Tillage effects on soil moisture and sulfur use efficiency by sesame *(Sesamum indicum* L.*)* on Vertisol of north Ethiopia

ABSTRACT

Sesame, produced in Humera is among the highest quality seeds grown in Ethiopia and even in the world. However, its productivity is by far less than the production potential due to nutrient depletion, moisture stress and lack of crop response to applied fertilizer.Anexperiment was conducted to evaluate the effects of tillage practices and sulfur fertilizer rates on moisture conservation and agronomic sulfur use efficiency of sesame crop in 2015. The treatments were tied ridges (M1) and flatbed tillage practices combined with five rates of sulfur fertilizer at a split plot design with three replications. M1 and flatbed treatments were assigned to the main plots, while sulfur fertilizer rates were assigned to the sub-plots. Measurements of soil moisture content at 0-20 cm, 20–40 cm and 40–60 cm depth were conducted throughout the growing season at an interval of 13 days using the gravimetric method. The results showed that M1 increased the soil moisture content up to 44% compared to the flatbed. The highest amount of agronomic sulfur use efficiency 14.4 kg kg^{-1} was also obtained from M1 tillage at 10 kg S ha^{-1}. On the other hand, the highest amount of agronomic sulfur use efficiencies under flatbed tillage was 9.5 kg kg^{-1} at 10 kg S ha^{-1}.M1 increased agronomic sulfur use efficiency by 51.6%.Tied ridging is the best option to significantly increased soil moisture availability in the root zone and as a consequence it increased agronomic sulfur use efficiency of the sesame. Therefore, in-situ moisture conservation using tillage practices like M1 at farm level should be demonstrated at farmer's fieldin the semi-arid Humera areas for improving sulfur fertilizer use efficiency.

Keywords*: Tied ridge, soil tillage, Soil moisture content, Sulfur use efficiency, Sesame, Vertisol*

1. Introduction

Sesame*(Sesamum indicum)* is grown for local consumption and export in Ethiopia. Among the oilseed crops sesame is the first in the area of production and as export crop [1]. Ethiopia is the 3rd sesame exporting country in the world next to Nigeria and India; and sesame is first export crop which accounts 79% from oilseeds and 2nd next to coffee which accounts 20% from agricultural export earnings in Ethiopia [2]. The sesame sector is one of the highest foreign currency earning sectors in Ethiopia and is even expected to contribute more in the future. In just the first ten months in 2013, about USD 345,967,164 has been generated from the export of sesame and more than 600,000 holders were engaged [3].

The average productivity in Ethiopia was 735 kg ha^{-1}. The total area and production were also increased by 61.2% and 17.9% respectively, while the total productivity was decreased by 27.2% when compared with the productivity in 2008 [4]. The causes for low productivity are lack of agronomic management for moisture conservation, low soil fertility, unsuitable pH level and lack of selected varieties which respond to inorganic fertilizers [4; 5]. Among the inorganic fertilizers, sulfur is one of the important nutrients expected for increasing yield of the oilseeds. Oilseed crops are particularly sensitive to sulfur deficiency[6]. According to Rahmatullah et al.[7],sulfur deficiency is becoming common throughout the world due to low sulfur returns.

Western lowlands Tigray of Ethiopia is producing below the maximum production potential quantity of sesame [8]. The productivity of sesame in the lowlands of western Tigray is 525 kg ha^{-1}[9]. While the national productivity is 757 kg ha^{-1} during the same year [3]. This is very low compared to the national average yield. To the worst, this yield is very low as compared to other countries like Mozambique where the productivity of sesame reaches up to 1500 kg ha^{-1}[10]. Therefore, there is something missing to reach the yield gap in western Tigray of Ethiopia.

Some researchers reported that agronomic management has been fundamental for crop productivity. For example, Lobb et al, [11] discussed tillage among all the agronomic management practices, can result in the degradation of soil, water, and air quality. Others, such as Dercon et al, [12] proved that interaction between fertilizer and agronomic management showed a significantdifference in productivity. Evidences suggested that fertilizer applied in Ethiopia is not as effective as it was hoped due soil moisture stress and low levels of soil organic matter content [13].

Drought and moisture stress had also a significant effect on yield and yield components of sesame [14]. Gebreyesus [15]reported that soil moisture content is the most limiting factor in the semi-arid Ethiopian highlands. Gebreyesus then suggested rainwater harvesting technologies such as M1 as very crucial option to increase plant available moisture so as to increase crop productivity. Heluf[16],investigated moisture conservation played a significant role in increasing crop productivityin arid, semi-arid areas.However, Kafta Humera district is known as one of the areas with alow level of soil sulfur [17]. That is why the low soil moisture content [18; 19] and nutrient depletion [14] are among the most important contributors for low sesame productivity. Therefore, soil moisture conservation using M1 and application of sulfur fertilizer are bettercontributorstoincrease productivity of sesame[19]. However, the efficiency of tied ridger as an in-situ moisture conservation and the result of conserved moisture on agronomic sulfur use efficiency needs to be investigated. Therefore, the aim of this study is to investigate the effects of tillage practices on soil moisture conservation and the consequences of moisture conservation on sulfur use efficiency of sesamein Kafta Humera district of the Western Tigray, Ethiopia.The null hypotheses of the research were, (I) different tillage practices have no significant effect on moisture content of the soil at the root zone (0-60 cm) depth, for the moisture conservation tillage practice, (II) different sulfur fertilizer rates have the somesulfur use efficiency, for sulfur rates, and (III) moisture content has no significant effect on sulfur use efficiency, for the interaction effect.

