 3). Accordingly, the textural class of soil of experimental site was clay. Soybean produced a high yield in loamy textured soil, but it can also grow well in clay soils (Butcher *et al*., 2018). The soil pH of experimental site was 4.6, which is strongly acidic according to (Bruce and Rayment, 1982).

Soybean has been found to grow well in pH values of 5.5-7.0 and any pH below and above these values will affect its growth and thus such soil needs amendment to neutralize the extreme soil reactions (Gordon *et al*., 2022). Chemical reaction like total N, available P, OC, and CEC of the soil before planting were 0.12%, 0.5 mg kg^{-1}, 1.14%, and 9.64 cmol (+) kg^{-1}, respectively (Table 3). The soil had low total N content based on the classification of total N content (%) (Joint, 2006). Moreover, the study site had very low available P content (Table 3) according to classification of Holford and Cullis (1985). The organic carbon content of the soil before planting was 1.14% indicating as very low (Table 3) according to (Joint, 2006) rating. The cation exchange capacity (CEC) of the soil was 9.64 cmol (+) kg^{-1} which is in the low range (Table 3) according to (USDA, 2007).

Generally, the soil analysis revealed that the soil sample is predominantly clay with a strong acidic pH, very low organic carbon content, low total nitrogen content, very low available phosphorus, and a low in cation exchange capacity (CEC) level. This result was in line with the findings of (Gedefa *et al*., 2021), who mapped the spatial

Table 3: Effect of P fertilizer rate, *Rhizobium* inoculation and varieties on selected soil chemical properties before Soybean planting

Soil properties	Value	Rating	Range	Reference
1. Particle size distribution				
Clay (%)	58			
Silt (%)	10			
Sand (%)	32			
Soil structural class	Clay			
2. Chemical Properties				
pH (1:2.5 H_2O) Suspension	4.6	Strongly acid	4.5-5.5	Bruce and Rayment (1982)
Organic carbon (%)	1.14	Very low	< 2	Joint (2006)
Total nitrogen (%)	0.12	Low	0.01-0.2	Joint (2006)
Available phosphorus mg kg^{-1} soil)	0.5	Very low	< 5	Holford and Cullis (1985)
CEC cmol (+) kg^{-1}	9.64	Low	6-12	Miller and Wolin (1982)

distribution of soil properties in the study area and found that 62.61%) of the soils had strongly acidic (pH < 5.5), 73.39% had low OC content (2-4%), and 80.23% of the available P (ppm) content was categorized between low (5-10) and very low (< 5). Understanding these soil properties is crucial for making informed decisions regarding soil management practices, nutrient amendments, and crop selection to optimize agricultural productivity in this specific soil type.

3.2 Effect of P fertilizer rate, *Rhizobium* inoculation and Soybean varieties on selected soil chemical properties after harvest

Soil pH

The interaction of variety×fertilizer×*Rhizobium* inoculation showed non-significant effect on soil pH (Appendix Table 1).The main effect of P fertilizer, *Rhizobium* inoculation and soybean varieties had very highly significant ($P<0.001$) influence on soil pH. On the other hand, the soil pH value of the experimental site increased by 5.13% over initial soil pH value of the experimental site increased by 5.13% over initial soil pH of 4.6%. The increment in soil pH by 5.13% over initial pH because of application of phosphorus at 30 kg ha^{-1} with *Rhizobium* inoculation might be ascribed to the impact of organic matter on soil pH through formation of complexes with acid forming cation such as Al and Fe. The highest soil pH value 4.82 was recorded at T_4 received 30 kg P ha^{-1} with *Rhizobium* inoculation, while the lowest soil pH 4.64 was recorded T_1 received control plot of P application and uninoculated (Table 4). Even though a slight increment was observed in strongly acidic (Bruce and Rayment, 1982).

Soil organic carbon

Analysis of variance indicated very highly significant ($P<0.0001$) main effect of P application, *Rhizobium* inoculation and Varieties on soil organic carbon (Appendix Table 1). However, the three factor interactions effect of P×V×Rh also had non-significant influences on soil organic carbon content of the experimental site (Appendix Table 1). The average organic carbon content of soil of each plot after harvesting was about 66.67% higher than the initial organic carbon content 3.51% (Table 4). The increased of organic carbon by 66.67% over initial soil organic carbon 3.51% content of the experimental site might be associated with the improvement of soil conditions, which might be enhanced biomass production, proliferation of soil microbial and their activity in the soil. An average organic carbon content of each treatment after harvesting was 8.4% higher than the initial organic carbon content of the soil at Bako (Dabesa and Tana, 2021a). This result is in agreement with the findings that the attributed increase in soil organic carbon to the dropping of leaves, which added organic carbon to the soil (Tisdall, 2020).

Total nitrogen

Analysis of variance indicated very highly significant ($P < 0.0001$) main effects of *Rhizobium* inoculation, P application rate and Varieties on total nitrogen content of the soil after harvesting of the soybean (Appendix Table 1). Also, the three factor interactions of P×V×Rh had non-significant ($P > 0.05$) effect on total nitrogen of the experimental site. The highest total nitrogen content 0.28% was recorded from plots that received Phosphorus application at 30 kg ha^{-1} and *Rhizobium* inoculation, while the lowest total nitrogen 0.18% was recorded for plots that received control plot of P application and un-inoculated plot (Table 4). The increment in total nitrogen content of the soil due to phosphorus application with *Rhizobium* inoculation might be due to increase of the organic matter content of the soil and still found in medium class according to (Joint, 2006). The total nitrogen content of the soil increased from 13.48% by Phosphorus application at 30 kg ha^{-1} and *Rhizobium* inoculation over the control at AlichoWuriro Highland Ethiopia (Woldekiros *et al*., 2018). Furthermore, the release of N from the applied phosphorus with *Rhizobium* might have contributed to the increase in total nitrogen, and soybean leaf dropped may also increase the Nitrogen.

Available phosphorus

The main effect of P fertilizer, varieties and *Rhizobium* inoculation had significant ($P<0.05$) effect on available soil phosphorous. However, the three factor interactions of P×V×Rh showed non-significant effect on soil available P (Appendix Table 1).

The highest soil available P content was recorded 0.82 mg ka^{-1} from the plots treated with 30 kg P ha^{-1} inoculated with *Rhizobium* with MAR-1495 strain followed by 20 kg P ha^{-1} with *Rhizobium* inoculated, while the lowest soil available P content was recorded 0.41 mg kg^{-1}. From the control plot of P application rate and un-inoculated *Rhizobium* (Table 4). Available phosphorus recorded at 30 kg P ha^{-1} with *Rhizobium* inoculated and control plot of P application and without *Rhizobium* inoculated are still in very low rating according to (Holford and Cullis, 1985). This result indicated integrated use of high rate of P fertilizer with *Rhizobium* inoculated significantly increased available phosphorus even if it was in medium rate according to Holford and Cullis, (1985). In general, at low P fertilizer rate and its combination with *Rhizobium* inoculation increased the available P content of the soil after harvest of soybean from the initial soil available P content (0.82 mg kg^{-1} of soil) (Table 4). This could be due to the fact that P is a key requirement for ATP production during the process of biological nitrogen fixation (Dabessa *et al*., 2018).

3.3 Effect of *BradyRhizobium* inoculation and P application rate on phenology of Soybean varieties

Flowering days

For the variety Ketta, the number of days to 50% flowering decreased with increasing phosphorus application rates for inoculated conditions. The lowest number of days to 50% flowering was observed 68 days at 30 kg ha^{-1} P for both inoculated and un-inoculated treatments. For the variety Cheri, a similar trend was observed with an increase in the number of days to 50% flowering with increasing phosphorus application rates for inoculated conditions. The highest number of days to 50% flowering was observed 80 days at 30 kg ha^{-1} P for both inoculated and un-inoculated treatments (Table 5).

The study revealed that *rhizobia* inoculation delayed the number of days to flowering, which suggests that inoculation, had influence on days to 50% flowering. The prolonged days to flowering could be due to the *rhizobia* inoculation that facilitated nitrogen fixation and enhanced vegetative growth, which in turn extended the flowering date. Nitrogen produced by biological nitrogen fixation, as part of the protein compound, enzyme and effective compound in energy transfer takes part in the structure of DNA, in the structure

Table 4: Effect of P fertilizer rate, *Rhizobium* inoculation and varieties on selected soil chemical properties after soybean harvest

Treatment	Soil pH (H_2O)	Rating	OC (%)	Rating	TN (%)	Rating	Av.P (mg kg^{-1})	Rating	CEC (mg kg^{-1})	Rating
Rhizobium inoculation										
Un-inoculated	4.70^b	Strongly acidic	2.53^b	Low	0.22^b	Medium	0.55^b	Very low	26.46^b	high
Inoculated	4.74^a		2.82^a		0.24^a	Medium	0.65^a		27.80^a	
LSD (0.05)	0.0066		0.1004		0.0084		0.0459		0.173	
P rate kg ha^{-1}										
T_1 (0)	4.64^d		2.03^d	Low	0.18^d	Medium	0.41^d	Very low	21.4^d	Medium
T_2 (10)	4.70^c		2.44^c		0.21^c		0.48^c		27.5^c	
T_3 (20)	4.74^b		2.97^b		0.25b		0.69^b		27.75^b	
T_4 (30)	4.82^a	Strongly acidic	3.29^a	Low	0.28^a	Medium	0.82^a	Very low	32.00^a	high
LSD (0.05)	0.0093		0.14		0.012		0.065		0.244	
Varieties										
Ketta	4.74^a	Strongly acidic	3.17^a	Low	0.27^a	Medium	0.63a	Very low	20.87b	Medium
Cheri	4.70^b		2.19^b		0.19^b		0.57^b		33.45a	high
LSD (0.05)	0.0066		0.10		0.00^8		0.05		0.17	
CV (0.05)	0.24		6.35		6.21		12.96		1.08	
Reference	Bruce and Rayment (1982)		Joint (2006)		Joint (2006)		Holford and Cullis (1985)		Miller and Wolin (1982)	

of chlorophyll, and direct impact on vegetative growth (Bhatla and Lal, 2023). Soybean inoculation increased the leaf chlorophyll content and plant biomass, and the leaf chlorophyll content of the plant remained at high levels until, the pod filling stage, as a result of delays in days to flowering (Grassini *et al*., 2021). This result is in agreement that inoculation induced late flowering in soybean in both glasshouse and field experiments (Adeyemi *et al*., 2020). This might be due to sufficient nitrogen produced by N_2 fixation promoted vegetative growth, which in turn extended days to flowering.

Phosphorus application was significantly (P=0.022) affected days to flowering. This could be due to the presence of adequate P applied to enhance shoot, root growth, and promote early flowering. Similarly, reported though the effect of P was significant, P application has slightly reduced the days to 50% flowering on soybean bean as P rate increased (Adjei-Nsiah *et al*., 2019). The three ways of interaction were significantly influenced on days 50% flowering. The significant effect of inoculation of *BradyRhizobium japonicum* and Phosphate Solubilizing *Pseudomonas* spp on days to 50% flowering (Irankhah *et al*., 2021).

Days to 90% physiological maturity

For both varieties, the number of days to reach 90% physiological maturity varied with phosphorus application rates and inoculation status. In general, there was no consistent trend across all treatments for both varieties. Comparison between Inoculated and Un-inoculated Treatments In general, there were differences in the number of days to reach 50% flowering and 90% physiological maturity between inoculated and un-inoculated treatments for both varieties across different phosphorus application rates. Cheri variety at 30 kg ha^{-1} P application and with the inoculation of *Rhizobium* bacteria was the latest matured with 165 days to maturity; while the earliest matured (124 days to maturity) variety was Ketta, with *Rhizobia* un-inoculation and control plot of P application (Table 5).

The result revealed that days to maturity delayed in response to phosphate fertilizer application

Table 5: Responses of two soybean varieties to *rhizobia* inoculation and rate of phosphorus application for flowering date and 90% days to physiological maturity

Varieties	Inoculation Status	Number of days 50% Flowering (days)				Number of days 90% Physiological maturity (days)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	75^{d}	72^{e}	70^{f}	68^{h}	130de	132^{d}	132^{d}	132^{d}
	Un-inoculated	64^{j}	65^{j}	65^{j}	66^{i}	124^{g}	128^{f}	125^{g}	129^{ef}
Cheri	Inoculated	79^{ab}	78^{b}	78^{b}	80^{a}	161^{bc}	162^{b}	161^{ab}	165^{a}
	Un-inoculated	69^{g}	70^{bc}	77^{c}	77^{c}	160^{c}	160^{c}	162^{bc}	162^{bc}
LSD (0.05)		1.17				2.17			
CV (%)		0.96				0.895			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

relative to control plot (Table 5). This might be due to the important role of phosphorus, as the vital component of adenosine triphosphate (ATP). Soybean needs phosphorus for adequate growth and nitrogen fixation. Sufficient phosphorus levels are also required to enhance different plant organs growth and promote nodulation and early maturity (Malhotra *et al*., 2018). Phosphorus is a very important nutrient for plant cell division, growth and root lengthening, seed and fruit development, and early ripening, as well. In line the observed the phosphorus is known for its effect to promote maturity. The other reason for hastening maturity could be due to the mobilization of leaf nitrogen to the reproductive organs for development (Snider *et al*., 2021).

Soybean maturity was delayed by a result of inoculation *rhizobia*. The delay in maturity of soybean might be because the N_2 fixed by inoculation promoted vegetative growth the crop. Similarly, inoculation enabled soybean to display better growth and increase in days to maturity (Kumawat *et al.*, 2019). The interaction between the varieties, inoculation and p application did not significantly (P=0.0602) influenced days to physiological maturity.

3.4 Effect of *Bradyrhizobium* inoculation and P application rate on growth of Soybean varieties

Leaf area

For the variety Ketta, in the inoculated condition, the leaf area increased with increasing phosphorus application rates up to 20 kg ha^{-1} P and then slightly decreased at 30 kg ha^{-1} P. The highest leaf area was observed 96.44 cm^2 at 20 kg ha^{-1} P. In the un-inoculated condition, a similar trend was observed, with the highest leaf area 95.06 cm^2 at 10 kg ha^{-1} phosphorus. For the variety Cheri, in both inoculated and un-inoculated conditions, the leaf area increased with increasing phosphorus application rates. The highest leaf area was observed 112.79 cm^2 at 20 kg ha^{-1} P for both inoculated and un-inoculated treatments (Table 6). The lowest leaf area was produced by the variety Ketta (75.25 cm^2) under the control plot of P application and no *rhizobia* inoculation. The top variety showed 33.35% leaf area increases over

Table 6: Responses of two soybean varieties to *rhizobia* inoculation and phosphorus application rate for leaf area and Leaf Area Index

Varieties	Inoculation Status	Leaf Area (cm^2)				Leaf area index			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	83.34^{de}	91.03^{b-e}	96.44^{a-e}	90.03^{b-e}	0.26^{de}	0.29^{bcd}	0.26^{de}	0.28^{cde}
	Un-inoculated	75.25^{e}	95.06^{bcd}	83.29^{de}	87.57^{cde}	0.23^{e}	0.24^{e}	0.26^{de}	0.27^{de}
Cheri	Inoculated	96.01^{a-d}	104.76^{ab}	112.79^{a}	103.38^{abc}	0.28^{cde}	0.35^{ab}	0.37^{a}	0.34^{ab}
	Un-inoculated	83.07^{de}	97.45^{a-d}	94.93^{bcd}	98.5^{a-d}	0.27^{cde}	0.32^{abc}	0.31^{bcd}	0.33^{abc}
LSD (0.05)		16.65				0.055	0.05		
CV (%)		10.94				10.92	10.94		

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

the genotype that produced the lowest leaf area.

This finding is in agreements the early maturing soybean genotypes achieve minimum leaf area values required for maximum potential yield at the early reproductive growth stage (Lopez *et al*., 2021). Phosphate is also very important for leaf expansion, increase in leaf surface area and higher number of leaves. Phosphate application has been reported to increase shoot growth and leaf growth of soybean and other leguminous crops (Akpalu *et al*., 2014). Reduction in phosphate supplementation resulted in decrease in shoot growth, specifically in leaf size. A reduction in leaf area with decrease phosphate fertilizer implied changes in leaf initiation rates and activity of shoot apical meristem. Decreased size of individual leaves could be related to changes in either cell division or cell expansion of both (Chiera *et al*., 2002).

Leaf area index

For the Ketta variety: Inoculated plants had higher leaf area index values compared to un-inoculated plants across all phosphorus application levels. The highest leaf area index for the Ketta variety was observed (0.29) at a phosphorus application level of 10 kg ha^{-1} for both inoculated and un-inoculated plants. The differences in leaf area index between phosphorus applications levels were more pronounced in inoculated plants compared to un-inoculated plants.

For the Cheri variety: Inoculated plants generally exhibited higher leaf area index values compared to un-inoculated plants. The highest leaf area index for the Cheri variety was observed 0.37 at a phosphorus application level of 20 kg ha^{-1} for inoculated plants. The differences in leaf area index between phosphorus application levels were more consistent compared to the Ketta variety.

Generally, the results suggest that phosphorus application has a significant effect on leaf area index, with variations depending on the variety and inoculation status. Inoculated plants generally showed higher leaf area index values, indicating a positive impact of inoculation on plant growth in response to phosphorus application.

This findings is in agreements that inoculation and phosphorus application levels play a significant role in influencing leaf area index (Adeyemi *et al*., 2021), with differences observed between inoculated and un-inoculated plants as well as variations in response to different phosphorus levels.

Plant height

For the variety Ketta, inoculated plants generally had higher plant heights compared to un-inoculated plants at all levels of phosphorus application. The difference in plant height between inoculated and un-inoculated plants was statistically significant (indicated by different letters) at most phosphorus application levels. The highest plant height for Ketta was observed in the inoculated group 95.80 cm at 30 kg ha^{-1} phosphorus application. For the variety Cheri, inoculated plants also showed higher plant heights compared to un-inoculated plants at most levels of phosphorus application. There were statistically significant differences in plant height between inoculated and un-inoculated plants at some phosphorus application levels. The highest plant height for Cheri was observed in the inoculated group 100.40 cm at 30 kg ha^{-1} phosphorus application. The shortest plant height of 70.33 cm was found with Ketta variety under no *Rhizobia* inoculation and control plot of P application (Table 7). Therefore, it can be concluded that inoculation and appropriate phosphorus application can positively influence plant growth in these varieties.

A linear increase in plant height was observed with the advancement in age of all the soybean varieties. The plant height became slow till maturity stage, which might be due to the fact that the plant converted from the vegetative to reproductive phase of growth and development. Thus, it was also observed from the data that the increase in plant height continued up to maturity stage. Phosphorus application affected the height of soybean. It was found that P application at the rate of 10, 20 and 30 kg P ha^{-1} significantly increased plant height of *rhizobia* inoculated soybean by 29.37, 30.48 and 29.17 % with inoculated respectively over the control plot of P application. Also, phosphate solubilizing fungi inoculated soybean plants scored significantly higher plant heights, which was 81% over the un-inoculated treatment (Argaw, 2012). This finding is in agreement phosphorus application of 60, 120 and 180 mg P kg^{-1} significantly influenced soybean height (Imenu *et al*., 2022). The increase in plant height, due to increase phosphorus application, might be attributed to pronounced vegetative growth in response to the applied P (Amanullah *et al*., 2019).

Number of primary branches

For the variety Ketta, in both inoculated and un-inoculated conditions, the number of primary branches increased with increasing phosphorus application rates. The highest number of primary branches was observed six at 30 kg ha^{-1} P for both inoculated and un-inoculated treatments. For the variety Cheri, a similar trend was observed with an increase in the number of primary branches with increasing phosphorus application rates for both inoculated and un-inoculated conditions (Table 7).

The lowest number of primary branch was recorded by the variety Cheri (2.8) under the

Table 7: Responses of two soybean varieties to *rhizobia* inoculation and rate of phosphorus application for plant height and Number of Primary Branches

Varieties	Inoculation Status	Plant Height (cm)				Number of Primary Branches (count)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	79.26^{de}	88.47^{bcd}	90.13^{abc}	95.80^{ab}	4.6^{c-f}	5.2^{abc}	4.8^{bcd}	6.0^{a}
	Un-inoculated	70.33^{e}	92.93^{abc}	87.80^{bcd}	92.46^{abc}	4.1^{d-g}	5.7^{ab}	4.6^{cde}	4.8^{bcd}
Cheri	Inoculated	94.66^{ab}	96.0^{ab}	97.53^{ab}	100.40^{a}	3.2^{hi}	3.8^{e-h}	4.1^{d-g}	4.7^{cde}
	Un-inoculated	82.80^{cd}	91.80^{abc}	93.86^{ab}	91.66^{abc}	2.8^{i}	3.7^{f-i}	4.2^{def}	3.2^{ghi}
LSD (0.05)		10.97				0.93			
CV (%)		7.28				12.78			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

control plot of P application and no *rhizobia* inoculation. The variety that produced the highest number of primary branch showed more than 53.3% increases over the lowest variety. There was significant effect on number of primary branches because of *Bradyrhizobium* inoculation or phosphorus application and their interaction (P=0.05). Similarly, the number of primary branches was significantly influenced by the application of *Bradyrhizobium* inoculation, phosphorus, and their combined effect (Dabesa and Tana, 2021a). The number of branches per plant was significantly affected by different rates of phosphorus application and this might probably be due to the cumulative effect of phosphorus on the process of cell division and balanced nutrition. Dissimilar report: The effect of *Bradyrhizobium* inoculation and phosphorus application on the number of primary branches was not statistically significant (Musa *et al*., 2018).

3.5 Effect of *Bradyrhizobium* inoculation and P application rate on nodulation of Soybean varieties

Number of nodule plant^{-1}

For the variety Ketta, inoculated plants generally had a higher number of nodules per plant compared to un-inoculated plants across all levels of phosphorus application. The difference in the number of nodules between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest number of nodules for Ketta was observed in the inoculated group 31.80 at 30 kg ha^{-1} phosphorus application (Fig. 3a), which is due to *rhizobia* inoculation and phosphorus application increases the number of nodule per plants by attributing nodule formation and nitrogen fixation of basic energy transfer of phosphorus. For the variety Cheri, a similar trend was observed with inoculated plants having a higher number of nodules compared to un-inoculated plants at most phosphorus application levels. The difference in the number of nodules between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest number of nodules for Cheri was observed in the inoculated group 25.6 at 20 kg ha^{-1} phosphorus application. The lowest number of nodules per plant (16.33) was recorded on the variety Cheri with no inoculation of *rhizobia*, and the control plot of P application (no application of P) (Fig. 3b), which showed about 94.73% decrease over

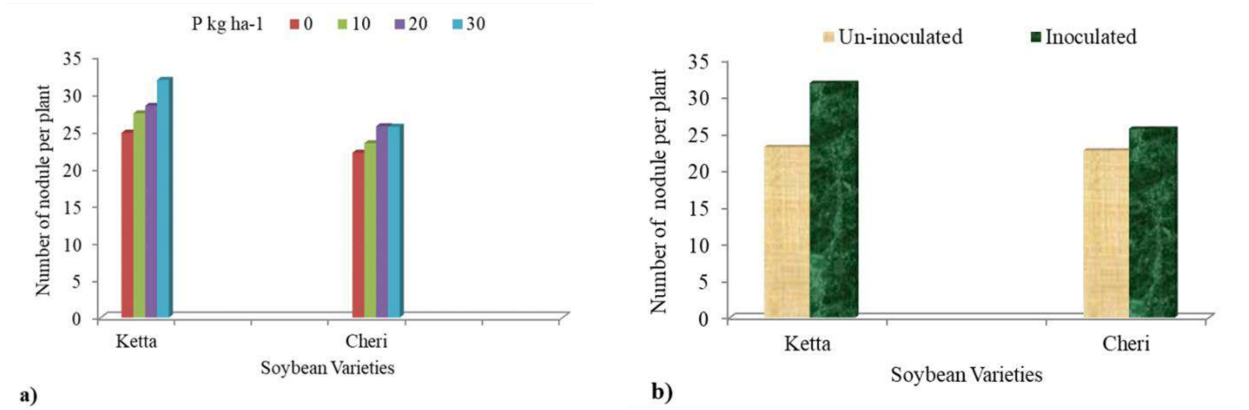

Fig. 3: Interaction effects of; a) variety × phosphorus and b) variety × *Bradyrhizobium* inoculation on Number of nodule per plant

the variety that produced the highest number of nodules. Likewise the application of P fertilizer at the rates of 0, 50, 100 and 150 kg P_2O_5 ha^{-1} significantly increased number of nodules (Houngnandan *et al*., 2020). Also an increased number of nodules per plant under the highest rate of phosphorus (30 kg P ha^{-1}) *Rhizobium* inoculation. Phosphate application increased the activity of *rhizobia*, which might have intern increased the formation of root nodule. Plant tissue develops around the infected area, forming the nodule and site for the bacterial growth, which creates environment for the fixation of elemental nitrogen from the soil. Correspondingly, the application of 46 kg ha^{-1} P_2O_5 and inoculation of *Rhizobium japonicum* significantly increased the number of nodules per plant by 240.7% and 123%, respectively (Tarekegn and Kibret, 2017). This result was in collaborate with the application of *Bradyrhizobium japonicum* strain USDA110 and 60 kg of P_2O_5 enhanced the number of nodule per plant (Houngnandan *et al*., 2020).

Effective nodule

Nodule effectiveness refers to the efficiency of nodules in fixing nitrogen. Higher values indicate better nitrogen fixation. For both varieties, inoculated plants generally showed higher nodule effectiveness compared to un-inoculated plants at most levels of phosphorus application. The difference in nodule effectiveness between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest nodule effectiveness for both varieties was observed in the inoculated group 13.66 and 10.80 at 30 kg ha^{-1} phosphorus application respectively. Phosphorus application affected the effective nodule of soybean. It was found that P application at the rate of 30 kg P ha^{-1} significantly increased effective nodule of *rhizobia* inoculated soybean by 90.26, and 87.69% with inoculated respectively over the control plot of P application. The lowest number of effective nodules was produced by the variety Cheri (1.33) under un-inoculated and the control plot of P application conditions (Fig. 4a and 4b). Nodules with deep dark red, slightly dark red and pink were considered effective and fixing nitrogen and typically of healthy and effective was due to presence of leghemoglobin protein responsible for oxygen binding (Kasper, 2019). In addition, other reported legume nodules having dark pink or red centers (due to leg hemoglobin presence) are an indication for effectiveness of the strain used and positively correlated with higher N_2 fixation (Meleta and Abera, 2019). This is due to compatibility between *rhizobia* inoculation and host plant. This is due to the deficiency of phosphorus and fixation of availability of P in the soil condition of the acidity (Billah *et al*., 2019). Larger response to inoculation and higher number of nodules per plant in comparison to un-inoculated treatments in a field that has no soybean cropping history was reported by (Rahim *et al*., 2016). This indicates suggested that inoculation does not always enhance nodulation. Improved soybean varieties (TGx 1448-2E) did not respond to inoculation in terms of nodule production in the Nigeria's moist savanna zone (Adjei-Nsiah *et al*., 2019).

However, P rates and their interaction with inoculation did not significantly (P=0.25) affect the number of effective nodules. The non-responsiveness of the number of effective nodules due to P application might be described to the high P fixation of the soil. Besides, iron, which is deficient in alkaline soils, plays vital role in leghemoglobin formations, which render pink or red color to nodules.

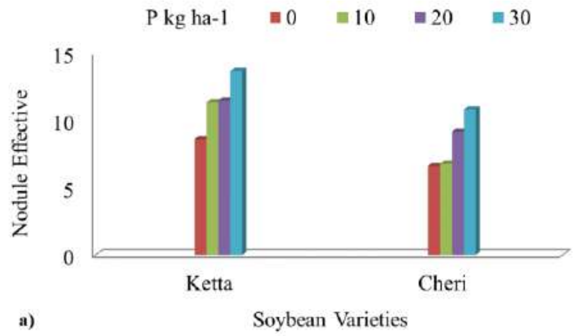

Fig. 4a: Interaction effects of variety × phosphorus

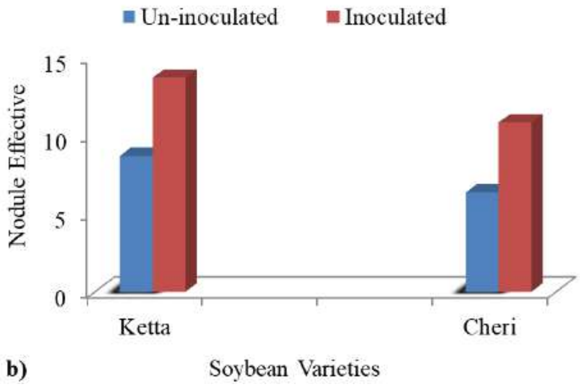

Fig. 4b: Interaction effects of variety × *BradyRhizobium* inoculation on effective nodule per plant

Nodule fresh weight

For the variety Ketta, inoculated plants generally had higher nodule fresh weights compared to un-inoculated plants across different levels of phosphorus application The difference in nodule fresh weight between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest nodule fresh weight for Ketta was observed in the inoculated group 12.45 g at 10 kg ha^{-1} phosphorus application. For the variety Cheri, a similar trend was observed with inoculated plants showing higher nodule fresh weights compared to un-inoculated plants at most phosphorus application levels. The difference in nodule fresh weight between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest nodule fresh weight for Cheri was observed in the inoculated group 12.35 g at 20 kg ha^{-1} phosphorus application, whereas the lowest nodule fresh weight of 5.54 g plant^{-1} were found on variety Cheri under no inoculated and control plot of P application conditions. The variety that produced the highest nodule fresh weight showed more than 55.5% increase over the variety that produced the lowest nodule fresh weight (Table 8).

In line the number and fresh weight of nodules are commonly used as the criteria of effective complementary between macro and micro with the rate of atmospheric nitrogen fixation (Tarekegn and Kibret, 2017). Similarly, reported that a simple relationship a rises between nodule number and nodule fresh weight and they are indices of nitrogen fixation (Sanyal *et al*., 2020).

Nodule dry weight

Similar to nodule fresh weight, inoculated plants generally exhibited higher nodule dry weights compared to un-inoculated plants for both varieties across different levels of phosphorus application. The difference in nodule dry weight between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest nodule dry weight for both Ketta and Cheri was observed in the inoculated group 8.85 and 8.65 g at 30 kg ha^{-1}

phosphorus application respectively, while, the lowest nodule dry weight per plant (3.17 g) was produced by the variety Cheri under no *rhizobia* inoculation and under control plot of P application (Table 8), which was about 179.17% of nodule dry weight reduction over the variety that produced the highest nodule dry weight. The reason might be due to the overall improvement in the performance of the plant in response to phosphorus fertilizer and inoculation, leading to better nodulation underlines phosphorus has on nodule development through its basic function of as an energy source. In soybean production, phosphorus and inoculation with the appropriate *rhizobia* strain have quite prominent effects on nodule number, dry weight and yield components. Similarly, a combination of 50 kg P_2O_5 ha^{-1} and STM3043 *rhizobia* strain gave the best nodule dry weight of 4.97 g plant^{-1} (Zoundji *et al.*, 2015). In the present study, however, nodule dry weight ranged between 3.17-8.85 g; where Ketta variety produced the highest nodule dry weight with the application of 30 kg P ha^{-1} and inoculation of *Rhizobia* bacteria, which is high relative to what is reported by (Zoundji *et al.*, 2015). In agreement the phosphorus application levels with inoculation influence nodule dry weight (Tarekegn and Kibret, 2017). *B. japonicum* strains with P fertilizer increased the nodule dry weight (Htwe *et al.*, 2018). Phosphorus application levels, without inoculation, did not influence nodule dry weight (Bekere and Hailemariam, 2012).

Taproot length

For the variety Ketta, inoculated plants generally had longer taproots compared to un-inoculated plants across different levels of phosphorus application. The difference in taproot length between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The longest taproot length for Ketta was observed in the inoculated group 25.66 cm at 30 kg ha^{-1} phosphorus application. For the variety Cheri, a similar trend was observed with inoculated plants, showing longer taproots compared to un-inoculated plants at most phosphorus application levels. The difference in

Table 8: Responses of two soybean varieties to *rhizobia* inoculation and rate of phosphorus application for nodule fresh and dry weight

Varieties	Inoculation Status	Nodule fresh weight (g)				Nodule dry weight (g)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	11.6^{cd}	12.45^{a}	11.88^{bc}	12.31^{ab}	8.70^{ab}	8.81^{ab}	8.67^{ab}	8.85^{a}
	Un-inoculated	6.1^{e}	11.71^{cd}	11.68^{cd}	11.65^{cd}	4.68^{c}	8.57^{b}	8.77^{ab}	8.63^{ab}
Cheri	Inoculated	11.3^{d}	11.37^{abc}	12.35^{ab}	12.31^{ab}	8.63^{ab}	8.63^{ab}	8.60^{ab}	8.65^{ab}
	Un-inoculated	5.54^{f}	11.97^{abc}	12.02^{abc}	11.23^{d}	3.17^{d}	8.60^{ab}	8.61^{ab}	8.60^{ab}
LSD (0.05)		0.53				0.25			
CV (%)		2.87				1.88			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

taproot length between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The longest taproot length for Cheri was observed in the inoculated group 23.36 cm at 30 kg ha^{-1} phosphorus application, while the shortest taproot length of 19.66 cm was produced by the variety Cheri with the control of P application (Table 9). Increasing Phosphate fertilizer could be due to P treatment, which causes root cells to grow.

The highest taproot length of Cheri (23.36 cm) was recorded on un-inoculated *rhizobia* and 20 kg P ha^{-1} and the shortest taproot length (19.66 cm) of the same variety without inoculated *rhizobia* and control plot of P ha^{-1}. This is due to un-inoculated *rhizobia* strain around the infected roots hairs which is not nutrient availability for plants is deep taproot length for nutrient absorption and the inoculated *rhizobia* and phosphorus application is fixation of nitrogen and nutrient availability which is used for vegetative growth and developments rather than taproot length. There was a significant difference level of phosphate rate for taproot length in this study, and other studies reported that systems with large root surface length and density ensures P uptake efficiency, on soils of low P availability (Battini *et al*., 2017). The average increase in root length by 41% as compared to un-inoculated control, due to *rhizobia* inoculation and phosphorus application (Dabesa and Tana, 2021a). Similarly, phosphate stimulates root growth, and it is associated with early crop maturity (Fathi and Mehdiniya, 2023).

Root volume

In terms of root volume, inoculated plants generally had higher root volumes compared to un-inoculated plants for both varieties across different levels of phosphorus application. The difference in root volume between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest root volume for Ketta was observed in the inoculated group 61.0 cm^3 at 30 kg ha^{-1} phosphorus application.

Similarly, the highest root volume for Cheri was observed in the inoculated group 52.3 cm^3 at 30

Table 9: Responses of two soybean varieties to *rhizobia* inoculation and rate of phosphorus application for root volume and taproot length

Varieties	Inoculation Status	Tap root length (cm)				Root volume (cm^3)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	21.33^{def}	24.60^{ab}	24.20^{b}	25.66^{a}	41.66^{def}	58.3^{ab}	55.0^{abc}	61.0^{a}
	Un-inoculated	20.46^{efg}	21.80^{de}	20.43^{efg}	21.10^{def}	39.33^{ef}	40.0^{ef}	40.0^{ef}	35.3^{f}
Cheri	Inoculated	21.06^{defg}	21.40^{def}	21.73^{de}	23.36^{bc}	33.60^{fg}	50.0^{bcd}	52.0^{bc}	52.3^{bc}
	Un-inoculated	19.66^{g}	20.40^{efg}	22.16^{dc}	20.27^{fg}	22.33^{h}	42.0^{edf}	47.7^{cde}	25.7^{gh}
LSD (0.05)		1.41				8.48			
CV (%)		3.87				11.68			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

kg ha^{-1} phosphorus application, while the lowest root volume of 22.33 cm^{3} was produced by the variety Cheri with the inoculation of *Rhizobium* bacteria and at the control plot of P application. The variety that produced the highest root volume showed 63.39% increase over the variety that produced the lowest root volume. Phosphate application and inoculation of soybean increased root volume and root biomass, due to the increased rate of nitrogen fixation. Similarly, increasing P_2O_5 application up to 150 kg ha^{-1} increases root volume (Masood *et al*., 2011). The application of 30 kg P_2O_5 ha^{-1} has increased the root volume by 63.39 and 36.79% under inoculated and un-inoculated conditions, respectively; while the application of 20 kg P_2O_5 ha^{-1} has increased root volume by 55.4 and 53.14 %, respectively and the application of 10 kg P_2O_5 ha^{-1} has increased root volume by 61.71% and 46.83% over the control plot of P application (Table 9).

4.6. Effect of *BradyRhizobium* inoculation and P application rate on yield and yield components of Soybean varieties

Number of pods plant^{-1}

For the variety Ketta, plants that were inoculated generally had a higher number of pods per plant compared to un-inoculated plants across different levels of phosphorus application. The number of pods per plant increased with increasing levels of phosphorus application for both inoculated and un-inoculated plants of variety Ketta. The difference in the number of pods per plant between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest number of pods per plant for Ketta was observed in the inoculated group 99.38 at 30 kg ha^{-1} phosphorus application. For the variety Cheri, a similar trend was observed with inoculated plants showing a higher number of pods per plant compared to un-inoculated plants at most phosphorus application levels. The number of pods per plant also increased with increasing levels of phosphorus application for both inoculated and un-inoculated plants of variety Cheri. The difference in the number of pods per plant between inoculated and un-inoculated plants was statistically significant at most P application levels. The highest number of

Table 10: Responses of two soybean varieties to *rhizobia* inoculation and rate of phosphorus application for number of pods per plant and number of seed per pods

Varieties	Inoculation Status	Number of pods plant^{-1} (count)				Number of seeds pod^{-1} (count)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	59.00^{g}	88.73^{b}	97.47^{a}	99.38^{a}	2.45^{f}	2.84^{b}	2.93^{a}	2.98^{a}
	Un-inoculated	57.80^{g}	73.86^{e}	82.46^{cd}	86.60^{bc}	2.10^{i}	2.77^{cd}	2.83^{bc}	2.79^{bc}
Cheri	Inoculated	56.94^{g}	78.12^{de}	83.40^{c}	88.75^{b}	2.17^{h}	2.63^{e}	2.73^{d}	2.85^{b}
	Un-inoculated	38.63^{i}	46.70^{h}	50.12^{h}	63.60^{f}	1.95^{j}	2.20^{gh}	2.20^{gh}	2.24^{g}
LSD (0.05)		4.518				0.059			
CV (%)		3.76				1.4			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

pods per plant for Cheri was observed in the inoculated group 88.75 at 30 kg ha^{-1} phosphorus application, while the lowest number of pods per plant (38.63) was produced by the variety Cheri with un- inoculated and the control plot of P application, which showed about 157.26% of pod number decrease over the variety and amendment that produced the highest pod number (Table 10).

Phosphorus applications at the rate of 10, 20 and 30 kg P ha^{-1} increased number of pods per plant by 54.46, 60.36 and 61.12% respectively, over the unfertilized control. This result support with that the higher numbers of pods per plant were produced in response to higher doses of phosphorus (Aryal *et al*., 2021). This result revealed increased number of pods per plant with increased rate of phosphorus application. This result is similar reported increased number of pods per plant in soybean following the application of P at the rate of 0, 10, 20 and 30 kg P ha^{-1} (Ikeogu and Nwofia, 2013).

One study that reported a similar result is effect of phosphorus application on soybean yield and quality. In this study, they found that increasing phosphorus application rates led to a higher number of pods per plant in soybean (Ferreira *et al*., 2018). Similarly, significant increase in the number of pods plant^{-1}, due to the interaction effect of *rhizobia* strain IRJ 2180A with the application of 50 kg of P_2O_5 ha^{-1} over the control (Zoundji *et al*., 2015). In general, mean pod number plant^{-1} enhanced due to the combined effect of *rhizobia* inoculation and phosphorus application.

Number of seeds pod^{-1}

For the variety Ketta, when inoculated, there is a clear trend of increasing number of pods per plant with increasing phosphorus application rates (0 kg P ha^{-1} to 30 kg P ha^{-1}). Similarly, the number of seeds per pod also increases with higher phosphorus application rates. The highest values are observed (2.98) at the highest phosphorus application rate of 30 kg P ha^{-1} For the variety Cheri, similar trends was observed with increasing phosphorus application rates leading to higher number of pods per plant and seeds per pod, especially when the plants was inoculated. Comparing the inoculated and un-inoculated plants, it is evident that inoculation generally results in higher numbers of pods per plant and seeds per pod across both varieties and phosphorus application rates. In terms of the number of seeds per pod, plants that were inoculated generally had a higher number of seeds per pod compared to un-inoculated plants for both varieties across different levels of phosphorus application. The number of seeds per pod increased with increasing levels of phosphorus application for both inoculated and un-inoculated plants of both varieties.