2. MATERIALS AND METHODS

2.1 Study area description

The study area is found in Kafta Humera district of Tigray, Northern Ethiopia (Figure 1) about 600 km far from Mekelle the capital city of Tigray in the west. Geographically it is located at $13^{o}14'$ to $14\,^{o}27$ N' and $36^{o}27'$ to $37\,^{o}32'$ E. The elevation of the study area is 609 ma.s.l.[19].

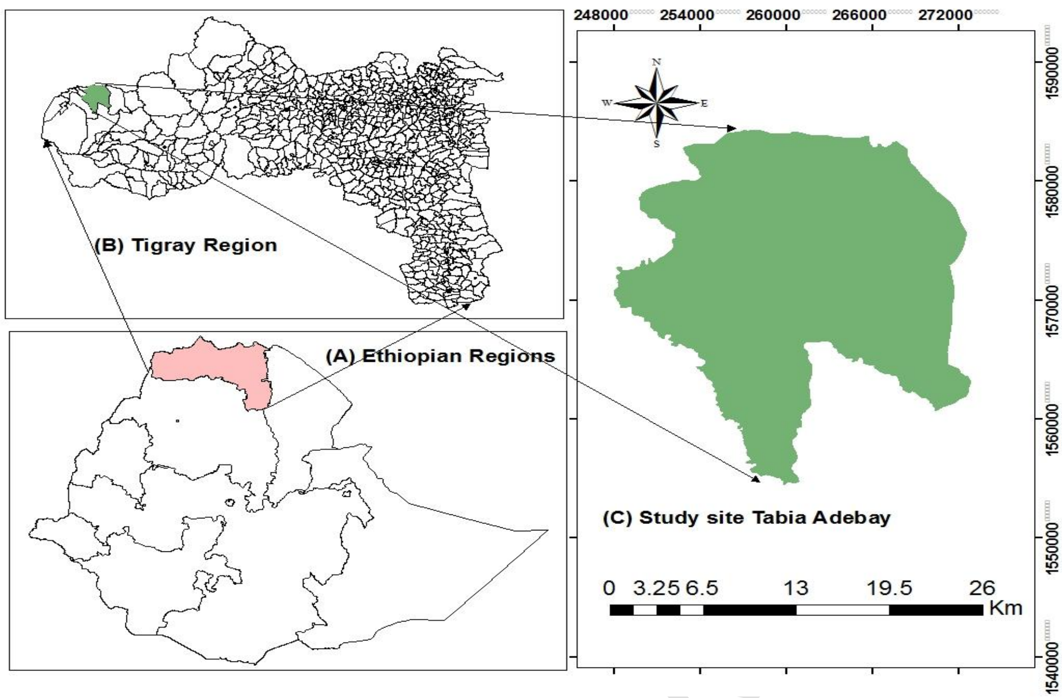

Figure 1. Map of the Study area

The mean annual rainfall of the area is 578 mm in the recent nine years. The hottest month is April with 42 ^{o}C and the coldest month is July with 17.5 ^{o}C (Figure 2)

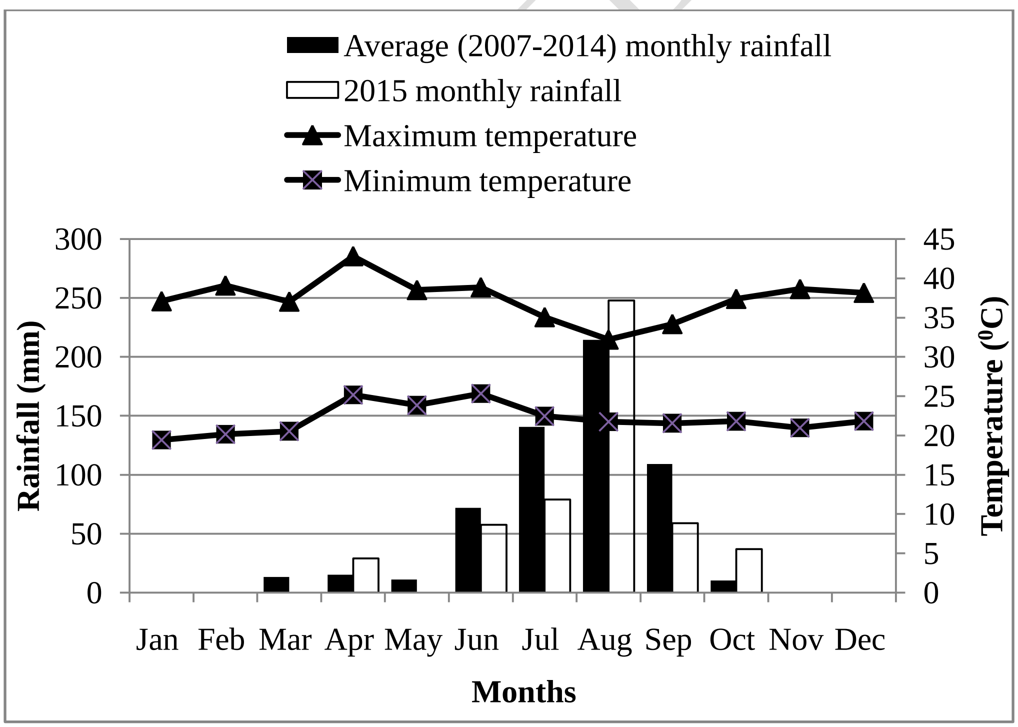

Figure 2. Average (2007-2014) and 2015 Monthly Rainfall Amounts (mm) and Distributions in a Year and Average (2008-2011) Monthly Temperature (^{0}C)

Source: [19]

The dominant soil reference group of the area is black Vertisol[20]. In this current study the area is characterized with a very deep soil profile (>150 cm), at <5% slope clay texture with 40-60% clay content, pH is 8.5, low Organic Matter (OM) content 0.98%[19]. The farming system of the study area is mixed farming where crop production and livestock raising are complementary to each other. Small farmers use traditional animal drawn tillage system, even the investors in the district are still using old technologies for tillage but no more combined harvester and row planter machineries used in the area. The dominant crops growing in the area are sesame and sorghum. Likewise cattle, equines, sheep and goats are the major livestock types.

2.2 Experimental design and land preparation

The experiment was a split plot design with three replications with 1.5 m spacing between replications, 1 m between plots. The main plot areas were 42 m^2 (3 m×2.8 m dimension) the sub-plot areas were 8.4 m^2 each (2.8 m×3 m) with net plot size 6 m^2 (2 m×3 m). The row spacing was 40 cm, and the spacing between plants was 10 cm with an interval of 300 cm ties in M1.

Five sulfur rates (0, 10, 20, 30 and 40 kg ha^{-1})were used as fertilizer from Calcium sulfate ($CaSO_4$) source with 19% sulfur purity.Nitrogen (N) 46 kg N $ha^{-1}$and Phosphorus (P) 46 kg P_2O_5 ha^{-1} were applied for each experimental plot as a basal application. The sources of N and P were Urea and TSP (Triple-super phosphate) respectively. Flatbed preparation was made by oxen according to farmers' conventional tillage practices whereas M1 preparation was made by tie ridger with some modifications manually to 20 cm height ridges and 15 cm height earthen ties along the contour. This ridged tillage method is named as *'derdero'* according to Tesfay et al. [21].

2.3 Soil sampling and analysis

A 1 m depth, 0.50 m width and 1 m length pit was opened and three undisturbed soil samples were collected using core samplers at 0.10 m, 0.30 m and 0.50 m depths along the profile for bulk density determination of the soil in the root zone [19]. Another disturbed composite soil sample was also collected using soil Auger from the top 0.20 m soil depth before planting for characterization of selected soil physical properties.

Bouyoucos hydrometer method [22] was used for particle size distribution. Bulk density was determined using core sampler at a known volume. The soil moisture contents at different stages of the plant growth were calculated by gravimetric method i.e. after collecting and drying soil samples at 13 days interval. Field capacity (FC), permanent wilting point (PWP), and the plant available soil water holding capacity were obtained using SPAW hydrology software, field and pond hydrology version 6.02.74. Bulk density was calculated from the ratio of the oven-dried mass of soil and the bulk volume. Total porosity (f) of the soil sample was estimated on the basis of measured bulk density (ρ_b) and average particle density (ρ_p) assumed for mineral soils as 2.65 g cm^{-3}as:

$f = [1 - \rho b/\rho p] \times 100$……………………………………………………………Eq. (1)

Soil samples were also collected for moisture content analysis at different stages of the plant growth i.e. during planting and at every thirteen days intervals from three depths i.e. 0-20, 20-40, and 40-60 cm for each ridges, furrows, and flatbeds using soil Auger. The fresh weight of the collected samples were taken immediately using sensitive balance and then the samples were oven-dried at 105 ^{0}C over 24 hours and then re-weighted to obtain the dried masses of the samples. Then the gravimetric soil moisture content (GSMC) was calculated with the following equation (Eq.2):

% GSMC = [Wt. of wet soil (g) – Wt. of ODS (g)] /Wt. of ODS (g).……………………..Eq. (2)

%GSMC is percentage gravimetric soil moisture content, ODS is oven dried soils, Wt. is weight. The volumetric soil moisture content (VSMC) was determined by multiplying the gravimetric soil moisture content by the corresponding representative dry bulk density for each depth since the bulk density of the profile is different (Table 1).

% VSMC = [%GSMC × Bulk density (g cm^{-3})]/[Density of water (g cm^{-3})]…………..Eq. (3)

% VSMC = % volumetric soil moisture content

Agronomic Sulfur Use Efficiency (AUES):Agronomic efficiency is the amount of additional yield produced for each additional kg of fertilizer applied [23]. Agronomic sulfur use efficiency was calculated using procedures described by Fageria and Baligar[24] as follows:

AUES(kg ha^{-1}) = [Gf − Gc]/SA…..Eq. (4)

G_f and G_c refers to the average grain yield (kg ha^{-1}) in the fertilized and control (unfertilized) plots, and SA is the amount of S fertilizer applied in kg ha^{-1}.

2.4 Statistical Analysis

GenStat16th edition [25] statistical software programs was used for analysis of variance (ANOVA). Statistical mean differences among and between treatments were tested using least significant difference (LSD) at 5% level of significance [26].

3. RESULTS

3.1 Selected Initial Soil Physical Properties of the Site

Table 1 shows the selected physical properties of the soil before planting. The results of the laboratory analysis for physical properties such as texture, bulk density (BD), total porosity (TP) and water content of the soil shows significant difference in the root zone (0-20, 20-40 and 40-60 cm) depths.