The difference in the number of seeds per pod between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The lowest number of seeds per pod (1.95) under un-inoculated *rhizobia* and control plot of P application of Cheri variety (Table 10). The number of seeds per pods perceived as a significant constituent that directly contributes to the recovery of potential yield in leguminous crops, like soybean (Devi *et al*., 2013). The number of seeds pod^{-1} significantly varied between genotypes. In agreement reported significant difference in number of seeds per pods after varying p rates (Alemu *et al*., 2018).

Grain yield

The highest grain yield was obtained by Ketta variety (3.45 ton ha^{-1}) and Cheri variety (2.57 ton ha^{-1}) under both *rhizobia* inoculation and application of 30 kg P ha^{-1} (Table 11). At the rate of 30 kg P ha^{-1} application, the yield of the highest yielding variety Ketta with *rhizobia* inoculation showed 64.35% increase over the un-inoculated control. Though, the difference in percentage increase was high, this finding supports grain yield can increase by 40-70%, when the proper *rhizobia* bacteria is inoculated (Gebremariam and Tesfay, 2021). The highest grain yield (3.45 ton ha^{-1}) obtained from study was moderate relative to the national average 2.43 ton ha^{-1} (CSA 2021/2022) and the productivity in the study area *i.e.*, in Bedele zone, which is 2.07 ton ha^{-1} (2021/2022), which indicates that the production and productivity of soybean can be increased significantly through *rhizobia* inoculation and application of phosphorus. The result is also in agreements the varietal difference in rice and soybean with *rhizobia* inoculation and phosphorus application, respectively (Adediran, 2019). Ketta variety showed grain yield increase of 38.7, 42.44 and 48.12 % at P application rates of 10, 20 and 30 kg P ha^{-1} respectively over the control plot of P application.

Similarly, Phosphorus applications at the rate of 22.5 and 45.0 kg P_2O_5 ha^{-1} increased grain yield by 33.9 and 35.4%, respectively, over the unfertilized control in Ghana (Davies, 2014). The seed yield of soybean increased in response to the application of phosphorus fertilizer at the rates of 20, 40 and 60 kg P_2O_5 ha^{-1} (Atnafu *et al*., 2020).

In line with the combined application of *rhizobia* inoculation and p application resulted in 21% increased grain yield (Abbasi *et al*., 2010). Adequate phosphorus application and *rhizobia* will lead to effective pod dry matter accumulation and subsequently to higher grain yield. Similarly, reported that P application with *rhizobia* inoculation significantly increased pod number, grain yield and dry matter yield, compared to un-inoculated treatment (Tarekegn and Kibret, 2017). The average grain yields recorded from the present study were lower, when compared to the yield of 7610 kg ha^{-1} obtained (Zoundji *et al*.,

Table 11: Responses of two soybean varieties to *rhizobia* inoculation and rate of phosphorus application for grain yield and hundred seed weight

Varieties	Inoculation Status	Grain Yield (ton ha^{-1})				Hundred (100) seed weight (g)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	0.36^{k}	2.92^{c}	3.11^{b}	3.45^{a}	13.49^{i}	14.54^{b}	14.53^{b}	14.63^{a}
	Un-inoculated	0.33^{k}	1.43^{hi}	1.97^{g}	2.19^{f}	13.26^{j}	13.52^{ghi}	13.57^{gh}	13.66^{f}
Cheri	Inoculated	0.35^{k}	2.15^{f}	2.39^{e}	2.57^{d}	13.59^{g}	14.15^{e}	14.27^{d}	14.44^{c}
	Un-inoculated	0.96^{j}	1.52^{h}	1.37^{i}	1.41^{hi}	13.17^{k}	13.47^{i}	13.45^{i}	13.51^{hi}
LSD (0.05)		0.14				0.076			
CV (%)		4.76				0.33			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

2015). However, the yield obtained from this study were comparable with the average soybean yields (770-3380 kg ha^{-1}) reported (Zoundji *et al*., 2015).

Hundred seed weight

The hundred-seed weight for both varieties generally increased with higher levels of phosphorus application. Inoculated plants tended to have higher hundred-seed weights compared to un-inoculated plants, especially at higher levels of phosphorus application.

Ketta variety had the highest hundred seed weight (14.63 g) under *rhizobia* inoculated and 30 kg P ha^{-1} application, followed by (14.54 g) under *rhizobia* inoculated 10 kg P ha^{-1} and (14.53 g) of the same soybean variety, while the lowest hundred seed weight (13.17 g) was recorded on Cheri variety under *rhizobia* un-inoculated and control plot of P application (Table 11). The interaction effect of inoculation and P rates on hundred seeds weight was very highly significant increased (P<0.0001). This could be due to combined application of *rhizobia* and N_2 fixation which supplied by biological compounds that play major roles in photosynthesis which eventually increased seeds weight.

Generally, the results suggest that phosphorus application plays a significant role in enhancing grain yield and seed weight in soybean varieties, with inoculation showing a positive impact on plant performance. The data indicates the importance of phosphorus management and inoculation strategies in optimizing soybean production for better yields and seed quality. Interaction effect of the factors under study 50 (I × P) on 1000-seed weight was significantly reported (Ngalamu *et al*., 2013). Also increasing P levels from 0 to 69 kg P_2O_5 ha^{-1} showed increase in thousand seeds weight, the highest thousand seeds weight (20.5 and 20.4 g) were scored at 23 and 69 kg P_2O_5 ha^{-1} application, respectively. Significant increase of thousand seeds weight by 5-18% due to P application from 20 to 80 kg P ha^{-1} over the control treatment (Fituma *et al*., 2018).

The Ketta variety that produced the highest hundred seed weight showed hundred seed weight increase of 9.98% P application over the variety that produced the lowest seed weight. In agreement with this result, Significant difference among soybean varieties for hundred seed weight, in which the highest hundred seed weight was produced by the variety BFS 39 and the lowest hundred seed weight was recorded by the variety Roba (Imenu *et al*., 2022).

Above ground biomass

The data shows that for the variety Ketta, the highest above ground biomass was observed 14.34 ton ha^{-1} at 30 kg ha^{-1} of phosphorus application for both inoculated and un-inoculated conditions. In general, inoculated plants tended to produce higher above ground biomass compared to un-inoculated plants across different levels of phosphorus application. Variety Cheri also displayed higher the highest above ground biomass with increasing levels of phosphorus application, especially for the inoculated plants; while the lowest above ground biomass yield (6.14 ton ha^{-1}) was recorded on variety Cheri under un-inoculated and the control main plots (no phosphorus), which was lower by about 54.18% over the variety that produced above ground biomass yield. The phosphorus application rate had very highly significantly (P<0.0001) affected above ground biomass of soybean. Phosphorus application of 10, 20 and 30 kg P ha^{-1} increased above ground biomass yields by 31.57, 33.75 and 37.59%, respectively, over the control plots of Ketta variety (Table 12). The application of 25 and 35 kg P ha^{-1} increased the soybean above ground biomass yields by 54 and 70%, respectively, over the control plots (Phiri *et al*., 2016).

The above ground biomass increased, due to the three way interaction effects of 30 kg P ha^{-1} application and inoculated *rhizobia* strain of Ketta variety. This might be due to the development of root system that might have increased water and nutrient uptake, and consequently, increased photosynthesis, and production of photosynthetic material that might have resulted in increased biological yield. In line phosphate application and inoculation of *B. japonicum* to legumes, as soybean increased plant biomass, due to increased rate of nitrogen fixation (Houngnandan *et al*., 2020).

Harvest index

The harvest index for both varieties generally increased with higher levels of phosphorus application. Inoculated plants tended to have a higher harvest index compared to un-inoculated plants, especially at higher levels of phosphorus application.

Ketta and Cheri varieties resulted in significantly higher harvest index (24%) under *rhizobia* inoculated and 30 kg ha^{-1} P application and lowest values of harvest index (15.66%) was obtained under un-inoculated and control plot of P application of Cheri variety (Table 12). Phosphate fertilizer application increases the number of nodule and size and grain formation due to increased nitrogen fixation. This can be explained by a good symbiotic activity induced by the strain of *rhizobia* and the host plant. The highest harvest index implies the higher partitioning of dry matter in grain. Whereas, the lowest harvest index (15.66%) gained from unfertilized plot.

Generally, the results suggest that phosphorus application has a significant impact on the above ground biomass production and harvest index of soybean varieties. Inoculation also plays a role in

Table 12: Response of two soybean varieties to *rhizobia* inoculation and rate of phosphorus application for above ground biomass and harvesting index

Varieties	Inoculation Status	Above ground biomass (ton ha^{-1})				Harvest index (%)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	8.95^{fg}	13.8^{b}	13.51^{b}	14.34^{a}	20.0^{dc}	22.33^{ab}	23.00^{ab}	24.0^{a}
	Un-inoculated	7.6j^{k}	8.64^{gh}	9.88^{e}	9.96^{de}	18.3^{de}	16.66^{ef}	20.00^{cd}	22.0^{abc}
Cheri	Inoculated	7.73^{ij}	9.27^{f}	10.45^{dc}	10.76^{c}	21.0^{bc}	23.66^{a}	22.66^{ba}	24.0^{a}
	Un-inoculated	6.14^{l}	7.13^{k}	7.7^{j}	8.25^{ij}	15.66^{f}	21.33^{bc}	18.00^{de}	17.0^{ef}
LSD(0.05)		0.54				0.02			
CV (%)		3.4				6.14			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

enhancing above ground biomass and harvest index values. These findings indicate the importance of phosphorus management and inoculation strategies in optimizing soybean production for better biomass yield and harvest index percentages.

In line the values of harvest index showed an increasing trend in the harvest index values with application of phosphorus *Rhizobia* inoculation is known to increase the yields of soybean of harvest index by way of increasing the nodulation and biomass of root and shoot (Houngnandan *et al*., 2020). In agreement inoculation of SB6 B1 and legume fix recorded significantly higher harvest indices of 54 and 53% over un-inoculated plot (Fituma, 2015). Soybean seeds inoculation increased the nodule number per plant and thus increasing harvest index by 3.36% (Tekola *et al*., 2018).

Phosphorus uptake efficiency

For the variety Ketta, the phosphorus uptake efficiency increased with higher phosphorus application rates for both inoculated and un-inoculated conditions. The highest phosphorus uptake efficiency was observed 1.53 kg ha^{-1} at 30 kg ha^{-1} P for the inoculated treatment.

For the variety Cheri, a similar trend was observed with an increase in phosphorus uptake efficiency with higher phosphorus application rates for both inoculated and un-inoculated conditions. The highest phosphorus uptake efficiency was also observed 1.23 kg ha^{-1} at 30 kg ha^{-1} P for the inoculated treatment (Table 13). The lowest GUP of 0.62 kg ha^{-1} was produced under un-inoculated and the control main plot (no phosphorus) by the variety Cheri. The increased PUE due to added supply of nutrients might enhance absorption of water and nutrients. In agreement with the findings, application of 46 kg P ha^{-1} and inoculation with *B. japonicum* increased P uptake by 18.78% compared to the un-inoculated treatment (Tarekegn and Kibret, 2017). Increased in P content of the seed and P uptakes in soybean, in response to the combined application of *B. japonicum* inoculation reported by (Tarekegn and Kibret, 2017).

In addition, *rhizobia* inoculation improved grain phosphorus uptake, due to *rhizobia* inoculation, which might be attributed to the fact that some isolates of *Rhizobium* have the ability to solubilize precipitated P components and thereby, increase P uptake in plants (Dabesa and Tana, 2021a). The result of this study, clearly demonstrates that *Rhizobium* inoculation improves the P uptake efficiency of soybean, which might also contributes ton-increased productivity of the crop.

Significant differences was noted in PUE among the varieties between the inoculated and un-inoculated treatments, when the rate of P application increased to 10, 20 and 30 kg P ha^{-1}, showing that *Rhizobia* inoculation enhanced the GPU efficiency of the responsive varieties, indicating the importance of combined application of *Rhizobia* inoculation together with P

Fertilization for better response. Higher rate of P application 30 kg ha^{-1} resulted in higher phosphorus uptake efficiency. This indicates that increasing the rate of phosphorus application to the optimum level increases phosphorus uptake efficiency. Similarly, reported that P uptake by soybean was increased with increasing levels of phosphorus (Devi *et al*., 2012).

Agronomic efficiency

The agronomic efficiency for both varieties and inoculation statuses showed varying trends with phosphorus application rates. For variety Ketta, the agronomic efficiency was highest 24.92 kg kg^{-1} at 10 kg ha^{-1} P for the inoculated treatment, while for variety Cheri, the highest agronomic efficiency was observed 11.35 at 10 kg ha^{-1} P for the inoculated treatment (Table 13).

The lowest agronomic efficiency (3.02 kg kg^{-1}) was obtained on Cheri variety under un-inoculated and application of 30 kg ha^{-1} P conditions. Comparison between Inoculated and Un-inoculated Treatments: In general, inoculated treatments showed higher phosphorus uptake efficiency and agronomic efficiency compared to un-inoculated treatments for both varieties across different phosphorus application rates. The efficiency of applied phosphorus in the soil reduces, mainly due to soil erosion, leaching and gaseous losses. The utilization of nutrient decreases, when increasing the rate of nutrient application by the law of limiting factors (Atkinson *et al.*, 2010).

This finding is in line phosphorus agronomic efficiency decrease in un-inoculated plots, but increased in the inoculated plots (Adeyemi *et al.*, 2021). The efficiency of the applied P in this study was within the range of 31.27-3.02 kg kg^{-1} at the rates of 10 to 30 kg P ha^{-1} application, respectively (Table 13). This is lower than the one reported declining trend of agronomic efficiency on common bean from 69.8 to 9.3 kg kg^{-1} when the rates of P increased from 10 to 60 kg P ha^{-1}. With the corresponding application of single super phosphate and inoculation, increased phosphorus uptake efficiency and yield with phosphorus application and *rhizobia* inoculation (Aziz *et al.*, 2016).

Under tropical conditions, the efficiency of applied nutrient has been estimated to be 10-30% for phosphorus (Fageria *et al.*, 2013). Estimates of agronomic efficiency showed that the lower level of P relatively responded better to grain yield, which is in agreement with (Qiao *et al.*, 2022) who reported that small amount of applied fertilizer optimized nutrient uptake efficiency.

Table 13: Response of two soybean varieties to *Rhizobia* inoculation and rate of phosphorus application for phosphorus uptake efficiency and agronomic efficiency

Varieties	Inoculation Status	Phosphorus uptake efficiency (kg ha^{-1})				Agronomic efficiency (kg kg^{-1})		
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})		
		0	10	20	30	10	20	30
Ketta	Inoculated	0.90^{gh}	1.34^{b}	1.40^{b}	1.53^{a}	24.92^{a}	14.19^{b}	11.82^{c}
	Un-inoculated	0.77^{ij}	0.87^{h}	1.01^{ef}	1.03^{de}	6.98^{de}	6.15^{e}	5.58^{ef}
Cheri	Inoculated	0.79^{ij}	0.95^{fg}	1.09^{cd}	1.23^{c}	11.35^{c}	8.13^{d}	6.61^{e}
	Un-inoculated	0.62^{k}	0.73^{j}	0.77^{ij}	0.86^{h}	11.18^{c}	4.24^{fg}	3.02^{g}
LSD (0.05)		0.06				1.41		
CV (%)		3.73				11.44		

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4. Conclusion

Soybean (*Glycine max* L.) farming in Ethiopia holds promise for enhancing food security and rural livelihoods, but nutrient deficiencies, particularly phosphorus, and soil acid is limiting factors. Nitisols in southwestern Ethiopia, characterized by high clay content and fertility potential, require specific interventions to improve soybean productivity. The symbiotic relationship between soybean plants and *rhizobia* bacteria plays a crucial role in nitrogen fixation, but the effective of *rhizobia* strains varies based on soil type and environmental conditions. The combined application of phosphorus fertilizer and compatible *rhizobia* strains can potentially enhance soybean growth and yield in Nitisols.

The study was conducted at Bedele district, Southwest Ethiopia with the objectives of determining the effects of P fertilizer rates on growth, nodulation and yield of soybean varieties, and grain yield of soybean, and to identifying economically feasible treatment(s) that can maximize the productivity. The treatments were laid out in a RCBD with three replications. The treatments included: *rhizobia* inoculation (MAR-1495 strains) and without inoculated as a control, soybean varieties Ketta (V1) and Cheri (V2) and phosphorus level (0, 10, 20 and 30 kg P ha^{-1}) as rates of fertilizers.

The results of highlight of this study indicated that: the physical and chemical properties of soil were analyzed before planting and after harvest. After harvest the available phosphorus and total nitrogen indicated a minor increase from initial soil analysis. This means available phosphorus from 0.5 to 0.82 mg kg^{-1} and total nitrogen from 0.12 to 0.28% before and after respectively.

The results of this study indicated that the combined application of *rhizobia* strain with phosphate fertilizer resulted in highly significant and significant improvement in the studied traits *i.e.* flowering days, root volume, number of nodules per plant, number of pods per plant, phosphorus use efficiency, agronomic efficiency, grain yields, number of effective nodule, nodule fresh weight, nodule dry weight, days of maturity, number of seeds per pods and above ground biomass of soybean respectively. These improvements have resulted in increased grain yield and yield related parameters of soybean grown on the Nitisol of study area. The combination of inoculated *rhizobia* and phosphorus fertilizer application gave significantly the highest Plant height (100.40 cm), The highest leaf area (112.79 cm^2) number of Nodule per plant (31.80), The highest nodule fresh weight (12.45 g), nodule dry weight (8.85 g plant^{-1}), The longest taproot length (25.66 cm), The highest root volume (61.10 cm^3), grain yield (3.45 ton ha^{-1}), the highest hundred seed weight (14.63 g), the highest above ground biomass (14.34 ton ha^{-1}), and grain phosphorus uptake (1.53 kg ha^{-1}), the highest agronomic efficiency (24.92 kg kg^{-1}) were recorded from the interaction of inoculated *rhizobia* and 10 kg P ha^{-1} of Ketta variety. Phosphorus fertilizer application of 30 kg P ha^{-1} with inoculated *rhizobia* were resulted in higher production and recommended for further evaluation. In conclusion on the combined application of *rhizobia* inoculation and 30 kg P ha^{-1} gave better nodulation and yield than the rest of the treatment and Ketta variety was tends better responds to growth parameters, nodulation and yield components on plant height, number of nodule and grain yields. Therefore, use of rhizobia strain and 30 kg P ha^{-1} increase nodulation, grain yield (3.45 ton ha^{-1}) and phosphorus uptake of soybean in the study area is recommended. The application of inoculated *rhizobia* and 30 kg P ha^{-1} produced the highest net benefit 113231.2 ETB ha^{-1}. The highest marginal rate of return (541.6%) was obtained from yield at inoculated *rhizobia* and 30 kg P ha^{-1} of Ketta soybean variety was the most profitable treatment. It has the highest return to the money invested in its production. However, the experiment was conducted for one cropping season and a single location. It is realistic to repeat similar experiment across wider ranges of agro ecology to give further recommendation. Furthermore, evaluating different types of effective and compatible *rhizobia* strain along with different source of phosphate to increase phosphorus utilization efficiency and grain yield of soybean should require further investigation in the future.

Therefore, the result should be verified for practical recommendation to be enhancing soybean production in the study region and Future research and agricultural practices should focus on identifying optimal treatment combinations to maximize soybean productivity in specific soil types and environmental conditions in region.

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Correlation analysis of Yellow Rust (*Puccinia striiformis* f. sp *tritici*) disease, and yield components of Bread Wheat (*Triticum aestivum* L.) in East Gojjam, Ethiopia

Adane Wondmaneh[1], **Hirut Kefale**[2] and **G/ Meskel Mequanint**[3]
[1]Department of Plant science (Plant Protection), Faculty of Agriculture, Debre Markos University, Ethiopia.
[2]Department of Horticulture (Plant Protection), Faculty of Agriculture, Debre Markos University, Ethiopia.
[3]Department of Plant science (Plant Breading), Faculty of Agriculture, Debre Markos University, Ethiopia.

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ABSTRACT

Field experiment was conducted in 2021/2022 cropping system at Debre Markos University Research and Demonstration site. The study area was selected based on wheat production potentials and hot spot for the occurrences of yellow rust on wheat. The study was aimed at investigating the correlation between yellow rust (*Puccinia striiformis* f. sp *tritici*) disease parameters, and yield components of bread wheat (*Triticum aestivum* L.). The experiment consisted of five wheat varieties (Kakaba, Honqolo, Liben, Lemu, and Wane) and three fungicides (Tilt (25 EC), Natura (250 EW) and Takeoff (293 SC)) including unsprayed fungicide plot (control) were used as treatment. It was conducted by using randomized complete block design with three replications in factorial arrangement. The result of Pearson correlation coefficient indicated that yellow rust (*Puccinia striiformis* f. sp *tritici*) disease parameters (severity, area under disease progress curve and incidence had positive and strong relationships among them but negatively and strongly related with yield components including thousand seed weight, test weight, biomass, yield and harvesting index of bread wheat. While there was strong and positive correlation among agronomical parameters except between harvesting index and biomass. Totally there was negative and high significant relationship between yellow rust disease and Agronomical parameters.

KEY WORDS: *Bread wheat*; *Correlation*; *Disease severity*; *Yellow rust disease*; *Yield component*

1. Introduction

Wheat is belongs to the Poaceae family, tribe Triticeae and it is one of the most important cereals crops in the world, with an area of cultivation that is larger than any other cereal crop and a large quantity of grain produced (Kumari *et al.*, 2020). This grain is an important industrial and food crop and ranks second among the most important cereal crops in the world. It is the top cereal grain and used by more than one third of the world's population as a staple food. It grew at a wider range from 1500 to 3000 meters above sea level (Belete *et al.*, 2018). The most suitable agricultural-economic zones for wheat production range from 1900 to 2700 m.a.s.l (Weiner *et al.*, 2017). The total production volume of wheat is 772.64 million metric tons on more than 240 million ha in the world (FAO, 2021).

CONTACT Adane Wondmaneh ✉ adanewondmaneh@gmail.com

Wheat is used in the production of traditional and modern processed foods, such as injera, bread and other industrial products like pasta and macaroni (Tidiane *et al*., 2019). Moreover, wheat straw is commonly used as a roof tacking material and as a feed for animals. Wheat grains are good source of minerals, fibers, protein and antioxidants which recommended for health purpose (Gemechu *et al*., 2019).

The major wheat-producing countries in the world are China, India, the USA, Russia, France, Canada, Germany, Pakistan, and Australia (Tanaka *et al*., 2015). Wheat producing countries in Sub-Saharan Africa are Egypt, Ethiopia, South Africa, Sudan, Kenya, Tanzania, Nigeria, Zimbabwe, and Zambia in descending order (Tadesse *et al*.,2020). As FAO (2021) indicated. Ethiopia is one of the largest wheat producers subsequently to Egypt in Sub Sahara Africa in terms of total wheat area cultivated and total production (Abebele *et al*, 2020). The national production volume of wheat is 2.83 million metric tons (CSA, 2020/2021). In spite of the production and yield increases, average grain yield of wheat is still low (< 1.68 t/ha) highly variable and below the world's average (3.54 t/ha). It ranks third in area coverage after teff and maize and second in terms of grain production next to maize (Anteneh and Dagninet, 2020).

Despite its importance as food and industrial crop, wheat production and productivity around the globe is hampered by a number of factors including biotic and abiotic stresses as well as low adoption of new agricultural technologies. Of the biotic stresses, diseases caused by fungi are the most important factors constraining wheat production. Septoria diseases (*Septoria tritici* blotch), stem rust (*P. graminis* f. sp *tritici*), leaf rust (*P. triticina*) and Yellow rust (*Puccinia striiformis* f. sp. *tritici*) are prevalent throughout the country (Figueroa *et al*., 2018).

Yellow rust disease is the most sever and destructive disease that cause reduction of wheat yield production and becoming more occurring often in midland and highland altitudes of Ethiopia (Alemu and Fininsa, 2016). However, the correlation between yellow rust disease and yield components of bread wheat have not been analyzed in the study area. So the objective of this study is to determine the relationship between yellow rust disease and yield components of bread wheat.

2. Material and Methods

Field experiment was conducted at major wheat growing area at Debre Markos University research site, in East Gojjam Zone, Ethiopia in the main cropping season in 2021. It far away 265 Km from Bahirdar and 304 Km from Addis Ababa. The area was selected based on wheat production potentials and hot spot for the occurrences of yellow rust on wheat. Debre Markos University is geographically located at 10° 19' 43" latitude North and 37° 44' 43" longitude East, with an altitude of 2,446 m.a.s.l.

The minimum and maximum temperatures are 11 °C and 25 °C, respectively. Annual average rainfall was 1,628 mm during 2021. The soil of the experimental area was dominated by Nitosols with a PH value of 5.6 (moderately acidic) (Fig. 1).

2.1 Treatments and Experimental Design

Five wheat varieties (Kakaba, Honqolo, Liben, Lemu, and Wane) and three fungicides (Tilt (25 EC), Natura (250 EW) and Takeoff (293 SC) including unsprayed (control) were used in the

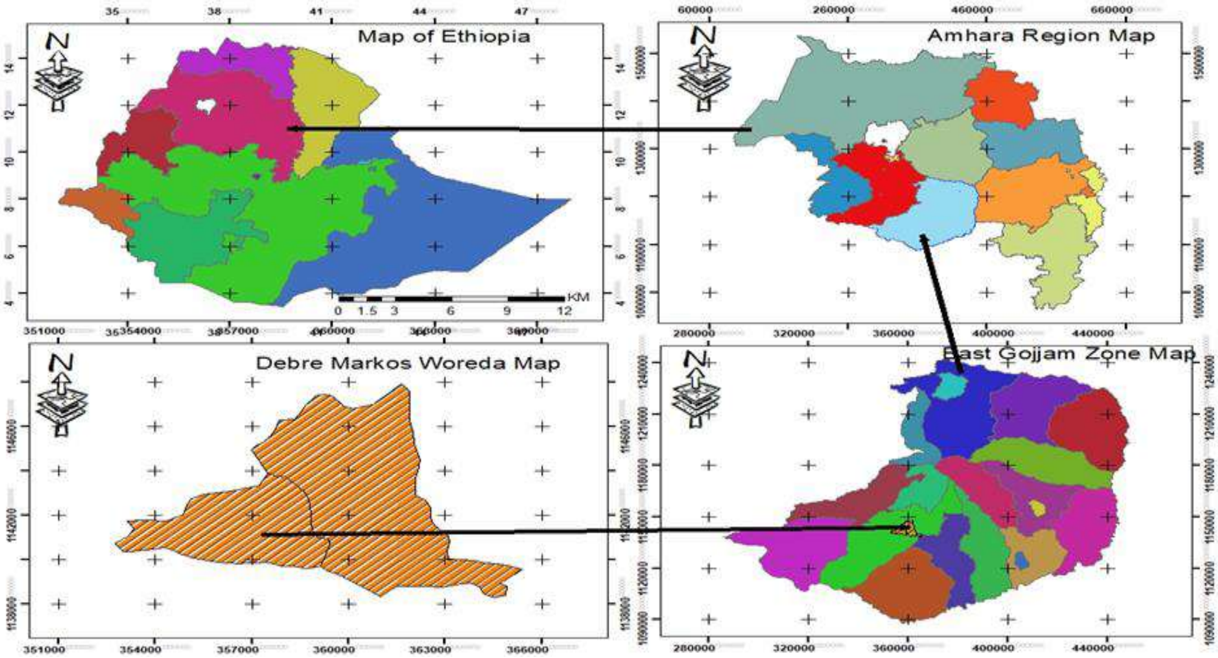

Fig. 1: Map of the study area

experiment. The experiment was done by using randomized complete block design with three replications in factorial arrangement and the treatments were assigned randomly to the experimental plots of a block. The size of the experimental plot was 1.6 m × 2 m (3.2 m^2) consisting of eight rows with six harvested rows. The space between rows, plots and blocks were 0.2 m, 1.5 m and 2 m, respectively. Seeds of each wheat variety were sown at a rate of 150 kg ha^{-1} on a well-prepared plots and seeds were sown manually (hand drill) in rows.

NPSB (nitrogen, phosphorus, sulfur, boron) called Blended fertilizer and Urea fertilizers were applied at the rate of 200 kg ha^{-1} and 322 kg ha^{-1} respectively. The total amount of NPSB (Blended) fertilizer was applied during sowing and Urea was applied by split application (1/3 of urea fertilizer were applied at the time of seed sowing and the remains 2/3 of urea was applied after 35 days of seed sowing).

2.2 Data collected

Data were recorded on plot and single plant basis in which plot basis data were taken from the central four rows.

2.3 Disease data

Disease severity data was recorded by visually observations of the proportion of infected plant part according to Modified Cobbs scale, (1948) (Mahmoud *et al*., 2015). Severity data was taken starting from the appearance of the sign or symptoms to physiological maturity of the crop on 15 randomly selected pre-tagged plants in the central six rows of each plot. Each plant with in each plot was visually evaluated for percent foliar infection (severity) at 7 days interval as soon as the occurrence of disease symptom.

$$\text{Disease severity} = \frac{\text{Area of plant tissue infected}}{\text{Total area of the plant part examined}} \times 100$$

Area under disease progress curve calculated using the coefficient of infection values from the first rust severity data by using the subsequent formula (Campbell and Madden, 1990).

$$UDPC = \sum_{i=1}^{n-1} 0.5(xi + xi + 1)(ti + 1 - ti)$$

Where: Xi and Xi+1 are the values of two consecutive severity assessments, and ti and ti+1 are the dates of the two consecutive assessments. The measurement unit of AUDPC is (%-day).

In addition to this disease incidence data was also recorded on each experimental plot by counting number of diseased plants from 30 randomly taken plants of six rows and calculated at the proportion of the diseased plants over the total stand count (30 plants) at 105 days after seed sown and calculated using the formula suggested by (Campbell and Madden, 1990).

$$\text{Disease incidence (\%)} = \frac{\text{Number of infected plant}}{\text{Total number of plant}} \times 100$$

2.4 Agronomic data

Thousand Seed Weight (TSW): The weight of thousand seeds was determined by carefully using a seed counter, adjusting to 12.5% moisture content and weighting them using sensitive balance and its weight expressed in grams.

Test Weight: The test weight of the grain was determined in kg/hectoliter (Kg/hl) following the American Association of Cereals Chemists, 1983 procedure and the moisture content was adjusted at 12.5% (Schuler *et al*., 1995).

Biomass and Grain Yield: grain yield in gram per plot at 12.5% moisture content was recorded and translated to t/ha. Only six of the internal rows of the plots were harvested for yield and biomass estimations, excluding 0.5 m on both sides along the length of the plot, and the net plot area was 1.4 m^2.

Harvesting Index: It is ratio of grain yield to the total above ground biomass was determined by using the formula suggested by (Kemanian *et al*., 2007).

$$\text{HI (\%)} = \frac{\text{Grain yield}}{\text{Above ground biomass}} \times 100$$

HI = Harvesting index

2.5 Data analysis

The data on disease severity was converted to area under disease progress curves (AUDPC), mean value of disease incidence, disease severity and yield components were subjected to GLM analysis of variance (ANOVA) to evaluate treatments effect using SAS computer package version 9.2 (SAS Institute Inc., 2008 version). Means for different fungicides and varieties combinations were compared using Fisher's list significant different at 5% (LSD 5 %). Correlation analysis was performed using PROC CORR procedure of the SAS computer package to determine the relationship between disease and yield parameters (Rodriguez, 2011).

3. Results and Discussion

Correlation analysis among wheat disease and yield parameters was described in (Table 1).

Disease severity, AUDPC and Disease incidence were positively associated, while they were negatively associated with biomass, thousand seed weight, test weight, grain yield and harvesting index. Area under the disease progress was positively correlated with disease severity (r = 0.99), yellow rust incidence correlated significantly and positively with yellow rust severity (r = 0.75) and Area under the disease progress curve (r = 0.73). Area under the disease progress curve (r = 0.83) and yellow rust incidence (r = 0.81). This correlation supported by Mabrouk *et al*. (2020) stated that, there was positive correlation between disease parameters and losses of grain yield and yield components of wheat.

Biomass of wheat was correlated with disease severity (r = - 0.51, Area under disease progress curve (r = - 0.48), and disease incidence (r = - 0.73), On the other hand thousand seed weight was positively and significantly correlated with biomass (r = 0.72), but negatively correlated with disease severity (r= - 0.38), Area under disease progress curve (r = - 0.37), and disease incidence (r = - 0.62). Also test weight of wheat was significantly correlated with biomass (r = 0.70) and thousand seed weight(r = 0.71), while it was negatively correlated with disease severity (r = - 0.45), area under disease progress curve (r = - 0.44), and disease incidence (r = - 0.78).

Nevertheless grain yield of wheat was highly and positively correlated with biomass (r = 0.81), thousand seed height (r = 0.72), test weight (r = 0.85), but it was negatively correlated with disease severity (r = - 0.55), area under disease progress curve (r = - 0.55), and disease incidence (r = - 0.84). Mengesha, (2020), who stated that biomass, thousand seed weight, test weight and grain yield were positively correlated with each other, while negatively correlated with disease incidence

Table 1: Correlations coefficient (r) of disease parameters of yellow rust, and yield components of bread wheat during 2021 cropping season.

	Severity	AUDPC	Incidence	DPR	BM	THW	TSW	GW	HI
Severity	1.00								
AUDPC	0.99**	1.00							
Incidence	0.75**	0.73**	1.00						
DPR	0.84**	0.83**	0.81**	1.00					
BM	-0.51**	-0.48**	-0.73**	-0.67**	1.00				
THW	-0.38**	-0.37**	-0.62**	-0.44**	0.72**	1.00			
TSW	-0.45**	-0.44**	-0.78**	-0.57**	0.71**	0.70**	1.00		
GW	-0.55**	-0.55**	-0.84**	-0.66**	0.81**	0.72**	0.85**	1.00	
HI	-0.39**	-0.37**	-0.64**	-0.40**	0.24^{ns}	0.41**	0.65**	0.76**	1.00

Note: DPR = Disease Progress Rate, AUDPC = Area Under The Disease Progress Curve, BM = Biomass, THW = Thousand Seed Weight, TSW = Test Weight, GW = Grain Weight, and HI = Harvesting Index.

severity, and AUDPC. Beyene, (2019), said that biomass positively correlated with grain yield and negatively correlated with severity, incidence and area under disease progress curve. However harvesting index was positively correlated with, thousand seed weight (r = 0.41), test weight (r = 0.65) and grain weight (r = 0.76), in which it was negatively correlated with disease severity (r = -0.39), Area under the disease progress curve (r = -0.37), and disease incidence (r = - 0.64) but non-significantly correlated with biomass. Based on this result it was concluded that the disease parameters were interrelated to each other, the presence of one has positive effluence on the other parameters. The correlation among disease parameters and parameters of yield and yield components of wheat were negatively related. Means, the level and infection of the disease (yellow rust) increased; the yield and yield components of wheat were reduced. Mengesha, (2020); Nigus *et al*. (2022), reported that yield and yield components of wheat reduced through severe infection of yellow rust at full growing stage of the crop, which progressively slayed the leaves and stems, and affected the normal physiological functions of the crop.

4. Conclusion

In general, plant biomass, thousand seed weight, test weight, grain weight and harvesting index have positive correlation among them but negatively and strongly correlated with disease incidence, severity, progress rate and area under disease progress curve. Implies that yellow rust disease highly and negatively affected the yield and yield components of bread wheat, while it is not managed by using fungicides and disease resistance bread wheat varieties.

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Comparative study on the effect of seed treatments and packaging types on seedling vigor and developmental traits

S P Kiran and **Chennakeshava B C**
Department of Seed Science and Technology, College of Agriculture, GKVK, Bengaluru.

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ABSTRACT

A field experiment was conducted at the College of Agriculture, University of Agricultural Sciences (UAS), Bengaluru, during the rainy seasons of 2016 and 2017 to evaluate the effect of seed treatments and packaging materials on seedling growth and development in hybrid maize cultivar ‘Hema’. The study aimed to assess seedling performance after prolonged storage under various conditions. Results revealed that after a 16-month storage period, the highest mean seedling length was recorded in seeds stored in polythene bags (700 gauge) and those treated with Thiram at 2 g kg^{-1}, measuring 27.45 cm and 27.75 cm, respectively. These were followed by super grain bags (26.75 cm) and halogen mixture treatment at 3 g kg^{-1} (27.25 cm), whereas the lowest seedling lengths were observed in cloth bags and untreated control (25.25 cm each). Similarly, seedling dry weight was highest in seeds stored in polythene bags (50.40 mg) and those treated with Thiram (51.83 mg), followed by super grain bags (48.35 mg) and halogen mixture (50.67 mg). The lowest seedling dry weights were observed in cloth bag storage (46.25 mg) and control (46.08 mg). The findings suggest that polythene packaging and Thiram treatment effectively preserve seed vigor and enhance seedling performance over extended storage periods in hybrid maize.

KEY WORDS: *Zea mays*; *Seed quality*; *Packaging material*; *Seed treatment*

1. Introduction

Maize (*Zea mays* L.) is a globally important cereal crop, ranking third after wheat and rice in terms of production and consumption. Its remarkable adaptability to diverse agro-climatic conditions and high yield potential make it a staple crop in many parts of the world, including India, where it plays a vital role in food security and the national economy. Beyond its importance as a staple food, maize serves as a key raw material in animal feed and numerous industrial applications, including the manufacture of starch, ethanol, sweeteners, organic acids, and bio-based products.

The establishment of a healthy crop begins with the use of high-quality seed, as it directly influences seedling vigor, uniform emergence, and ultimately crop yield. In maize cultivation, ensuring optimal seed performance is particularly critical, given the crop's sensitivity to early growth conditions. Seed treatment has emerged as a vital strategy to enhance seed longevity, vigor, and resistance to both biotic and abiotic stresses during storage and germination. Harris *et al*. (2007) emphasized the importance of on-farm seed treatments as a cost-effective approach for

CONTACT S P Kiran ✉ kiransp.12@gmail.com

smallholder farmers to improve crop establishment and productivity.

Equally significant is the role of proper seed storage. Seed viability and vigor during storage are influenced by several factors, including initial seed quality, moisture content, ambient temperature, relative humidity, seed composition, and the choice of packaging material (Doijode, 1990). Hybrid maize seeds are known to deteriorate more rapidly than open-pollinated or high-yielding varieties, often due to increased membrane damage and accelerated physiological ageing (Chen and Zhou, 1990; Rame Gowda *et al*., 2002). Deterioration processes begin soon after the seed reaches physiological maturity and can be exacerbated by microbial activity, which leads to the degradation of vital macromolecules such as proteins and carbohydrates.

To mitigate these effects and preserve seed quality for subsequent planting seasons, a variety of seed treatment and packaging interventions have been developed. Treatments with fungicides, insecticides, halogen compounds, and botanical extracts have shown promise in prolonging seed viability. Additionally, packaging materials such as cloth bags, polythene bags, and hermetic storage systems like super grain bags have been evaluated for their efficacy in maintaining seed integrity under prolonged storage.

Despite the existing body of work, there remains a need for comparative evaluations of the interactive effects of seed treatment chemicals and packaging types on the vigor and developmental traits of seedlings, especially under long-term storage conditions. The present study was undertaken to assess the performance of hybrid maize seeds subjected to different treatment and packaging combinations, with a focus on seedling vigor parameters such as seedling length and dry weight after extended storage.

2. Material and Methods

2.1 Experimental site and duration

The present investigation was carried out during the rainy seasons of 2016 and 2017 at the Department of Seed Science and Technology, College of Agriculture, University of Agricultural Sciences (UAS), Bengaluru, India. The primary objective of the study was to evaluate the effects of selected seed treatment chemicals and different packaging materials on seedling vigor and developmental traits in hybrid maize (*Zea mays* L. cv. Hema) under ambient storage conditions.

2.2 Seed source and pre-storage handling

Freshly harvested seeds of hybrid maize cultivar 'Hema' were obtained from a preceding field experiment. The seeds were shade-dried to attain a safe storage moisture level of 10.01%, as determined by the low constant temperature oven method, and used for subsequent storage and evaluation. Only uniform, damage-free, and viable seeds were selected for the experiment to maintain consistency across treatments.