Table 1. Physical properties of soil before sowing

Parameters	**Depth (cm)**		
	0-20	**20-40**	**40-60**
Sand (%)	26	24	22
Silt (%)	19	19	21
Clay (%)	55	57	57
Textural class	Clay	Clay	Clay
Bulk density (g cm^{-3})	1.37	1.48	1.5
Total porosity (%)	48	44	43
Field capacity (%)	44.2	44.3	42.9
Permanent wilting point (%)	32.5	33.6	33.5
Available water holdingcapacity (mm)	120	110	90

Source:[19]

3.2 Effect of Tied Ridging on Evolution of Soil Moisture Content

The results (Figure 3) showed that the VSMC was affected by M1. Low VSMC was recorded at plating (initial sampling) for both plots with M1 (ridge and furrow) and flatbed. The VSMC of the plots with ridge and furrow remained higher than the VSMC obtained from plots under conventional tillage (flatbed) throughout the sampling days i.e. planting (day 0) to harvesting (day 104).

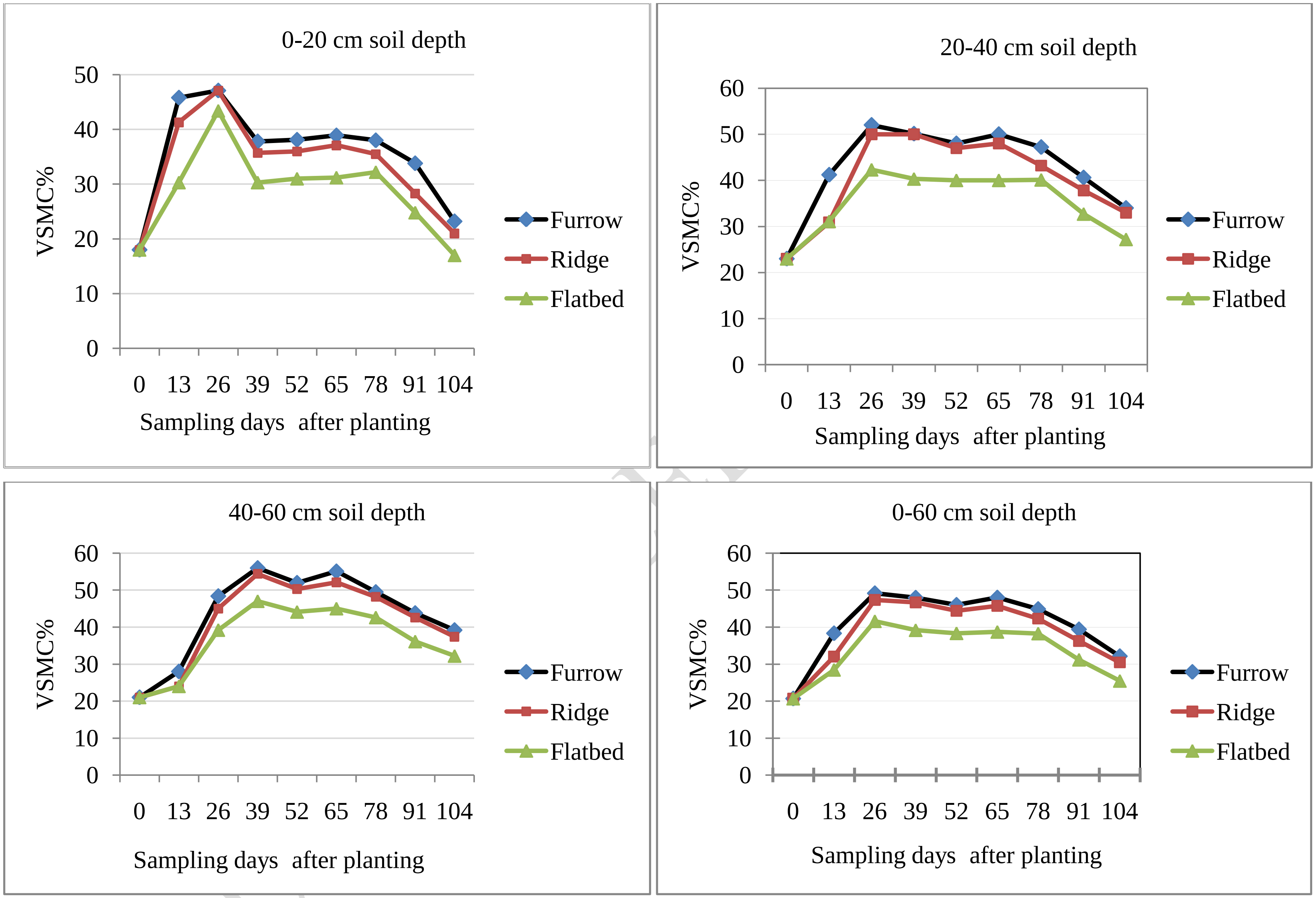

Figure 3. Volumetric Soil Moisture Content (%VSMC) as Affected by Ridge, Furrow and Flatbed

VSMC (%): Volumetric Soil Moisture Content; 0, 13, 26, 39, 52, 65, 78, 91, 104 are sampling days from planting (0) to harvest (104).

3.3 Effect of M1 on Agronomic Sulfur Use Efficiency

M1 have high significant effect on agronomic sulfur use efficiency as compared to the conventional (flatbed) tillage practice (M0). The sulfur use efficiency for plots with M1 decreased with increasing sulfur rate while there is no clear pattern for plots without M1 (Figure 4).

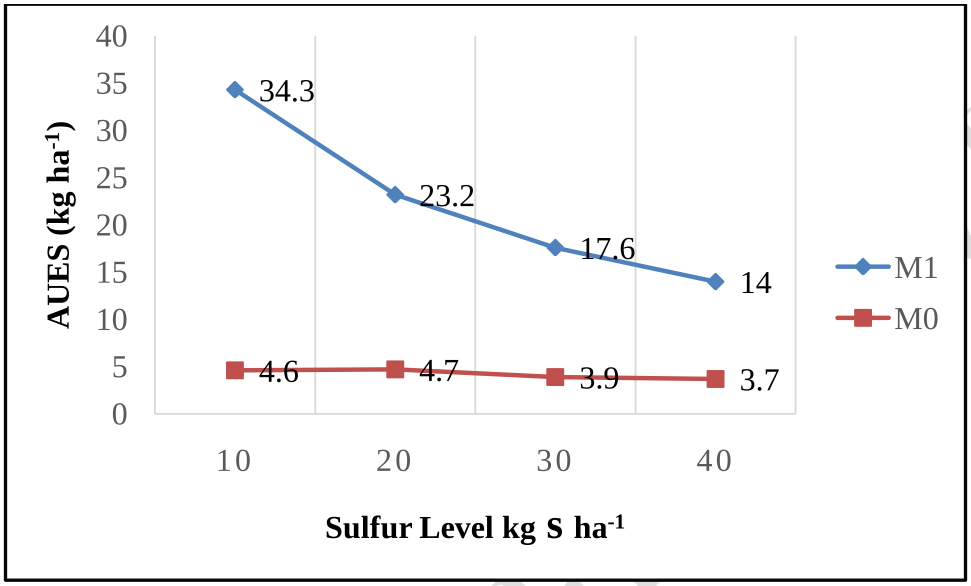

Figure 4. Effect of Tied Ridging on Agronomic Sulfur Use Efficiency

NB:AUES= Agronomic use efficiency of Sulfur, (S1=10, S2=20, S3=30, and S4=40) are sulfur fertilizer rates in kg S ha^{-1}. M1= plot with M1, M0= Flatbed.

4. Discussion

The results of the laboratory analysis for physical properties such as texture, bulk density, total porosity and water content of the soil show significant difference in the root zone (0-20, 20-40 and 40-60 cm) depths. The physical properties of the soil of the study area were characterized based on the analytical results of the soil samples collected from the surface as well as profile pits of the experimental field.

The laboratory results (Table 1) showed that the soil at the site is predominantly clay in texture throughout the 60 cm soil depth. The particle size distribution is almost similar within the profile but the sand percentage decreased slightly with increasing depth. On the contrary, the clay and silt contents were increased with increasing soil depth. Aydinalp[27] found higher clay contents due to more prolonged weathering. The slightly higher sand content at the surface can be probably due to sheet erosion and the higher clay content at the bottom depth is due to illuviation.

The bulkdensity of the soil profile increased with increasing soil depth. The area is plowed by disc plow tractor, therefore, this might be the reason for the high bulk density with increasing soil depth. The results of this study are in line with the findings of Brady & Weil [28] who reported a consistent increase in bulk density values with increasing soil depth in Vertisol. Hazeltonand Murphy [29] also reported lower organic matter content and weight of the overlay soil material as the possible reasons for increased trends of soil bulk density with soil depth. According to Hunt and Gilkes [30], clay soils with abulk density ranging from 1.2 to 1.4 g cm^{-3} are somewhat compacted, 1.4 to1.6 g cm^{-3} are very compacted and 1.6 to 1.8 g cm^{-3} are highly compacted. Therefore, soils of the study area are characterized by somewhat compacted in the surface0-20 cm depth and very compacted in the sub-soil (i.e. 20-60 cm). The totalporosity of the soil profile decreased with increasing depth. The reason for theconsistent decrease in total soil porosity of the soil of the study site could be attributed to low organic matter content. In line with this Landon [31] indicated that soil structure and organic matter content results in the formation of soil pore spaces but decreases with increasing depth of the soil profile.

Soil water content at field capacity (FC) was higher at 20-40 cm soil depth and the surface soil (0-20 cm) has high water content than the layer at the deeper soil profile 40-60 cm (Table 1). The highest permanent wilting point was also recorded at 20-40 cm. The available water holding capacity (AWHC) was higher at the surface (0-20 cm) but decreased with increasing depth. The possible reason for high AWHC at the surface could be due to higher organic matter content than the organic matter content in the subsurface comparatively. The difference in clay content in the profile depth (Table 1) is very small to bring a change in porosity. According to Hazelton & Murphy [29] water holding capacity of the soil is dependent on a range of soil properties such as particle size distribution, type of clay mineralogy, amount of organic matter content in the soil, the bulk density and structure of the soil.

Results presented in Figure 3showsthe variation of volumetric soil moisture content (VSMC) due to tillage treatments (ridge, furrow, and flatbed) determined at different depths of the soil and at different sampling days of the crop growth period. The results showed that the VSMC was affected by M1. Low VSMC was recorded duringplanting (initial sampling) for both plots treated with M1 (ridge and furrow) and flatbed. However, the VSMC of the plots with ridge and furrow remained higher than the VSMC obtained from plots under conventional tillage (flatbed) throughout the sampling period in all depths (0-20, 20-40, 40-60 and 0-60).

The average VSMC at 0-60 cm indicated in Figure 3 showed that at the planting time the moisture status of the experimental site was low and there was no difference between the treatments at the beginning of the rainy season. Nevertheless, the VSMC increased in an increasing rate through the second and third sampling i. e. day2 and day3 sampling days after planting. Then it was relatively constant in the day4, day5, and day6 sampling days after planting but started decreasing from day7, day8 and day9 sampling days after planting which is towards the end of the growing season. The amount of SMC recorded followed the order: Furrow>Ridge>Flatbed throughout the sampling days except at planting time. This is in line with the findings of Rana [32] who reported that ridges and furrows conserved more moisture than aflatbed. Nyssen et al. [33] also reported that ridges increased SMC in field experiments. The general trend of the average SMC status declined in the 104 and day9 sampling days. The SMC of the soil at 0-20 cm was very close to a state of PWP towards the end of the growing season Figure 3.Evaporation from the soil surface or transpiration from plant leaves removes water from micropores, and second critical state in relation to soil water is reached when plants permanently wilt, termed PWP [34].