2.3 Experimental treatments

The experiment followed a two-factor factorial design, comprising three types of packaging materials and five seed treatment options. The treatment details are as follows:

Packaging Materials (Factor P):
P1: Cloth bag
P2: Polythene bag (700 gauge thickness)
P3: Super grain bag (hermetic storage bag)

Seed Treatments (Factor T):
T1: Untreated Control
T2: Halogen mixture @ 3 g per kg of seed
T3: Sweet flag (*Acorus calamus*) rhizome powder @ 10 g kg^{-1} of seed
T4: Thiram (fungicide) @ 2 g per kg of seed
T5: Imidacloprid (insecticide) @ 3.5 g per kg of seed

The seeds were thoroughly mixed with the respective treatment chemicals to ensure uniform coating and were subsequently packed into the designated packaging materials. The treated and packed seeds were stored under ambient laboratory conditions (average temperature ranging from 23°C to 32°C and relative humidity 50–75%) for a period of sixteen months.

2.4 Experimental design and replication

The study was laid out in a completely randomized design (CRD) with a two-factor factorial arrangement and replicated thrice. The entire experiment was repeated for two consecutive years (2016 and 2017) to validate the consistency and reliability of the results across storage durations and environmental fluctuations.

2.5 Data collection

Seedling vigor traits were assessed at bimonthly intervals (every two months) over the sixteen-month storage period. For each treatment combination, 100 seeds were randomly sampled and subjected to standard germination tests as per ISTA (International Seed Testing Association) guidelines.

The following seedling growth parameters were recorded:

Seedling Length (cm): Measured from the root tip to the tip of the primary shoot for ten randomly selected normal seedlings per replicate. The average was recorded in centimeters (cm).

Seedling Dry Weight (mg): After measurement, the same seedlings were oven-dried at 80°C for 24 hours and weighed using a precision digital balance. The average dry weight per seedling was recorded in milligrams (mg).

2.6 Statistical analysis

All collected data were subjected to statistical analysis using SPSS software. Analysis of variance (ANOVA) was performed to test the significance of main and interaction effects of seed treatments and packaging materials on seedling traits. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at a 5% level of significance ($p < 0.05$). Graphs and tables were prepared to illustrate significant trends and treatment effects.

3. Results and Discussion

3.1 Initial seed quality parameters

At the commencement of the storage study, hybrid maize cultivar 'Hema' exhibited high initial seed quality. The seed moisture content was recorded at 10.01%, with a germination rate of 96.50%, a mean seedling length of 32.20 cm, and a seedling dry weight of 64.00 mg. No seed-borne infection was detected at the time of packaging, indicating the suitability of the seed lot for storage experimentation under controlled ambient conditions.

3.2 Effect on mean seedling length (cm)

The data revealed a progressive decline in mean seedling length over time, influenced significantly by both packaging materials and seed treatments, with interactions between the two becoming more evident in the later stages of storage (Table 1). Statistically significant differences were observed among the packaging materials during the 2nd to 16th months of storage ($p < 0.05$). At the end of the 16-month period, seeds stored in polythene bags (700 gauge) recorded the highest mean seedling length (27.45 cm), followed closely by the super grain bag (26.75 cm). In contrast, the cloth bag exhibited the lowest mean seedling length (25.25 cm), highlighting its limited capacity to maintain seed vigor over extended storage.

Among the seed treatment groups, statistically significant differences in seedling length emerged during the 8th, 12th, 14th, and 16th months. By the 16th month, seeds treated with Thiram @ 2 g kg^{-1} recorded the maximum mean seedling length (27.75 cm), followed by Halogen mixture @ 3 g kg^{-1} (27.25 cm), while untreated control seeds showed the lowest value (25.25 cm). These findings indicate the efficacy of fungicidal seed treatments in mitigating deterioration and promoting physiological integrity during prolonged storage.

Significant interaction effects between seed treatment and packaging material were evident from the 10th month onward, with the most pronounced differences observed by the end of the study. The combination of polythene bag + Thiram (P_2T_4) resulted in the highest mean seedling length (29.00 cm), followed closely by P_2T_2 (28.25 cm) and P_3T_4 (28.00 cm), whereas P_1T_1 (cloth bag + untreated) registered the lowest seedling length (24.25 cm).

The reduction in seedling length across storage durations is a classic indicator of seed deterioration, which often begins with physiological aging. This decline reflects a reduction in the mobilization and conversion of stored seed reserves into shoot and root tissues. Heterotrophic seedling growth is influenced by the seed's initial dry matter content, the mobilizable fraction of stored reserves, and the efficiency of reserve conversion into biomass. As the storage duration increases, biochemical and structural damage - particularly to mitochondrial membranes - impairs these functions, ultimately reducing seedling elongation.

Packaging material significantly influenced seedling vigor. Polythene and hermetic bags minimized moisture fluctuations and oxidative degradation, preserving seed metabolic integrity. Cloth bags, due to their porous nature, are more susceptible to ambient humidity and pest ingress, accelerating the aging process. Similar trends in seedling length reduction with storage duration were previously documented in maize by Anil (2009), Mulla Mohammad (2012), Asha (2012), and Azad *et al*. (2014).

3.3 Effect on mean seedling dry weight (mg)

Mean seedling dry weight followed a trend similar to seedling length (Table 2), demonstrating significant declines with storage time, influenced by both packaging type and treatment method. Significant differences among packaging materials were observed throughout the storage period, from the 2nd to the 16th month. At the end of 16 months, polythene bags maintained the highest seedling

Table 1: Mean seedling length (cm) as influenced by packaging materials and seed treatments during storage of hybrid maize-Hema

Treatment details	Mean seedling length (cm)							
	Storage period (From February 2016 to June 2017)							
	2	4	6	8	10	12	14	16
Packaging materials (P)								
P_1: Cloth bag	31.40	30.45	28.55	27.65	27.10	26.55	26.00	25.25
P_2: Polythenebag (700 guage)	32.02	31.65	31.20	31.15	30.90	29.65	28.40	27.45
P_3: Super grain bag	31.50	30.10	29.00	28.50	28.10	27.90	27.55	26.75
S. Em±	0.15	0.36	0.43	0.26	0.39	0.36	0.40	0.47
CD (P=0.05)	0.42	1.04	1.22	0.74	1.12	1.02	1.13	1.33
Treatments (T)								
T_1: Control	31.50	30.42	28.92	28.25	27.83	27.08	26.33	25.25
T_2: Halogen mixture@ 3g kg^{-1}	31.73	30.83	29.83	29.50	29.17	28.50	27.67	27.25
T_3: Sweetflagpowder @ 10g kg^{-1}	31.57	30.83	29.58	29.00	28.50	27.92	26.67	25.58
T_4: Thiram@ 2g kg^{-1}	31.77	31.00	30.08	29.83	29.50	29.00	28.58	27.75
T_5: Imidacloprid @ 3.5g kg^{-1}	31.63	30.58	29.50	28.92	28.50	27.67	27.33	26.58
S. Em±	0.19	0.47	0.55	0.34	0.51	0.46	0.51	0.60
CD (P=0.05)	NS	NS	NS	0.96	NS	1.31	1.46	1.72
P × T								
P_1T_1	31.30	30.25	28.00	27.00	26.50	25.75	25.00	24.25
P_1T_2	31.50	30.25	28.50	28.00	27.50	26.75	26.00	25.75
P_1T_3	31.30	31.25	29.25	28.00	27.50	26.75	26.00	24.75
P_1T_4	31.50	30.50	28.75	28.00	27.50	27.25	27.00	26.25
P_1T_5	31.40	30.00	28.25	27.25	26.50	26.25	26.00	25.25
P_2T_1	31.90	31.50	30.50	30.25	30.00	28.75	27.50	26.25
P_2T_2	32.10	31.75	31.50	31.50	31.50	30.25	29.00	28.25
P_2T_3	32.00	31.50	31.00	31.00	30.50	29.50	27.00	26.25
P_2T_4	32.10	32.00	31.75	32.00	31.50	30.75	30.00	29.00
P_2T_5	32.00	31.50	31.25	31.00	31.00	29.00	28.50	27.50
P_3T_1	31.30	29.50	28.25	27.50	27.00	26.75	26.50	25.25
P_3T_2	31.60	30.50	29.50	29.00	28.50	28.50	28.00	27.75
P_3T_3	31.40	29.75	28.50	28.00	27.50	27.50	27.00	25.75
P_3T_4	31.70	30.50	29.75	29.50	29.50	29.00	28.75	28.00
P_3T_5	31.50	30.25	29.00	28.50	28.00	27.75	27.50	27.00
S. Em±	0.33	0.81	0.96	0.58	0.88	0.80	0.89	1.05
CD (P=0.05)	NS	NS	NS	NS	2.50	2.27	2.54	2.98
CV (%)	2.1	5.3	6.5	4.0	6.1	5.7	6.5	7.9

Table 2: Mean seedling dry weight (mg) as influenced by packaging materials and seed treatments during storage of hybrid maize-Hema

Treatment details	Mean seedling dry-weight (mg)							
	Storage period (From February 2016 to June 2017)							
	2	4	6	8	10	12	14	16
Packaging materials (P)								
P_1: Cloth bag	58.60	57.75	57.40	53.60	53.10	49.45	47.90	46.25
P_2: Polythene bag (700 guage)	63.14	61.90	61.65	58.50	56.60	54.30	52.15	50.40
P_3: Super grain bag	61.56	60.50	60.25	56.80	56.40	53.85	50.50	48.35
S. Em±	0.60	0.86	0.57	0.77	0.65	0.42	0.53	0.48
CD (P=0.05)	1.72	2.45	1.63	2.19	1.84	1.20	1.52	1.37
Treatments (T)								
T_1: Control	60.23	59.33	58.92	55.42	54.17	51.00	48.17	46.08
T_2: Halogen mixture@ 3g kg^{-1}	61.60	60.50	60.33	56.83	56.33	53.58	52.00	50.67
T_3: Sweetflagpowder @10g kg^{-1}	60.60	59.67	59.25	55.75	54.33	50.75	48.08	45.25
T_4: Thiram@ 2g kg^{-1}	61.90	60.67	60.58	57.17	56.83	54.67	52.83	51.83
T_5: Imidacloprid @ 3.5g kg^{-1}	61.17	60.08	59.75	56.33	55.17	52.67	49.83	47.83
S. Em±	0.78	1.11	0.74	0.99	0.84	0.55	0.69	0.62
CD (P=0.05)	NS	NS	NS	NS	2.38	1.56	1.96	1.77
P × T								
P_1T_1	57.40	56.50	56.25	52.25	51.50	47.50	45.50	43.75
P_1T_2	58.80	58.00	57.75	54.00	53.50	50.00	48.50	47.00
P_1T_3	58.30	57.50	57.00	53.25	52.50	48.50	47.00	45.00
P_1T_4	59.90	59.00	58.75	55.00	54.50	51.50	50.00	48.50
P_1T_5	58.60	57.75	57.25	53.50	53.50	49.75	48.50	47.00
P_2T_1	62.50	61.50	61.00	58.00	55.50	52.50	50.00	47.75
P_2T_2	63.80	62.50	62.25	59.00	58.50	55.75	55.00	54.00
P_2T_3	62.70	61.50	61.25	58.00	55.00	51.75	48.75	45.75
P_2T_4	63.50	62.00	62.00	59.00	58.50	57.00	55.50	55.00
P_2T_5	63.20	62.00	61.75	58.50	55.50	54.50	51.50	49.50
P_3T_1	60.80	60.00	59.50	56.00	55.50	53.00	49.00	46.75
P_3T_2	62.20	61.00	61.00	57.50	57.00	55.00	52.50	51.00
P_3T_3	60.80	60.00	59.50	56.00	55.50	52.00	48.50	45.00
P_3T_4	62.30	61.00	61.00	57.50	57.50	55.50	53.00	52.00
P_3T_5	61.70	60.50	60.25	57.00	56.50	53.75	49.50	47.00
S. Em±	1.35	1.92	1.28	1.72	1.45	0.95	1.19	1.08
CD (P=0.05)	NS	NS	NS	NS	4.12	2.69	3.40	3.07
CV(%)	4.4	6.4	4.3	6.1	5.2	3.6	4.8	4.5

dry weight (50.40 mg), statistically comparable to super grain bags (48.35 mg), while the lowest dry weight (46.25 mg) was recorded in cloth bag storage.

Among the seed treatments, significant variation in dry weight was evident during the 10th to 16th months. Thiram @ 2 g kg^{-1} again showed superior performance, with a mean dry weight of 51.83 mg, closely followed by Halogen mixture @ 3 g kg^{-1} (50.67 mg). The untreated control group recorded the lowest dry weight of 46.08 mg. These results reinforce the beneficial effect of fungicidal seed treatment in delaying physiological degradation and promoting seed reserve mobilization under storage stress.

Interaction effects between packaging and treatment were significant during the later storage months. The highest seedling dry weight was recorded in the P_2T_4 combination (55.00 mg), followed by P_2T_2 (54.00 mg) and P_3T_4 (52.00 mg). The lowest value (43.75 mg) was observed in the P_1T_1 (cloth bag + control) combination. The synergy of airtight packaging and effective chemical protection appeared to minimize oxidative and microbial degradation, enhancing the biochemical processes necessary for seedling tissue development.

The decline in dry weight over storage duration is attributed to reduced enzymatic activity, impaired mitochondrial respiration, and restricted mobilization of reserve compounds such as starch, protein, and lipids. Reduced metabolic efficiency during germination leads to underdeveloped shoots and roots, as observed in this study. These findings align with the earlier reports of Mahanjan (2002) in hybrid maize, Moon *et al*. (2011) in rice, Rahima (2008) in wheat, and Mohammad *et al*. (2016) in rice.

4. Conclusion

Collectively, the results affirm the critical role of both seed treatment and packaging material in preserving the physiological vigor of maize seeds over extended storage. The superior performance of Thiram-treated seeds stored in polythene or super grain bags illustrates the importance of integrating chemical and physical storage interventions for seed conservation. The deterioration pattern observed in untreated and cloth bag-stored seeds underscores the vulnerability of conventional storage methods to environmental and biological stressors.

These insights are of particular relevance to seed producers and distributors aiming to maintain hybrid seed quality across seasons and geographies. The study highlights viable strategies for enhancing seed longevity and maintaining seedling vigor, ultimately contributing to improved crop establishment and yield potential.

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Farmers perception and knowledge in the management of major pests of rice in Sierra Leone

Alie Hindolo Dembeh Mansaray[1], **Alusaine Edward Samura**[2], **Vandi Amara**[2] and **Dan David Quee**[2]
[1]Ministry of Agriculture and Food Security, Freetown, Sierra Leone
[2]Dept. of Crop Protection, School of Agriculture and Food Science, Njala University, Njala Campus, Sierra Leone

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ABSTRACT

Pest infestation has been a major challenge for famers Sierra Leone, and this limited the production of rice thereby posing serious threat to food security issues in the country. Unfortunately, there is a limited study on farmers' perception and knowledge on the identification and management of these pests. Therefore, a study was conducted to assess rice farmers' perception and knowledge on the management of pests in Sierra Leone. The study was carried out in three major rice growing districts and employed a mixed-methods approach. The study targeted 300 farmers across three districts and data collected using structured questionnaire. Data were analyzed using Statistical packages for social science and both descriptive and inferential statistics were performed. The findings revealed that middle aged farmers were the most dominant and played a critical role in rice production while there was limited engagement from the younger and older farmers posing serious concern about further production. There were more male farmers indicating gender disparities and thus emphasizing the need for women inclusion in farming activities. The findings also revealed that farmers relied heavily on traditional pest control methods such as manual pest removal and farm sanitation which are not effective and less scabble. There was a low adoption of integrated pest management among farmers and lack of capital was seen as the most dominate constraints faced by farmers. The findings observed regional differences in yield loss and pest management practices. This study therefore underscores the importance of education, training, and financial support in promoting IPM adoption and sustainable pest management.

KEY WORDS: *Perception*; *Knowledge*; *Pests*; *Management*; *Rice*

1. Introduction

Rice is the main staple crop in Sierra Leone and provides 80% of its caloric intake (Vangahun, 2019). Rice cultivation in Sierra Leone is primarily undertaken by smallholder farmers who produce barely enough for home consumption with little or none for the market across both upland and diverse lowland ecologies. The smallholder farmers in Sierra Leone are generally resource-poor with only the hoe, axe, and cutlass as the main implements, while labour is mainly supplied by family members, thereby severely limiting their scale of production (GOSL, 2018). According to FAO (2020), of the total global rice production of 499.6 million tonnes in 2020, SSA contributed about 3%. Of the rice produced in SSA, more than 80% was from eight countries

CONTACT Vandi Amara ✉ vandiamara66@gmail.com

(Nigeria, Madagascar, Ivory Coast, Tanzania, Mali, Guinea, Sierra Leone, and Senegal; with Nigeria and Madagascar accounting for one third of the rice production in the sub region (FAO, 2020). A steady increase in rice cultivation has occurred over the years, but not sufficient to meet basic requirement of demand, hence a deficit in the country's rice supply chain. Consumption of rice, however, exceeds production in the country. Sierra Leone produces 712,092 metric tonnes of rice while it consumes 1,094 million metric tonnes of rice annually (USDA, 2018), moreover, the country has long struggled to meet its local rice consumption demands. In Sierra Leone, pest and disease attacks are among the major factors limiting the production and high yield in rice. However, little is known about pests' management options and status of farmers' fields regarding yield loss caused by major rice diseases of Sierra Leone. This makes a study in this area very necessary because every successful breeding program should be based on distinct identification of farmers' constraints and preferences of end users. Insect pests attack has become a major challenge limiting rice production couple with other challenging factors such as climate change, poor irrigation, poor soil fertility and diseases infection (Pokhrel, 2011). Pokhrel, 2011, also reported insects like Rice Gundhi bug (*Leptocorisa acuta*), Rice hispa (*Dicladispa armigera*), Mealybug (*Ripersia oryzae*), Plant hoppers (*Nephotettix apicalis*, *Sogatella fercifera* and *Ceeadela spectra*), Yellow stem borer, striped borer, and Armyworm (*Mythimna seprata*) to be found invasive in the rice field and are responsible for about 80% yield loss. As a result of the limited knowledge and subsistence nature of our rice faming system in Sierra Leone, insect pests' damages have been fully recognized by farmers and absolute scarcity of rice have not been experienced this why farmers seem to be neglecting plant protection issues. Therefore, the aim of the study is to access farmer's perception and knowledge on the identification and management of major insect pests of rice in three major rice growing regions of Sierra Leone.

2. Material and Methods

2.1 Description of the study area

This study assesses farmers' perceptions and conducts field assessments of major insect pests in three districts of Sierra Leone: Kambia, Kenema, and Moyamba, chosen for their diverse agro-ecological conditions and agricultural significance. Kambia, located in the northern part of Sierra Leone, is characterized by a tropical climate with wet and dry seasons. Kenema, in the Eastern Province, has a humid tropical climate favorable for rice, cocoa, oil palm, and vegetables. Rice cultivation is especially common in the lowland areas.

2.2 Research Design

The study utilized a non-experimental design that incorporated both quantitative and qualitative methods to ensure triangulation and establish the validity of the research findings. Qualitative methods were employed to examine social phenomena and understand their significance to the participants, while quantitative methods aimed to quantify and analysed variables using statistical methods.

2.3 Sampling population of research

The sampling population considered the population of farmers involved in rice production, and not farmers involved in other farming enterprises were not part of the study since the researcher wanted to have a manageable size of the research work and to satisfy the study objective. The population comprised both sexes with no exception to someone being disable or physically challenged.

2.4 Sampling technique and sample size of research

The study selected a sample size of 300 rice farmers from three districts that is 100 farmers randomly selected. The study employed both probability and non-probability sampling techniques. For the non-probability sampling, a purposive approach was used to select cassava farmers in selected chiefdoms of the seven districts. In the probability sampling method, a systematic sampling technique was used to select communities within the chosen chiefdoms. The communities were then clustered, with separate clusters for males and females. Samples were selected from each stratum using a simple random sampling procedure. There were about 7,800 farmers in the three districts according to Ministry of Agriculture and Food Security (MAFS), 2023 and to avoid bias in the determination of the actual sample size, Yamane (1973) mathematical model for selecting appropriate sample size was adopted. The model is expressed as;

$$n = \frac{N}{1+ N(e)2}$$

Where n = required sample size

N = Total population of the study,

e = Error margin

1= Constant

$$n = \frac{7,800}{1+ 7,800(0.05)2}$$

n = 300

2.5 Data collection

The data collection procedure involved three components: two primary data collection methods and one secondary data collection method. Data was collected using a structured questionnaire administered to the sampled respondents by trained enumerators with Diploma and BSc degree qualifications. The interviews took place at the respondents' homes and lasted a maximum of 45 min. Enumerators explained the study's purpose and questionnaire content, ensuring respondents of data confidentiality. Verbal consent was obtained from participants before starting the interview, and they had the option to terminate the interview if they felt uncomfortable. During the interview, questions about insect pest’s encounters and management were repeated and clarified for accurate responses. Farmers' responses were read back to them for confirmation, and contact details were collected for potential follow-up during analysis. Farmers' reactions and knowledge of insect pests were assessed through the presentation of photos of some insect pests or infestations.

In addition to primary data, secondary information was collected from archived data sources such as the Ministry of Agriculture and Food Security (MAFS) and some Farmer-Based Organizations (FBOs) in the districts.

2.6Ethical consideration of research

At the beginning of the data collection process, permission was sought from the relevant institution authorities who introduced the researcher and team to the rice farmers. Each questionnaire included an introductory letter requesting the respondents’ cooperation in providing the required information for the study. The farmers were assured that their information would be kept confidential and that the study findings are going to be used for academic purposes only. Rice farmers were assured of their personal protection and that they have the mandate of accepting or rejecting the interview.

2.7 Validity and reliability of research

The questionnaire underwent a process to ensure its validity and reliability. For validity, the instrument was developed under the supervision of research supervisors, considering both content and face validity protocols. Experts also provided feedback on the draft which was incorporated into the final questionnaire. Additionally, English and formatting were validated by individuals with knowledge and experience in the field. To ensure reliability, the instrument was pre-tested. Ten variables of the questionnaire were subjected to a Cronbach Alpha test using SPSS for reliability analysis. The results showed a reliability value of 0.75, indicating the consistency of the research instrument.

2.8 Data analysis

The survey data were entered into the SPSS 25 software for analysis. The analysis involved the use of descriptive and inferential statistics.

The preferences identified were ranked using numerals, following the Likert scale (1, 2, 3, 4... N), from the most preferred to the least preferred. The mean rank score for constraint was computed, with the factor receiving the lowest score considered the most preferred or highest constraint. Conversely, the factor with the highest score was ranked as the least preferred.

Determination of the degree of agreement among the respondents was done using a technique proposed by Kendall. The coefficient of concordance was estimated using the relation;

$$W = \frac{12[\sum T^2 - \frac{(\sum T)^2}{n}]}{nm^2(n^2-1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where: W = Kendall's value; N = total sample size; R = mean of the rank; T = sum of rank of factors being ranked; m = number of respondents (farmers); n = number of factors being ranked; W = coefficient of concordance. The W was tested for significance in terms of the F distribution.

The F-ratio is given by

$$F = \frac{(m-n)\times(1-W)}{(1-W)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

With numerator and denominator degrees of freedom being $(n-1)-(\frac{2}{m})$and $m-1[(n-1)-\left(\frac{2}{m}\right)]$, respectively.

3. Results and Discussion

3.1 Socio-demographic and farming experience characteristics of rice famers across three regions in Sierra Leone

The results on the age distribution of rice farmers revealed that 202(67.3%) out 300 farmers interviewed were within range 31-60. This age group generally represents the most physically active and economically productive stage of life, indicating that rice farming in these districts is largely sustained by an active working-age population. Farmers within the old age group (above 61) accounted for only 12.6%(38) which suggest that there is future potential labor limitation in the study area because farmers in this age group might face physical constraints couple with health challenges which will eventually hinder their involvement in physical farming activities thus relying on younger family members to maintain their faming activities. The findings revealed that there were more male farmers accounting for 77.3% (232) and their female counterpart. The study indicates the dominance of male in rice farming further reflecting on the social and cultural norms that influence gender role in agricultural labor. The study also showed that most farmers 138(46.0%) do not have formal education and only 12.0% (36) of the farmers have tertiary education, few farmers 64(21.3%) have secondary and primary 62(20.6%) education. The high number of farmers with no formal education may pose serious limitation to them effectively understanding and adopted improved technologies that will increase yield and control pest. The distribution experience among respondents showed that a greater number 92(30.6%) of the respondents have 6-10 years' experience in farming followed by farmers with 16 years and more experience 86(28.7%) which suggest that there is a mix of both relatively new and well experienced farmers with a diversity of perception and knowledge within the family community in the study area. Farmers with 6-10 years of experience may bring fresh ideas or a willingness to explore new farming practices, while those with 16 or more years possess accumulated local knowledge and skills that are invaluable in managing rice farming efficiently (Table 1).

3.2 Knowledge and management of pests across three districts

A higher proportion of farmers from the Kambia (63.0%), Kenema (71.6%), and Moyamba (93.0%)

Table 1: Socio-demographic and farming experience characteristics of rice famers across three regions in Sierra Leone

Variable	Kenema	Kambia	Moyamba	All
Age				
18-30	20(20.0)	24(24)	16(16)	60(20)
31-45	30(30.0)	36(36)	34(34)	100(33.3)
46-60	36(36.0)	28(28)	38(38)	102(34)
61 above	14(14)	12(12)	12(12)	38(12.6)
Gender				
Male	80(80)	74(74)	78(78)	232(77.3)
Female	20(20)	26(26)	22(22)	68(22.7)
Educational Level				
No Formal Education	42(42.0%)	50(50.0%)	46(46.0%)	138(46.0%)
Primary education	24(24.0%)	20(20.0%)	18(18.0%)	62(20.6%)
Secondary education	20(20.0%)	22(22.0%)	22(22.0%)	64(21.3%)
Tertiary education	12(12.0%)	10(10.0%)	14(14.0%)	36(12.0%)
Rice farming experience (Years)				
0-5	16(16.0%)	20(20.0%)	14(14.0%)	50(16.7%)
6-10	30(30.0)	36(36.0)	26(26.0%)	92(30.6%)
11-15	20(20.0)	24(24.0%)	28(28.0%)	72(24.0%)
16 above	30(30.0%)	20(20.0%)	36(36.0%)	86(28.7%)

Source: Field survey data, 2024

districts have reported the occurrence or experience of pests in their rice farms (Table 2).

The key pests identified as infesting cassava farms included Birds (*Ploceus philippinus*), grass-cutter (*Thryonomys swinderianus*), stem borer (*Scipophaga incertulas*), rice ear bug (Alydidae), leaf hopper (*Nephotettix virescens*), and termites (Isoptera). Among these, Birds (82.6%) were perceived as the most troublesome pests by farmers in all the district followed by grass-cutter (63.3%). Other pests mentioned by farmers included stem borer, rice ear bug, leaf hopper and termite.

The distribution of farmers based on their awareness and willingness to implement IPM is presented in Fig. 1. Majority of the farmers (55.0%) were not aware of integrated pest management practice, while 45.0% of them reported that they are aware of IPM practices. However, a higher percentage of the farmers (78.5%) express their willingness to implement integrated pests management technologies, while only (21.5%) of the farmers insisted that they are not willing to implement such (Fig. 1).

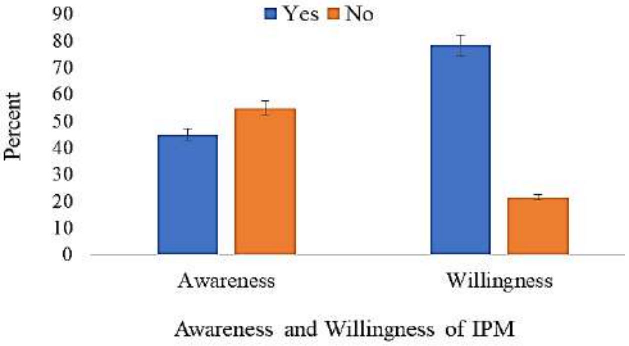

Fig. 1: Distribution of farmers based on their awareness and willingness to implement IPM

Findings on pests and diseases management strategies utilized by farmers are presented in Fig. 2. Most (45.3%) of the farmers relied on farm physical and cultural control practices, which involved manual picking of grasshoppers, setting traps, hunting, and constructing fences to protect their crops from animals like grass-cutters, squirrels, and cows. This method aims to maintain a clean environment and reduce the presence of pests. The second most important pest management technique utilized by 24.0% of the farmers was farm sanitation. This included regular weeding and brushing around the farm. Chemical

Table 2: Farmers knowledge of rice pests across the three districts

Variables	Kambia	Kenema	Moyamba	All
Experience with pests				
Yes	189(63.0%)	215(71.6%)	225(75.0%)	210(70.0%)
No	111(37.0%)	85(28.4%)	75(25.0%)	90(30.0%)
Name of common pests				
Birds	220(73.3%)	278(92.6%)	245(81.6%)	248(82.6%)
Grass-cutter (%)	180(60.0%)	290(96.6%)	126(42.0%)	199(63.3%)
Stem borer	167(55.6%)	170(56.7%)	145(48.3%)	161(53.7%)
Rice ear bug	180(60.0%)	175(58.3)	168(56.0)	174(58.0%)
Leafhopper	165(55.0%)	179(59.6%)	183(61.0%)	176(58.6%)
Termite	94(31.3%)	155(51.6%)	170(56.6%)	140(46.7%)

pesticides were also used by 10.0% of the farmers to control pests on their farms. However, 20.2% of farmers employ no pest control measures on their farms, possibly due to limited resources, lack of awareness, or personal preferences. This indicates that extension services and training support for pest and disease management are inadequate.

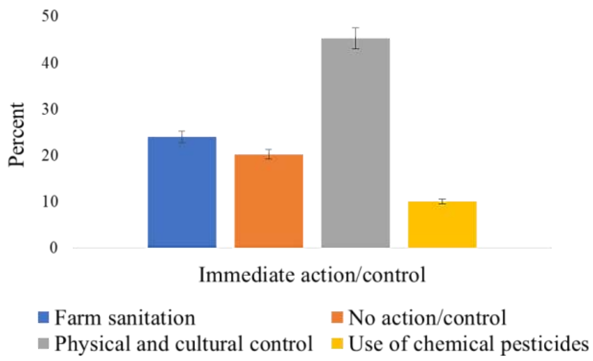

Fig. 2: Distribution of pest management strategies by farmers in the study area

Rating of the level of pest management practice is presented in Table 3. Most farmers (70.0%) opined that their pest management practices were moderately effective compared to 30.0% of farmers who indicated that their pest management practices were not effective. The mean score for the level of effectiveness of farmers' pest management practices was 2.20, with a standard deviation of 0.47. This suggests that the overall level of effectiveness of the pest management strategies was perceived to be moderately effective.

3.3 Analysis of factors influencing the adoption of Integrated Pest Management (IPM)

The logistic regression prediction model, on the factor influencing the adoption of integrated pests management by farmers with a coefficient of (B = -1.21 and a P-value (0.006) revealed a baseline likelihood of farmers adoption of IPM in the absence of demographic and knowledge factors with the odds ratio (OR= 0.28) which clearly reflect a low baseline probability indicating farmers are generally less in inclined towards adopting IPM with factors influencing them (Table 4). This underlines the role of additional predictors, particularly age, education, and pest knowledge, in positively influencing IPM adoption rates. The model revealed that farmers between the ages 30-45(odd ratio = 1.76, p-value-0.02) are significantly more likely to adopt IPM technologies than younger reference group (18-29). This might be because of more physical readiness and economic motivation that will serve as a catalyst for this age group (30-45) to embrace and implement new agricultural practices. The higher likelihood of adoption of IPM by farmers with this age group may indicate their increased exposure to agricultural innovations and a willingness to invest in sustainable practices like IPM. Farmers ages 46-60 years showed a positive but not significant association with IPM adoption

Table 3: Rating of the level of pest and disease management practice

Variables	Pooled sample		Mean score	Standard deviation
	No	%		
Effectiveness of pest management measures				
Moderately effective	210	70.0	2.20	0.47
Not effective	90	30.0		

(OR = 1.50,P= 0.131) which suggest that these farmers might be receptive to IPM but often face barriers or challenges such as limited access to resources which are needed for proper adoption. The model revealed that farmers within age group 61+ showed negative but not significant association with IPM (OR = 0.72,P = 0.38). The low adoption is because farmers within this age group might have resistance to change, have physical limitations and even lack motivation to engage in new agricultural endeavors or practice.

It was revealed from the finding that Education as a significant predictor of IPM adoption, with results indicating a clear trend. The model predicted that farmers with higher level of education have increased likelihood association with IPM adoption. Farmers with primary school education have weak positive but significant association with IPM adoption(OR = 1.53, P = 018) which suggest that even minimal formal education may encourage openness to adoption of IPM, potentially due to improved literacy and basic understanding of agricultural practices. It was also predicted that farmers with secondary school alone are significantly three times (OR = 3.0, P = 0.006) more likely to adopt IPM compared to those without formal education. This finding suggest that farmers with secondary education are equipped with critical thinking skills and more aware of sustainable Agricultural practice which enables to adopt IPM.

Knowledge of pests plays a crucial role in IPM adoption, as demonstrated by a strong and statistically significant positive association (OR = 3.1, P = 0.002). It was revealed from the findings that farmers with pests’ identification and management practice knowledge are three times more likely to adopt IPM compared to those that lack such knowledge. The findings suggest that understanding pest behavior and their control strategies can significantly impact farmers’ perception of IPM and hence increased greater acceptance of the integrated control strategies.

3.4 Association between key variables and IPM adoption indicators

The chi-square (χ^2) tests result in Table 5 showed

Table 4: Logistic Regression Analysis of Factors Influencing the Adoption of Integrated Pest Management (IPM)

Variables	Coefficient (B)	Standard Error	Wald-Statistic	P-value	Odds Ratio (Exp(B))
Intercept	-1.21	0.44	7.40	0.006	0.28
Age (Reference 18-29)					
Age: 30-45	0.58	0.25	5.38	0.021	1.76
Age: 46-60	0.42	0.28	2.25	0.131	1.50
Age:61+	-0.30	0.34	0.72	0.38	0.72
Educational Level Reference (no formal education)					
Primary	0.41	0.31	1.75	0.18	1.53
Secondary	1.10	0.40	7.56	0.006	3.01
Tertiary	1.58	0.45	12.39	0.00	4.85
Knowledge of pest (No Reference)					
Knowledge of pest: Yes	1.15	0.38	9.15	0.002	3.1

Source: Field survey data, 2024

the association between specific demographic and experience-based variables and indicators relevant to IPM adoption. Significant (p = 0.002) association was observed between regions and pest identification knowledge which indicate geographical location influences farmers ability to identify pest species accurately. The variation at regional level in pest recognition among farmers can be attributed to differences in access to pest management resources, educational programs, or extension services across regions. It can be seen from the findings that a strong knowledge of pest identification can also be linked to high IPM adoption rate as farmers who can recognize pests are better positioned to make informed management decisions

The level of farmers familiarity with IPM was highly significant (p < 0.001) which suggests that higher education perfectly correlates with greater awareness and familiarity with IPM practices. This significant association might be likely because of the ability of farmers to access education chances, understand, and apply agricultural innovations as familiarity with IPM is critical for adoption because it equips farmers with the skills and knowledge to assess the benefit of the technology over the conventional. The association between farming experience and farmers' perception with regards pests' severity was significant (p = 0.02) as predicted by the model which suggest that time spent on agricultural practices can influence their view of pest impacts. The model explained that more experienced farmers may have developed more awareness of pests associated risk due to the prolonged exposure to pest management challenges.

3.5 Perceived causes of pest problems

This factor represents farmers' beliefs about the environmental and operational causes contributing to pest problems (Table 6). The findings revealed high loadings for pest control (0.70) followed by weather changes (0.62) but low loadings (0.43) for poor soil health as farmers environmental factors contributing to pest problem which indicate pest control and weather changes are strongly perceived by farmers as a catalyst for pest problem. Farmers do not perceive poor soil health as a major driving force that fosters pests' problems which indicate farmers in the study are not concerned about soil health and consequently even soil fertility which pose serious problems for good yield irrespective of problem. During the study it was observed farmers often attribute pests' problems to limited proper pest control measures changing weather patterns such as increased temperatures or unpredictable rainfall that can foster pest proliferation similarly, though with low loadings, few farmers perceived that poor soil health might lead to weakened crop resilience hence making them vulnerable to pests.

Table 5: Association between key variables and IPM adoption indicators

Variable Association	χ^2	df	p-value
Region and Knowledge of Pest Identification	12.35	3	0.002
Educational Level and Familiarity with IPM	20.68	3	<0.001
Farming Experience and Pest Severity Perception	9.72	3	0.021

Findings on operational causes to the pest problem revealed that lack of financial support and training programs have high loadings (0.84 and 0.78) respectively. The findings clearly indicate that farmers consider structured training and financial aid for more efficient management of pests as training programs are essential for equipping farmers with up-to-date IPM techniques, while financial support can help in accessing necessary resources for implementation.

Highly loadings (0.69) were observed for lack of access to IPM resources as one of the contributing factors for the pest problem emphasizing the importance of the availability of resources necessary for effective IPM implementation. Farmers who can readily access IPM inputs, such as bio pesticides or pest-resistant crop varieties, are more likely to adopt these sustainable practices.

Table 6: Factor analysis of perceived influences on IPM adoption

Factor	Variable loaded	Factor loadings
Perceived causes of pest problems	Weather Changes	0.62
	Poor Pest Control	0.70
	Poor Soil Health	0.43
	Training Programs	0.78
	Financial Support	0.84
	Access to IPM resources	0.69

Source: Field survey data, 2024

3.6 Impact of insect pest infestation on rice yields

The findings found out that pest infestation across the three studies significantly result in yield reduction as it was reported by farmers. In each district, negative mean yield (t ha^{-1}) was revealed indicating reduction as result of post-infestation. The yield loss was relatively similar between Kenema and Moyamba district with Kenema district having a yield recording yield of 0.9 t ha^{-1} and Moyamba district with yield loss of 0.8 t ha^{-1} but was different from Kambia where the higher of 1.2 t ha^{-1} was observed. The t-statistics and p-values confirm the significance of these reductions. For instance, Kenema shows a t-statistic of -4.50 with a p-value of 0.001, which indicates that there is a substantial difference between yields before and after infestation, similar trends were also observed for the Kenema and Moyamba districts (Table 7).

3.7 Constraints on rice production

Rice production constraints were classified into six categories to identify major production constraints faced by farmers. These constraints were ranked to identify the most important constraints to the least important ones. Findings from the survey research revealed that lack of capital was the most important constraint faced by farmers (Table 8). This was followed by limited access to credit facilities, Limited Access to Extension was ranked as the least important

Table 7: Impact of Pest Infestation on Rice Yields in Three Districts

District	Mean yield before infestation(t/ha)	Mean Yield after infestation(t/ha)	Mean Difference	t-statistic	P-value
Kenema	3.0	2.1	-0.9	-3.10	0.04
Kambia	4.2	3.0	-1.2	-4.50	0.001
Moyamba	3.3	2.5	-0.8	-3.00	0.03

Source: Field survey data, 2024

constraint. There was a higher level (66.0%) of agreement among the farmers across the study locations on the ranking of these constraints (Kendall's W = 0.660). There was an agreement among farmers in all three districts, Kenema (19.0%), Kambia (27.0%) and Moyamba (20.0%) that lack of capital was the most important constraints faced by rice farmers in all region's region (Kendall's W = 0.19 , 0.27 and 0.20, respectively). Limited Access to credit was ranked as the second most important constraints in Kenema (19.0%) and Kambia (27.0%), High cost of inputs was ranted the second most important constraints in Moyamba (0.20%). However, Limited Access to Extension was ranked the least important constraints faced by rice farmers in all the three districts (Kenema, Kambia and Moyamba).

4. Discussion

The findings of this research revealed critical insight into the socio demographic characteristics of rice farmers, pest management practice and factors that influence the adoption of integrated pests' management by farmers. The middle-aged group farmers were predominant in the study area which suggested that they serve as a backbone for rice farming the area, although there was low presentation of older-aged group farmers, but this raises serious concerns about labor shortage and knowledge transfer due to limited mechanization (FAO, 2020). Male farmers dominated the farming system in the study area suggesting gender disparities which reflect socio-cultural norms but empowering women through training and incentive could significantly enhance productivity and food security (Doss *et al.*, 2018). Integrated pest management was strongly influenced by education, with literacy enhancing farmers' ability to understand and implement sustainable practice (World Bank, 2021; Feder *et al.*, 2004). Experience also correlates with pest risk awareness which indicates that supporting the role of prolonged exposure in improving decision-making (Asfaw *et al.*, 2015). Traditional pest control methods, such as manual removal and farm sanitation, remain common but are labor-intensive and lack scalability. The limited adoption of chemical pesticides reflects resources constraints and limited extension support while the prevalence of unmanaged pests increases crop vulnerability (Abate *et al.*, 2020).

The findings observed significant yield loss in all the study districts because of pests' infestation with Kambia district suffering the highest yield loss which indicates regional disparity in pests'

Table 8: Farmers production constraints in three districts of four regions of Sierra Leone

Constraints	Kenema		Kambia		Moyamba		Combined	
	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
Capital	1.1	1	1.0	1	1.2	1	1.1	1
Lack of pests control resource	1.5	4	1.8	4	2.0	4	1.7	4
Limited Access to credit	1.3	2	1.5	2	1.7	3	1.5	2
Poor infrastructure	1.4	3	1.7	3	1.7	3	1.6	3
High cost of inputs	1.4	3	1.8	3	1.6	2	1.6	3
Limited Access to Extension	2.1	5	2.2	5	2.1	5	2.1	5
Kendall's(W)	0.19		0.27		0.20		0.660	

management knowledge, and this further highlights the need for a tailored extension service. The operation constraint of which financial support (loadings, 0.84) and limited training access (0.78), underscore the importance of resource availability and structured outreach to improve IPM adoption (Abate *et al.*, 2020). Addressing barriers through education, financial aid, and gender-inclusive policies can foster sustainable agricultural practices and mitigate yield losses effectively.

5. Conclusion

The study sheds light on the socio-demographic characteristics of rice farmers, their pest management practices and the determinant of adopting integrated pest' management technologies. The study concluded that there were more middle-aged male farmers indicating their critical role in agricultural productivity, suggesting the need for gender inclusivity and the importance of education in fostering innovation. It was further concluded from the findings that traditional pests control methods were the most prevalent, whilst there was a limited adoption of IPM technologies indicating that there are gaps in the availability of resources, awareness to ward off the management of pests and even extension services. The study also concluded that addressing these challenges requires targeted policies, enhanced training and the community-driven initiative, which will promote sustainable practice and thus ensure the long-term resilience and productivity of the farming system.

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Assessment of wild edible fruit plants in east Oromia region, Ethiopia

Alemayehu Diriba, **Wasihun Gizaw** and **Shimelis Dekeba**
Mechara Agricultural Research Center, Oromia Agricultural Research Institute, Ethiopia

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ABSTRACT

Wild edible fruit plants are essential standing in all parts of the world as a subsidiary food basket on daily basis. They are means of survival for rural communities with food and feed consumption, especially during times of drought, famine, shocks, and risks. This study intended to identify, and document scientific data, to get the constraint and opportunity potential of Wild edible fruit plants. Implementation through assessed species, partly used, habitat, mode of uses, flowering months, fruiting months, and factors of threats of wild edible fruits plants. Structured and semi-structured questionnaire interviews, key informant guided, and species quantification along 18 transact lines on 60 sampled quadrants were used to collect data in the west Hararghe zone at Daro-Lebu, Chiro, and Gumbi Bordode Weredas on six PAs. A total of 120 randomly selected sample households were interviewed for data collection. Both quantitative and qualitative data analyses were made. Descriptive analyses were made to analyze the data using SPSS version 16.0. The study embraced a total of 55 Wild edible fruit plants In addition to food values, these plants provide diverse benefits to the existing community including income, fuel wood, fencing, construction, medicine, and fodder. The top five highly impersonated wild edible fruit plant species by respondents were *Psidium guajava*, *Mimusops kummel*, *Carissa spinarum* L., *Rosa abyssinica*, *Ficus sycomorus*, and *Oncoba spinosa* forssk. However, most of them were threatened by anthropogenic factors through misconception utilities. The threat factors such as land degradation and grazing, clearing of forests for agriculture, fire, timber and charcoal, Stem, leaves, root, and bark harvest. To alleviate, the entire threat of wild edible fruit plant species; a community-based forest management system, awareness creation, and growing of wild edible fruit plant species at farms and homesteads level, is mandatory for any forest resource users. The other point is the absence of seedlings and saplings under wild edible fruit plant species in its habitat is an indicator of a regeneration problem. Therefore; the most threatened and unregenerated wild edible fruit plant species of the study areas priority should be given to the critical collection, domestication, in-situ and ex-situ conservation, and promotion of on-farm cultivation in the form of agroforestry systems. Further investigation should be considered on the collection, nutrient content analyses, in-situ and ex-situ conservation, wise utilization, and popularization of Wild edible fruit plants through forest management. These are vital points to be deliberated forward.

KEY WORDS: *Threat factors*; *Forest*; *Anthropogenic effect*; *Wild edible fruit plant*

1. Introduction

Wild edible fruit plants refer to species that are neither cultivated nor domesticated, which are available from their wild natural habitat and used as sources of food (Beluhan and Ranogajec,

CONTACT Alemayehu Diriba ✉ alemayhudiriba@gmail.com

2010). Even though the primary dependence of most agricultural societies on staple crop plants such as wheat, maize, and rice, the conventional eating of wild edible plant products is used as food. In human history continues until the present day observed over worldwide are more than 7,000 wild edible plant species (Grivetti and Ogle, 2000). Wild edible fruit plants are closing food gaps and play an important role in maintaining livelihood security for many people in developing countries during seasonal food shortages, as emergency food aid (Afolayan and Jimoh, 2009). Moreover, the indigenous Wild edible fruit plants are adapted to the local culture and environment welfare through natural growing manner with a minimum requirement of external inputs and maintenance such as management, fertilizer, and pesticides are the main advantage (Ruffo *et al.*, 2002).

Even though Wild edible fruit plants can easily be integrated into sustainable farming systems by the majority of the rural population, they are still not treasured as cultivated fruit trees, such as mango, avocado, Papaya, and orange due to lack of scientific support. Many countries have given priority to the documenting of Wild edible fruit plants and the associated indigenous knowledge. Countries such as India, Mexico, Bolivia, Spain, and Turkey have in-depth Ethnobotanical information on Wild edible fruit plant's utility. By contrast, in Ethiopia conducted on Wild edible fruit plants utilities and dietary analyses were shallow and addressed only an insignificant portion of the country (Ermias *et al*., 2011).

Therefore; traditional knowledge of wild plants, generally in Africa and particularly in Ethiopia is endangered of being lost, as habits, value systems, and the natural environment change (Ruffo *et al.*, 2002). This study also reflected that the endangered of Wild edible fruit plants is due to more anthropogenic factors, such as land degradation and grazing, clearing of forest for Agriculture, fire, timber and charcoal, Stem, leaves, root, and bark harvest. These factors might be occurred as a result of care failure knowledge especially among the new generations, modernization, and urban dwellers to preserve Wild edible fruit plants to be valuable for future generations. So it needs to be conserved and maintained through sustainable utilization without jeopardizing it for future generations (Demel *et al*., 2010).

In general, regardless of their importance, Wild edible fruit plants are faced with serious threats of anthropogenic and environmental factors in the country due to agricultural expansion, overgrazing/overstocking, deforestation, and urbanization (Addis, 2009; Asfaw, 2009; Tilahun and Mirutse (2010). In Ethiopia, where more than 80% of the population is rural, the people have depended on their traditional knowledge of the utility of Wild edible fruit plants with shallow form without exhaustive documentation of their contribution, management, and utilization in their surroundings. This is particularly true in study areas and in the rural population of West Hararghe Zone, where rural communities of the area depend on Wild edible fruit plants for various purposes such as supplementary food, feed during bad times, and income and medicine with barely.

However, there are no any researches so far done, on Wild edible fruit plants in the study area to be as the impetus for policymakers, NGOs, and end users to sustain utilization and management without jeopardizing the future generation. Therefore; the study intended to identify and document Wild edible fruit plants associated with Ethnobotanical knowledge of indigenous communities on part used, habitat, perception, threat factors, related to utility and management as well as constraint and opportunity potentials as to be input for West Hararghe community and other related areas of the country.

General Objective

- To assess Wild edible fruit plants in the West Hararghe zone, Oromia Region.

Specific objectives

- To identify Wild edible fruit plants in the study area.
- To document scientific information and utilization of commonly used Wild edible fruit plants.
- To know the constraint and opportunity potential of Wild edible fruit plants in combating food insecurity for rural communities.

2. Material and Methods

2.1 Selection of the study area

Before the socio-economic survey, all Weredas' of the Zone which have the potential on growing edible fruit trees and shrub species could be identified. Based on the information gathered, three potential Weredas from each agroecology zones could be selected. From three selected Weredas (Daro-Lebu, Chiro, and Gumbi-Bordode), from each Wereda, two PAs were selected (Fig. 1). A total of six kebele (Metegudesa and Jilbo PA from Daro-Lebu Wereda, Halewagora, and Nejabas PA from Chiro Wereda and Burqaberkele and Legarba PA from Gumbi-Bordode Wereda could be selected and used for the socio-economic survey.

2.2 Description of the study areas

All The study was carried out in the west Hararghe zone, at three Weredas (Namely Daro-Lebu, Chiro, and Gumbi-Bordode). From each of the selected Weredas; 2 PAs and over 6 PAs were selected to obtain all necessary information about edible fruit tree and shrub species of the study areas.

Daro-Lebu Wereda is one of Wereda of West Hararghe zone in Oromia Regional State. It is located at 80 15'00" N-80 43'00" N latitudes and 400 17'00" E- 400 45'00" E longitudes. The Wereda is bordered by Habro in the northeast, East Arsi Zone, in the south-west, Hawi Gudina Wereda, in the north, Anchar Wereda, in the north, and Boke Wereda in the east. Daro-Lebu Wereda located at a distance of 118km and 478km from the Zonal town is Chiro and Addis Ababa; respectively. The average altitude is (1147-2300 m.a.s.l.).

The basic agro-climatic conditions are Weyina-dega (44%) and Kola (56%). Mechara Agricultural Research Center receives on average during the belg rainy season (February 26, March 90, April 157, and May 128mm) and the kiremt rainy season (June 101, July 144, August 158, and September 127mm). The mean annual temperature is 21°C with a mean annual minimum temperature of 15°C and a maximum of 28°C Mechara Agricultural Research Center. The farming system of Daro-Lebu Wereda is mixed farming. The main types of crops grown were Cash and cereal crops such as chat, coffee and teff, barley, maize, sorghum, etc. respectively.

Daro-Lebu had rapid population changes which demanded expanding of agricultural land, fuel wood consumption, and residential area. The woreda had a total human population of 364613 of which 186097 (51.04%) are male and 178514.04 (48.96%) are female. Out of the total population, 13.56 % are urban dwellers. Population density is 82.53 persons per square kilometer and had a total area of 441788.7 hectares (4417.95/km^2). The land use pattern of Wereda that cultivable land 86.8 %, pasture (1.8%), forest (4.14%), and remaining (7.26%) is considered mountainous and swampy.

Chiro Wereda is located in the West Hararghe Zone of the Oromia National Regional state at about 324 km East of Finfinne, the capital city of the Oromia regional state. The capital town of the Wereda is Chiro, which is also the capital town of the Zone. Normally the Wereda is divided into three major agro-ecological zones. These are Lowland with 22 kebele, Midland with 13 kebele, and highland altitude with 4 kebele. The Wereda bordered Mieso in the North, Gemechis in the South, Guba-koricha in the West, and Tulo in the East. Mixed farming is the dominant practice in the Wereda (98%) and the rest is of the pastoral production system (2%).

The Wereda is founded at an average altitude between (1100-2500 m.a.s.l.). From the total land area/topography of the Wereda, 45% is plain and 55% is a steep slope. The Wereda is mainly characterized by steep slopes and mountains with rugged topography, which is highly vulnerable to erosion problems.

The Wereda has a maximum and minimum temperature of 23 ^{o}C and 12 ^{o}C respectively and maximum and minimum rainfall of 1800 mm and 900 mm respectively. The rainfall type is bimodal and erratic. The main rainy season is from June to September for the highland and midland areas and from March to April for the lowland. The short rainy season is from March to May for the highland and midland and for the lowland around July. The amount of rainfall is relatively adequate in the highland and midland than in the lowland.

Soil types of Wereda are sandy soil, clay soil (black soil), and loamy soil types that are 25.5%, 32%, and 42.5%; respectively according to 2003 E.C. data from the Office of Agriculture and Rural Development. The soil types vary with the topography mainly black soils are observed in the highland and midlands, while one can see red soil in the lowland areas. The total land area of the Wereda is 70,912.8 hectares out of which 31659.1 hectares is cultivated land, 30667.4 hectares is uncultivated land, 8104.3 hectares is covered by forest, and 482 hectares is grazing land. Shortage of land is common in the Wereda. Among the main reasons is the increasing population density at a very alarming rate and land fragmentation due to the high number of children in the household. The average land holding status in the area is 4 (0.5-0.25 ha)

Gumbi-Bordode Wereda is found in the West Hararghe Zone of the Oromia National Regional state at about 300 km East of Finfinne, the capital city of Oromia regional state, and at the longitude, 09^{o} 13’ 05.2” North and 040^{o} 45’ 27.7” East. The capital town of distract is Bordode, which is located at 65 km North of Chiro, the capital town of the zone. The Wereda has only one major agro-ecological zone which is lowland. In the Wereda more of the farming community is agro-pastoralist covering 98% and 2% is pastoral community.

The Wereda is founded at an average altitude of 1310 m.a.s.l. Almost about 95% of the Wereda has plain topography (data from the Office of Agriculture).

The Wereda has a maximum and minimum temperature of 28 ^{o}C and 16 ^{o}C respectively and maximum and minimum rainfall of 750 mm and 500 mm respectively (data from Office of Pastoral and Agro-pastoral Development of the Wereda). The rainfall type is mono-modal and erratic. The main rainy season is from mid-June to mid-August and the amount of rainfall is inadequate.

In the Wereda there are sandy soil, clay soil (black soil), and loamy soil types covering 10%, 75%, and 15%; respectively that data from the Office of Agriculture and Rural Development.

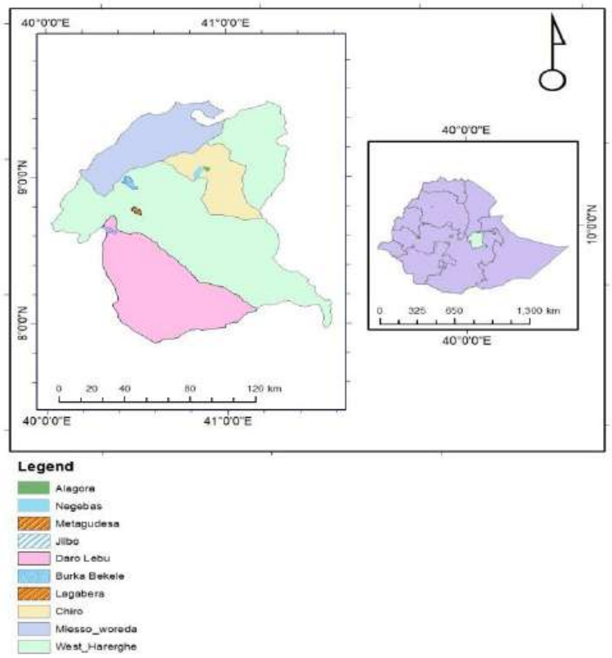

Fig. 1: Study area Map

2.3 Method of data collection

Socio-economy survey

The socioeconomic survey involved various data collection techniques, such as key informant interviews, semi-structured questionnaires, focus-group discussions, and field observations. Semi-structured interviews were used with 120 respondent households that were randomly selected from 3 selected Weredas of the zone. From each of the selected Weredas; 2 PAs were selected to obtain all necessary information about Wild edible fruit plants of the study areas. This is an effective method that can even be used with children or illiterate people. All sampled households were asked independently the same question to freely name orally all the Wild edible fruit plants they know as it comes into their memory. During the survey took place; different socio-economic factors (age, household size, sex, education, *etc*) of the respondents were identified. In addition to the household interviews, important information was collected from key informants. These key informants were those living in the study area for a long time and who have a good understanding of Wild edible fruit plants

The collected data were providing an overview of the socio-economic and biophysical environment of the study areas. As well, field visits and vegetation inventory was applied at each of the study areas/Kebele along the border of the natural forest near the study area to cross-check the reality and to observe the potential of all wild edible fruit plants for more information.

By using the above various data collection techniques, necessary data were collected to know indigenous knowledge of rural communities on utilization, role in food security, opportunity, constraints, perception, and factors of the threat of wild edible fruit plants of the study area.

Vegetation inventory

Inventories on vegetation coverage of wild edible fruit plants of the study area were carried out, to obtain information on the type, trend, and production potential based on their existence and retrieval of sapling and seedling regeneration. The inventory was produced that 'shrub' used to describe woody perennial plants that remain low and produce multiple shoots from the base, while 'trees' refers to woody perennial plants that produce one main trunk or bole and a more or less distinct and elevated crown.

Inventories on vegetation coverage of wild fruit plants in the study area were conducted by systematic transect sampling. Two agroecology zones (midland and lowland) in each of the study areas, with 3 parallel lines, 200 m apart between each transect line and with an interval of 200m distance were laid. On each transect line, 20×20 m (400 m^2) quadrants were implemented. Therefore; in this study 18 transect lines and 60 quadrants were laid out over all the study areas. On each plot/quadrant, all Wild edible fruit plants were documented by their vernacular name, later converted to the scientific name using a tree identification manual. The density of Wild edible fruit plants on each plot/quadrant was expressed by counting stems and converting the number to a per hectare basis that over all of the study area coverage was about (2.4 ha). Data on the estimated quantity of edible fruit plants' products expected from each tree/shrub were collected by interviewing the collectors. The number of edible parts expected from each plant species of a certain size class could be estimated by asking the same question of several collectors. Following this method, in this study, 12 collectors participated from both agroecology zone, to obtain the real identification of edible parts of the various trees and shrubs on each plot.

2.4 Data analysis

The collected data were analyzed employing descriptive statistics, with Microsoft Excel and SPSS (Statistical Package for Social Sciences, version 16) to meet the objectives based on the given parameters.

3. Results and Discussion

3.1 Characteristics of Sample Household

Because of the country's cultural significance, men constituted the majority of the respondents in this study. Thus, 120 (91=76%) of the total responses were male, while the remaining (29=24%) were female. The survey result showed that the highest percentage of the respondents' age was found between 31-45 years (53%); while the lowest percentage was 66-70 years (5%) (Table 1). This indicated that the respondents were at a mature, adult age stage for data quality. The survey result showed that only 48% of the respondents were educated, while 52% were uneducated. The result of the household size of respondents indicated that the highest household size was 2-4 (59%); while the lowest household size was 10-12 (12%). The result of the agro-ecological zone of the study areas observed that (67%) was midland, while (33%) was lowland coverage.

The other main point is the result of farmland size showed that the highest percentage of farmland size was 0.13 ha (37%); while the lowest percentage was 2.5 ha (7%). This indicated that farmers suffered from farmland shortage.

Generally; socio-economic scenarios have an indirect impact on wild edible fruits neither managing nor destroying. For example; according to the respondents' responses; during the bad time, Wild edible fruit plants were eaten as food and feed. On the other hand; as a result of farmland shortage; there is the distraction of Wild edible fruit plants for agricultural expansion.

Table 1: Socio-economics of respondents' information

Sex	Frequency	Percent
- Men	91	76
- Women	29	24
Total	120	100
Age		
- 18-30	22	18
- 31-45	64	53
- 46-65	28	23
- 66-70	6	5
Total	120	100
Educational status		
- Non-educated	62	52
- Primary school	56	46
- Secondary school	2	2
Total	120	100
Average land holding (ha)		
0.025 ha	28	23
0.125 ha	11	9
0.13 ha	44	37
0.25 ha	11	9
0.5 ha	13	11
1 ha	8	7
2.5 ha	5	4
Total	120	100
Agroecology zone		
- Mid-land	80	67
- Low-land	40	33
Total	120	100
Household size		
10-12	14	12
7-9	35	29
2-6	71	59
Total	120	100

3.2 Qualitative description of respondents on wild edible fruit plants

The respondents were asked crosscheck questions that were listed in (Table 2) below. The respondents were gotten from different sources those are from natural forests, river banks, farm boundaries, and postural lands.

The result of wild edible fruit plants observed that the highest percentage source of Wild edible fruit plants was collected from the natural forest (34.2%); while the lowest source was collected from postural lands (9.2%).

The infusing factors of wild edible fruit plants utilization were listed by respondents. The result of infusing factors of wild edible fruits indicated that the highest percentage (23.4%) was observed from supplementary food, feed, and income; while the lowest percentage (10%) was observed from Tradition and hunger of children during keeping of livestock (Table 2). This study in agreement with the other findings elsewhere indicates the supplemental role of wild edible fruit plants needed during food gaps and famine (Abera, 2022).

The role of wild edible fruit plants in ecological and environmental values indicated that the highest value (35.1%) was observed from maintaining weather conditions and sustaining ecological balance, while the lowest value (16.6%) was recorded from attracting rainfall and making a green environment (Table 2).

The result of opportunities in utilizing wild edible fruit plants indicated that the highest value (67.7%) was observed under the ability to grow naturally; while the lowest value (2%) was under income opportunity (Table 2).

The result of the limitation of wild edible fruit plants indicated that the highest value (37%) was observed deforestation and overgrazing; the lowest observation (8%) was obtained from

"Some of them have invasiveness manner" (Table 2).

The result of the trend of wild edible fruit plant production over the last 10 years observed that the highest value (90.8) was recorded as "decreasing"; while the lowest value (1.7) was observed as a "no change" alternative (Table 2).

The result on the perception of respondents in

Table 2: Qualitative description of respondents about wild edible fruits across the study areas

1	Source of Wild edible fruit plants	Frequency	Percent
-	Natural forests	50	34.2
-	Around river area	33	27.5
-	Around farm boundary	26	21.7
-	On pasture land	11	9.2
	Total	120	100
2	Influencing factors to use Wild edible fruit plants		
-	It is sweaty, Medicinal, and has no side effect	13	11.7
-	Supplementary food, feed& income	26	23.4
-	Supplementary food, feed& income during hanger	25	22.5
-	Tradition and hunger of children during keeping livestock	12	10.8
	Total	76	100
3	Role of Wild edible fruit plants in ecological and environmental values		
-	Attract rainfall and make a green environment	19	16.6
-	Improve soil and water conservation	34	28.3
-	Maintain climate change	24	20.0
-	Maintain weather conditions and sustain ecological balance	32	35.1
	Total	120	100
4	Opportunities in utilizing Wild edible fruit plants		
-	Ability to grow naturally	65	67.7
-	Income opportunity	2	2.0
-	Self-distribution	29	30.2
	Total	96	100
5	Constraints in utilizing Wild edible fruit plants		
-	Climate change	13	11
-	Deforestation and overgrazing	44	37
-	Some of them have an invasiveness manner	9	8
-	Lack of enough information	14	12
-	Agricultural expansion	40	33
	Total	120	100
6	The trend of Wild edible fruit plants production over the last 10 years		
-	Increasing	9	7.5
-	Decreasing	109	90.8
-	No change	2	1.7
	Total	120	1
7	Perception of respondents in utilizing Wild edible fruit plants		
-	All people should conserve those trees/shrubs	36	30.0
-	Have to be protected and sustained for future	34	28.3
-	Seedlings have to be planted on farms and reduce deforestation	50	41.7
	Total	120	10

utilizing wild edible fruit plants indicated that the highest value (41.7) was observed in "Seedlings have to be planted on farms and reduce deforestation"; while the lowest value (28.3%) was observed under "protected and sustained for future" (Table 2).

Some farmers are practiced limited management actions (growing in farms and homesteads). This is an indication of the community understands the value and brings under control wild edible fruit plants However, the management practices are limited compared to other staple food plants. Moreover, Wild edible fruit plants gathered in natural environments without care of the management and exposed to anthropogenic threats, which are deterioration of forest products, being choice/alternative food, cultural ignorance and lack of awareness about the nutritional value of the products could make them being ignored for management. This study in line with Fentahun and Hager (2008) reports a lower level of management for wild edible fruit plants (Tebkew et *al.*, 2014).

3.3 Diversity of wild edible fruit plants across the study area

The study revealed that about 55 wild edible fruit tree/shrub species were identified and documented based on important parameters. The results of the habit of wild edible fruit plants were highly dominated by shrub species and followed by tree species, and the remaining were herbaceous. Species richness observation of wild edible fruit plants in the study areas was poor based on the Shannon diversity index (0.01): A total of 55 wild edible plant species were recorded in 3 Weredas on 6 PAs (Table 3).

In Daro-Lebu Wereda at Jilbo PA; observation of wild fruit plants showed that the highest percentage (11.8, 8.5 and 7.8%) were recorded under *Mimusops kummel*, *Psidium guajava*, and *Vangueiria arisepala*, respectively; while the lowest percentage (0.7%) was under *Myrica salicifolia.Rich*, *Capparis decidua*, *Rubus apetalusPoir.*, *Acokanthera schimperi*, *Rhus glutinosa* and *Acokanthera schimperi* with similar figures (Table 3). In Metagudesa PA; observation of wild fruit plants indicated that the highest percentage (15.9, 13.5, 13.5, and 12.7) were verified under *Mimusops kummel*, *Rosa abyssincia*, *Psidium guajava*, and *Syzygium guineense*; respectively; while the lowest percentage (0.8%) was under *Tamarindus indica*, *Myrica salicifolia.Rich* and *Rubus apetalus* with similar figures (Table 3).

In the other study area in Chiro Wereda at Halewagora PA; observation of Wild edible fruit plants indicated that the highest percentage (12.7, 12, and 11.7%) were under *Oncoba spinosa Forssk.*, *Acacia seyal Del.* and *Carissa spinarum* L., respectively; while the lowest percentage (0.7%) was under *Cordia africana*, *Mimusops kummel*, *Rytigynia neglecta*, *Physalis micrantha*, *Myrica salicifolia.Rich* and *Piper nigrum* with similar figures (Table 3). In Nejabas PA; observation of wild fruit plants indicated that the highest percentage (11.4, 7.9 and 7.1) were under *Carissa spinarum* L. and *Acacia seyal Del.*, *Oncoba spinosa Forssk* and *Rubus apetalus Poir.*; respectively; while the lowest percentage (0.7%) was under *Myrica salicifolia. Rich*, *Celosia anthelminthica*, *Rhus natalensis Krauss*, *Rhoicissus tridentata*, and *Albizia grandibracteata* with similar figures (Table 3).

In the other study area in Gumbi-Bordode Wereda at Burqabarkele PA; observation of Wild edible fruit plants indicated that the highest

Table 3: Observation frequency of wild edible fruit plants by study areas

Sl. No.	Scientific name	Family name	*Gumbi-Bordode Wereda*				Chiro Wereda				Daro-Lebu Wereda				Total
			Burqabarkele PA		Legarba PA		Halewagora PA		Nejabas PA		Jilbo PA		Metagudesa PA		
			F	%	F	%	F	%	F	%	F	%	F	%	
1	*Puntia ficus-indica*	*Cactaceae*			4	1.8									4
2	*Carissa spinarum L.*	*Apocynaceae*	11	5.6	15	6.6	16	11.3	16	11.4	6	3.9	7	5.6	71
3	*Hypoestes aristata*	*Acanthaceae*	9	4.6											9
4	*flavescens*	*Tiliaceae*											1	0.8	1
5	*Piper nigrum*	*Piperaceae*					1	0.7	1	0.7					2
6	*Balanites aegyptiaca*	*Balantiaceae*	2	1.0											2
7	*Toddalia asiatica*	*Rutaceae*									1	0.7			1
8	*Portulaca quadrifida.*	*Portulacaceae*									3	2.0	3	2.4	6
9	*Myrica salicifolia.Rich*	*Loganiaceae*	3	1.5	7	3.1	1	0.7	1	0.7	1	0.7	1	0.8	14
10	*Physalis micrantha*	*Solanaceae*					1	0.7							1
11	*Vangueiria arisepala*	*Rubiaceae*					10	7.0	7	5.0	12	7.8	6	4.8	35
12	*Celosia anthelminthica.*	*Amaranthaceae*	1	0.5	14	6.1			1	0.7	2	1.3			18
13	*Rhus natalensis Krauss*	*Anacardiacea*	5	2.6	17	7.5	2	1.4	1	0.7					25
14	*Rhoicissus tridentate*	*Vitaceae.*	1	0.5					1	0.7					2
15	*Grewia tenax (Forssk.)*	*Tiliaceae*	12	6.2	14	6.1									26
16	*Salvadora persica*	*Salvadoraceae*	1	0.5	1	0.4									2
17	*Annona reticulata L.*	*Annonaceae*									1	0.7			1
18	*Syzygium guineense*	*Myrtaceae*	2	1.0	1	0.4					17	11.1	16	12.7	36
19	*Capparis decidua*	*Capparidaceae*									1	0.7			1
20	*Rosa abyssincia*	*Rosaceae*	4	2.1	5	2.2	11	7.7	9	6.4	13	8.5	17	13.5	59
21	*Rubus apetalus Poir.*	*Rosaceae*			1	0.4	3	2.1	10	7.1	1	0.7	1	0.8	16
22	*Momordica foetida*	*Cucurbitaceae*									1	0.7			1
23	*Albizia grandibracteata*	*Leguminosae-*							1	0.7					1
24	*Phoenix reclinata Jacq*	*Arecaceae*	4	2.1											4
25	*Capsicum chinense*	*Solanaceae*							3	2.1					3
26	*Ficus sur (F. Capensis)*	*Moraceae*							4	2.9					4
27	*Grewia bicolour*	*Tiliacea*	6	3.1	1	0.4									7

Continued..

Sl. No.	Scientific name	Family name	*Gumbi-Bordode Wereda*				Chiro Wereda				Daro-Lebu Wereda				Total
			Burqabarkele PA		Legarba PA		Halewagora PA		Nejabas PA		Jilbo PA		Metagudesa PA		
			F	%	F	%	F	%	F	%	F	%	F	%	
28	*Ficus sycomorus*	*Anacardiacea*	18	9.2	16	7.0					10	6.5	3	2.4	47
29	*Boscia salicifolia*	*Capparidaceae*	3	1.5											3
30	*Berchemia discolor*	*Rhamnaceae*	5	2.6											5
31	*Oncoba spinosa Forssk*	*Flacourtiaceae*			4	1.8	3	2.1	1	0.7	5	3.3	3	2.4	16
32	*Dovyalis abyssinica*	*Flacourtiacea*											2	1.6	2
33	*Cordia sinensis Lam*	*Boraginaceae*	8	4.1	17	7.5									25
34	*Meriandra benegalensis*	*Verbenaceae*			4	1.8									4
35	*Lex mitis*	*Ebenaceae*	1	0.5	5	2.2	6	4.2	2	1.4	2	1.3	2	1.6	18
36	*Rytigynia neglecta*	*Rubiaceae*					1	0.7							1
37	*Grewia schweinfurthii*	*Tiliaceae*	4	2.1							1	0.7			5
38	*Grewia ferruginea*	*Tiliaceae*	7	3.6	3	1.3					1	0.7			11
39	*Mimusops kummel*	*Sapotaceae*	13	6.7	20	8.8	1	0.7	6	4.3	18	11.8	20	15.9	78
40	*Myrsine africana L.*	*Myrsinaceae*			1	0.4									1
41	*Embelia schimperi*	*Myrsinaceae*					14	9.9	9	6.4	3	2.0			26
42	*Acokanthera schimperi*	*Sterculiaceae*	2	1.0			3	2.1			1	0.7			6
43	*Euclea racemosa*	*Ebenaceae*	1	0.5	1	0.5			1	0.7	1	0.7	8	6.3	12
44	*Ziziphus spina-*	*Rhamnaceae.*	16	8.2	15	6.6									31
45	*Tamarindus indica*	*Fabaceae*	3	1.5	5	2.2			2	1.4	3	2.0	1	0.8	14
46	*Oncoba spinosa Forssk.*	*Flacourtiaceae*	1	0.5	1	0.4	18	12.7	11	7.9	6	3.9	9	7.1	46
47	*Acacia senegal (L.)*	*Fabaceae*	3	1.5											3
48	*Rhus glutinosa*	*Anacardiaceae*									1	0.7			1
49	*Combretum molle*	*Combretaceae*	19	9.7	13	5.7	13	9.2	6	4.3	9	5.9	4	3.2	64
50	*Osyris quadripartita*	*Santalaceae*					2	1.4							2
51	*Cordia Africana*	*Boraginaceae*	2	1.0	1	0.4	17	12.0	16	11.4					36
52	*Acacia seyal Del.*	*Fabaceae*	3	1.5	7	3.1	1	0.7	4	2.9	3	2.0			18
53	*Allophylus abyssinicus*	*Anacardiacea*	1	0.5	2	0.9	3	2.1	7	5.0	11	7.2	3	2.4	27
54	*Acacaia seyal del.***	*Fabaceae*	10	5.1											10
55	*Psidium guajava*	*Myrtaceae)*	12	6.2	20	8.8	14	9.9	18	12.9	18	11.8	17	13.5	99
		Total	195	100	228	100	142	100	140	100	153	100	126	100	984

F= Frequency, % = Percent, PA = Peasant Association

percentage (9.7, 9.2, and 8.2%) were noted under *Opuntia ficus-indica/cactus, Ficus sycomorus* and *Ziziphus spina-*, respectively; while the lowest percentage (0.5%) was under *Lex mitis*, *Oncoba spinosa Forssk.*, *Combretum molle* and *Allophylus abyssinicus* with similar figure (Table 3). In Legarba PA; observation of wild fruits indicated that the highest percentage (8.8, 77.5.9, and 7) were illustrated under *Mimusops kummel*, *Psidium guajava*, *Cordia sinensis Lam* and *Rhus natalensis Krauss*, *Ficus sycomorus*; respectively; while the lowest percentage (0.4%) was under *Acacia seyal Del.*, *Oncoba spinosa Forssk. Euclea racemosa*, *Grewia bicolour*, *Rubus apetalus*, *Syzygium guineense* and *Physalis micrantha Link* with similar figures (Table 3).

3.4 Operational description of wild edible fruit plants on adaptation, part used, habitat, mode of use, flowering and fruiting months

The respondents were asked crosscheck questions that were listed in (Table 4) below. The respondents answered the questionnaires about wild edible fruits about habituate, part used habitat, mode of use, flowering, and fruiting months. In these processes; the adaptation result of wild fruits showed that the highest percentage (72%) was found from wild habituation; while the lowest percentage (16%) was from both wild /domestic habituation.

In terms of part used of the wild fruits revealed that the highest percentage (98.2%) of part used was got from the fruit and this result coincides with Adal *et al.* (2004), their study findings in a different part of Ethiopia reported that most of the Wild edible fruit plants' parts used were fruits; while the lowest percentage (1.8%) was got from /leaf/bark/root (Table 4). This study is in line with the work of Adal *et al.*, 2004 that fruit uses accounted for 80% of wild edible food.

Table 4: Structural descriptions of wild edible fruits in percent on habituate, part used, habitat, mode of use, flowering months, and fruiting months.

Adaptation of the species	Frequency	Percent
- Wild	46	72.0
- Wild / Domestic	9	16.1
Total	55	100.0
Part of the species used		
- Fruit	55	98.2
- Fruit/Leaf/Bark/ Root	1	1.8
Total	56	100.0
Habitat of the species		
- Herb	2	3.6
- Shrubs	41	73.2
- Tree	13	23.2
Total	56	100.0
Mode of uses		
- as it is	54	96.4
- as it is/cooked	2	3.6
Total	56	100.0
Flowering Months		
- April and July	20	35.7
- April and May	7	12.5
- February	1	1.8
- February & April	2	3.6
- January	3	5.4
- January & February	2	3.6
- June	4	7.1
- March	2	3.6
- May	15	26.8
Total	56	100.0
Fruiting month		
October & November	8	21.1
June	6	15.8
April	4	10.5
February	4	10.5
January	4	10.5
July	4	10.5
March	4	10.5
May	4	10.5
Total	38	100.0

But, this is contrasted with the finding of Tilahun, and Mirutse (2010) studied in southern Ethiopia, that most Wild edible fruit plants were used as vegetables by harvesting their leaves, young twigs, and upper parts (leaf and stem). The other disagreement finding of this study reported by (Ali *et al.*, 2008) was that most of the edible plant parts were leaves that were consumed after cooking.

The result on the habitat of wild edible fruit species observed that the highest percentage (73.2%) was indicated from shrubs species; while the lowest percentage (3.6%) was got from herb species (Table 4). This study is in line with (Ameni *et al.*, 2003; Balemie *et al.*, 2004) that the most harvested wild edible fruits were recorded from shrubs than other categories.

The result on the mode of use of wild edible fruit plants indicated that the highest percentage (96.4%) was used fresh; while the lowest percentage (3.6%) was gotten undercooked (Table 4). This study agrees with the findings of Kebu and Fasil (2006), who reported that raw fruits contain the largest percentage of raw edible fruits.

Table 5a: Observation of species and Sapling trends of a given tees/shrubs in Daro-Lebu Wereda, from 3 transect lines and 12 quadrants in both PA

Observation of species

Scientific name	Frequency	Percent
Psidium guajava	12	30.8
Carissa spinarum L.	6	15.4
Oncoba spinosa Forssk.	6	15.4
Allophylus abyssinicus	5	12.8
Mimusops kummel	4	10.3
Syzygium guineense	3	7.7
Vangueiria arisepala	2	5.1
Total	39	100

Sapling trends of a given tees/shrubs in *Metagudisa PA*, from 3 transect lines and 12 quadrants

Scientific name	Number of sampled trees/shrubs	Total	Percent (%)
Psidium guajava	59	95	62.1
Rosa abyssincia	47	84	56.0
Oncoba spinosa Forssk.	49	89	55.1
Allophylus abyssinicus	32	63	50.8
Carissa spinarum L.	8	19	42.1
Mimusops kummel	1	12	8.3

Number of transacts = 3
Number of quadrants = 12

Observation of species

Scientific name	Frequency	Percent
Rosa abyssinica	11	26.2
Psidium guajava	8	19.0
Oncoba spinosa Forssk.	7	16.7
Allophylus abyssinicus	7	16.7
Mimusops kummel	6	14.3
Carissa spinarum L.	2	4.8
Total	42	100

Sapling trends of a given tees/shrubs *Jilbo PA*, from 3 transect lines and 11 quadrants

Scientific name	Number sampled trees/shrubs	Total	Percent (%)
Psidium guajava	59	95	62.1
Carissa spinarum L.	9	15	60.0
Rosa abyssincia	47	84	56.0
Oncoba spinosa	49	89	55.1
Allophylus abyssinicus	32	63	50.8
Mimusops kummel	1	12	8.3

Number of transacts = 3
Number of quadrants = 11

Raw edible fruits might be a good source of nutrients that does not lose their nutrients fresh; while boiled or cooked, some essential nutrients might be lost. The other results on flowering and fruiting months of wild edible fruits observed that the highest percentage (35.7% and 14.4%) months were April and July, and October and November, respectively; while the lowest percentage (1.8% and 7.1%) months were flowered in February, September, July, February, and April, respectively (Table 4).

In the parameters, in which wild edible fruit plants correlated and related with adaptation, part used, habitat, mode of use, flowering, and fruiting months were well stated and counted in (Appendix Table 1).

3.5 Regeneration trend and species diversity of wild edible fruit plants in the study areas

In Daro-Lebu Wereda at Metegudesa PA, the surveillance of Wild edible fruit plants revealed that the highest percentage (30.8%) occurred under *Psidium guajava* species; while the lowest percentage (5.1%) was under *Vangueiria arisepala* species (Table 5a). On the other hand; an indicator of regeneration trend results with saplings and seedlings of wild edible fruits revealed that the highest percentage (62.1%) occurred under *Psidium guajava* species; while the lowest percentage (8.3%) occurred under *Mimusops kummel,* species (Table 5a). At Jilbo PA; in Daro-Lebu Wereda likewise; the results on observation of Wild edible fruit plants revealed that the highest percentage (26.2%) occurred under *Rosa abyssinica* species; while the lowest percentage (4.8%) occurred under *Carissa spinarum* L. species (Table 5a). Similarly; an indicator of regeneration trend results with saplings and seedlings of wild edible fruits revealed that the highest percentage (62.1%) occurred under *Psidium guajava* species; while the lowest percentage (8.3%) occurred under *Mimusops kummel,* species (Table 5a).