The soil moisture content at planting time or day 0 (Appendix 1) revealed no significant ($p>0.05$) difference in VSMC among ridge, furrow, and flatbed at 0-20, 20-40, and 40-60 cm soil depths. This is because the field experiment was uniform across the plotsi.e. there was no rainfall recorded after the installation of M1. The lowest VSMC (18%) was recorded in this stage at 0-20 cm soil depth. The results in sampling day, day2 indicated significant ($p<0.05$) difference in VSMC among ridge, furrow, and flatbed at 0-20, 20-40 cm depths, but there was no significant ($p>0.05$) difference at 40-60 cm depths. The highest VSMC increment of M1 over flatbed was by 44% and this was recorded at 0-20 cm depth in the 13-sampling day. The VSMC is higher at the surface ranked in order of 0-20>20-40>40-60 cm soil depths. Soil moisture content was different at different depths. The surface 0-20 cm soil was between PWP and FC (Table 1) but the subsurface (40-60 cm) depth was at PWP. This showed that the soil was not wetted by the rainfall because of limited infiltration depth due to saturation of topsoil and swelling of clay minerals leading to thecrusted soil surface. This is in line with Hazelton & Murphy [29] who reported that infiltration is much higher before rainfall packs and decreases due to swelling of surface soil.

The average VSMC shown in Appendix 1 at 0-60 cm depth (sampling day 26) showed that the Furrow has the highest SMC while on the contrary Flatbed has the lowest SMC. However, the difference between ridge and furrow was insignificant because they are complementary, that is the VSMC stored in the furrow can rise to the ridge by capillary action which is a general truth. The highest average VSMC in-furrow, ridge, and flatbed were recorded at this sampling day 26. This is due to slow infiltration rates that gradually wet the soil profile. Tewodros et al. [35] and Nyssen et al., [36] indicated thatat the beginning of the rainy season, most rains infiltrated quickly into the dry, tilled fields; Furthermore, on Vertisol, which is well represented in Ethiopia, the first rains are well absorbed by the soil, in deep shrinkage cracks. After absorbing some moisture, the soil starts swelling, the cracks close; the soil becomes less permeable and generates important runoff. The results in Appendix 1 revealed that VSMC determined at day4, day5, and day6 sampling days was significantly ($p<0.05$) influenced by a ridge, furrow, and flatbed at all the soil depth intervals (0-20, 20-40, 40-60 cm).

Agronomic sulfur use efficiency of sesame is affected by the tillage treatments i.e.M1 and flatbed tillage (Figure 4). M1 (Figure 4) have a significant effect on agronomic sulfur use efficiency as compared to the conventional (flatbed) tillage practice (Figure 4). The sulfur use efficiency for plots with M1 and flatbedtillage practices decreased with increasing sulfur fertilizer rate.

Agronomic efficiency of sesame crop generally decreased with increasing sulfur fertilizer applied in the combination of sulfur with M1 (Figure 4). The highest amount of agronomic efficiency (14.4 kg kg^{-1}) of sulfur was obtained from the lowest sulfur rate applied i.e. 10 kg S ha^{-1} and the lowest agronomic use efficiency (9.0 kg kg^{-1}) was recorded from the highest sulfur fertilizer rate applied i.e. 40 kg S ha^{-1} under M1. These results agree with that of Verma et al. [37] who reported that as the level of sulfur fertilizer increases, the agronomic use efficiency decreases under sesame production system which is an inverse trend with anincrease in its fertilizer rates. Regimes et al. [38] also reported highest sulfur use efficiency was recorded under moisture conservation in sesame. Similarly, the general trend of agronomic sulfur use efficiency in flatbed sowing was decreasing with increasing sulfur rateand the highest amount of agronomic use efficiency was 9.5 kg kg^{-1} at 10 kg S ha^{-1}. The lowest agronomic use efficiency (4.9 kg kg^{-1})

was recorded from the highest sulfur fertilizer applied at 40 kg S ha^{-1}.From this, it can be concluded that M1has significant contributionin enhancing the agronomic sulfur use efficiency of sesame especially at the lower rate of sulfur (10, 20, and 30 kg S ha^{-1}) due to the ability of conserving moisture (Figure 3) at the root zone which is available for the crop.This is in line with the findings of Puste et al. [39] who found thatinteraction between water stressed and sulfur fertilizers decreased grain yield than the grain yield gained from the interaction of sulfur fertilizer rates with optimum moisture for sesame crop. Agronomic sulfur use efficiency decreases with increasing sulfur fertilizer rates.

5. CONCLUSION AND RECOMMENDATIONS

The study revealed the potential advantages of M1 and sulfur fertilizer rates for the high pH soils of Kafta Humera district in the semi-arid zone of Western Tigray lowlands. Based on the results of this study the following conclusions can be forwarded.M1tillage practice increased moisture at the root zone for the semi-arid Humera areas. The sulfur fertilizer rates revealed different responses in agronomic sulfur use efficiency. The highest sulfur use efficiency was recorded at the lowest (zero) sulfur level.M1 combined with sulfur fertilizer resulted for the highest agronomic sulfur use efficiency of the sesame crop.In moisture stressed areas like Humera, crop plants faced ashortage of moisture availability in the soil root zone in the growing season,unless it is suppliedwith in-situ moisture conservation techniques. Sulfur fertilizer did not show response in sulfur use efficiency by sesame crop in the flatbed tillage practice. Therefore, M1 tillage practice should be demonstrated at farmers' field for conserving moisture in the root zone andimproving sulfur use efficiency.