In Chiro Wereda at Nejabas PA; the results of observation of Wild edible fruit plants revealed that the highest percentage (24.3%) has occurred under *Carissa spinarum* L*;* while the lowest percentage (2.7%) happened under *Cactaceae* species (Table 5b). On the contrary; the indicator of regeneration trend results with saplings and seedlings of wild edible fruits revealed that the highest percentage (43.8%) was observed under *Carissa spinarum* L. species; while the lowest percentage (16.7%) occurred under *Acacia seyal del.* species. On the other hand; the species that hadn't any indicator of regeneration trend results with saplings and seedlings of wild edible fruits trees/shrubs were occurred under *Opuntia ficus-indica/cactus*, *Allophylus abyssinicus* and *Myrica salicifolia.Rich* species (Table 5b).

Whereas at Halewagora PA; in Chiro Wereda the same as other study areas; the results on observation of wild edible fruit plants discovered that the highest percentage (18.8%) was observed under *Carissa spinarum* L. species; while the lowest percentage (4.2%) occurred under *Oncoba spinosa Forssk.* and *Rhus natalensis Krauss* species (Table 5b). Similarly; an indicator of regeneration trend results with saplings and seedlings of wild edible fruit plants revealed that the highest percentage (57.9%) was observed under *Carissa spinarum* L. species; while the lowest percentage (37.5%) was observed under *Rhus natalensis Krauss* species (Table 5b). Likewise; the species that hadn't any indicator of regeneration trend results with saplings and seedlings of wild edible fruits plant was observed under *Opuntia ficus-indica/cuctus* species (Table 5b).

In Gumbi-Bordode Wereda, at Legarba PA; the results of observation of wild edible fruit plants revealed that the highest percentage (14.6%) has occurred under *Rhus natalensis Krauss* and *Lex mitis* species; while the lowest percentage (2.4%) was observed under *Toddalia asiatica*, *Syzygium guineense* and *Euclea racemosa* species (Table 5c). On the contrary; the indicator of regeneration trend results with saplings and seedlings of wild edible fruit plants revealed that the highest percentage (57.1%) occurred under *Acokanthera schimperi* species; while the lowest percentage

Table 5b: Observation of species and sapling trends of a given tees/shrubs in Chiro Wereda, from 3 transect lines and 9 quadrants in both PA

Observation of species

Scientific name	Frequency	Percent (%)
Carissa spinarum L.	9	24.3
Lex mitis	7	18.9
Cactaceae	5	13.5
Acacia seyal Del.	4	10.8
Euphorbia abyssinica / cuctus	3	8.1
Allophylus abyssinicus	2	5.4
Myrica salicifolia	1	2.7
Myrsine africana L.	1	2.7
Oncoba spinosa Forssk.	1	2.7
Total	37	100

Sapling trends of a given tees/shrubs in *Nejabas PA*, from 3 transect lines and 9 quadrants

Scientific name	Number sampled trees/shrubs	Total	Percent (%)
Carissa spinarum L	16	58	27.6
Cactaceae	0	8	0.0
Embelia schimperi	14	32	43.8
Acacia seyal Del.	2	12	16.7
Lex mitis	19	54	35.2
Oncoba spinosa Forssk.	1	4	25.0
Allophylus abyssinicus	0	3	0.0
Myrsine africana L.	4	10	40.0
Myrica salicifolia	0	2	0.0

Number of transacts = 3
Number of quadrants = 9

Observation of species

Scientific name	Frequency	Percent (%)
Carissa spinarum L.	9	18.8
Rhus natalensis Krauss	7	14.6
Rosa abyssincia	2	4.2
Lex mitis	6	12.5
Embelia schimperi	6	12.5
Acokanthera schimperi	4	8.3
Oncoba spinosa Forssk	2	4.2
Cactaceae	3	6.3
Acacia seyal Del.	5	10.4
Allophylus abyssinicus	3	6.3
Total	48	100

Sapling trends of a given tees/shrubs in shrubs in, *Halewagora PA*, from 3 transect lines and 9 quadrants

Scientific name	Number sampled trees/shrubs	Total	Percent (%)
Carissa spinarum L.	66	114	57.9
Embelia schimperi	83	147	56.5
Lex mitis	51	101	50.5
Acokanthera schimperi	8	16	50.0
Rosa abyssincia	7	15	46.7
Allophylus abyssinicus	5	12	41.7
Acacia seyal Del.	11	29	37.9
Rhus natalensis Krauss	9	24	37.5
Cactaceae	0	14	0.0

Number of transacts = 3
Number of quadrants = 9

(8.3%) occurred under *Mimusops kummel*, species (Table 5c).

Whereas at Burqabarkele PA; in Gumbi-Bordode Wereda similarly; the results on observation of wild edible fruit plants discovered that the highest percentage (18%) occurred under *Grewia tenax*

Table 5c: Observation of species and sapling trends of a given tees/shrubs in Gumbi-Bordode Wereda, from 3 transect lines and 9 quadrants in Both PA

Observation of species

Scientific name	Frequency	Percent
Rhus natalensis Krauss	6	14.6
Lex mitis	6	14.6
Carissa spinarum L.	4	9.8
Mimusops kummel	4	9.8
Acokanthera schimperi	4	9.8
Grewia tenax (Forssk.)	3	7.3
Grewia bicolour	3	7.3
Myrica salicifolia.Rich	2	4.9
Vangueiria arisepala	2	4.9
Celosia anthelminthica.	2	4.9
Oncoba spinosa Forssk.	2	4.9
Toddalia asiatica	1	2.4
Syzygium guineense	1	2.4
Euclea racemosa	1	2.4
Total	41	100

Sapling trends of a given tees/shrubs in, *Legarba PA* from 3 transect lines and 9 quadrants

Scientific name	Number sampled trees	Total	Percent
Acokanthera schimperi	4	7	57.1
Celosia anthelminthica.	9	17	52.9
Rhus natalensis Krauss	25	49	51.0
Grewia tenax (Forssk.)	14	28	50.0
Lex mitis	18	36	50.0
Myrica salicifolia.Rich	17	41	41.5
Rhus natalensis Krauss	2	5	40.0
Vangueiria arisepala	2	5	40.0
Grewia bicolour	8	20	40.0
Acokanthera schimperi	7	18	38.9
Carissa spinarum L.	11	29	37.9
Syzygium guineense	1	4	25.0
Mimusops kummel	1	12	8.3

Number of transacts = 3
Number of quadrants = 9

Observation of species

Scientific name	Frequency	Percent
Grewia tenax (Forssk.)	8	18
Cactaceae	6	14
Grewia ferruginea	5	11
Grewia schweinfurthii	4	9
Euclea racemosa	4	9
Celosia anthelminthica.	3	7
Grewia bicolour	3	7
Ficus sycomorus	3	7
Boscia salicifolia	3	7
Mimusops kummel	3	7
Balanites aegyptiaca	2	5
Total	44	100

Sapling trends of a given tees/shrubs *Burqaberkele PA* from 3 transect lines and 9 quadrants

Scientific name	Number sampled trees	Total	Percent
Grewia tenax (Forssk.)	28	55	50.9
Celosia anthelminthica.	10	22	45.5
Grewia ferruginea	11	26	42.3
Grewia schweinfurthii	8	19	42.1
Boscia salicifolia	5	12	41.7
Grewia bicolour	7	17	41.2
Mimusops kummel	3	13	23.1
Balanites aegyptiaca	1	5	20.0
Euclea racemosa	3	23	13.0
Ficus sycomorus	0	4	0.0
Cactaceae	0	33	0.0

Number of transacts = 3
Number of quadrants = 10

species; while the lowest percentage (5%) resulted under *Balanites aegyptiaca* species (Table 5c). likewise; an indicator of regeneration trend result with saplings and seedlings of wild edible fruits revealed that the highest percentage (50.9%) occurred under *Grewia tenax* species; while the lowest percentage (13%) resulted under *Euclea racemosa* species (Table 5c). Likewise; the species those hadn't any indicator of regeneration trend result with sapling and seedlings of wild edible fruit plants /shrubs occurred under *Ficus sycomorus* and *Cactaceae* species; respectively (Table 5c).

The absence of seedlings and saplings under any wild edible plant species in its habitat is an indicator of the regeneration problem. However, this scenario might be occurred due to different factors. Relevant biotic factors can be human activities, grazing, deforestation dispersal agents, and competition. Nevertheless, the exact points of factors of threat for wild edible fruit plants in the study area are well stated in the following portion and in (Appendix 1-Table 2).

3.6 Major factors of threat for wild edible fruit plants in the study areas

High population pressure, agricultural growth, energy consumption, and inefficient natural resource utilization are the major threats to wild edible fruit plants. So the threat to wild edible fruit plants in the research areas was (land degradation and grazing, forest removal for agriculture, fuel wood, charcoal, and timber, and harvesting of stems, leaves, and bark.

The result on major threats of wild edible fruit plants showed that the highest percentage (45%) was observed with the Clearing of forest for Agriculture; while the lowest percentage (5.70%) was recorded with Stem, leaves, and bark harvest (Table 6 and Appendix 1-Table 2). Furthermore, construction, settlement, and unwise utilization are the common threat to Wild edible fruit plants The result of this study is consistent with the reports of (Tebkew *et al.*, 2014) that high population growth, agricultural land demand, lack of alternative fuel energies and plantations, resource use interest conflict between local communities.

Table 6: Major threats to wild edible fruit plants in the study areas

	Threat factors	Frequency	Percent (%)
1	Land degradation and grazing	414	42.3
2	Clearing of forest for Agriculture	440	45.0
3	Fire, timber, and charcoal	68	6.9
4	Stem, leaves, and bark harvest	56	5.7
	Total	978	100.

Generally; wild edible fruit plants gathered in the natural environments without care of management which is a deterioration of forest products, being unfamiliar food, public ignorance and nonexistence of consciousness may make them violated for exclusive. These scenarios are being exposed to threats of Wild edible fruit plants as a result of the anthropogenic effects. This study in line with (Tebkew *et al.*, 2014) reported that a lower level of management and undermine were given for wild edible fruit plants

3.7 Association between socio-economic factors and wild edible fruit plants' parameter

Age correlated positively with household size ($p<0.006$) which is statistically significant, and the other negatively correlated that land hold size with

Table 7: Pearson Correlation between socio-economic factors. (N = 120), Prob > |r| under H0: Rho=0

Correlation with:	Sex	Age	Household size	Land hold size	Education status
Age	-0.006 0.949				
Household size	-0.031 0.740	0.251 0.006			
Land hold size	-0.054 0.56	-0.319 0.004	-0.06 0.514		
Education status	-0.083 0.370	0.079 0.392	-0.198 0.031	-0.02359 0.8033	

Age (p<-0.004), and Education status with household size (p <0.031) which showed statistically significant in (Table 7). A positive correlation indicated that both variables are increased with each other. In this situation, as age ranges rise or drop concurrently, household size increases or decreases (Table 7). On the other hand, a negative correlation indicates that as one variable decreases, the other increases. Therefore; when lands hold size increases; age categories decrease; and when education status increases; household size decreases (Table 7).

Shrubs correlated with fruits; direct uses correlated with trees and shrubs; food correlated with fruit, shrubs, and direct uses; feed correlated with fruit and direct uses; income correlated with fruit and direct uses; pasture correlated with fruit, trees, shrubs, direct uses, food and income; farmers correlated with fruits, shrubs, direct uses, food, income, and pasture; young collectors correlated with fruits, trees, shrubs, direct uses, food, income, pastures, and farmers; men collectors correlated with fruits, direct uses, food, income, pastures, and farmers and young; women collectors correlated with fruits, shrubs, direct uses, food, income, pastures, farmers, young and men; elder collectors correlated with feed are highly significant (P<0.0001) and positively associated under the operational description of Wild edible fruit plants based on a given parameter (Table 8).

On the other hand, Land degradation correlated with farmers; forest clear for Agriculture correlated with fruit, trees, direct uses, food, income, pastures, farmers, young and women; fire and charcoal correlated with women are highly significant (P<0.001) and positively associated under factors of threat for Wild edible fruit plants based on the given parameters (Table 8).

4. Conclusion and Recommendation

Wild edible fruit plants have a considerable character in complementary food provision, income generation, modification, and nutritional security in different parts of the country. Furthermore, the species are versatile, thus significant in supplementary food delivery, fodder, fuel-wood, income generation, biodiversity conservation, and nutritional security in various regions at the bad and good times among others. However, the species are underutilized and threatened by misconception factors of anthropogenic pressure in natural ecosystems.

The misconception factors are land degradation and grazing, clearing of forest for agriculture, fire, timber and charcoal, Stem, leaves, root, and bar

Table 8: Pearson Correlation Coefficients and relationship within the wild edible fruits variable

Variables		Part used	Habitat		Use mode	Purpose of utilization				More inspired by		Collected by			
		Fruit	Tree	Shrubs	Direct	Food	Feed	Medicine	Income	Pasture	Farmers	Young	Men	Women	Elder
Habitat	Tree	0.477**													
	Shrubs	0.681***	-0.176^{NS}												
Use mode	Direct	0.992***	0.450**	0.716***											
Purpose of utilization	Food	0.951***	0.455**	0.728***	0.952***										
	Feed	0.515***	-0.022^{NS}	0.399**	0.501***	0.322*									
	Medicine	0.112^{NS}	0.087^{NS}	-0.033^{NS}	0.111^{NS}	-0.119^{NS}	0.284**								
	Income	0.706***	0.464**	0.361**	0.680***	0.575***	0.487**	0.150^{NS}							
More inspired by	Pastures	0.971***	0.515***	0.645***	0.955***	0.952***	0.472**	0.014^{NS}	0.696***						
	Farmers	0.949***	0.493**	0.616***	0.920***	0.941***	0.421**	0.014^{NS}	0.574***	0.937***					
Collected by	Young	0.911***	0.546***	0.576***	0.904***	0.944***	0.303**	-0.081^{NS}	0.594***	0.950***	0.893***				
	Men	0.794***	0.478**	0.428**	0.801***	0.680***	0.380**	0.475**	0.488**	0.690***	0.720***	0.626***			
	Women	0.879***	0.422**	0.708***	0.923***	0.872***	0.396**	0.079^{NS}	0.559***	0.849***	0.764***	0.815***	0.719***		
	Elder	0.488**	0.122^{NS}	0.234^{NS}	0.463***	0.318*	0.524***	0.316**	0.377**	0.388**	0.462***	0.223^{NS}	0.441**	0.308**	
Factor of threat	Land degrading	0.493**	-0.162^{NS}	0.409**	0.468**	0.450**	0.313**	0.147^{NS}	0.104^{NS}	0.468**	0.515***	0.482**	0.425**	0.339**	0.260^{NS}
	F.Cr. Agriculture	0.757***	0.625***	0.428**	0.736***	0.750***	0.322*	-0.116^{NS}	0.774***	0.778***	0.736***	0.690***	0.472**	0.625***	0.391**
	Fire and charcoal	0.235^{NS}	0.019^{NS}	0.424**	0.356**	0.293*	-0.007^{NS}	0.017^{NS}	0.027^{NS}	0.183^{NS}	0.059^{NS}	0.250^{NS}	0.281*	0.610***	-0.082^{NS}

Note: Correlation is significant at the 0.001 level; **. Significant at the 0.01 level. *. Significant at the 0.05 level; ^{NS}, Not Significant harvest. Consequently, a community-based forest management system, awareness creation, and growing of wild edible fruit plants on farms and homesteads level are mandatory for any users to save such kinds of delusion problems.

Therefore; the absence and the lowest number of seedlings and saplings under the sampled quadrant of wild edible fruit plants in its habitat is an indicator of a regeneration problem. In this study, imperfection and threatened species might be occurred due to misconceptions about utilities across Wereda. Those are *Mimusops kummel* is the lowest regeneration species in Daro-Lebu Wereda. Cactaceae */cactus, Allophylus abyssinicus and Myrica salicifolia* and *Ficus sycomorus species* are *the* absence of seedlings and saplings under the sampled quadrants in Chiro and Gumbi-bordode Weredas; respectively.

Generally; supporting and promoting indigenous knowledge of farmers towards encourage domestication, and *in-situ* and *ex-situ* conservation through awareness creation, value addition, and commercialization of wild edible fruit plants are mandatory. All these arguments should help to maximize the multidimensional advantage of communities; while contributing to the sustainable utilization of wild edible fruit plant species eco-friendly.

Specifically; the most threatened and under-regenerated wild edible fruit plant species of the study area priority should be given to the critical collection, domestication, in-situ and ex-situ conservation, and promotion of on-farm cultivation in the form of agroforestry systems.

The research gap should be focused on nutrient analysis, collection and *in-situ* and *ex-situ* conservation, genetic improvement, fruit processing, and analysis of the economic contribution of Wild edible fruit plant species.

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GIS-Based soil erosion assessment and severity mapping using RUSLE model for planning of conservation measures at selected watershed in North Shewa zone, Oromia

Endale Bedada and **Woubalem Abera**
Oromia Agricultural Research Institute, Fitche Agricultural Research Center, Fitche, North Shewa Zone, Ethiopia

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ABSTRACT

Soil erosion is a common phenomenon and major threat in many parts of Ethiopian highlands and it remains difficult to quantify and measure the amount of soil erosion. Geographic Information System (GIS) provides spatial information to identify erosion potential areas and useful tools to estimate the annual soil loss based on Revised Universal Soil Loss Equation (RUSLE). This research was conducted in Central Highlands of Ethiopia, Muziye watershed which is 112 Km far from Addis Ababa north direction and covers 475 ha area. The aim of this research was to estimate the annual soil loss from the watershed and to map the topographic and anthropogenic factors for planning and implementation of sustainable soil conservation and management system in the watershed. A Revised Universal Soil Loss Equation (RUSLE) preferred for Ethiopian conditions and GIS was used to estimate soil losses and identify potential effect of erosion factors. We employed IDW- interpolation map for rainfall erosivity (R) factor, soil map soil erodibility (k) factor, a 30m×30m Digital Elevation Model (DEM) for topography (LS) factor, satellite image for vegetation cover (C) factor, land use and slope class map for management (P) factor. The mean annual soil loss estimated in watershed was 44.67 tons $ha^{-1}yr^{-1}$ from 569.35 ha. The results revealed that about 23.44 % of the watershed area undergoes moderate (5-10 tones ha^{-1} yr^{-1}) to very slight (>2 tones ha^{-1} yr^{-1}) erosion classes, 22.54 % high (10-50 tones ha^{-1} yr^{-1}) erosion class, 38.8 % from severe (50-100 tones ha^{-1} yr^{-1}) to very severe (100-500 tones ha^{-1} yr^{-1}) erosion classes, and 15.23 % catastrophic (>500 tones ha^{-1} yr^{-1}) erosion class. Based on our findings we recommended that, high to catastrophic erosion risk area of the watershed requires various soil and water conservation activities that intercept runoff by decreasing the transport capacity of flow and improving soil infiltration in the steep slope using terracing, contouring, and strip cropping, reducing the intensity of tillage and growing cover crops and rehabilitating hillside slope areas with different indigenous and exotic tree species should be embarked upon by participating farmers in conservation strategies from plan preparation to implementation. Soil erosion hot spot areas that were identified in the soil erosion map should be given a serious attention and priorities for implementing soil conservation activities before the areas reached to irreversible soil degradations.

KEY WORDS: *Watershed*; *RUSLE*; *Identification*; *Prioritization*

1. Introduction

Soil is a basic resource for economic development and for maintaining sustainable, productive landscapes and people's livelihoods, especially for countries with agrarian economies like Ethiopia.

CONTACT Endale Bedada ✉ endenat2008@gmail.com

However, soil degradation is a serious threat in agro-ecosystems and one of the global environmental problems (Abate, 2011). Globally, one-third of agricultural soils are reported to be affected by soil degradation (Hurni, 2002), of which water and wind erosion account for 56% and 28% of the observed damage, respectively (Blanco-Canqui and Lal, 2008). Obviously, soil erosion by water is the most serious form of soil degradation, and this problem is most significant in the tropics and sub-tropics compared to the rest of the world (Lal, 2001).

Soil erosion by water has been a challenging and persistent problem in Ethiopia for decades (Gete, 2000; Bewket and Teferi, 2009; Kebede *et al.*, 2015). The average annual soil loss in Ethiopia is estimated to be 18 tons $ha^{-1}year^{-1}$ (Hurni, 1985). However, the problem is more severe in the Ethiopian highlands (Gete, 2000; Nyssen *et al.*, 2004; Bewket and Teferi, 2009; Abate, 2011). In the Ethiopian highlands, soil erosion ranges from 16 to 300 tons $ha^{-1}year^{-1}$ in cultivated lands (Hurni, 1988). In the past, Gete (2000) also reported 130–170 tons $ha^{-1}year^{-1}$ soil loss on similar land use in the northwestern highlands of Ethiopia.

Every year, an estimated 1.9 to 3.5 billion tons of topsoil in the Ethiopian highlands has been lost, and as a result, about 20,000–30,000 ha of cropland was taken out of production due to severe soil erosion in earlier decades (EFAP, 1993). Tadesse (2001) also indicated that 1.5 million tons of soils have been lost in the Ethiopian highlands each year, which has also resulted in a significant loss of grain from the country's annual harvest. As a result of soil erosion, poverty and food insecurity are concentrated in rural areas (MoARD, 2010). Thus, in order to achieve food security, poverty reduction, and environmental sustainability in the country, reversing soil erosion is a high priority (Bewket and Teferi, 2009; Abate, 2011).

In order to reverse soil erosion, several efforts have been exerted since the 1970s (Menale *et al.*, 2009; Nigussie *et al.*, 2012). However, past soil conservation efforts did not bring significant changes to the ongoing soil degradation problems (Menale *et al.*, 2009). Erosion prediction involves the use of process-based, empirical, and conceptual models. Most recently, watershed management is an approach followed by the government of Ethiopia to protect soil from erosion in particular, and to reverse land degradation in general (Desta *et al.*, 2005; Gete, 2006; Nigussie *et al.*, 2012). Although dramatic reductions have been made in arresting soil erosion (Nigussie *et al.*, 2012), the approach has not been supported with intervention-prioritizing techniques that identify highly susceptible areas using geospatial analysis. The intervention requires an understanding of the rates of on-site soil erosion processes and the controlling factors that enhance or retard these processes. However, since direct measurements of soil erosion are costly, labor-intensive, and time-consuming, spatial soil erosion models play a vital role in the design of these interventions (Mirco *et al.*, 2003). A Revised Universal Soil Loss Equation (RUSLE), preferred for Ethiopian conditions, and GIS were used to estimate soil losses and identify the potential effect of erosion factors due to its clear and relatively simple computational input requirements compared to other models.

North Shewa Zone is one of the northern parts of the Ethiopian highlands where soil erosion is severe. Hence, identifying and prioritizing erosion-susceptible areas for soil and water conservation measures planning is quite essential. Therefore, the objective of this study is to assess and identify the erosion risk-prone areas across the landscape of the watershed for planning conservation measures in the watershed.

Objectives of the study

- To estimate the spatial distribution of soil erosion of the entire watershed.
- To provide a complete map of soil erosion susceptibility and land use/cover changes.
- To identify and prioritize erosion risk prone areas for intervention.

2. Material and Methods

2.1 Description of the study area

Geographical Location

The study was conducted at the Muziye watershed in Girar Jarso district of the North Shewa Zone, which is approximately located 117 km north of the capital city of Ethiopia (Addis Ababa), and 5 km from Fitche town, the capital of the North Shewa Zone. The watershed is situated between 38°44'30''E – 38°47'30''E and 9°47'30''N – 9°49'30''N (Fig. 1). The watershed covers a total area of 569.35 ha and drains into the Abay Basin.

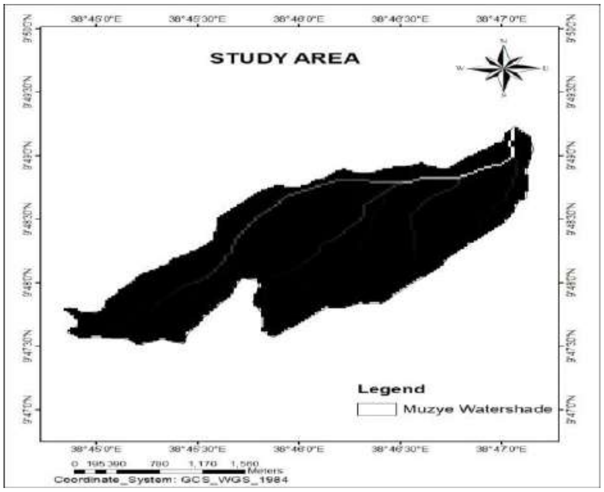

Fig. 1: Map of Muziye watershed

Topography and Climate

The landforms of the watershed are characterized by valleys, plateaus, hills, and plains (GJWARDO, 2022), and the altitude ranges from 1,763 m to 3,096 m above sea level. The watershed exhibits two major agroecological conditions: lowland (*gammojji*) and midland (*badda-daree*), which account for 71% and 29% of the watershed area, respectively. The area receives an average annual rainfall of 1,013 mm. The mean monthly temperature ranges from 12.2°C to 28°C, with a mean annual temperature of 20.4°C.

Vegetation, Soil, and Land Use

The dominant trees and shrubs found in the watershed include *Cordia Africana*, *Ficus* spp., and *Eucalyptus*. These species provide various economic and social benefits, such as firewood, livestock forage, beekeeping, fencing, soil erosion control, soil fertility maintenance, and shading. The major crops grown in the watershed include sorghum, wheat, barley, and teff. In addition, various vegetable crops are cultivated such as potato, onion, cabbage, and others-with onion being the most dominant among the vegetables.

The farming system is a mixed one, primarily oxen-plowed cereal crop production alongside livestock rearing, a system that has been practiced for centuries. The major land use types in the watershed include cultivated land, grazing land, shrub/bushland, settlements, natural forest, and woodlands. However, the distribution of these land use types is very fragmented.

Due to the exploitative nature of land use practices, the watershed is generally characterized by severe land degradation, evidenced by soil erosion, declining soil fertility, deforestation, low vegetation cover, and declining land productivity. Most parts of the watershed have relatively steep slopes and shallow soils, placing the remaining soil on cultivated and grazing lands at risk. This is primarily due to the total removal of topsoil through accelerated erosion on steep lands.

Population

The total population of the peasant association within the watershed is approximately 14,287-comprising 7,220 males and 7,067 females. These represent a total of 2,926 households (HH), with 2,507 male-headed and 419 female-headed households. The average family size is five persons per household, with males being slightly more in number.

2.2 Site selection and mapping of the watershed

The watershed was purposively selected based on the prevalence of resource management and land degradation problems, topographical features, and road accessibility. Based on the preliminary outlet identified during the site selection process, the watershed boundary was delineated using primary data (GPS readings). Finally, a map of the watershed was produced, and other information such as elevation range and slopes was extracted.

2.3 Source of data

Both primary and secondary data were used in the study.

Primary data was collected through topographic transect walks and field observation. During these walks, information was gathered on vegetation types, major land use/land cover (LULC) patterns, and soil and water conservation practices (both improved and traditional) implemented on agricultural lands with different slope classes. Additionally, a Global Positioning System (GPS) was used to collect ground-truth data for image classification and soil loss vulnerability verification.

Secondary data included:

- Landsat 6 ETM+ imagery with a spatial resolution of 30 × 30 m, acquired from the Ethiopian Mapping Agency for LULC classification;
- A digital soil map from FAO with a resolution of 30 × 30 m;
- Digital Elevation Model (DEM) at 30 × 30 m resolution;
- Time series climatic data (especially rainfall) from the National Meteorology Agency;
- Farm management data from the Woreda Agriculture and Natural Resource Development Office.

2.4 Methods of determining RUSLE factors

GIS techniques were integrated with the Revised Universal Soil Loss Equation (RUSLE), an empirical soil loss model, to estimate the mean annual soil loss of the watershed. The five major factors considered in the RUSLE model are:

1. Rainfall pattern (R)
2. Soil type (K)
3. Topography (LS)
4. Crop management (C)
5. Conservation practices (P)

RUSLE is widely used to estimate soil loss from watersheds with various land use types (Gelagay and Minale, 2016). It is preferred due to its simplicity and relatively low data input requirements compared to other models. The basic

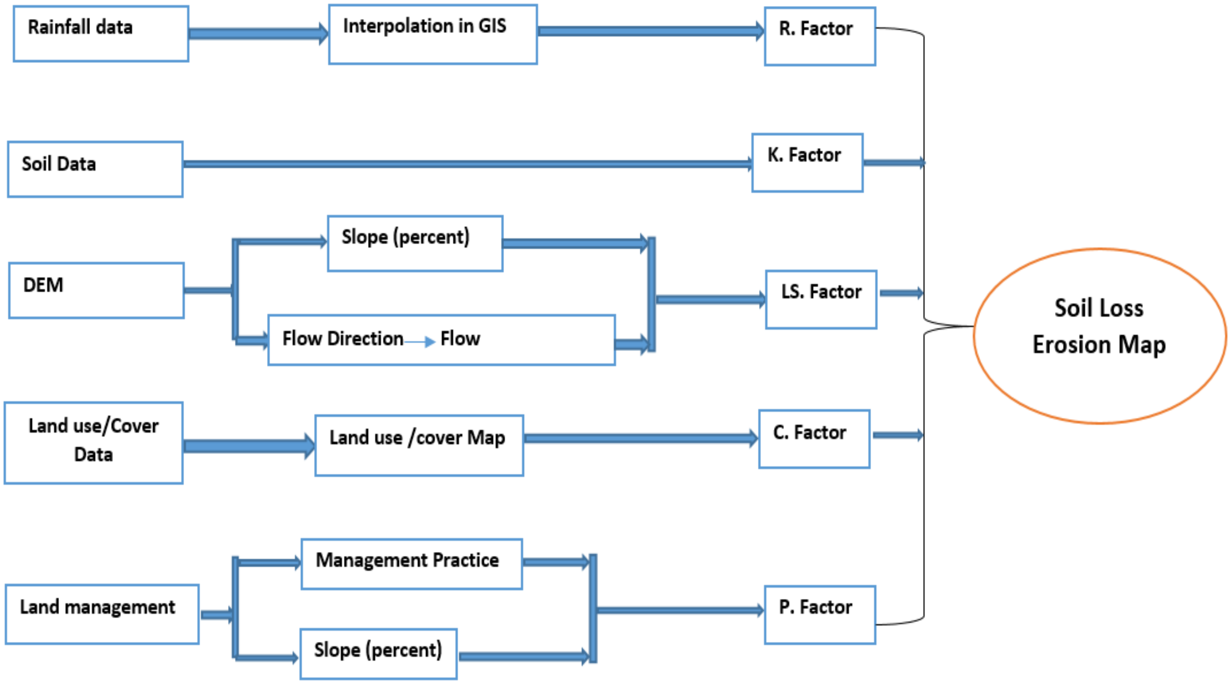

Fig. 2: Conceptual framework of soil loss estimation

methodological approach followed in the application of RUSLE is illustrated in the simplified flow chart (Fig. 2).

2.5 Determination of rainfall erosivity (R-factor)

The Rainfall Erosivity Factor (R) represents the erosive force of a specific rainfall event (Alexakis *et al*., 2013). It is primarily determined by the amount, intensity, and distribution of rainfall (Tadesse and Abebe, 2014). Due to the absence of rainfall intensity data, we adopted the R-correlation established by Hurni (1985) for Ethiopia, which has been used in other similar studies (Bewket and Teferi, 2009; Abate, 2011; Derege *et al*., 2012; Tadesse and Abebe, 2014; Kebede *et al*., 2015; Gelagay and Minale, 2016).

We calculated the mean annual rainfall based on monthly rainfall data from nine meteorological stations for the period 1990–2022 and computed the R-factor for each station using the following equation (Hurni, 1985):

$$R = -8.12 + (0.562 \times P) \text{------------------------------} (1)$$

Where:

- R - Rainfall erosivity factor in $MJ \cdot mm \cdot ha^{-1} \cdot yr^{-1}$
- P - Mean annual rainfall (mm)

To produce an R-factor map, the interpolated R-values were converted into a raster format with 30 m resolution and extracted for the studied watershed.

2.6 Determination of soil erodibility (K-factor)

The Soil Erodibility Factor (K) expresses a soil's inherent resistance to particle detachment and transport by rainfall. It is influenced by the cohesive forces between soil particles, which may vary based on plant cover, soil moisture content, and the development of soil structure (Wischmeier and Smith, 1978). It also depends on factors such as organic matter content, soil texture, surface horizon structure, and permeability (Robert and Hilborn, 2000).

For this study, a digital soil map from the Ministry of Agriculture (MoA) was used to derive the soil map of the study watershed. The K-factor was estimated based on soil color information referenced from the FAO (2012) soil database, adapted for Ethiopia by Hurni (1985) and Hellden (1987), as shown in Table 1.

Once the dominant soil type map of the study area was clipped in the ArcGIS environment, each soil characteristic - particularly soil color - was obtained from the FAO digital soil map.

Table 1: Soil color and K - value based on Hurni (1985), Hellden (1987)

Soil color	Black	Brown	Red	Yellow
K-factor	0.15	0.2	0.25	0.3

2.7 Determination of topographic factor (LS-factor)

The LS-factor in the Revised Universal Soil Loss Equation (RUSLE) is a combination of slope length (L) and slope steepness (S) factors (Alexakis *et al.*, 2013). The steeper and longer the slope, the greater the rate of soil erosion due to the higher accumulation and velocity of surface runoff (Abate, 2011; Alexakis *et al.*, 2013; Tadesse and Abebe, 2014).

In this study, slope length and slope steepness values were derived from a Digital Elevation Model (DEM) with 30m resolution using the ArcGIS Spatial Analyst tool and the Arc Hydro tool. The LS-factor was then calculated and mapped using methods applied in previous studies such as Bewket and Teferi (2009) and Kamaludin *et al.* (2013).

The following equations were used:

$$L = \left(\frac{\text{FA} \times \text{Cell size}}{22.1}\right) \text{--------------------------------}(2)$$

$$S = 0.065 + 0.045S + 0.0065S^2 \text{-----------------}(3)$$

$$LS = \left(\frac{\text{FA} \times \text{Cell size}}{22.1}\right) \times 0.065 + 0.045S + 0.0065S^2\text{-}(4)$$

Where:

FA - Flow accumulation
S - Slope in percentage
Cell size is 30 m (DEM resolution)
LS is the topographic factor

2.8 Determination of crop and management cover (C-factor)

The C-factor represents the ratio of soil loss from land covered by vegetation to the corresponding loss from bare or continuously fallow land (Morgan, 2005). It reflects the influence of vegetation cover, crop type, and land management practices on soil erosion.

To determine the C-factor for the study area, a land use and land cover (LULC) map was prepared using a Landsat 6 ETM+ satellite image with a spatial resolution of 30 m × 30 m. A supervised digital image classification technique was employed to identify different land cover types. Ground truth data were collected through field verification to improve the accuracy of the classification.

C-values for each LULC category were assigned based on values suggested by various authors, as presented in Table 2.

Table 2: Land cover and their C-values suggested by different authors for different LULC

Land cover	C value	References
Agricultural land	0.15	Hurni (1985); Bewket and Teferi (2009); Tadesse and Abebe (2014)
Forest land	0.001	Hurni (1985); Morgan (2005)
Degraded forest	0.005	Hurni (1985); Morgan (2005)
Shrub land	0.014	Wischmeier and Smith (1978); Abate (2011); Gelagay and Minale (2016)
Grazing land	0.01	Hurni (1985); Morgan (2005); Abate (2011); Tadesse and Abebe (2014)
Bare land	0.6	Hurni (1985); Morgan (2005)
Settlement area	0.09	Ganasri and Ramesh (2015)

2.9 Determination of conservation practice factor (P-factor)

The P-factor represents the effect of specific soil and water conservation practices on reducing the velocity of surface runoff, enhancing water infiltration, and consequently minimizing soil loss and sediment transport (Renard and Foster, 1983).

To determine the P-factor in the RUSLE model, data were collected through field observations and assessment of existing conservation practices within the study area using ArcGIS. A topographic transect walk was conducted to evaluate major land use/land cover types and identify the types of soil and water conservation measures implemented, particularly on agricultural land.

Agricultural lands were categorized into six slope classes. Since no permanent soil and water conservation structures were present to control runoff, P-values for each slope class were assigned based on values from similar studies, including those by Wischmeier and Smith (1978), as shown in Table 3.

Finally, the assigned P-factor values were applied using the Spatial Analyst Tool's "Reclassify" function in ArcGIS. The resulting data were converted into a grid format with a cell size of 30 m × 30 m.

Table 3: P - values suggested by Wischmeier and Smith (1978) for the different slope classes of agricultural land and other land.

Land use	Slope (%)	P-value
Agricultural land	0-5	0.1
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
Other land	All	1.00

2.10 Total soil loss analysis (A)

The average annual soil loss rate was calculated using a cell-by-cell analysis of the soil loss surface. This was achieved by multiplying the respective RUSLE factor values - R, K, LS, C, and P - using the Spatial Analyst Tool – Map Algebra function in ArcGIS, as per the equation developed by Hurni (1985). The resulting soil loss map was then converted to a hectare basis to express annual soil loss in tons per hectare per year.

$$A = R \times K \times LS \times C \times P \text{----------------------------} (5)$$

Where:

- A = Computed spatial average soil loss (ton/ha/year)
- R = Rainfall erosivity factor (MJ·mm/(ha·h·yr))
- K = Soil erodibility factor (t·ha·h/(ha·MJ·mm))
- LS = Slope length and steepness factor (dimensionless)
- C = Cover management factor (dimensionless)
- P = Conservation practice factor (dimensionless)

2.11 Data analysis

Data processing and analysis were conducted by digitizing, calculating, and classifying the required information for each thematic layer using ArcGIS. Additionally, simple statistical methods - such as percentage and average - were employed to assist in the analysis and interpretation of the results.

3. Results and Discussion

3.1 Estimation of soil erosion factor values

Rainfall erosivity factor (R)

The distribution of average annual rainfall over the 32-year period in the study area varies across different locations within the watershed. The results indicate that annual rainfall in the watershed ranged from 1213.78 mm to 1293.18 mm. correspondingly, the R-values (rainfall erosivity factor) in the study area ranged from 674.02 to 718.65 MJ·mm·ha^{-1} yr^{-1}, as illustrated in Fig. 3. The average R-factor value for the watershed was 695.76 MJ·mm·ha^{-1} yr^{-1}. This value falls within the range of 441.5 to 1166.4 MJ·mm·ha^{-1} yr^{-1}, as estimated by Amsalu and Mengaw (2014) for Jabi Tehinan Woreda, Amhara National Regional State (ANRS), Ethiopia.

Soil Erodibility Factor (K-Values)

Two major soil types were identified within the study watershed: Orthic Luvisols and Pellic Vertisols. The corresponding soil erodibility (K) values and their proportions relative to the total

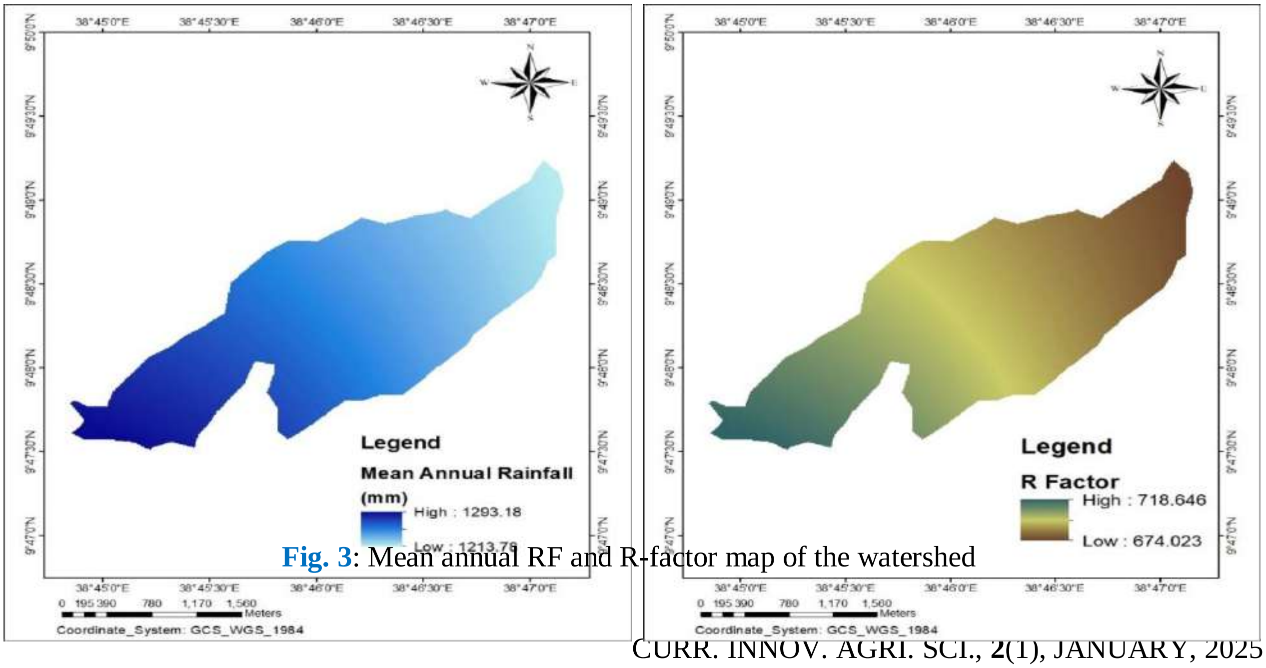

Fig. 3: Mean annual RF and R-factor map of the watershed

watershed area are as follows: Orthic Luvisols – 0.20 (70.77%), and Pellic Vertisols – 0.15 (29.23%) (Table 4). The soils in the study area exhibit two distinct K-values, ranging from 0.15 to 0.20. A higher K-value indicates greater susceptibility to erosion, whereas a lower value suggests more resistance.

Table 4: Soil types, coverage and K value based on Hurni (1985), Hellden (1987)

Soil types	Soil color	K-value	Area (ha)	Area (%)
Orthic Luvisols	Brown to dark brown	0.2	403.32	70.77
Pellic Vertisols	Black	0.15	166.03	29.23
Total			569.35	100

The watershed is predominantly covered by Orthic Luvisols, which are characterized by a brown to dark brown color. According to Mati *et al*. (2000), soils with a brown hue and high sand content tend to have weak structural stability, making them more prone to disintegration. As a result, these soils are more easily detached and transported by surface runoff (Fig. 4).

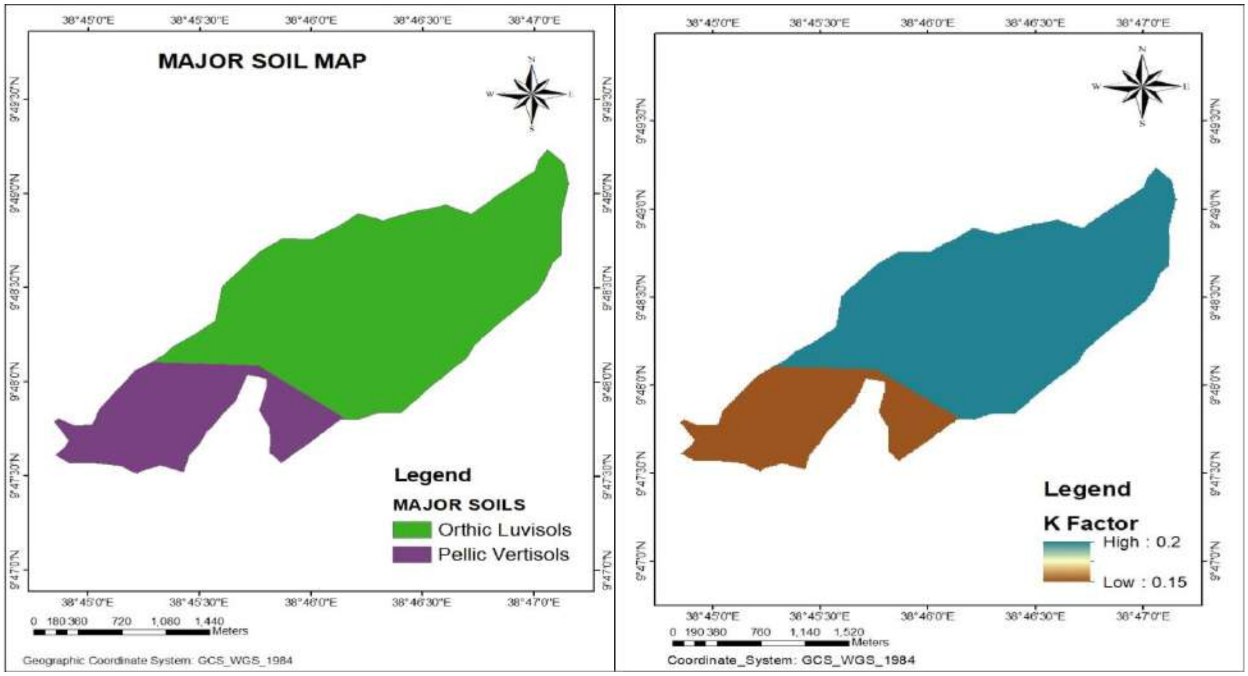

Fig. 4: Soil types and K-factor map of the watershed

Slope Length and Slope Steepness Factor (LS-Values)

The interaction between slope length and slope steepness significantly influences the magnitude of soil erosion. Due to this relationship, both factors should always be considered together when assessing erosion potential (Alexakis *et al.*, 2013). The results of this study indicate that LS-factor values in the watershed range from 0 in flat areas to as high as 1842.23 in regions with steeper and longer slopes. This increasing LS value demonstrates that potential erosion intensifies with increasing slope steepness.

The topography of the watershed clearly contributes to higher rates of soil loss.

Approximately 68.95% of the study area consists of steep and long slopes, which lead to higher surface runoff velocities and, consequently, greater erosion potential. Longer and steeper slopes - especially those lacking sufficient vegetative cover - are particularly vulnerable to severe erosion during heavy rainfall events (Blanco-Canqui and Lal, 2008). These findings emphasize that topographic factors, as represented by the LS-factor, play a dominant role in the erosion process (Adediji *et al*., 2010) (Fig. 5).

3.2 Crop management factor (C-Values)

Based on the land use/land cover (LULC) analysis, the study watershed was classified into seven categories: agricultural land, forest land, degraded forest land, shrubland, grazing land, bare land, and settlement areas. Agricultural land is the predominant land use type, covering 50.65% (288.33 ha) of the total watershed area, while the remaining 49.35% (311.02 ha) is occupied by other land use types, as shown in Table 5.

Table 5: Land use land cover area coverage and their C values suggested by different authors for different land use land cover.

Land cover	C-value	Area (ha)	Area (%)
Agricultural land	0.15	288.33	50.65
Forest	0.001	10.51	1.85
Degraded forest	0.005	23.90	4.20
Shrub land	0.014	110.27	19.37
Grazing land	0.01	73.29	12.87
Bare land	0.6	54.10	9.50
Settlement area	0.09	8.95	1.57
Total		569.35	100

The C-factor values within the watershed range from 0.001 in areas covered by dense forest to 0.6 in bare land. This variation in C-values reflects the differences in vegetative cover and land management practices. Bare land exhibits the

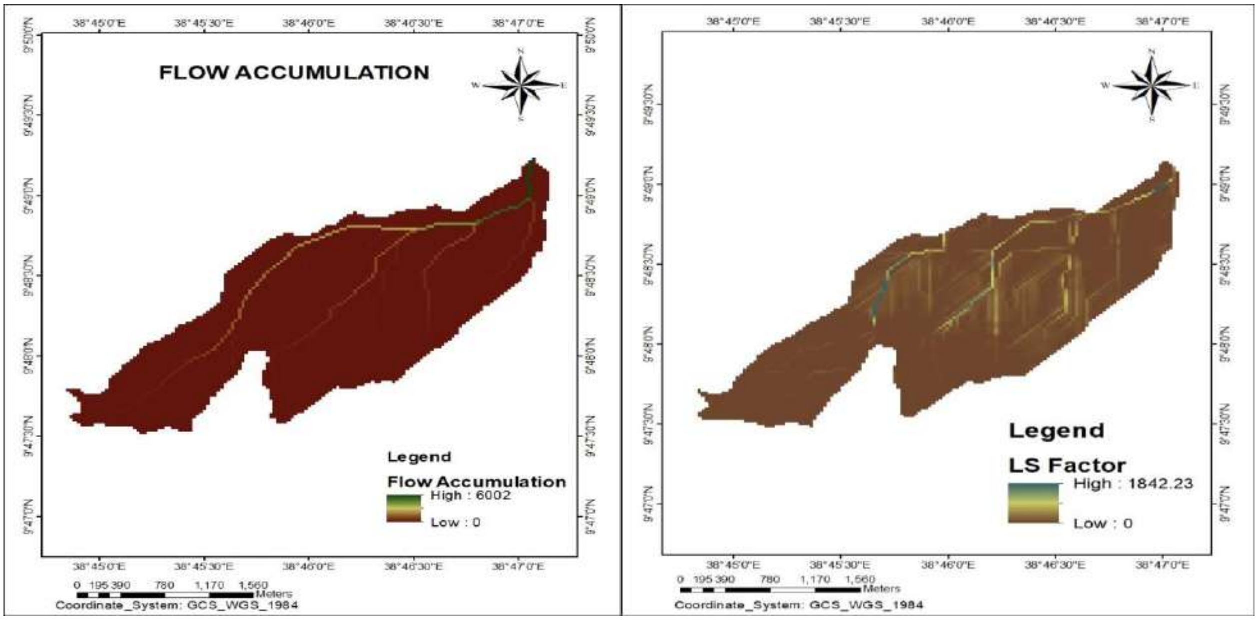

Fig. 5: Flow accumulation and LS-factor map of the watershed

highest C-value, indicating the greatest potential for soil erosion. These findings suggest that areas with minimal or no vegetation, such as bare land, are more susceptible to runoff and soil loss (Vander *et al*., 2000). This is illustrated in Fig. 6, which highlights the spatial distribution of C-values across the watershed.

3.3 Conservation practice factor (P)

In the study watershed, there is only a small part of watershed area was treated by terracing; periodic maintenance of structure by land users was ignored. Such condition coupled with poor vegetation cover in watershed area has large influence on soil loss rate. The result the study shows that, the minimum p-value is 0.1 for the cultivated land with a slope of less than 5% and the maximum P-value is 1 which is the value assigned for other land use types excluding agricultural land (Fig. 7). Renard *et al.* (1997) defined conservation practice factor as an expression of supporting conservation practices such as contour farming, strip cropping, terracing, and subsurface drainage on soil loss at a particular site, which principally affect water erosion by modifying the flow pattern, grade, or direction of surface runoff and by reducing the volume and rate of runoff.

3.4 Total soil loss analysis (A)

The annual soil loss rate of the study watershed was determined by a cell-by-cell analysis of each RUSLE factor. The annual soil loss rate of the study watershed ranges from less than 2 tons ha^{-1} yr^{-1} in the flat areas to over 500 tons ha^{-1} yr^{-1} in the very steep slopes of the watershed. The mean annual soil loss rate estimated by the RUSLE model for the study watershed was 44.67 tons ha^{-1} yr^{-1} from 569.35 ha. The estimated annual average soil loss rate for the study watershed is high compared to previous studies. For example, Tadesse and Abebe (2014) reported 30.4 tons ha^{-1} yr^{-1} soil loss for Jabi Tehinan Woreda in the northwestern highlands, while Gerawork (2014) estimated soil loss from Loma Woreda as 10.28 tons ha^{-1} yr^{-1}. Similarly, Gebreyesus and Kirubel (2009) estimated soil loss due to erosion in the Medego watershed as 9.63 tons ha^{-1} yr^{-1}. Hurni *et*

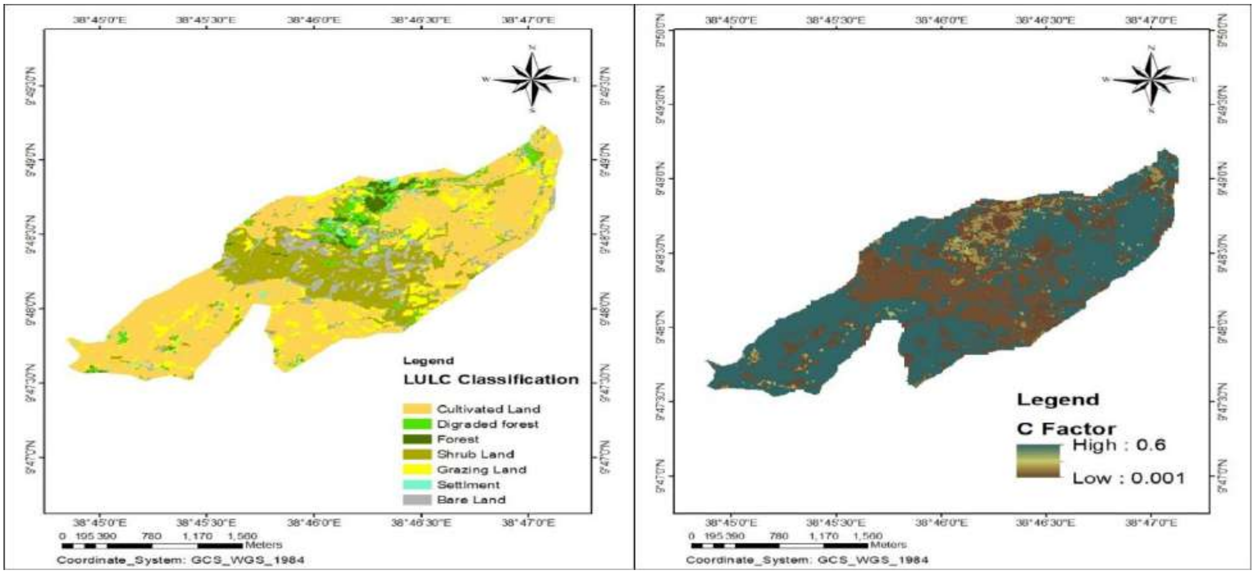

Fig. 6: Land use land cover and C-factor map of the watershed

al. (2008) estimated that soil loss due to erosion in cultivated fields in Ethiopia amounts to about 42 tons ha^{-1} yr^{-1}, and FAO (1986) reported the annual average soil loss rate for the Central and Northern Highlands as 35 tons ha^{-1} yr^{-1}. Therefore, the relatively high estimated average annual soil loss in the current study watershed could be due to the topography, which is largely sloping (8-15%) to very steep (>50%), accounting for 65.24% of the watershed area. Another contributing factor is that only a small part of the watershed area has been treated with terracing, and there is a lack of periodic maintenance of constructed conservation structures by land users.

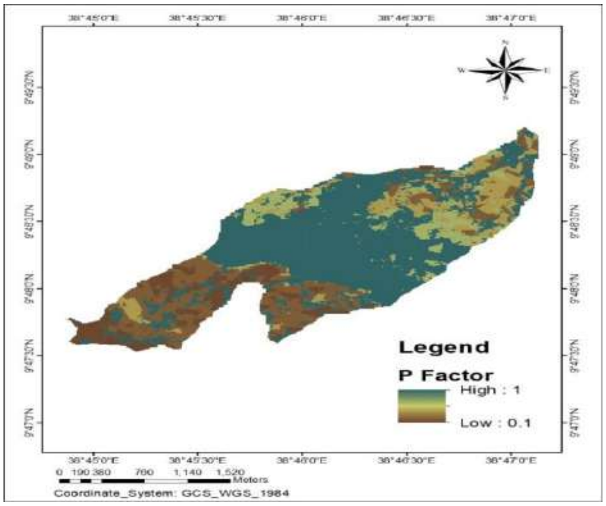

Fig. 7: P-factor map of the watershed

3.5 Classification and prioritization of critical erosion-prone areas for conservation planning

One of the objectives of this study was to classify and prioritize critical erosion-prone areas for conservation planning. Accordingly, the delineation of the watershed into erosion-prone areas was based on the severity level of soil loss, giving priority to targeted and cost-effective conservation planning (Kaltenrieder, 2007). According to Morgan (2009), the total annual soil loss potential of the study watershed was classified into seven soil erosion severity classes: less than 2 tons ha^{-1}yr^{-1} as very slight, 2–5 tons ha^{-1} yr^{-1} as slight, 5–10 tons ha^{-1} yr^{-1} as moderate, 10-50 tons ha^{-1} yr^{-1} as high, 50–100 tons ha^{-1} yr^{-1} as severe, 100–500 tons ha^{-1} yr^{-1} as very severe, and more than 500 tons ha^{-1} yr^{-1} as catastrophic, as shown in Table 6.

The final risk classes were prioritized for intervention based on the maximum allowable soil loss that sustains economic and high productivity levels (Wischmeier and Smith, 1978). Based on the results, the mean annual soil loss rate for the entire watershed (44.67 tons ha^{-1} yr^{-1}) is above the tolerable soil loss threshold of 5–11 tons ha^{-1} yr^{-1} estimated for Ethiopia by Hurni (1985). The results of the study show that about 23.44% of the watershed area undergoes erosion ranging from moderate to very slight classes, 22.54% falls under the high erosion class, 38.8% experiences severe to very severe erosion, and 15.23% is classified under the catastrophic erosion class, according to Morgan's classification (2009), as shown in Table 6. In the study area, slope classes with the largest soil loss rates are primarily due to high erosivity (R-factor) from intense rainfall, high soil erodibility (K-factor), high LS-values - especially due to slope steepness - and the absence of support practices (P = 1). Field observations further indicated that the steeper parts of the land lack vegetative cover and are subject to intensive tillage operations, inadequate soil and water conservation measures, and a general disregard by land users for maintaining conservation structures. This includes failure to remove sediment from channels and repair embankments, which has significantly contributed to the high soil loss potential in the area (Fig. 8).

Table 6: Annual soil loss rates and severity classes with their conservation priority in the watershed (Morgan, 2009)

Soil loss ($t\ ha^{-1}\ y^{-1}$)	Severity class	Priority classes	Area (ha)	Area (%)
<2	Very slight	VII	93.52	16.43
2-5	Slight	VI	17.53	3.08
5-10	Moderate	V	22.37	3.93
10–50	High	IV	128.35	22.54
50-100	Severe	III	79.19	13.91
100-500	Very severe	II	141.68	24.89
>500	Catastrophic	I	86.68	15.23
	Total		569.35	100.0

4. Conclusion

The mean annual soil loss estimated in the Muziye watershed was 44.67 tons ha^{-1} yr^{-1} across a total area of 569.35 hectares. The results indicate that approximately 23.44% of the watershed falls under the moderate (5–10 tons ha^{-1} yr^{-1}) to very slight (<2 tons ha^{-1} yr^{-1}) erosion classes, 22.54% under the high (10–50 tons ha^{-1} yr^{-1}) erosion class, 38.8% under the severe (50–100 tons ha^{-1} yr^{-1}) to very severe (100–500 tons ha^{-1} yr^{-1}) erosion classes, and 15.23% under the catastrophic (>500 tons ha^{-1} yr^{-1}) erosion class, according to Morgan's classification (Morgan, 2009).

The high soil loss observed in the watershed is primarily aggravated by topographic factors, particularly slope steepness, as well as high rainfall erosivity (R-factor), elevated soil erodibility (K-factor), and the lack of effective conservation practices (P-factor). These factors collectively contribute to severe changes in the watershed's hydrological and biological functions, ultimately affecting the ecosystem services that soil provides to human communities. This degradation can significantly impact annual crop yields and overall land productivity, threatening local food security. In addition, the severity of erosion may cause off-site effects such as sedimentation in nearby water bodies.

To reduce soil loss in the study area, several watershed rehabilitation measures are recommended. High to catastrophic erosion-risk zones require the implementation of soil and water

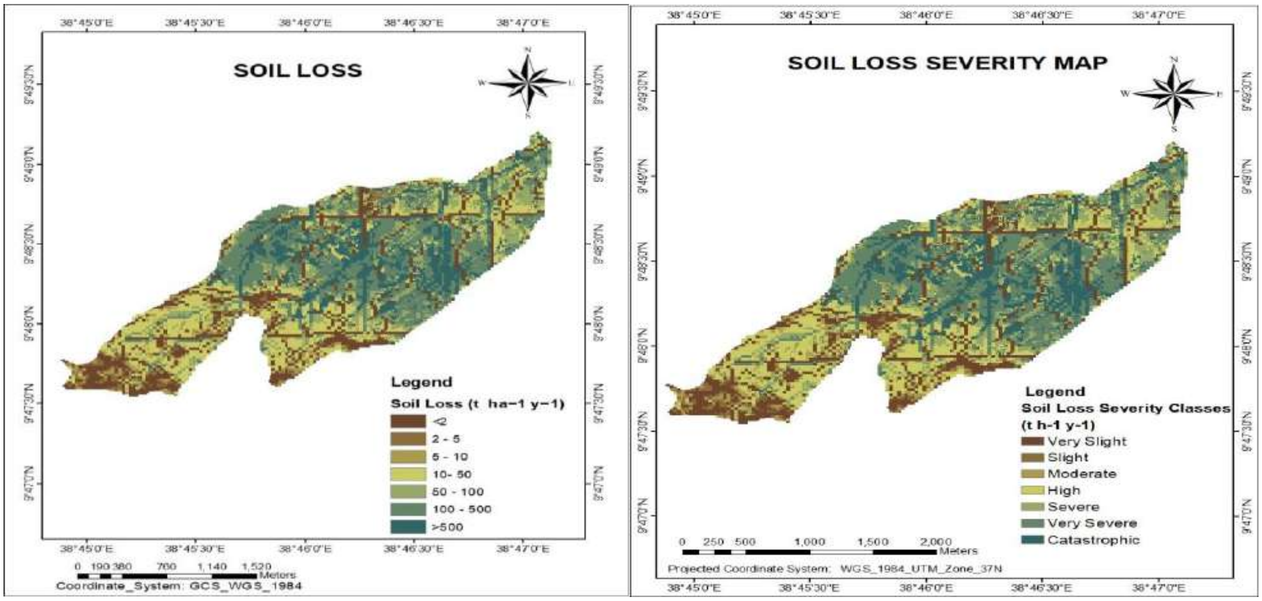

Fig. 8: Annual soil loss and severity classes of the watershed

conservation practices designed to intercept runoff, reduce the transport capacity of surface flow, and improve soil infiltration. These include techniques such as terracing, contour farming, strip cropping, reduced tillage intensity, and the use of cover crops. Rehabilitation of hillside areas with indigenous and exotic tree species should also be encouraged, with active participation from farmers in planning and implementation. Special attention should be given to soil erosion hotspot areas identified on the erosion severity map, prioritizing them for immediate intervention to prevent irreversible land degradation.

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6. Conflicts of interests

Authors declare that there is no conflict of interest exists.

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Evaluation of fertilizer recommendation for Sesame (*Sesamum indicum* L.) in Sudan Savannahs of Nigeria

Bassam Abdulrahman Lawan
Department of Soil Science, Bayero University Kano, PMB 3011

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ABSTRACT

Sesame (*Sesamum indicum* L.) is an important oilseed crop in the Sudan savannahs of Nigeria, but its productivity remains low due to inadequate fertilizer management. This study evaluated the effects of five nitrogen fertilizer rates (0, 30, 60, 90, and 100 kg N ha^{-1}) on growth, yield, and economic returns of sesame during the 2024 rainy season at Bayero University Kano Research Farm. The experiment was laid out in a randomized complete block design with three replications. Phosphorus and potassium were applied uniformly at 30 kg ha^{-1} each across all treatments except the control. Results showed that plant height, number of branches per plant, number of capsules per plant, 1000 seed weight, seed yield, oil content, and harvest index increased significantly ($p<0.05$) with increasing N rates up to 90 kg N ha^{-1}, beyond which no significant differences were observed. The highest seed yield (1085.7 kg ha^{-1}) was recorded at 90 kg N ha^{-1}, representing a 157% increase over the control. Oil content increased from 46.2% in the control to 51.8% at 90 kg N ha^{-1}. Economic analysis revealed that application of 90 kg N ha^{-1} gave the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64). Agronomic efficiency and nitrogen use efficiency decreased with increasing N rates, indicating diminishing returns at higher application rates. The quadratic response model ($y = -0.0353x^2 + 10.4374x + 415.7663$, $R^2 = 0.99$) best described the yield response to nitrogen application. Based on economic and agronomic considerations, application of 90 kg N ha^{-1} is recommended for optimal sesame production in the Sudan savannahs of Nigeria. This finding provides valuable guidance for sesame farmers to maximize productivity and profitability in this agroecological zone.

KEY WORDS: *Sesame*; *Nitrogen fertilizer*; *Yield response*; *Economic analysis*; *Sudan savannah*

1. Introduction

Sesame (*Sesamum indicum* L.) is one of the oldest cultivated oilseed crops in the world, with its cultivation dating back to over 5,000 years ago. It is highly valued for its nutritional, medicinal, and industrial properties. The seeds contain approximately 50-60% high-quality oil that is rich in unsaturated fatty acids, particularly oleic and linoleic acids, and has excellent oxidative stability due to the presence of natural antioxidants such as sesamolin, sesamin, and sesamol (Morris, 2002). Additionally, sesame seeds are a good source of protein (18-25%), carbohydrates (13.5%), and various minerals and vitamins (Langham *et al.*, 2008).

CONTACT Bassam Abdulrahaman ✉ balawan.ssc@buk.edu.ng

In Nigeria, sesame is predominantly cultivated in the northern regions, particularly in the Sudan savannah agroecological zone, which covers parts of Jigawa, Kano, Katsina, Sokoto, Zamfara, Kebbi, Bauchi, Yobe, and Borno states (Umar *et al*., 2014). The crop is well-adapted to this zone due to its drought tolerance, ability to grow in various soil types, and relatively short growing season (90-120 days). Nigeria ranks among the top ten sesame-producing countries globally, with an estimated annual production of 480,000 metric tons from approximately 580,000 hectares (FAOSTAT, 2023). The crop has emerged as an important non-oil export commodity for Nigeria, generating significant foreign exchange earnings and providing livelihood opportunities for millions of smallholder farmers.

Despite its economic importance, the productivity of sesame in Nigeria remains low, with average yields of 500-700 kg ha^{-1}, which is significantly below the global average of 1,200 kg/ha and the potential yield of 2,000 kg ha^{-1} (Haruna, 2016). This yield gap is attributed to several factors, including the use of low-yielding varieties, poor agronomic practices, pest and disease pressure, and most importantly, inadequate soil fertility management (Shehu *et al*., 2010). The Sudan savannah soils are generally characterized by low organic matter content, nitrogen deficiency, and high susceptibility to erosion, which necessitates proper fertilizer management for optimal crop production (Malgwi *et al*., 2000).

Nitrogen (N) is one of the most critical nutrients for sesame production, as it plays a vital role in vegetative growth, photosynthetic efficiency, seed development, and oil synthesis (Shehu, 2014). Several studies have demonstrated positive responses of sesame to nitrogen application in different agroecological zones. For instance, Haruna and Abimiku (2012) reported significant increases in growth and yield parameters of sesame with nitrogen application up to 60 kg N ha^{-1} in the Guinea savannah of Nigeria. Similarly, Ogbonna and Umar-Shaaba (2011) observed that application of 45 kg N ha^{-1} significantly improved sesame yield in the Northern Guinea savannah. However, there is limited information on the optimal nitrogen rate for sesame production specifically in the Sudan savannah agroecological zone of Nigeria.

The response of crops to fertilizer application is influenced by various factors, including soil type, climate, crop variety, and management practices. Therefore, fertilizer recommendations should be site-specific and based on empirical evidence from field experiments conducted under local conditions. Furthermore, in the face of rising fertilizer costs and environmental concerns associated with excessive fertilizer use, it is essential to determine not only the agronomically optimal but also the economically optimal fertilizer rates for sustainable crop production (Vanlauwe *et al*., 2011).

The economic analysis of fertilizer use is particularly important for smallholder farmers who have limited resources and need to maximize returns on their investments. The profitability of fertilizer application depends on the yield response, the cost of fertilizer, and the market price of the produce. By integrating agronomic and economic considerations, farmers can make informed decisions on fertilizer management that optimize both productivity and profitability (Shehu *et al*., 2010).

In light of these considerations, this study was conducted to evaluate the effects of different nitrogen fertilizer rates on the growth, yield, and economic returns of sesame in the Sudan savannah agroecological zone of Nigeria. The specific objectives were to: (1) determine the effects of different nitrogen rates on the growth and yield parameters of sesame; (2) establish the relationship between nitrogen application rate and sesame yield; (3) determine the agronomically and economically optimal nitrogen rates for sesame production; and (4) assess the nitrogen use efficiency at different application rates. The findings of this study will provide valuable guidance for sesame farmers, extension agents, and policymakers in developing appropriate fertilizer management strategies for sustainable sesame production in the Sudan savannah of Nigeria.

2. Material and Methods

The experiment was conducted during the 2024 rainy season (June to October) at the Research Farm of Bayero University Kano, New Campus (latitude 11°58' N, longitude 8°25' E, altitude 466 m above sea level), located in the Sudan savannah agroecological zone of Nigeria. The climate of the area is characterized by a single rainy season that typically begins in May and ends in October, with an average annual rainfall of 850 mm. The soil at the experimental site is classified as sandy loam with moderate fertility status.

2.1 Soil sampling and analysis

Prior to land preparation, soil samples were collected from 0-15 cm and 15-30 cm depths using a soil auger. Fifteen core samples were taken randomly across the experimental field and bulked to form composite samples for each depth. The samples were air-dried, crushed, and passed through a 2-mm sieve before analysis. Soil pH was determined in a 1:2.5 soil-water suspension using a glass electrode pH meter. Organic carbon was determined by the Walkley-Black wet oxidation method, while total nitrogen was determined by the micro-Kjeldahl digestion method. Available phosphorus was extracted using Bray-1 solution and determined colorimetrically. Exchangeable cations (K, Ca, Mg, and Na) were extracted with 1N ammonium acetate solution and determined by atomic absorption spectrophotometry. Particle size analysis was conducted using the hydrometer method.

2.2 Experimental design and treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. The treatments consisted of five nitrogen fertilizer rates: 0 kg N ha^{-1} (control), 30 kg N ha^{-1}, 60 kg N ha^{-1}, 90 kg N ha^{-1}, and 100 kg N ha^{-1}. Phosphorus (P) and potassium (K) were applied uniformly across all treatments (except the control) at the rate of 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}, respectively. The plot size was 4 m × 3 m (12 m^2) with a 0.5 m pathway between plots and a 1 m pathway between replications. The total experimental area was 252 m^2 (including pathways).

2.3 Planting material and crop management

The sesame variety used was NCRIBEN-01M, an improved variety developed by the National Cereals Research Institute, Badeggi, Nigeria, and recommended for the Sudan savannah agroecological zone. The variety has a maturity period of 110-120 days, is resistant to major pests and diseases, and has a potential yield of 1,500-1,800 kg ha^{-1} under optimal management conditions.

Land preparation involved plowing, harrowing, and ridging. Planting was done on June 15, 2024, by direct seeding at a spacing of 75 cm between rows and 15 cm within rows, giving a plant population of approximately 88,889 plants per hectare. Seeds were sown at a depth of 2-3 cm with 3-4 seeds per hole, which were later thinned to one plant per stand at two weeks after emergence.

Fertilizers were applied in two splits: 50% N, 100% P, and 100% K at two weeks after planting (WAP), and the remaining 50% N at five WAP (early flowering stage). The fertilizer sources were urea (46% N), single superphosphate (18% P_2O_5), and muriate of potash (60% K_2O). The fertilizers were applied using the band placement method, 5-7 cm away from the plant rows and incorporated into the soil.

Weed control was done manually at 3, 6, and 9 WAP to ensure weed-free conditions throughout the growing period. Pest management was carried out using an Integrated Pest Management (IPM) approach, with cypermethrin insecticide applied at the rate of 1 L ha^{-1} when pest populations reached economic threshold levels. Disease management involved regular monitoring and prompt control measures when necessary.

2.4 Data collection

Data were collected on growth parameters, yield components, and yield. Plant height was measured from the ground level to the tip of the main stem at 30 days after planting (DAP), 60 DAP, and at maturity (110 DAP) using a measuring tape. Days to 50% flowering was recorded when half of the plants in each plot had at least one open flower. The number of branches per plant and number of capsules per plant were determined from ten randomly selected plants per plot at harvest and averaged.

At physiological maturity (117 days after planting), plants from the net plot area (excluding border rows) were harvested by cutting at the base, sun-dried for one week, and threshed manually. The seeds were cleaned and weighed to determine the seed yield per plot, which was then converted to kilograms per hectare. A sample of 1000 seeds was counted from each plot and weighed to determine the 1000-seed weight. Oil content was determined using the Soxhlet extraction method with n-hexane as the solvent. Harvest index was calculated as the ratio of economic yield (seed yield) to biological yield (total above-ground dry matter) expressed as a percentage.

Nitrogen use efficiency (NUE) metrics were calculated according to the following formulas:

1. Agronomic Efficiency (AE) = $(Yf - Y0) / F$
2. Partial Factor Productivity (PFP) = Yf / F
3. Fertilizer Recovery Efficiency (FRE) = $(Nf - N0) / F \times 100$

Where:

Yf = Seed yield in fertilized plot (kg ha^{-1})
Y0 = Seed yield in control plot (kg ha^{-1})
F = Amount of N fertilizer applied (kg ha^{-1})
Nf = N uptake in fertilized plot (kg ha^{-1})
N0 = N uptake in control plot (kg ha^{-1})

2.5 Weather data

Weather data for the 2024 growing season (May to October) were obtained from the meteorological station at Bayero University Kano, located approximately 500m from the experimental site. The data included daily rainfall, minimum and maximum temperatures, relative humidity, and solar radiation.

2.6 Economic analysis

Economic analysis was conducted to determine the profitability of the different nitrogen fertilizer rates. The total variable costs included land preparation, seeds, planting, weeding, pest control, harvesting, threshing, cleaning, transportation, and fertilizer costs. The cost of urea fertilizer was ₦750 kg^{-1}, single superphosphate was ₦500 kg^{-1}, and muriate of potash was ₦600 kg^{-1}. The market price of sesame seed was ₦1,200 kg^{-1}, based on the prevailing market price in Kano at the time of harvest (October 2024).

Gross revenue was calculated by multiplying the seed yield by the market price. Net returns were calculated as the difference between gross revenue and total production costs. The benefit-cost ratio (BCR) was calculated by dividing the gross revenue by the total production costs.

2.7 Statistical analysis

The data collected were subjected to analysis of variance (ANOVA) using the general linear model procedure of Statistical Analysis System (SAS) software. Treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at a 5% level of probability. Regression analysis was performed to establish the relationship between nitrogen application rates and seed yield. Linear, quadratic, and cubic models were fitted, and the best-fit model was selected based on the coefficient of determination (R^2) and the significance of the regression coefficients.

The economic optimum nitrogen rate was determined by equating the first derivative of the yield response function to the ratio of the price of nitrogen to the price of sesame seed.

3. Results

3.1 Soil physicochemical properties

The physicochemical properties of the soil at the experimental site are presented in **Table 1**. The soil was slightly acidic with pH values of 6.2 and 6.0 at 0-15 cm and 15-30 cm depths, respectively. The organic carbon content was low (0.68% at 0-15 cm and 0.52% at 15-30 cm), as was the total nitrogen content (0.058% at 0-15 cm and 0.042% at 15-30 cm). Available phosphorus was moderate (8.45 mg kg^{-1} at 0-15 cm and 6.32 mg kg^{-1} at 15-30 cm), while exchangeable potassium was low (0.24 cmol kg^{-1} at 0-15 cm and 0.18 cmol kg^{-1} at 15-30 cm). The soil had a sandy loam texture with sand as the dominant particle size fraction (72.4% at 0-15 cm and 70.8% at 15-30 cm).

Table 1: Soil physicochemical properties

Parameter	Value (0-15 cm)	Value (15-30 cm)
pH (H_2O)	6.2	6.0
Organic Carbon (%)	0.68	0.52
Total Nitrogen (%)	0.058	0.042
Available P (mg/kg)	8.45	6.32
Exchangeable K (cmol kg^{-1})	0.24	0.18
Exchangeable Ca (cmol kg^{-1})	2.86	2.54
Exchangeable Mg (cmol kg^{-1})	0.92	0.78
Exchangeable Na (cmol kg^{-1})	0.18	0.15
CEC (cmol kg^{-1})	6.84	5.96
Sand (%)	72.4	70.8
Silt (%)	15.2	16.4
Clay (%)	12.4	12.8
Textural Class	Sandy loam	Sandy loam

3.2 Weather conditions

The weather conditions during the 2024 growing season are summarized in **Table 2**. The total

Table 2: Monthly weather summary (2024 Rainy Season)

Month	Total Rainfall (mm)	Rainy Days	Avg. Min. Temp. (°C)	Avg. Max. Temp. (°C)	Avg. Temp. (°C)	Avg. RH (%)	Avg. Solar Radiation (MJ/m²/day)
May	8.8	2	25.1	39.2	32.2	31	25.0
June	64.4	5	24.9	37.7	31.3	42	23.9
July	252.6	10	23.9	35.6	29.8	64	21.8
August	315.6	10	23.3	34.3	28.8	74	20.3
September	175.8	8	23.3	34.1	28.7	73	20.2
October	62.6	5	23.4	34.6	29.0	69	20.5
Total/Avg.	879.8	40	24.0	35.9	30.0	59	21.9

rainfall during the growing season (May to October) was 879.8 mm, which was slightly above the long-term average for the region (850 mm). The rainfall distribution showed a typical unimodal pattern, with peak rainfall occurring in July (252.6 mm) and August (315.6 mm), which coincided with the vegetative and flowering stages of the crop. The average minimum and maximum temperatures during the growing season were 24.0°C and 35.9°C, respectively, with the highest temperatures recorded in May and the lowest in August. Relative humidity ranged from 31% in May to 74% in August, while solar radiation ranged from 25.0 MJ/m²/day in May to 20.2 MJ/m²/day in September.

3.3 Growth parameters

The effects of different nitrogen rates on the growth parameters of sesame are presented in **Table 3.** Nitrogen application significantly ($p<0.05$) influenced plant height, days to 50% flowering, number of branches per plant, and leaf area index. Plant height at maturity increased progressively with increasing nitrogen rates from 98.1 cm in the control to 162.3 cm at 90 kg N ha^{-1}, representing a 65.4% increase. However, there was no significant difference in plant height between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments.

Days to 50% flowering decreased significantly with increasing nitrogen rates, from 48.3 days in the control to 42.0 days at 90 kg N ha^{-1} and 100 kg N ha^{-1}, indicating that nitrogen application accelerated the flowering process. The number of branches per plant increased from 4.2 in the control to 8.5 at 90 kg N ha^{-1}, but no significant difference was observed between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments. Similarly, leaf area index increased from 2.24 in the control to 4.28 at 90 kg N ha^{-1}, with no significant difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments.

Table 3: Growth Parameters of Sesame at Different Nitrogen Rates

Treatment (kg N ha^{-1})	Plant Height (cm)	Days to 50% Flowering	Number of Branches per Plant	Leaf Area Index
0	98.1±1.6	48.3 ± 0.9	4.2 ± 0.2	2.24±0.05
30	124.4±1.7	45.3 ± 0.9	5.8 ± 0.2	3.18±0.05
60	146.5±1.7	43.3 ± 0.9	7.3 ± 0.2	3.86±0.05
90	162.3±1.5	42.0 ± 0.6	8.5 ± 0.2	4.28±0.05
100	163.2±1.3	42.0 ± 0.6	8.6 ± 0.2	4.30±0.05

Table 4: Yield components and yield of Sesame at different Nitrogen rates

Treatment (kg N/ha)	Capsules per Plant	1000 Seed Weight (g)	Seed Yield (kg/ha)	Oil Content (%)	Harvest Index (%)
0	42.3 ± 1.4	2.84 ± 0.05	422.3 ± 12.9	46.2 ± 0.3	22.4 ± 0.5
30	68.1 ± 1.6	3.12 ± 0.04	680.9 ± 14.7	48.4 ± 0.3	26.8 ± 0.5
60	92.6 ± 1.7	3.35 ± 0.04	923.1 ± 15.2	50.6 ± 0.3	30.5 ± 0.4
90	112.5 ± 1.9	3.48 ± 0.03	1085.7 ± 15.7	51.8 ± 0.3	32.6 ± 0.5
100	113.4 ± 1.7	3.49 ± 0.03	1092.1 ± 15.2	51.9 ± 0.3	32.7 ± 0.5

3.4 Yield components and yield

The effects of different nitrogen rates on yield components and yield of sesame are presented in **Table 4**. Nitrogen application significantly ($p<0.05$) influenced the number of capsules per plant, 1000-seed weight, seed yield, oil content, and harvest index. The number of capsules per plant increased from 42.3 in the control to 112.5 at 90 kg N ha^{-1}, representing a 166% increase. However, there was no significant difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments.