REFERENCES

1. CSA, Agricultural sample survey for the 2014/2015 crop season. Volume I. Report on area and production of major crops for private peasant holdings (Meher Season). Statistical Bulletin 278. FDRE/CSA, Addis Ababa, Ethiopia, 2015.
2. Ministry of Trade, Oilseed production and marketing situation in Ethiopia, November 14-15 Addis Ababa, Ethiopia, 2013.

3. CSA, Agricultural sample survey. Report on area and production, volume 3, Addis Ababa, Ethiopia, 2013.
4. Negash, G., Status of production and marketing of Ethiopian sesame seeds (*Sesamum indicum* L.): A Review, Agricultural, and biological sciences journal. 1(5), 217-223, 2015.
5. Rathore, S. S., Shekhawat, K., Babu, S., & Singh, V. K., Heliyon Mitigating moisture stress in Brassica juncea through de fi cit irrigation scheduling and hydrogel in ustocherpts soils of semi-arid India, *6*(September). https://doi.org/10.1016/j.heliyon.2020.e05786, 2020.
6. Tahir, M., Ibrahim, M. A., Tahir, S., Aimen, A., Tanveer, A., & Rehman H., Effect of sulfur levels on two sesame (*Sesamum indicum*L.) varieties under climatic conditions of Pakistan, International Journal of plant and soil science. 3(3), 281-288, 2014.
7. Rahmatullah, G., Nabi, M., Salim, S. & Zia, M.S., The relationship between seed sulfur and seed phosphorus and seed yield of Brassica nap son two alfisols fertilized with different sulfur sources. Pakistan Journal of biological science. 2, 262–265, 1999.
8. Anonymous, The business case for investing in a sesame hulling plant in Ethiopia, 2012.
9. Sibhatu, K., Sesame production and productivity in Western Tigray. December, 9 May, 2013.
10. Buss, J (2007) Sesame production in Nampula: Baseline survey report, Mozambique, pp.2-20.
11. Lobb, D. A., Huffman, E., & Reicosky, D. C., Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators, (October 2021), 2007.
12. Dercon, S. & Hill, V., Growth from agriculture in Ethiopia. Identifying key constraints. Paper prepared as part of a study on agriculture and growth in Ethiopia. DFID, UK., 2009.
13. Zelleke, G., Agegnehu, G., Abera, D., & Rashid, S., Fertilizer and soil fertility potential in Ethiopia, International food policy institute: working paper, 2010.
14. Seyed, N. & Reza T., Effect of the exogenous foliar salicylic acid application on sesame

(*Sesamum indicum*L.) morphological characters, seed yield and oil content under different irrigation regimes. International journal of biosciences. 5, 70-74, 2014.

15. Gebreyesus, B., Effect of tillage and fertilizer practices on sorghum production in Northern Ethiopia. Momona Ethiopian journal of science. 4(2), 52-69, 2012**.**
16. Heluf, G., Grain yield response of sorghum (*Sorghum bicolor* L) to tied ridges and planting methods on Entisols and Vertisol of Alemaya Area, Eastern Ethiopian Highlands. Journal of agriculture and rural development in the tropics and subtropics. 104, 113-128, 2003.
17. EthioSIS, Report on soil fertility status and fertilizer recommendation Atlas for Tigray Regional State. Ministry of agriculture and Ethiopian ATA. Addis Ababa, Ethiopia, PP.76, 2014.
18. Vays, S., Garg, B., Kathju, S., &Lahiris, A, Sensitivity of *sesamumindicum L*. to moisture stress at different development stages, Ann. Arid Zone. 22, 191-197, 1983.
19. Abrha, H., Grain Yield and Economic Returns of Sesame *(Sesamum indicum* L.*)* Induced by *In-situ* Moisture Conservation and Sulfur Fertilization on Vertisol of Western Tigray, Ethiopia. Asian Soil Research Journal. 1(2): 1-15, 2018.
20. EARO, An assessment of agricultural production base, technological packages and innovation strategies for commercial farmers in Kafta Humera District Tigray regional state, Ethiopia, 2002.
21. Tesfay, A., Cornelis, W., Nyssen, J., Govaerts, B., Bauer, H., Tewodros, G., Tigist, O., Raes, K., Sayre, D., Mitiku, H., Deckers, J., Effects of conservation agriculture on runoff, soil loss and crop yield under rain-fed conditions in Tigray, Northern Ethiopia. *Soil Use and Management*, 27:404–414, 2011.

22. Bouyoucos, J (1962) Hydrometer method improved for making particle size analysis of soil. Agronomy journals. 54, 464-465.
23. Mengel, K, & Kirkby, E., Principles of plant nutrition, 4^{th} ed. International potash institute, Bern, Switzerland, 2001.
24. Fageria, N. K.,&Baligar, V. C., Methodology for evaluation of Lowland Rice, 2003.
25. VSN International, Installation database window installer package, GenStat16 ed. Registered to: ICARDA, 2013.