The 1000 seed weight increased from 2.84 g in the control to 3.48 g at 90 kg N ha^{-1}, but no significant difference was observed between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments. Seed yield showed a similar trend, increasing from 422.3 kg ha^{-1} in the control to 1085.7 kg ha^{-1} at 90 kg N ha^{-1}, representing a 157% increase. The difference in seed yield between 90 kg N ha^{-1} (1085.7 kg ha^{-1}) and 100 kg N ha^{-1} (1092.1 kg ha^{-1}) was not statistically significant.

Oil content increased from 46.2% in the control to 51.8% at 90 kg N ha^{-1}, with no significant difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments. Harvest index also increased from 22.4% in the control to 32.6% at 90 kg N ha^{-1}, but the difference between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments was not statistically significant.

3.5 Yield response to Nitrogen

The relationship between nitrogen application rate and sesame seed yield was best described by a quadratic model: $Y = -0.0353x^2 + 10.4374x + 415.7663$ ($R^2 = 0.99$), where Y is the seed yield (kg ha^{-1}) and x is the nitrogen application rate (kg N ha^{-1}). The high coefficient of determination ($R^2 = 0.99$) indicates that 99% of the variation in seed yield could be explained by the nitrogen application rate.

Based on the quadratic model, the agronomic optimum nitrogen rate (the rate that gives the maximum yield) was calculated to be 147.8 kg N ha^{-1}. However, the economic optimum nitrogen rate, determined by equating the first derivative of the yield response function to the ratio of the price of nitrogen to the price of sesame seed, was 90 kg N ha^{-1}. This rate gave the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64) among all the treatments tested.

3.6 Nitrogen use efficiency

The nitrogen use efficiency metrics at different nitrogen application rates are presented in **Table 5**. Agronomic efficiency (AE) decreased with increasing nitrogen rates, from 8.62 kg seed/kg N at 30 kg N ha^{-1} to 6.70 kg seed kg^{-1} N at 100 kg N ha^{-1}. Similarly, partial factor productivity (PFP) decreased from 22.70 kg seed kg^{-1} N at 30 kg N ha^{-1} to 10.92 kg seed kg^{-1} N at 100 kg N ha^{-1}. Fertilizer recovery efficiency (FRE) also decreased with increasing nitrogen rates, from 42.60% at 30 kg N ha^{-1} to 32.80% at 100 kg N ha^{-1}. These trends indicate diminishing returns with increasing nitrogen application rates.

3.7 Economic analysis

The economic analysis of sesame production at different nitrogen rates is presented in **Table 6**. Total production costs increased with increasing nitrogen rates, from ₦220,500 ha^{-1} in the control to ₦369,196 ha^{-1} at 100 kg N/ha, primarily due to the increased fertilizer costs. Gross revenue also increased with increasing nitrogen rates, from ₦506,760 ha^{-1} in the control to ₦1,310,520 ha^{-1} at 100 kg N ha^{-1}, reflecting the higher yields obtained with nitrogen application.

Net returns increased from ₦286,260 ha^{-1} in the control to ₦944,514 ha^{-1} at 90 kg N ha^{-1}, representing a 230% increase. However, there was a slight decrease in net returns at 100 kg N/ha (₦941,324 ha^{-1}) compared to 90 kg N ha^{-1}, indicating that the additional yield obtained with the higher nitrogen rate did not compensate for the increased fertilizer cost.

The benefit-cost ratio (BCR) increased from 2.30 in the control to 3.64 at 90 kg N ha^{-1}, then decreased slightly to 3.55 at 100 kg N ha^{-1}. The highest BCR at 90 kg N ha^{-1} indicates that this nitrogen rate provided the most economically efficient production, with each naira invested in production yielding 3.64 naira in return.

4. Discussion

The results of this study demonstrate the significant influence of nitrogen fertilization on the growth, yield, and economic returns of sesame in the Sudan savannah agroecological zone of Nigeria. The observed responses can be attributed to the essential role of nitrogen in various physiological and biochemical processes in plants, including photosynthesis, protein synthesis, enzyme activation, and overall metabolic activities (Shehu, 2014).

Table 5: Nitrogen use efficiency metrics at different application rates

Treatment (kg N ha^{-1})	Agronomic Efficiency (kg yield increase kg^{-1} N)	Partial Factor Productivity (kg seed kg^{-1} N)	Fertilizer Recovery Efficiency (%)
0	-	-	-
30	8.62	22.70	42.60
60	8.35	15.39	38.40
90	7.37	12.06	34.20
100	6.70	10.92	32.80

Table 6: Economic analysis of Sesame production at different Nitrogen rates

Treatment (kg N ha^{-1})	Total Production Cost (₦ ha^{-1})	Average Yield (kg ha^{-1})	Gross Revenue (₦ ha^{-1})	Net Returns (₦ ha^{-1})	Benefit-Cost Ratio
0	220,500	422.3	506,760	286,260	2.30
30	293,109	680.9	817,080	523,971	2.79
60	325,717	923.1	1,107,720	782,003	3.40
90	358,326	1085.7	1,302,840	944,514	3.64
100	369,196	1092.1	1,310,520	941,324	3.55

4.1 Effects on growth parameters

The significant increase in plant height with increasing nitrogen rates up to 90 kg N ha^{-1} observed in this study is consistent with findings

from previous research. Haruna and Abimiku (2012) reported similar increases in plant height of sesame with nitrogen application in the Guinea savannah of Nigeria. The enhanced vegetative growth can be attributed to the role of nitrogen in cell division and elongation, which promotes stem and leaf development (Langham *et al*., 2008). The lack of significant difference in plant height between 90 kg N ha^{-1} and 100 kg N ha^{-1} treatments suggests that 90 kg N ha^{-1} was sufficient to meet the nitrogen requirement for vegetative growth of sesame under the conditions of this study.

The reduction in days to 50% flowering with increasing nitrogen rates indicates that nitrogen application accelerated the transition from vegetative to reproductive phase. This finding contradicts some earlier reports that high nitrogen levels delay flowering in sesame (Ogbonna and Umar-Shaaba, 2011). However, it aligns with the observations of Shehu *et al*. (2010), who reported earlier flowering in sesame with moderate nitrogen application in the Sudan savannah. The contrasting results may be due to differences in environmental conditions, sesame varieties, and the range of nitrogen rates tested. In our study, the accelerated flowering with nitrogen application could be advantageous in the Sudan savannah, where the growing season is relatively short and early maturity can help avoid terminal drought stress.

The increase in the number of branches per plant with nitrogen application is an important finding, as branching is directly related to the number of fruiting points and, consequently, yield potential in sesame (Langham *et al*., 2008). The enhanced branching with nitrogen application can be attributed to the role of nitrogen in promoting lateral bud development and reducing apical dominance (Morris, 2002). The plateau in branching observed at 90 kg N ha^{-1} suggests that this rate was optimal for branch development under the conditions of this study.

The leaf area index (LAI) showed a similar response pattern to nitrogen application as other growth parameters, with significant increases up to 90 kg N ha^{-1}. LAI is a critical determinant of light interception, photosynthetic capacity, and ultimately, biomass production (Shehu, 2014). The enhanced LAI with nitrogen application can be attributed to increased leaf number, leaf size, and leaf longevity, all of which contribute to greater light interception and photosynthetic efficiency (Haruna, 2016).

4.2 Effects on yield components and yield

The significant increase in the number of capsules per plant with nitrogen application is a key factor contributing to the enhanced seed yield. Capsule number is considered the most important yield component in sesame, as it directly influences the number of seeds produced per plant (Langham *et al.*, 2008). The increased capsule number with nitrogen application can be attributed to the combined effects of enhanced branching, which provides more fruiting points, and improved plant nutrition, which supports capsule development and reduces capsule abortion (Shehu *et al.*, 2010).

The improvement in 1000 seed weight with nitrogen application indicates that nitrogen not only increased the number of seeds but also enhanced seed filling and development. This can be attributed to the role of nitrogen in photosynthate production and translocation to developing seeds (Haruna and Abimiku, 2012). The plateau in seed weight observed at 90 kg N ha^{-1} suggests that this rate was sufficient to optimize seed development under the conditions of this study.

The seed yield response to nitrogen application followed a quadratic pattern, with significant increases up to 90 kg N ha^{-1}, beyond which no significant improvement was observed. The maximum yield of 1085.7 kg ha^{-1} obtained at 90 kg N ha^{-1} represents a 157% increase over the control, highlighting the substantial yield benefit of appropriate nitrogen fertilization. This yield level is comparable to the global average of 1,200 kg ha^{-1} (FAOSTAT, 2023) and significantly higher than the national average of 500-700 kg ha^{-1} (Haruna, 2016), indicating the potential for substantial yield improvements in sesame production in Nigeria through proper fertilizer management.

The quadratic yield response to nitrogen observed in this study is consistent with the law of diminishing returns, which states that as more of a variable input (in this case, nitrogen) is added to a fixed set of resources, the incremental output (yield) eventually decreases (Vanlauwe *et al.*, 2011). The diminishing returns at higher nitrogen rates can be attributed to several factors, including potential nutrient imbalances, increased vegetative growth at the expense of reproductive development, and possible environmental losses of nitrogen through leaching, volatilization, or denitrification (Shehu, 2014).

The optimal nitrogen rate for sesame production depends on both agronomic and economic considerations. While the agronomic optimum (the rate that gives the maximum yield) was calculated to be 147.8 kg N ha^{-1} based on the quadratic model, the economic optimum (the rate that gives the maximum net return) was determined to be 90 kg N ha^{-1}. This discrepancy highlights the importance of considering economic factors in fertilizer recommendations, as the additional yield obtained with higher nitrogen rates may not always justify the increased fertilizer cost (Vanlauwe *et al.*, 2011).

4.3 Effects on oil content and quality

The increase in oil content with nitrogen application up to 90 kg N ha^{-1} observed in this study is noteworthy, as it indicates that nitrogen not only enhanced seed yield but also improved seed quality. This finding contradicts some earlier reports that high nitrogen levels reduce oil content in oilseed crops due to a shift in carbon allocation from oil synthesis to protein synthesis (Ogbonna and Umar-Shaaba, 2011). However, it aligns with the observations of Haruna (2016), who reported increased oil content in sesame with moderate nitrogen application in the Northern Guinea savannah.

The positive effect of nitrogen on oil content in our study can be attributed to several factors. First, nitrogen is a constituent of enzymes involved in oil synthesis, such as acetyl-CoA carboxylase and fatty acid synthase (Morris, 2002). Second, adequate nitrogen nutrition enhances photosynthetic efficiency and carbon assimilation, providing more substrates for oil synthesis (Shehu, 2014). Third, nitrogen promotes root development and nutrient uptake, which can improve the overall nutritional status of the plant and support oil accumulation in seeds (Langham *et al*., 2008).

The plateau in oil content observed at 90 kg N ha^{-1} suggests that this rate was optimal for oil synthesis under the conditions of this study. The slight decrease in oil content at 100 kg N ha^{-1}, although not statistically significant, may indicate a shift in carbon allocation from oil synthesis to protein synthesis at very high nitrogen levels, as suggested by some researchers (Ogbonna and Umar-Shaaba, 2011).

4.4 Nitrogen use efficiency

The decreasing trends in agronomic efficiency (AE), partial factor productivity (PFP), and fertilizer recovery efficiency (FRE) with increasing nitrogen rates observed in this study are consistent with the law of diminishing returns and have important implications for sustainable fertilizer management. The highest AE (8.62 kg seed kg^{-1} N) and PFP (22.70 kg seed kg^{-1} N) were obtained at the lowest nitrogen rate (30 kg N ha^{-1}), indicating that nitrogen use efficiency was maximized at this rate. However, the yield and economic returns were suboptimal at this rate, highlighting the trade-off between nitrogen use efficiency and productivity.

The FRE values ranged from 42.60% at 30 kg N ha^{-1} to 32.80% at 100 kg N ha^{-1}, indicating that a substantial portion of the applied nitrogen was not recovered by the crop. This could be due to various loss pathways, including leaching, volatilization, denitrification, and immobilization (Vanlauwe *et al*., 2011). The sandy loam texture of the soil at the experimental site, with its relatively low clay and organic matter content, may have contributed to nitrogen losses through leaching, particularly during periods of heavy rainfall in July and August.

To improve nitrogen use efficiency while maintaining high productivity, several strategies could be explored in future research, including the use of slow-release nitrogen fertilizers, split applications tailored to crop demand, precision application methods, and integrated nutrient management approaches that combine mineral fertilizers with organic inputs (Shehu, 2014).

4.5 Economic implications

The economic analysis revealed that nitrogen application significantly enhanced the profitability of sesame production, with the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64) obtained at 90 kg N ha^{-1}. This represents a 230%

increase in net return compared to the control, highlighting the substantial economic benefit of appropriate nitrogen fertilization. The slight decrease in net return and BCR at 100 kg N ha^{-1} indicates that the additional yield obtained with the higher nitrogen rate did not compensate for the increased fertilizer cost, further supporting the recommendation of 90 kg N ha^{-1} as the economically optimal rate.

The high BCR values (ranging from 2.30 in the control to 3.64 at 90 kg N ha^{-1}) indicate that sesame production is a profitable enterprise in the Sudan savannah of Nigeria, even without fertilizer application. However, the substantial increase in BCR with nitrogen application suggests that fertilizer use can significantly enhance the economic returns of sesame production, making it an attractive investment for farmers.

It is important to note that the economic optimum nitrogen rate may vary with changes in input and output prices. For instance, an increase in fertilizer prices or a decrease in sesame seed prices would lower the economic optimum, while a decrease in fertilizer prices or an increase in sesame seed prices would raise it (Vanlauwe *et al*., 2011). Therefore, fertilizer recommendations should be flexible and adaptable to changing economic conditions.

4.6 Practical implications and recommendations

Based on the findings of this study, application of 90 kg N ha^{-1}, along with 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}, is recommended for optimal sesame production in the Sudan savannah agroecological zone of Nigeria. This recommendation is based on both agronomic and economic considerations, as this rate gave the highest net return and benefit-cost ratio among all the treatments tested.

For practical implementation, the recommended fertilizer rate translates to approximately 196 kg ha^{-1} of urea (46% N), 167 kg ha^{-1} of single superphosphate (18% P_2O_5), and 50 kg ha^{-1} of muriate of potash (60% K_2O). The fertilizers should be applied in two splits: 50% N, 100% P, and 100% K at two weeks after planting, and the remaining 50% N at five weeks after planting (early flowering stage).

It is important to note that this recommendation is based on a single-season experiment at one location, and the optimal fertilizer rate may vary with soil type, climate, crop variety, and management practices. Therefore, farmers are encouraged to consider their specific conditions and, if possible, conduct simple on-farm trials to fine-tune the fertilizer rates for their particular situations.

Furthermore, fertilizer application should be integrated with other good agronomic practices, such as timely planting, appropriate plant spacing, effective weed management, and adequate pest and disease control, to maximize the benefits of fertilizer use and achieve optimal crop productivity and profitability.

5. Conclusion

This study evaluated the effects of different nitrogen fertilizer rates (0, 30, 60, 90, and 100 kg N ha^{-1}) on the growth, yield, and economic returns of sesame in the Sudan savannah agroecological zone of Nigeria. Based on the findings, the following conclusions can be drawn:

1. Nitrogen application significantly enhanced the growth parameters of sesame, including plant height, number of branches per plant, and leaf area index, with optimal responses observed at 90 kg N ha^{-1}.

2. Nitrogen fertilization accelerated the flowering process, with days to 50% flowering decreasing from 48.3 days in the control to 42.0 days at 90 kg N ha^{-1}, which is advantageous in the Sudan savannah where the growing season is relatively short.

3. Yield components, including number of capsules per plant and 1000 seed weight, increased significantly with nitrogen application up to 90 kg N ha^{-1}, beyond which no significant improvements were observed.

4. Seed yield showed a quadratic response to nitrogen application, increasing from 422.3 kg ha^{-1} in the control to 1085.7 kg ha^{-1} at 90 kg N ha^{-1} (a 157% increase), with no significant yield advantage at 100 kg N ha^{-1}.

5. Oil content increased from 46.2% in the control to 51.8% at 90 kg N ha^{-1}, indicating that appropriate nitrogen fertilization can enhance both seed yield and quality.

6. Nitrogen use efficiency metrics (agronomic efficiency, partial factor productivity, and fertilizer recovery efficiency) decreased with increasing nitrogen rates, indicating diminishing returns at higher application rates.

7. Economic analysis revealed that application of 90 kg N ha^{-1} gave the highest net return (₦944,514 ha^{-1}) and benefit-cost ratio (3.64), making it the economically optimal rate for sesame production under the conditions of this study.

Based on these findings, application of 90 kg N ha^{-1}, along with 30 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}, is recommended for optimal sesame production in the Sudan savannah agroecological zone of Nigeria. This recommendation provides a balance between agronomic performance, economic returns, and resource use efficiency.

Future research should focus on validating these findings across multiple locations and seasons, exploring the interactions between nitrogen and other nutrients, investigating the effects of different nitrogen sources and application methods on sesame performance, and developing site-specific fertilizer recommendations based on soil testing and crop monitoring. Additionally, studies on the residual effects of fertilizer application and the sustainability of different fertilizer management strategies would contribute to the development of more comprehensive and environmentally sound recommendations for sesame production in the Sudan savannah of Nigeria.

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Gender participation in climate-resilient agriculture: A study of food security outcomes in Kebbi state, Nigeria

Alhassan Y J[1], **Sanchi I D**[2] and **Manga T A**[2]
[1]Department of Agricultural Economics and Extension Federal University Wukari, Taraba State, Nigeria
[2]Department of Agricultural economics and Extension Federal University of Agriculture, Zuru, Kebbi State, Nigeria

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ABSTRACT

The study examines gender participation in climate-resilient agriculture (CRA) practices and its implications for food security in Kebbi State, Nigeria. Data were collected through surveys and interviews with 220 farmers, focusing on understanding the participation rates of male and female farmers in various CRA practices, the constraints they face, and the factors influencing food security outcomes. Results show that male farmers had higher participation rates in most CRA practices, including drought-resistant crops, water harvesting, and agroforestry, with an average participation rate of 59% for males and 54% for females. The study also identifies several constraints that hinder participation, with female farmers facing more significant challenges than their male counterparts. These include land ownership, access to credit, cultural restrictions, and domestic workload. Logistic regression analysis reveals that factors such as gender, access to CRA inputs, extension contact, land ownership, education level, household size, access to credit, and experience with climate shocks significantly influence food security. Male-headed households, households with access to CRA inputs, and those with regular extension contact were more likely to be food secure. The study concludes that gender disparities in participation in climate-resilient agriculture practices contribute to unequal food security outcomes. Although both male and female farmers participate in CRA practices, women face more barriers that limit their full participation and ability to enhance their food security. It is essential to recognize the role of gender in agricultural decision-making processes and to address the socio-economic factors that limit women's access to resources. Recommendations include the need for targeted interventions that reduce the gender gap in CRA practices by providing women with better access to land, credit, and extension services. Empowering female farmers through training, promoting gender-inclusive policies in agricultural development, and improving women's access to climate-resilient agricultural inputs are critical steps. Additionally, addressing cultural and social barriers that restrict women's mobility and participation in decision-making will be crucial in enhancing their contribution to climate-resilient agriculture and improving overall food security in the region.

KEY WORDS: *Gender participation*; *Climate-resilient agriculture*; *Food security*; *Agricultural practices*

1. Introduction

Climate change represents a formidable threat to agricultural sustainability and food security globally, particularly in Sub-Saharan Africa, where agriculture is predominantly rain-fed and highly climate-sensitive. Rising temperatures, erratic rainfall, prolonged droughts,

CONTACT Alhassan Y J ✉ yohannaj@fuwukari.edu.ng

desertification, and flooding are among the major climate-related stressors that have significantly disrupted agricultural livelihoods and rural economies across the continent. Nigeria, like many other African countries, is grappling with these adverse impacts, which are projected to intensify in both frequency and severity. Kebbi State, located in the northwestern region of Nigeria, is notably vulnerable due to its reliance on smallholder, subsistence agriculture that depends on predictable climatic patterns. The state's agro-ecological zones have been experiencing increasing variability in rainfall patterns, shortened growing seasons, declining crop yields, and frequent pest and disease outbreaks—all of which undermine food availability and rural livelihoods. In response to these mounting pressures, the adoption of Climate-Resilient Agriculture (CRA) practices has emerged as a promising pathway to enhance adaptive capacity, safeguard food systems, and foster environmental sustainability.

CRA encompasses a variety of practices and technologies, including agroforestry, drought-tolerant crop varieties, water conservation techniques, integrated pest management, organic composting, and improved livestock management. These innovations not only buffer against climate shocks but also contribute to long-term productivity and ecological balance. However, the effectiveness of CRA interventions is closely tied to social factors such as access to resources, decision-making power, and institutional support - elements that are often shaped by gender dynamics. Gender plays a pivotal role in shaping agricultural adaptation strategies, as men and women experience different vulnerabilities and possess distinct capacities to respond to climate-induced challenges. Although both male and female farmers contribute significantly to agricultural production in Kebbi State, prevailing gender disparities in access to land, agricultural inputs, extension services, and climate information hinder women's full participation in CRA. These disparities are often rooted in traditional norms, legal constraints, and institutional biases that marginalize women in rural development processes.

Thus, understanding gender differences in participation in CRA is critical to designing inclusive policies and interventions that effectively enhance food security. This study seeks to empirically examine the relationship between gender participation in CRA and food security outcomes in Kebbi State. By highlighting the structural barriers that limit women’s engagement in CRA and analyzing their implications on household food security, the study aims to inform gender-sensitive climate adaptation strategies and contribute to the broader discourse on sustainable development in Nigeria.

Climate-resilient agriculture (CRA) has emerged as a vital strategy to mitigate the adverse effects of climate change on agricultural productivity and food systems. With climate shocks becoming increasingly frequent and severe - particularly in vulnerable regions such as Kebbi State - the adoption of adaptive agricultural practices is crucial for safeguarding rural livelihoods and ensuring long-term food security. Despite growing awareness and institutional backing for CRA initiatives in Nigeria, gender disparities remain a significant barrier to the full realization of their benefits. In many rural communities of Kebbi State, women comprise a substantial share of the agricultural workforce. However, they continue to face marginalization in terms of access to essential resources such as land, credit, extension services, and climate-related information.

Structural obstacles, including patriarchal land tenure systems, gender-based financial schemes, and the underrepresentation of women in decision-making bodies, hinder their ability to actively and effectively participate in climate adaptation initiatives.

These gender-based constraints not only weaken the impact of CRA interventions but also heighten household vulnerability to food insecurity. Moreover, the formulation and execution of agricultural policies and programs in Nigeria have often been gender-blind, overlooking the distinct needs, responsibilities, and adaptive capacities of men and women. Empirical evidence examining the influence of gender participation on CRA outcomes and household food security - especially in the specific context of Kebbi State - is limited. The absence of gender-disaggregated data impedes the development of inclusive, evidence-based strategies for climate adaptation and resilience-building within the food system.

In light of these challenges, this study seeks to explore the extent and determinants of male and female participation in climate-resilient agricultural practices, identify gender-specific constraints, and assess how such participation impacts household food security outcomes. Addressing this research gap is essential for informing the development of gender-responsive agricultural policies that promote equity, resilience, and sustainable development in climate-vulnerable regions.

The general objective of the study is to examine the impact of gender participation in climate-resilient agriculture on household food security outcomes in Kebbi State, Nigeria. Specifically, the study aims to: (1) assess the level of male and female participation in climate-resilient agricultural practices; (2) identify the key constraints affecting gender participation in CRA; and (3) evaluate how gender participation in CRA influences household food security outcomes.

2. Material and Methods

2.1 Description of the study area

Kebbi State is situated in North-western Nigeria, located approximately between latitudes 10°05'N and 13°45'N and longitudes 3°30'E and 6°02'E. It shares international boundaries with the Republic of Niger to the north and Benin Republic to the west, and borders domestically with Sokoto State to the northwest, Zamfara State to the east, and Niger State to the south. The state covers a land area of about 36,800 square kilometers and has a projected population of approximately 5 million people as of the 2023 estimate (National Population Commission, 2023).

Administratively, the state comprises four major agricultural zones: Argungu, Zuru, Yauri, and Birnin Kebbi. The economy of Kebbi State is predominantly agrarian, with major economic activities including rice, millet, sorghum, and maize farming, as well as livestock rearing and artisanal fishing.

Kebbi is recognized as one of Nigeria’s leading rice-producing states and hosts several irrigation schemes to support dry season farming. The region experiences a tropical climate characterized by a distinct wet season (May to October) and dry season (November to April), with annual rainfall ranging between 800 mm and 1,000 mm. The state’s ecological diversity and dependence on rain-fed agriculture make it highly vulnerable to climate-induced hazards such as drought, floods, and soil degradation.

2.2 Population of the study

The target population for this study includes all male and female smallholder farmers engaged in crop and livestock production across the four agricultural zones of Kebbi State.

2.3 Research design

This study employs a descriptive survey research design complemented by inferential statistical analysis to assess gender participation in CRA and its effects on food security outcomes.

2.4 Sampling procedure and sample size

A multistage sampling technique was adopted to ensure representativeness and gender balance: In Stage 1,One Local Government Area (LGA) was purposively selected from each of the four agricultural zones in Kebbi State: Argungu (Central), Zuru (South), Yauri (East), and Birnin Kebbi (Northwest). These LGAs were selected based on the prominence of farming activities and the presence of CRA-related interventions. In Stage 2, two farming communities were randomly selected from each selected LGA to capture intra-LGA diversity. In Stage 3**,** within each community, farmers were stratified by gender. From each stratum, simple random sampling was used to select an equal number of male and female farmers. A total of 220 respondents were selected, comprising 110 male and 110 female farmers, ensuring gender parity across the sample (Table 1).

2.5 Data collection procedures

Primary data were collected using a structured questionnaire. The questionnaire was designed to capture quantitative data on socio-demographic characteristics, CRA practices, access to resources, and household food security status, measured using the Household Food Insecurity Access Scale (HFIAS). The instrument was pre-tested for reliability and administered by trained enumerators across all selected communities. Responses were recorded and coded for statistical analysis.

2.6 Data analysis procedure and model specification

Data analysis will be conducted in two main phases: descriptive and inferential analysis.Descriptive statistics such as frequencies, percentages, means, and standard deviations will be used to summarize and present the socio-demographic characteristics of respondents, their participation in climate-resilient agriculture (CRA) practices, and household food security status. This will help provide an overview of the

Table 1: Distribution of Sampled Respondents by LGA and Gender

Agricultural Zone	LGA	Communities Sampled	Male Farmers	Female Farmers	Total
Central	Argungu	2	28	28	56
South	Zuru	2	27	27	54
East	Yauri	2	28	28	56
Northwest	Birnin Kebbi	2	27	27	54
Total		8	110	110	220

data before applying any inferential techniques.To examine the relationship between gender participation in CRA and household food security, a Binary Logistic Regression model will be used. This is appropriate since the dependent variable (household food security) is binary, coded as 1 (food secure) and 0 (food insecure).The binary logistic regression model will allow us to estimate the probability of a household being food secure based on various independent variables, including gender participation in CRA and other relevant socio-economic factors.

2.7 Model specification

The Logit model can be expressed as follows: The dependent variable (household food security) is binary, coded as 1 (food secure) and 0 (food insecure). The binary logistic regression model will allow us to estimate the probability of a household being food secure based on various independent variables, including gender participation in CRA and other relevant socio-economic factors.

Logit (P) = $\ln(P1-P)=\beta0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_5X_5+\beta_6X_6+\beta_7X_7+\beta_8X_8+\epsilon$

Where:
P = Probability of a household being food secure
$\beta0$ = Constant term
ϵ = Error term
β_1- β_8- Coefficients estimated

Parameter measured:
X_1 Gender of the Respondent (Male = 1, Female = 0):
X_2 - Access to Climate-Resilient Agriculture Inputs (Scale 1-5)
X_3 -Frequency of Contact with Extension Services (Scale 1-5)
X_4- Land Ownership (1 = Owned, 0 = Rented/Sharecropped)
X_5 - Household Income (Log of Monthly Income in Naira)
X_6- Availability of Water Resources (Scale 1-5)
X_7 - Education Level of Household Head (Years of Formal Education):
X_8- Social Capital (Scale 1-5)

3. Results and Discussion

Table 2 presents gender-disaggregated participation rates in nine climate-resilient agricultural (CRA) practices. The data reveals significant variation across practices and between genders. Male farmers demonstrated higher participation in drought-resistant crops (78%), water harvesting (69%), and crop diversification (70%), suggesting better access to climate adaptation inputs, which aligns with findings by Nhemachena and Hassan (2007) who noted that men tend to dominate practices that require capital and technological knowledge. Conversely, female farmers slightly outpaced males in organic composting (60% vs. 55%), indicating their stronger engagement in low-cost sustainable soil fertility management. This is consistent with studies such as those by Jost *et al.* (2016), who observed that women tend to adopt low-input and labor-intensive practices due to their limited access to productive resources.

The mean participation rates range from 52% (zero/reduced tillage) to 66% (drought-resistant crops), with an overall average of approximately 59%. The highest gender disparity is observed in drought-resistant crops (SD = 16.97%), suggesting a gender gap in access to improved seed varieties and information. This supports the argument of Doss (2001) that unequal access to extension

Table 2: Level of participation in CRA practices by gender (N = 220)

CRA Practice	Male (%)	Female (%)	Mean	Std. Dev. (%)
Drought-resistant crops	78	54	66.0	16.97
Water harvesting	69	42	55.5	19.09
Organic composting	55	60	57.5	3.54
Agroforestry	64	51	57.5	9.19
Crop diversification	70	58	64.0	8.49
Mulching	62	50	56.0	8.49
Integrated pest management	59	47	53.0	8.49
Use of cover crops	66	52	59.0	9.90
Zero/reduced tillage	61	43	52.0	12.73

Source: Field survey, 2025

services and inputs contributes to lower adoption rates among women. On the other hand, practices like organic composting (SD = 3.54%) show minimal disparity, suggesting these may serve as viable entry points for promoting inclusive CRA adoption. Similarly, practices such as agroforestry, mulching, and integrated pest management show moderate gender gaps and can be enhanced through targeted capacity-building programs. These findings underline the importance of gender-responsive approaches in the design and implementation of CRA interventions in Kebbi State. Policies must address structural barriers, including unequal land tenure, access to credit, and technical training. As Meinzen-Dick *et al.* (2011) argue, enhancing women's participation in agricultural innovation is crucial for climate resilience and food security.

The data in Table 3 clearly indicate that female farmers experience significantly greater constraints than their male counterparts in engaging with Climate-Resilient Agriculture (CRA) practices. These findings are consistent with prior studies in sub-Saharan Africa that document gender-based disparities in agricultural access and productivity (FAO, 2011; Peterman *et al.*, 2014). Land ownership is one of the most pressing challenges for women, with 74% of female respondents citing it as a constraint compared to only 32% of males**.** This reflects entrenched patriarchal land tenure systems that restrict women’s legal rights to land a key resource for agricultural innovation and resilience (Agarwal, 1994).

Limited access to credit also disproportionately affects women (65%) compared to men (48%). This limits women's ability to invest in improved seeds, irrigation tools, and other climate-smart technologies, reinforcing a cycle of low productivity and vulnerability (World Bank, 2009). A poor extension contact rate among females (68%) underscores their exclusion from critical information channels needed for adopting CRA. Men's better access (39%) still indicates a gap, but one that is significantly narrower. Women often miss out on extension services due to time constraints and societal norms (Meinzen-Dick *et al*., 2011). Cultural restrictions, such as mobility limitations and gender-based roles, were cited by 61% of women, compared to 22% of men. These barriers significantly restrict women's ability to attend training, join cooperatives, or market their produce.

Educational attainment also influences participation, with 56% of females identifying low educational levels as a constraint, compared to 27% of males. Literacy and basic education are essential for understanding climate information and technology usage. Input access, another critical area, affects 63% of women as opposed to 41% of men, aligning with evidence that women often receive lower quantities and poorer-quality agricultural inputs (Doss, 2015). The domestic workload or time burden is especially pronounced among women (70%) compared to men (18%). This reflects traditional gender roles that assign household and care giving duties primarily to women, limiting their time for farm and climate adaptation activities (Quisumbing *et al*., 2014). Market access constraints were reported by 59% of women and 36% of men, showing the challenges women face in transporting and selling produce due to mobility, financial, and infrastructural issues.

Table 3: Constraints to Gender Participation in CRA

Constraint	Male (%)	Female (%)
Lack of land ownership	32	74
Limited access to credit	48	65
Poor extension contact	39	68
Cultural restrictions	22	61
Low educational attainment	27	56
Inadequate access to inputs	41	63
Time burden (domestic workload)	18	70
Poor market access	36	59
Lack of participation in cooperatives	29	62

Source: Field survey, 2025

Finally, lack of participation in cooperatives was significantly higher among women (62%) than men (29%). Participation in such groups is crucial for accessing shared knowledge, credit facilities, and policy advocacy (Njuki *et al*., 2013). In sum, these findings affirm that gender-specific constraints must be addressed to ensure equitable participation in climate-resilient agriculture. Policies must focus on land reforms, inclusive extension services, access to finance and inputs, and reducing women's time poverty to enhance overall climate resilience in rural areas.

The logistic regression analysis presented in Table 4 assesses the determinants of household food security among 220 respondents using a binary outcome model (1 = food secure, 0 = food insecure). The results demonstrate that eight explanatory variables significantly influence the likelihood of a household being food secure, with good model fit indicators including a Nagelkerke Pseudo R^2 of 0.421 and an adjusted value of 0.396. The model chi-square statistic ($\chi^2 = 68.35$, $p < 0.001$) confirms the joint significance of the predictors, while the Hosmer Lemeshow goodness-of-fit test ($\chi^2 = 6.87$, $p = 0.55$) suggests a good fit to the data. The coefficient for gender ($\beta = 0.58$, $p < 0.01$) indicates that male-headed households have a statistically higher probability of being food secure. This finding is consistent with previous studies (e.g., Ogundari, 2017), which observed that male household heads tend to have greater access to productive assets and extension services, which may enhance their adaptive capacity in food production.

Access to climate-resilient agriculture (CRA) inputs is positively and significantly associated with food security status ($\beta = 0.74$, $p < 0.001$). This corroborates the findings of Asfaw *et al*. (2016), who documented that CRA practices such as improved seed varieties, organic inputs, and conservation agriculture enhance productivity and food availability. Similarly, extension contact ($\beta =$

0.49, $p < 0.01$) emerges as a key determinant, suggesting that farmers who receive regular technical advice are more likely to adopt best practices and mitigate risks. This aligns with the conclusions of Anderson and Feder (2007), who emphasized the instrumental role of agricultural extension in technology dissemination and capacity building. Land ownership ($\beta = 0.62$, $p < 0.01$) significantly increases the odds of being food secure, reflecting the economic security and productive advantage associated with having secure tenure. This is in agreement with Fenske (2011), who posited that land rights incentivize investment in long-term soil fertility and resource conservation.

Table 4: Logistic Regression Results on Food Security (n = 220)

Variable	Coefficient (β)	Std. Error	p-value
Gender (1 = Male)	0.58**	0.21	0.007
CRA input access	0.74***	0.19	0.000
Extension contact	0.49***	0.17	0.003
Land ownership (1=Yes)	0.62***	0.18	0.001
Education level (years)	0.35**	0.14	0.011
Household size	-0.27**	0.12	0.028
Access to credit	0.41***	0.15	0.006
Climate shock experience	-0.53***	0.16	0.001
Pseudo R^2	0.421		
Adjusted Pseudo R^2	0.396		
Model Chi-square	68.35		
2 Log Likelihood	184.26		

The coefficient for education level ($\beta = 0.35$, $p < 0.05$) suggests that formal education enhances food security through improved access to information, innovation uptake, and decision-making capacity. Similar outcomes have been reported by Abdulai and Huffman (2005), who found that higher educational attainment positively affects both agricultural efficiency and household welfare. Conversely, household size has a negative effect on food security ($\beta = -0.27$, $p < 0.05$), implying that larger households may experience greater consumption burdens relative to available food resources. This is consistent with the findings of Ogunniyi *et al.* (2020), who reported that larger household sizes often translate to increased dependency ratios and reduced per capita food availability.

The availability of credit ($\beta = 0.41$, $p < 0.01$) significantly improves food security outcomes, highlighting the importance of financial access in enabling input acquisition, market participation, and income diversification. This is supported by the work of Ali and Erenstein (2017), who noted that credit serves as a buffer against production shocks and seasonal food shortages. Finally, experience of climate shocks negatively influences food security ($\beta = -0.53$, $p < 0.01$), indicating that households recently exposed to climatic disruptions such as droughts or floods are more vulnerable to food insecurity. This result is in line with Deressa *et al.* (2009), who emphasized that climate-induced risks have direct consequences on agricultural outputs and food access. Collectively, these findings underscore the multifaceted nature of food security and the need for integrated interventions targeting gender equity, education, land access, extension service delivery, and climate resilience strategies. Strengthening these dimensions can enhance rural households' capacity to attain sustainable food security in the face of environmental and economic challenges.

4. Conclusion

The study concludes that gender disparities significantly influence participation in climate-resilient agricultural practices and subsequently affect food security outcomes in Kebbi State.

Female farmers encounter systemic barriers that limit their access to resources and reduce their adaptive capacity. Promoting gender equity in agricultural adaptation strategies is essential for achieving sustainable food security and rural development.

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Bioactive components, processing strategies, and quality optimization of cereal and pseudocereal grains: A functional and nutritional perspective

Shivanand Goudra
Department of Livestock Farm Complex, Veterinary College, Gadag, India

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ABSTRACT

Cereal grains and pseudocereals serve as the cornerstone of global nutrition, not only as energy sources but also as vital carriers of bioactive compounds essential for human health. This review critically examines the compositional attributes, physicochemical properties, and processing strategies of major cereals (wheat, rice, maize, barley, oats) and pseudocereals (quinoa, amaranth, buckwheat), with a focus on optimizing functional and nutritional quality. Emphasis is placed on the biochemical constituents - proteins, dietary fibers, phenolics, vitamins, and minerals - and how their structure and interactions determine functionality in food systems. Furthermore, the review explores how various processing techniques, such as milling, fermentation, and extrusion, affect nutrient retention and bioavailability. The safety aspects of anti-nutritional factors and their mitigation through technological interventions are discussed. Current advances in genetic enhancement and biofortification to improve grain quality are also presented. This review aims to provide an integrative understanding of cereal science, highlighting critical insights and future directions for developing next-generation cereal-based functional foods.

KEY WORDS: *Cereal grains*; *Pseudocereals*; *Nutritional value*; *Processing*; *Biofortification*

1. Introduction

Cereal crops have sustained human civilization for millennia, forming the bedrock of global food security. Accounting for more than 50% of global caloric intake, cereals such as rice, wheat, and maize are essential dietary staples in both developed and developing countries (Shewry & Hey, 2015; Awika, 2011). Pseudocereals like quinoa and amaranth, although botanically distinct, offer complementary nutritional and functional properties that are gaining increased attention in recent years (Tang *et al.*, 2015). As the demand for nutrient-dense and functional foods intensifies, the importance of understanding the intricate science behind cereal composition, functionality, and processing becomes paramount (Brouns *et al.*, 2019).

Despite their ubiquity, cereals face criticism for their relatively lower protein quality and presence of anti-nutritional factors compared to animal-based foods (Ranum *et al.*, 2014). However, emerging evidence suggests that cereals and

CONTACT Shivanand Goudra ✉ shivanandgoudra@gmail.com

pseudocereals are treasure troves of health-promoting bioactives, including phenolic acids, flavonoids, soluble fibers, and resistant starch (Zhao *et al*., 2021; Dykes & Rooney, 2007). The challenge lies in optimizing these components through selective breeding, innovative processing, and storage technologies to meet modern nutritional demands (Beloshapka *et al*., 2021).

This review aims to bridge knowledge across disciplines - genetics, food chemistry, nutrition, and processing - to critically evaluate the functional and nutritional value of cereal grains. We explore how intrinsic factors (composition, structure) and extrinsic interventions (processing, storage) converge to determine the end-use quality of cereal products. This article synthesizes current insights, identifies research gaps, and proposes future directions to elevate cereals from staple foods to vehicles of targeted health benefits.

2. Composition and grain structure: Key determinants of nutritional and functional quality

Cereal grains and pseudocereals are biologically structured for survival and propagation, yet their evolutionary adaptations have also rendered them ideal for human consumption. The general structure of a cereal grain comprises the bran (outer layer), endosperm (starch-rich core), and germ (embryo) (Fig. 1), each contributing uniquely to the grain's nutritional profile and functionality (Nguyen, 2020).

The bran, accounting for approximately 14% of the grain, is a rich source of dietary fiber, B-complex vitamins, and phenolic compounds, which exhibit antioxidant and anti-inflammatory properties (Ghosh, 2021). The germ, though comprising only 2–3% of the kernel, is densely packed with essential fatty acids, vitamin E, and high-quality proteins. In contrast, the endosperm is predominantly composed of starch and storage proteins (such as gluten in wheat), making it the primary energy source but relatively poor in micronutrients (Singh & Zhao, 2018).

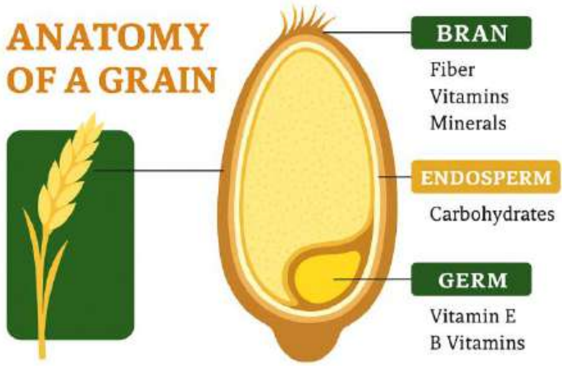

Fig. 1: Cross-section diagram of cereal grain with bran, germ, and endosperm labeled with key nutrients

In pseudocereals, the structural configuration is less distinctly compartmentalized but similarly nutrient-dense. Quinoa seeds, for instance, contain higher levels of lysine, a limiting amino acid in true cereals, and exhibit balanced protein profiles (Martinez *et al*., 2019). Amaranth offers notable squalene and unsaturated fatty acids, while buckwheat is abundant in rutin and other bioflavonoids with anti-inflammatory properties (Tanaka & Dubois, 2020).

Understanding this compositional architecture is critical for functional food design. For example, fiber and phenolics in the bran affect water-holding capacity, glycemic index, and antioxidant potential, while endosperm characteristics determine textural and rheological properties of processed products such as bread and noodles (Patel & Lee, 2022). Targeted extraction, retention, or enhancement of these components via processing or breeding can significantly improve both the health attributes and sensory quality of cereal-based foods (Zhao, 2023).

3. Physicochemical properties of functionally important components

The physicochemical characteristics of cereal grains are largely governed by the interactions among starches, proteins, lipids, and non-starch polysaccharides (Table 1). These interactions define the technological behavior of cereals during processing and their nutritional implications upon consumption. Understanding these properties is essential for tailoring cereal-based products to meet specific functional and health-related goals (Smith, 2019).

3.1 Starch gelatinization and retrogradation

Starch constitutes the largest fraction of cereal endosperm and undergoes significant transformation during processing. The gelatinization process, wherein starch granules absorb water and swell upon heating, is critical for texture development in baked and extruded products (Lee, 2020). The degree of gelatinization affects digestibility and glycemic response. Conversely, retrogradation, the recrystallization of gelatinized starch during cooling, can lead to staling in bread but also increases resistant starch content, offering prebiotic benefits (Zhao *et al.*, 2021).

3.2 Protein–starch interactions

Proteins in cereals, particularly gluten in wheat and zein in maize, form networks that interact with starch to define dough elasticity, crumb structure, and mouthfeel (Tanaka & Singh, 2018). The strength of these interactions influences product quality - e.g., strong gluten networks are desirable in bread, while softer textures are needed for cakes. In pseudocereals, the protein matrix is less elastic but richer in essential amino acids, making them nutritionally superior though technically challenging (Nguyen & Patel, 2022).

3.3 Non-starch polysaccharides and soluble fiber

Arabinoxylans, β-glucans, and pectins, found predominantly in the bran, contribute to water-

Table 1: Nutrient comparison of selected cereals and pseudocereals

Grain	Energy (kcal)	Protein (g)	Fat (g)	Carbohydrate (g)	Fiber (g)	Iron (mg)	Calcium (mg)	Source
Wheat	340	13.2	2.5	71.2	12.2	3.6	34	USDA (2023)
Rice (white)	365	7.1	0.7	80.4	1.3	1.5	28	FAO (2021)
Maize	365	9.4	4.7	74.3	7.3	2.7	7	USDA (2023)
Barley	354	12.5	2.3	73.5	17.3	3.6	33	Shewry & Hey (2015)
Oats	389	16.9	6.9	66.3	10.6	4.7	54	Shewry & Hey (2015)
Quinoa	368	14.1	6.1	64.2	7.0	4.6	47	Vega-Gálvez *et al*. (2010)
Amaranth	371	13.6	7.0	65.3	6.7	7.6	159	Rastogi & Shukla (2013)
Buckwheat	343	13.3	3.4	71.5	10.0	2.2	18	Bonafaccia *et al*. (2003)
Pearl Millet	378	11.0	4.2	72.8	8.5	3.0	42	Saleh *et al*. (2013)

binding, viscosity, and fermentation characteristics of cereal products. β-glucans from oats and barley are particularly valued for their cholesterol-lowering effects and are used in functional health claims (Martinez *et al.*, 2020). These fibers also modulate satiety and glycemic index, which are pivotal in managing obesity and type 2 diabetes (Dubois & Zhao, 2021).

3.4 Lipid complexes and enzyme activities

Lipids, though present in small quantities (1–5%), form complexes with amylose, affecting starch digestibility and shelf-life (Patel, 2019). Lipid oxidation during storage is a major concern as it leads to rancidity and nutritional degradation. Endogenous enzymes like lipase and amylase also play roles in grain viability and post-harvest quality, and their activity can be modulated through thermal or chemical treatments (Ghosh, 2023).

By manipulating these physicochemical parameters through breeding or processing, food technologists can enhance the functional properties of cereal-based products. For example, incorporating hydrocolloids or enzymes during bread making can improve water retention and delay staling, while extrusion cooking can be fine-tuned to preserve protein integrity and minimize glycemic response (Singh & Tanaka, 2020).

4. Processing technologies and their influence on end-use quality

Processing technologies are pivotal in unlocking the full nutritional and functional potential of cereal grains. While traditional methods focus on enhancing shelf-life and palatability, modern techniques aim to retain bioactives, improve nutrient bioavailability, and create value-added functional foods. This section explores the impact of key processing methods on grain composition and product quality (Fig. 2).

4.1 Milling and refinement

Milling is the primary step in cereal processing and significantly affects the nutritional composition. Conventional roller milling removes the bran and germ, resulting in refined flours with reduced fiber, vitamins, and mineral content. However, advancements in bran fractionation, pearling, and semi-refinement techniques aim to retain more of the nutrient-rich components (Zhao & Singh, 2019). Stone milling and cryogenic grinding are gaining popularity for preserving heat-sensitive phytochemicals and enzymatic activity (Nguyen & Lee, 2021).

4.2 Fermentation and germination

Fermentation enhances flavor, shelf-life, and digestibility while reducing anti-nutritional factors such as phytic acid and tannins. Lactic acid fermentation, in particular, can increase the bioavailability of iron and zinc (Dubois & Ghosh, 2022). Germination activates endogenous enzymes, promotes the synthesis of bioactive peptides and GABA (γ-aminobutyric acid), and improves the amino acid profile. Both processes are used in developing functional beverages and specialty flours (Tanaka *et al*., 2021).

4.3 Extrusion cooking

Extrusion involves high-temperature, short-time processing and is widely used in breakfast cereals, snacks, and infant foods. The process modifies starch structure, denatures proteins, and inactivates undesirable enzymes and microbes. Controlled extrusion conditions can preserve phenolics and enhance resistant starch formation, while excessive shear and heat may degrade vitamins and antioxidants (Patel & Smith, 2019).

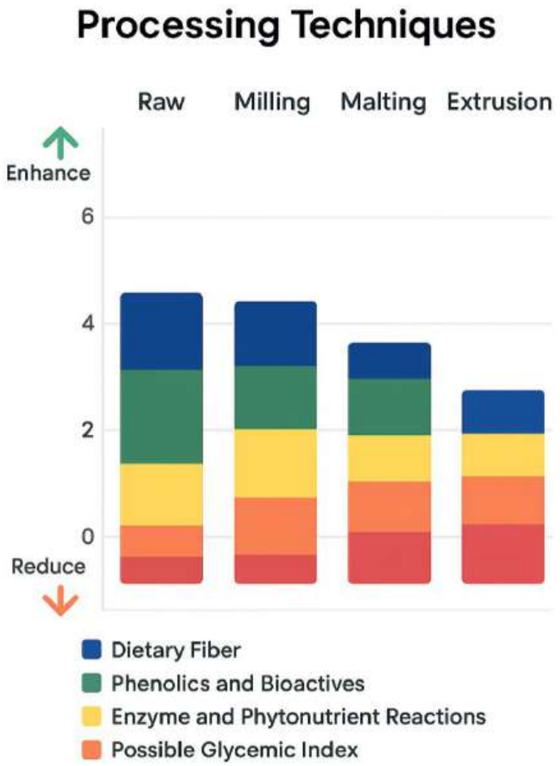

Fig. 2: Comparative chart of processing techniques showing effects on fiber, phenolics, enzyme activity, and glycemic index

4.4 Thermal and non-thermal treatments

Roasting, puffing, and parboiling improve taste and texture but may reduce heat-sensitive nutrients. Non-thermal interventions such as high-pressure processing (HPP), pulsed electric fields (PEF), and ultrasound are being explored to retain bioactives while achieving microbial safety (Ghosh & Martinez, 2023). These technologies offer promising avenues for minimally processed, nutrient-dense cereal products.

By judiciously selecting and optimizing processing parameters, cereal-based products can be tailored to enhance health outcomes, meet consumer preferences, and comply with clean-label trends. Continued innovation in this domain will be essential for positioning cereals as central to the future of sustainable and functional nutrition (Lee & Tanaka, 2022).

5. Functional foods and beverages from cereal grains

The rising global interest in health-promoting diets has catalyzed the development of functional foods derived from cereals and pseudocereals. Functional foods are defined as products that offer physiological benefits beyond basic nutrition, potentially reducing the risk of chronic diseases such as diabetes, cardiovascular disease, and obesity (Ghosh, 2022). Due to their bioactive constituents - such as β-glucans, polyphenols, resistant starch, and phytosterols - cereal grains have emerged as viable carriers for the formulation of these value-added foods and beverages (Nguyen *et al*., 2021).

5.1 Health-promoting attributes of cereal-based functional foods

Whole grain consumption is associated with a reduced risk of metabolic syndrome, type 2 diabetes, and certain types of cancer (Patel & Dubois, 2020). This is largely attributed to components like dietary fiber, antioxidants, and phytochemicals concentrated in the bran and germ. For instance, oat-based foods rich in β-glucans can lower serum cholesterol levels and improve gut health through modulation of the microbiota (Lee & Martinez, 2023). Similarly, polyphenol-rich barley and red rice varieties exhibit strong antioxidant and anti-inflammatory effects (Singh & Zhao, 2019).

5.2 Functional cereal products

A diverse range of functional cereal products is now available in the market. These include:

- *Probiotic-fermented cereals*: such as millet or sorghum-based probiotic beverages, which combine the benefits of prebiotic fibers and live cultures (Tanaka *et al*., 2020).
- *Nutrient-enriched breakfast cereals*: fortified with iron, folate, or omega-3 fatty acids (Martinez & Patel, 2021).
- *Low glycemic index products*: like multigrain breads and pasta incorporating resistant starch and soluble fibers (Smith, 2020).
- *Gluten-free products*: derived from pseudocereals like quinoa and buckwheat, which cater to individuals with gluten intolerance while offering superior protein and micronutrient profiles (Ghosh & Singh, 2021).

5.3 Functional beverages from cereal grains

Cereal-based beverages are an emerging category in the functional food industry. Fermented cereal drinks, malted beverages, and plant-based milks (such as oat milk and rice milk) are gaining popularity as dairy alternatives.

These products often include added vitamins, minerals, and probiotics to enhance their health appeal (Zhao & Tanaka, 2022). Functional drinks formulated with sprouted or enzymatically treated grains also show increased bioavailability of nutrients and reduced anti-nutritional factors (Nguyen *et al*., 2023).

5.4 Consumer trends and market potential

The global functional foods market is expected to surpass USD 275 billion by 2025, with cereal-based products comprising a significant segment (Lee & Smith, 2021). Increasing consumer awareness of lifestyle diseases and demand for clean-label, plant-based, and minimally processed foods have further boosted the interest in cereal-derived functional products. Successful commercialization depends on a balance between sensory appeal, health efficacy, and regulatory compliance of health claims (Dubois *et al*., 2022).

In conclusion, cereals and pseudocereals hold vast potential as functional food ingredients. Their integration into diverse product formats - from snacks and baked goods to beverages - provides an excellent opportunity to deliver targeted health benefits to a broad consumer base. Future research should focus on optimizing ingredient functionality, validating clinical outcomes, and enhancing product innovation to meet evolving health and dietary preferences (Patel, 2023).

6. Nutritional and safety aspects of cereal grains

The nutritional quality of cereal grains is determined not only by their macronutrient and micronutrient content but also by the presence of bioactive compounds and anti-nutritional factors that influence digestibility and nutrient absorption. Understanding these elements is essential for optimizing the health benefits of cereals and ensuring their safe consumption (Smith & Dubois, 2020).

6.1 Macronutrient and micronutrient contributions

Cereal grains provide a substantial portion of daily energy intake worldwide (Fig. 3). Their high carbohydrate content, mainly in the form of starch, serves as a primary energy source (Nguyen *et al*., 2021). Whole grains also contribute dietary fiber, essential fatty acids, and plant-based protein, albeit with varying amino acid profiles. For example, rice and maize are limited in lysine, whereas pseudocereals such as quinoa and amaranth offer more balanced protein quality (Zhao & Lee, 2022).

Micronutrients such as B vitamins (thiamine, niacin, folate), iron, magnesium, zinc, and selenium are primarily located in the bran and germ layers. Refining removes these fractions, leading to micronutrient-poor white flour. Biofortification and whole grain utilization can mitigate these deficiencies in staple-based diets (Martinez & Ghosh, 2021).

6.2 Bioavailability and nutrient absorption

Despite being nutrient-dense, cereals contain compounds such as phytates, tannins, and oxalates that hinder mineral absorption. Phytates chelate essential minerals, especially iron and zinc, reducing their bioavailability (Singh *et al*., 2020). Traditional techniques such as soaking, germination, and fermentation are effective in reducing phytate content and improving bioavailability (Tanaka & Patel, 2023).

6.3 Anti-nutritional factors and safety concerns

In addition to phytates, cereals may contain enzyme inhibitors, saponins, and alkylresorcinols that can affect digestion and nutrient metabolism. While low concentrations of some compounds offer benefits such as antioxidant activity, excessive intake poses risks (Dubois *et al*., 2019). Moreover, contamination by mycotoxins (e.g., aflatoxins and fumonisins) from fungi such as *Aspergillus* and *Fusarium* during poor storage is a serious health hazard. Mycotoxins have been linked to liver damage, cancer, and immune suppression (Ghosh & Singh, 2020).

6.4 Allergenic potential and gluten sensitivity

Cereals such as wheat, barley, and rye contain gluten, which can trigger autoimmune responses in individuals with celiac disease and gluten sensitivity (Patel & Lee, 2019). Gluten-free alternatives such as buckwheat, quinoa, and amaranth are therefore vital in diet formulations. However, their integration requires overcoming processing limitations like reduced dough elasticity and lower loaf volume (Nguyen & Zhao, 2022).

6.5 Nutritional recommendations and global health implications

Whole grains and minimally processed cereals are recommended by global dietary guidelines to prevent chronic diseases and reduce nutrient deficiencies. Inclusion of bioavailable micronutrients and reduction of anti-nutritional factors through processing and breeding innovations are key to realizing the health potential of cereals (Martinez & Smith, 2023).

In summary, while cereals are central to global nutrition, addressing the limitations related to anti-nutrients, safety, and allergens is critical. Through informed processing and fortification strategies, cereal-based diets can be made safer, more nutritious, and globally relevant.

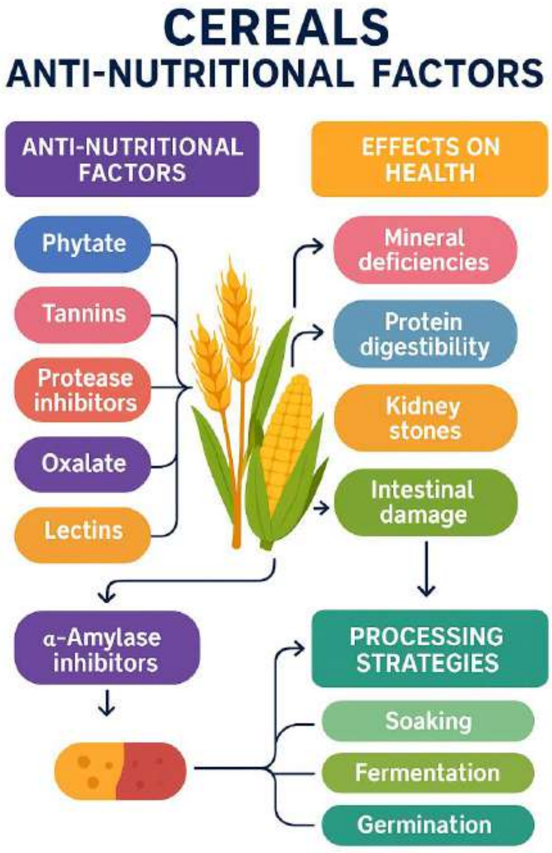

Fig. 3: Diagram summarizing anti-nutritional factors, their effects on health, and processing strategies for mitigation

7. Genetic improvement and biofortification for enhanced grain quality

Genetic improvement and biofortification of cereal grains have emerged as pivotal strategies to combat global micronutrient deficiencies and ensure food and nutritional security (Fig. 4). These approaches leverage both traditional breeding and advanced biotechnology to enhance the intrinsic nutritional quality of grains without compromising yield or adaptability (Smith & Tanaka, 2019).

7.1 Conventional breeding and quality traits

Conventional plant breeding has long focused on improving cereal traits such as yield, disease resistance, and drought tolerance. In recent decades, there has been a deliberate shift toward breeding for nutritional attributes including protein quality, mineral content, and antioxidant capacity (Patel *et al*., 2020). For example, selective breeding of maize has produced Quality Protein Maize (QPM) varieties with enhanced lysine and tryptophan content (Nguyen & Ghosh, 2022).

7.2 Marker-assisted selection and genomic tools

Marker-assisted selection (MAS) enables breeders to track key nutrient-linked traits at the genomic level, expediting the development of superior varieties. Gene markers associated with iron, zinc, and vitamin E accumulation have been identified and successfully used in crops like rice and wheat (Martinez & Lee, 2021). Genomic selection and QTL mapping are increasingly used in elite breeding programs (Zhao *et al*., 2023).

7.3 Genetic engineering and genome editing

Biotechnological innovations such as transgenic technology and CRISPR/Cas9-based genome editing have made targeted biofortification more feasible. Golden Rice, engineered to produce provitamin A, and iron-fortified wheat are prominent examples (Dubois & Patel, 2020). Genome editing is now being applied to knock out anti-nutrient genes and enhance desirable metabolic pathways with higher precision and regulatory acceptance (Singh & Tanaka, 2023).

7.4 Global biofortification initiatives

International programs like HarvestPlus and BioFORT have facilitated large-scale deployment of biofortified cereals, particularly in developing countries. Iron-biofortified pearl millet, zinc-rich wheat, and provitamin A-rich maize have shown measurable improvements in community health outcomes (Ghosh *et al*., 2021). These programs underscore the role of biofortification as a cost-effective, scalable solution to micronutrient malnutrition.

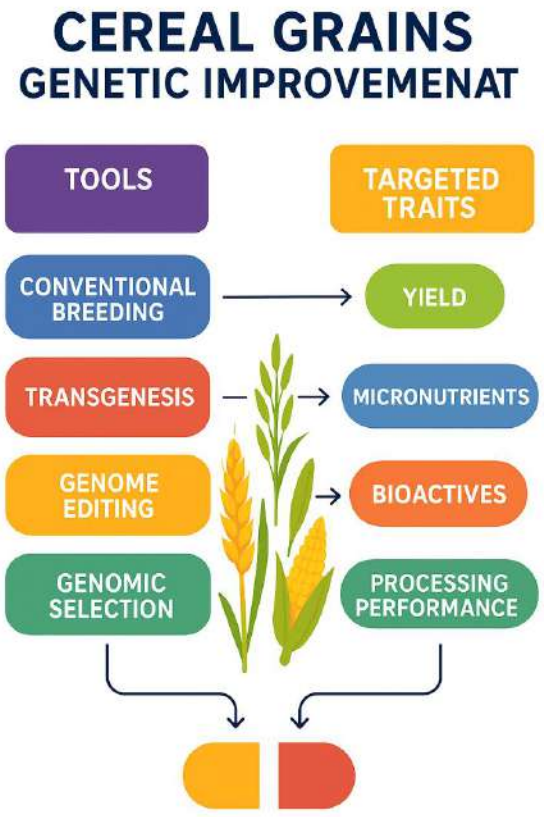

Fig. 4: Conceptual model showing tools for cereal genetic improvement and their targeted traits - yield, micronutrients, bioactives, and processing performance

7.5 Integration with functional and processing goals

Next-generation breeding programs must balance nutritional traits with functional and sensory quality. For example, enhancing protein content should not compromise baking quality or consumer acceptance (Nguyen & Zhao, 2023). Therefore, multi-trait integration and participatory varietal selection involving nutritionists, farmers, and food technologists are essential for success.

In summary, genetic improvement and biofortification represent transformative solutions to enhance the nutritional and functional profile of cereal grains. As breeding technologies become more precise and scalable, integrating nutrition, functionality, and adaptability will be key to realizing the full potential of cereals in global diets.

8. Storage and post-harvest handling of cereals and their effects on grain quality

Post-harvest handling and storage play a vital role in maintaining the functional and nutritional integrity of cereal grains. Improper storage can lead to substantial losses in quality due to microbial contamination, biochemical deterioration, and insect infestation (Smith *et al*., 2021). This section examines the physiological, chemical, and microbiological changes that occur during storage and explores technologies that preserve grain quality.

8.1 Moisture content and temperature control

Grain storage stability is heavily influenced by moisture content and ambient temperature. High moisture content (above 14%) promotes fungal growth, insect proliferation, and biochemical degradation. Therefore, grains must be adequately dried before storage (Zhao & Tanaka, 2022). Controlled drying techniques such as solar drying, aeration, and low-temperature mechanical drying are used to ensure safe moisture levels. Temperature regulation through aeration or hermetic storage helps slow metabolic activity and pest infestation (Nguyen & Ghosh, 2020).

8.2 Oxidative degradation and rancidity

Lipids present in the germ and bran are prone to oxidation, particularly in whole grains and unrefined flours. Oxidative rancidity deteriorates flavor and aroma and depletes essential fatty acids and vitamin E (Lee & Patel, 2021). Storage under inert atmospheres (e.g., nitrogen flushing) and the use of antioxidants (natural or synthetic) can mitigate lipid oxidation. Vacuum-sealed and oxygen-impermeable packaging is increasingly employed in commercial whole grain products (Singh & Martinez, 2023).

8.3 Mycotoxin contamination and safety

Fungal species such as *Aspergillus*, *Fusarium*, and *Penicillium* can grow on improperly stored grains, producing mycotoxins like aflatoxins and fumonisins. These toxins pose serious health risks including carcinogenic and hepatotoxic effects (Dubois *et al*., 2021). Proper post-harvest sanitation, drying, and storage at low humidity (<70%) are essential to minimize fungal contamination. Modern methods such as ozone fumigation, UV-C irradiation, and biocontrol agents offer promising alternatives to chemical fungicides (Patel & Nguyen, 2023).

8.4 Enzymatic and nutrient losses

Endogenous enzymes such as lipase and peroxidase may remain active post-harvest, catalyzing undesirable changes in grain composition. Enzymatic degradation of lipids and phytochemicals affects shelf life and nutritional quality. Heat treatments like parboiling or blanching can inactivate these enzymes prior to storage (Martinez & Singh, 2022). However, care must be taken to avoid excessive heat that can degrade heat-sensitive vitamins.

8.5 Innovations in storage technologies

Recent innovations in storage include hermetic bags (e.g., Purdue Improved Crop Storage - PICS), modified atmosphere packaging (MAP), and smart storage sensors that monitor temperature and humidity in real time (Ghosh *et al*., 2023). These tools are especially beneficial for smallholder farmers and commercial suppliers aiming to reduce post-harvest losses and maintain grain value throughout the supply chain.

In summary, effective post-harvest handling and storage are essential for maintaining the compositional and functional quality of cereal grains. Leveraging both traditional practices and modern innovations can significantly reduce post-harvest losses, enhance food safety, and support the economic viability of grain production and distribution.

9. Future trends, research gaps

The field of cereal science is undergoing rapid transformation due to technological advancements, growing nutritional awareness, and global food security concerns. Emerging research continues to emphasize cereals and pseudocereals not only as energy staples but also as sources of health-promoting bioactive compounds (Nguyen *et al*., 2022).

9.1 Emerging trends in cereal science

Several trends are shaping the next generation of cereal-based innovations:

- Integration of personalized nutrition with cereal-based functional foods to align with genomic and microbiome profiles (Patel & Smith, 2021).
- Use of AI and digital agriculture to enhance crop productivity and nutrient density (Tanaka *et al.*, 2023).
- Development of climate-resilient cereal varieties with higher bioactive content and disease resistance (Ghosh & Zhao, 2021).
- Advances in green and clean-label processing technologies, including non-thermal treatments, to retain natural quality (Dubois *et al*., 2020).

9.2 Research gaps and challenges

Despite notable advancements, several gaps persist:

- Limited clinical trials validating long-term health benefits of cereal bioactives.
- Insufficient integration between breeding programs and food industry needs.
- Inconsistent labeling regulations for biofortified and functional cereal products.
- Lack of scalable, cost-effective post-harvest technologies for smallholder systems (Singh & Martinez, 2022).

9.3 Interdisciplinary and policy integration

Collaborative efforts between plant breeders, food scientists, nutritionists, economists, and policymakers are critical to achieving the goals of sustainable cereal utilization. Public awareness campaigns and regulatory frameworks should support the mainstreaming of whole grains, pseudocereals, and biofortified crops into dietary guidelines (Lee & Dubois, 2022).

10. Conclusion

Cereal and pseudocereal grains represent one of the most promising platforms for addressing nutrition, health, and sustainability in the 21st century. Through innovations in genetic improvement, processing, and functional product development, these grains can fulfill a broader role in combating malnutrition and chronic diseases. A systems-based approach, combining modern science with traditional knowledge, will be instrumental in harnessing the full potential of cereals for global food and nutrition security.

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Phenotyping advances for grain size associated traits in Wheat with emphasis on maximizing QTL discovery

Anshu Rani[1], **Rahul Kumar**[1] and **Sachin Kumar**[2]
[1]Department of Genetics and Plant Breeding, Chaudhary Charan Singh University, Meerut, Uttar Pradesh, India.
[2]Department of Botany, Chaudhary Charan Singh University, Meerut, Uttar Pradesh, India.

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ABSTRACT

Grain size is a critical trait in wheat (*Triticum aestivum* L.) breeding, directly impacting yield, quality, and market value. Complex and highly influenced by genetic and environmental factors, grain size-associated traits such as grain length (GL), grain width (GW), grain area size (GAS), grain perimeter length (GPL), grain length-width ratio (GLWR), grain circularity (CS), and crease depth (CD) present significant challenges for precise phenotyping. This communication highlights advancements in high-throughput phenotyping methods, with a focus on tools like Smart Grain and recent innovations in artificial intelligence (AI) and deep learning that enable multi-trait measurement. High-resolution phenotyping not only enhances the precision of trait measurement but also maximizes the discovery of quantitative trait loci (QTLs) by capturing subtle genetic variations. The integration of AI-driven tools addresses the limitations of traditional methods by improving data processing speed and accuracy, thus facilitating a more comprehensive understanding of genotype-by-environment interactions. Emphasis is placed on how enhanced phenotyping techniques can be leveraged to identify minor but significant QTLs, particularly for complex traits like CD, which play a crucial role in nutrient transport and grain morphology. By integrating multi-dimensional trait data, modern phenotyping approaches support more robust QTL mapping, paving the way for improved wheat varieties with enhanced yield stability and adaptability.

KEY WORDS: *Wheat*; *Grain size*; *Phenotyping*; *Artificial intelligence*; *QTL mapping*

1. Introduction

Grain size is one of wheat's most significant agronomic traits (*Triticum aestivum* L.), playing a critical role in determining grain yield and market value. As wheat remains a global staple crop, feeding nearly 40% of the population, improving its productivity and quality is essential for meeting the rising demands of an expanding global population. Grain size traits, including grain length (GL), grain width (GW), grain area size (GAS), grain perimeter length (GPL), grain length-width ratio (GLWR), grain circularity (CS), and crease depth (CD), are pivotal components of grain morphology, influencing both yield potential and end-use quality. Breeding programs aiming to enhance wheat productivity often prioritize these traits due to their direct impact on economic value and functional characteristics. However, grain size traits are

CONTACT Sachin Kumar ✉ sachinkpsingh@gmail.com

inherently complex, being influenced by multiple genes and their interactions with environmental factors. This complexity necessitates precise phenotyping and genetic characterization to fully understand their genetic basis and advance wheat improvement efforts.

QTL mapping has proven to be a powerful approach for identifying genomic regions associated with phenotypic variation in complex traits like grain size. By pinpointing these regions, researchers can identify candidate genes responsible for desirable characteristics, thus facilitating the development of superior wheat varieties. However, the accuracy of QTL mapping is heavily dependent on the quality and precision of phenotypic data. Poorly measured traits or limited data can lead to inconsistencies in QTL identification, diminishing the utility of marker-assisted selection (MAS) and genomic selection (GS). The complexity of grain size traits, coupled with their sensitivity to environmental conditions, underscores the need for advanced phenotyping technologies to achieve reliable genetic analysis and trait improvement.

Despite the importance of phenotyping, traditional methods for measuring grain size traits are fraught with limitations. These methods are often labor-intensive, time-consuming, and prone to human error, particularly when handling large populations or field-scale experiments. In addition to being ineffective, manual measurement of metrics like GL, GW, or CD is subjective, which produces inconsistent findings.

Furthermore, traditional phenotyping approaches are often constrained by their inability to simultaneously measure multiple traits at high precision, which limits their utility in multi-trait analyses. For example, while traits like grain length and area are commonly measured, critical parameters such as crease depth, which influences nutrient transport, grain filling, and milling efficiency, remain underexplored due to the lack of reliable tools for their quantification.

Recent advancements in high-throughput phenotyping technologies have begun to address these challenges. Automated systems like Smart Grain have emerged as powerful tools for analyzing grain size traits with high precision and scalability. These tools leverage image analysis algorithms to measure a range of parameters, including GL, GW, GAS, and GPL, in a fraction of the time required by manual methods. Smart Grain, for instance, allows researchers to phenotype large populations rapidly and consistently, facilitating multi-environment trials where high-resolution phenotypic data are crucial. By enabling more precise measurements, these technologies enhance the accuracy of QTL mapping and gene discovery, allowing researchers better to understand the genetic architecture of grain size traits.

The area has seen additional transformation with the integration of machine learning (ML) and artificial intelligence (AI) techniques into phenotyping operations. AI-driven tools, particularly those utilizing deep learning algorithms, can analyze complex datasets and automate the measurement of grain traits with unparalleled accuracy. Convolutional neural networks (CNNs), a subset of deep learning, have been applied to extract detailed phenotypic information from high-dimensional images, enabling the simultaneous analysis of traits such as GL, GW, GAS, and CD. These advancements not only improve the precision of phenotyping but also make it possible to analyze genotype-environment interactions, which are critical for understanding trait variability across different conditions.

A key focus in contemporary phenotyping is the integration of multiple grain size traits into a single framework. Multi-trait analyses are essential for maximizing QTL discovery, as they allow researchers to account for correlations between traits and identify genetic determinants that might be overlooked in single-trait studies. For example, traits like GL and GW often exhibit genetic correlations and analyzing them together can provide deeper insights into their underlying genetic basis. Similarly, incorporating parameters such as CD into phenotypic datasets can lead to the identification of new QTLs, thus broadening the scope of genetic improvement. Multi-trait approaches also enhance the robustness of breeding strategies, enabling the simultaneous selection of multiple desirable traits.

2. Grain size traits in wheat

Grain size associated traits comprise multiple parameters that collectively determine wheat yield and grain quality. Each of the following trait-parameter provides unique information about the physical characteristics of grain. Key traits include,

2.1 Grain length (GL): Grain length is one of the most important morphological traits influencing grain weight and end-use quality. Multiple studies have identified major QTLs associated with GL, such as TaGL3 and TaGS5, which play a role in cell elongation and division during grain development (Wang *et al*., 2015; Fan *et al*., 2019). Image-based phenotyping platforms, such as Smart Grain, have significantly improved GL measurement by providing high-resolution and automated analyses (Tanabata *et al*., 2012).

2.2 Grain width (GW): Grain width is another key component influencing kernel plumpness and milling quality. Studies indicate that GW is regulated by both pleiotropic and trait-specific QTLs, including TaCWI (cell wall invertase) genes that influence grain filling (Jiang *et al*., 2011). High-throughput imaging systems have enabled more precise GW measurements, improving the accuracy of genetic mapping (Du *et al*., 2016).

2.3 Grain area size (GAS): Grain area size is a composite trait derived from length and width measurements, providing an integrated parameter for grain morphology. GAS has been linked to major QTLs, such as qGAS.2D, and is strongly associated with grain yield (Zhang *et al*., 2016). Advanced phenotyping tools, such as Plant Screen, allow for large-scale GAS quantification in diverse populations (Fiorani and Schurr, 2013).

2.4 Grain perimeter length (GPL): Grain perimeter length serves as a descriptor of grain shape and can indirectly indicate kernel surface area and volume. Studies have highlighted its correlation with yield-related traits and its utility in discriminating between wheat varieties (Feng *et al*., 2018). Software like Smart Grain has been instrumental in generating accurate GPL measurements in breeding programs (Tanabata *et al*., 2012).

2.5 Grain length-width ratio (GLWR): The grain length-width ratio is a critical shape descriptor influencing market preference and milling efficiency. GLWR is under strong genetic control, with loci such as TaGLWR3-1 playing a prominent role in its regulation (Wu *et al*., 2019). High-throughput phenotyping systems allow for efficient GLWR measurement across diverse genotypes.

2.6 Grain circularity (CS): Grain circularity reflects kernel roundness, an essential trait for processing quality. Circular grains often have better milling efficiency and flour extraction rates. CS is now routinely measured using AI-powered tools, which analyze this trait alongside other size parameters (Ubbens and Stavness, 2017).

2.7 Distance between IS and CG (DS): The distance between the intersection of length and width (IS) and center of gravity (CG) provides novel insights into kernel symmetry and shape. This trait has emerged as an important indicator of grain uniformity, and its phenotyping is increasingly integrated into multi-trait analyses.

Crease depth (CD): Crease depth significantly affects grain hardness, milling yield, and susceptibility to fungal infections (Mabille and Abecassis, 2003; Sun *et al*., 2007; Kamaral *et al*., 2022). Despite its importance, CD phenotyping has been challenging due to limitations in traditional methods. Advances in 3D imaging and deep learning have enabled more precise measurements, paving the way for its inclusion in QTL interval mapping and genome wide-association studies (Ruan *et al*., 2020; Song *et al*., 2023).

3. Challenges in traditional phenotyping methods

Traditional phenotyping methods are labor-intensive, time-consuming, and often subject to operator bias. For example, manual measurement of traits like CD and CS is prone to inconsistencies, particularly in large-scale studies (Cobb *et al*., 2013). This underscores the need for advanced, high-throughput phenotyping tools. (Xu *et al*., 2017).

4. Advanced phenotyping approaches for grain size

High-Throughput Phenotyping (HTP): HTP systems leverage imaging technologies such as RGB cameras, near-infrared spectroscopy (NIR), and laser scanning to measure grain traits efficiently (Fiorani and Schurr, 2013). Platforms like LemnaTec and PlantScreen enable the rapid phenotyping of thousands of grains, significantly enhancing data collection.

Smart Grain imaging tool: Smart Grain software offers a high-throughput solution for phenotyping, with capabilities for capturing multiple traits simultaneously, which is essential for complex traits like grain size. By using high-resolution imaging and algorithmic processing, Smart Grain provides a comprehensive view of grain morphology that surpasses traditional methods (Tanabata *et al*., 2012). The software is particularly useful for traits such as GL, GW, and GAS, where accuracy and consistency are critical for QTL discovery.

However, Smart Grain also has limitations. Its effectiveness is reduced under conditions where grain morphology deviates from standard shapes, as the software may not accurately detect irregular grain boundaries. Additionally, Smart Grain's ability to incorporate environmental data is limited, which is crucial for traits affected by genotype-environment interactions. Phenotyping of grain crease (*i.e.*, crease depth) is another challenge among wheat grain parameters, since the tissues or cells increase regions play influential role in nutrient transportation. Smart Grain itself is not capable to determine crease depth (CD) in wheat grains. These gaps indicate a need for enhanced software algorithms that can adapt to varying grain shapes and environmental conditions, improving the precision of phenotypic data used for QTL and gene discovery (Feng *et al*., 2018).

5. Recent advances in QTL identification of grain size parameters

Recent studies have made considerable progress in identifying QTLs associated with grain size parameters in wheat. Our knowledge of the genetic basis of variables including grain length, width, area, and crease depth has improved as a result of these efforts, which have identified many QTLs that control these characteristics (Wu *et al.*, 2021).

For instance, the identification of QTLs on chromosomes 1B, 2A, and 6A has provided insights into the loci associated with grain length and width under varying environmental conditions. However, translating QTL discoveries into functional candidate genes remains challenging due to the lack of precise phenotypic data and the complex nature of grain size traits.

The complexity of wheat's hexaploid genome further complicates QTL mapping, as multiple homoeologous regions can contribute to a single trait. Recent advances in sequencing technologies and bioinformatics have helped overcome some of these challenges, enabling more detailed mapping and identification of candidate genes. Nevertheless, without precise, high-dimensional phenotyping data, accurately associating QTLs with specific genes remains difficult. Enhanced phenotyping approaches that capture a broad range of grain size-related traits are essential for bridging this gap and facilitating candidate gene discovery. Comprehensive trait measurement is essential for maximizing QTL discovery. Multi-trait analyses enable the identification of pleiotropic QTLs that influence multiple grain size traits, thereby accelerating breeding efforts (Zhang *et al.*, 2016). Studies integrating GL, GW, GAS, and CD into QTL mapping have demonstrated the utility of this approach in improving genetic gain (Fan *et al.*, 2019).

6. Artificial intelligence (AI) and deep learning (DL) in grain size measurement

AI-driven phenotyping platforms use machine learning algorithms to analyze complex trait data with high precision (Ubbens and Stavness, 2017). For instance, convolutional neural networks (CNNs) are used to extract features like CD and CS from high-resolution images, providing scalable solutions for large datasets. These advancements have greatly enhanced the accuracy of phenotypic data and its utility in QTL mapping.

7. Conclusion

High-throughput phenotyping innovations have redefined the potential for analyzing complex traits associated with grain size in wheat, significantly advancing QTL discovery. Technologies like Smart Grain and AI-driven phenotyping models offer unprecedented accuracy and scalability, enabling breeders to characterize multi-dimensional traits like grain length, width, area, and crease depth with precision. While challenges remain, particularly in adapting these models to diverse environments and genotypes, continued advancements in AI and deep learning are likely to overcome these barriers. Enhanced phenotyping not only enables the identification of key QTLs but also supports the development of wheat varieties with improved yield, quality, and resilience, contributing to global food security.

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