26. Gomez, & Gomez, H., Statistical analysis for agricultural research. John Willy and Sons Inc, 120-155, 1984.
27. Aydinalp, Some important properties and classification of vertisol under Mediterranean climate. African Journal of agricultural research. 5 (6), 449-452, 2010.
28. Brady, N.C. & Weil. R.R (2002) The nature and properties of soils (13th ed). Pearson.
29. Hazelton, P. & Murphy, B., Interpreting soil test results: What do all the numbers mean? 2nd ed. CSIRO Publishing. pp 152, 2007.
30. Hunt, N. & Gilkes, R (1992) 'Farm Monitoring Handbook – A practical down-to-earth manual for farmers and other land use
31. Landon, J.R., Booker tropical soil manual: A Handbook for soil survey and agricultural land evaluation in the tropics and sub-tropics. Longman Scientific and Technical, Essex, New York, pp 474, 1991.
32. Rana, D. S., Integrated water management, Management of Rain-fed Agriculture. Indian Agricultural Research Institute New Delhi 110 012, 2007.
33. Nyssen, J., Govaerts, B., Tesfay, A., Cornelis, W.M., Bauer, H., Mitiku, H, M., Sayre, K., & Deckers, J., The use of the marasha ardplow for conservation agriculture in northern Ethiopia. Agron. Sustain. Dev. 31, 287-297, 2011.
34. Rawell, D.L., Soil Science-Methods and Applications. Dept. of soil management, University of Reading UK p 62, 1994.
35. Tewodros, M., Gebreyesus, B., Wortmann, C.S., Nikus, O., & Mamo, M., Tied ridging and fertilizer use for sorghum production in semi-arid Ethiopia. Nutr. Cycl. Agroecosys. 85, 87-94, 2009.
36. Nyssen, J., Poesen, J., Mitiku H., Moeyersons, J., Deckers, J. & Hurni, H., Effects of land use and land cover on sheet and rill erosion rates in the Tigray highlands, Ethiopia. Z. Geomorph. N. F.53 **(**2), 171–197, 2009.
37. Verma, R.K., Yadav, S.S., Puniya, M.M., Yadav, L.R., Yadav B.L. &Shivran, A.C., Effect of phosphorus and sulfur fertilization on growth and yield of sesame (*Sesamum indicum*L.) under loamy sand soils of Rajasthan, Ann. Agric. Res. New Series. 35 (1), 2014.
38. Regimes, D. M., Retardants, G., Consumptive, O. N., Use, W., In, E., & Sesame, S., Effect of Different Moisture Regimes and Growth Retardants on Consumptive Use and,

22(2), 96–98, 2002.

39. Puste, A., Pramanik, B., Jana, K., Roy S., & Devi, T., Effect of irrigation and sulfur on growth, yield and water use of summer sesame (*Sesamum indicum* L.) in New Alluvial zone of West Bengal, Journal crop and weed, 11(Special Issue), 2015.

Appendix 1. Volumetric soil moisture content (%) of furrow, ridge, and flatbed at different soil depths on different days of measurement during the growing season

	0	**13**	**26**	**39**	**52**	**65**	**78**	**91**	**104**
		(0-20 cm)							
Furrow	18	45.8^{a}	47.1^{a}	37.8^{a}	38.1^{a}	38.9^{a}	38.0^{a}	33.8^{a}	23.2^{a}
Ridge	18	41.3^{a}	47.1^{a}	35.7^{a}	36.0^{a}	37.1^{a}	35.5^{a}	28.3^{b}	21.0^{a}
Flatbed	18	30.3^{b}	43.4^{b}	30.3^{b}	31.0^{b}	31.2^{b}	32.2^{b}	24.8^{c}	17.0^{b}
LSD (5%)	-	4.6	2.4	3.5	2.7	3.6	2.1	2.1	2.3
CV (%)	-	15.6	6.7	13.2	10	13.0	7.9	9.6	14.5
		(20-40 cm)							
Furrow	23	41.2^{a}	52.0^{a}	50.1^{a}	48.0^{a}	50^{a}	47.2^{a}	40.6^{a}	34.0^{a}
Ridge	23	30.9^{b}	50.0^{a}	50.0^{a}	47.0^{a}	48^{a}	43.2^{b}	37.8^{a}	33.0^{a}
Flatbed	23	31.1^{b}	42.3^{b}	40.3^{b}	40.0^{b}	40^{b}	40.1^{b}	32.7^{b}	27.2^{b}
LSD (5%)		4.3	3.3	3.7	4.5	2.8	15	2.4	2.7
CV (%)		16.3	9	10.3	13.3	7.9	7.6	8.6	11.5
		(40-60 cm)							
Furrow	21	28	48.4^{a}	56.0^{a}	52.0^{a}	55.1^{a}	49.5^{a}	43.8^{a}	39.2^{a}
Ridge	21	24	45.0^{b}	54.4^{a}	50.3^{a}	52.1^{b}	48.2^{a}	42.6^{a}	37.4^{a}
Flatbed	21	24	39.2^{c}	47.0^{b}	44.1^{b}	45.0^{c}	42.6^{b}	36.1^{b}	32.2^{b}
LSD (5%)	-	4.3	3.7	4.4	3.5	2.2	2.4	1.7	3.5
CV (%)	-	22	11.1	11.1	9.3	5.8	6.7	5.4	12.8
		Average **(0-60 cm)**							
Furrow	21	38	49	48	46	48	45	39	32
Ridge	21	32	47	47	44	46	42	36	30
Flatbed	21	28	42	39	38	39	38	31	25

NB: In tied ridges moisture was taken from the Furrow and Ridge on the same plot. 0, 13, 26…104 are sampling days from planting to harvest at an interval of 13 days.