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Research Article

Effect of Supplemental Irrigation at Different Irrigation Levels on Cotton Yield and Water Use Efficiency at Werer, Middle Awash, Ethiopia

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Abstract

Effects of supplemental irrigation at different irrigation levels on Cotton Yield and Water use efficiency conducted in Werer, Middle Awash, Ethiopia on 2018, 2019 and 2021 fiscal years. Cotton was planted in 18 experimental plots with irrigation treatment (No SI, 100% ETC, 80% ETC, 60% ETC, 40% ETC, and 20% ETC). Supplemental irrigation was conducted based on gravimetric soil moisture measurements. The results show more significant improvement in supplemental irrigation on water use efficiency at supplemental irrigation application rates than at full irrigation. Highest water use efficiency (WUE) (0.87 kg/m^3) was achieved at rates of 80% ETc water requirement of crop. The lowest water use efficiency had recorded from application of 60% evapotranspiration requirement by supplemental irrigation. The highest cotton seed yield on average (3,252 kg/ha) was achieved from 80% application of supplementary irrigation to satisfy the water demand of cotton crop. The trend of water use efficiency increases as the application of supplemental irrigation decreases.

Keywords

Irrigation, Cotton, Fiber Quality, Yield, Nitrogen

1. Introduction

In Ethiopia, cotton-producing areas with high potential account for 65%, while the remaining areas are considered medium potential. Regarding the total land under cotton cultivation, 45% is owned by private farms, 33% by smallholders, and the remaining 22% is state-owned farms. Cotton production has increased in both areas and total production. Most large-scale cotton production has been grown on irrigated state farms, primarily in the Awash valley area. Production increased from 5,000 tons in 1964/65 to 15,000 tons in 1974/75, while the area of cultivation increased from 40,500 hectares in 1964/65 to 72,800 hectares in 1974/75 [3]. Cotton (*Gossypium hirsutum* L.) serves as the primary raw material for the global textile industry, being the most valuable natural fiber and the second most crucial oil-seed crop on a global scale [1]. Cotton is a major cash crop in Ethiopia, extensively grown in both irrigated and rain-fed areas on large and small scales. It serves as a significant input for the textile industry.

About 41% of the Earth's geographical surface is classed as dryland, where the farming system is characterized by annual rainfall of 300–500 mm, with the majority of it falling in the winter and spring [9]. Ethiopia's enormous swaths of rich land, varied climate, generally enough rainfall, and large labor pool

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all contribute to the country's agricultural potential. Ethiopian agriculture, however, has remained underdeveloped despite its potential. Droughts are common in the agricultural industry, and farming practices are often substandard. Evaporation and runoff waste some of the extremely valuable rainwater in the arid zones. Dryland farming occurs primarily in semiarid areas where annual precipitation is < 25 – 50% of the potential evapotranspiration (ET) demands.

Low rainfall, which is not only insufficient for many crops but also inconsistent, poses a significant barrier to economic farming in dry places [14]. Agricultural production remains the primary source of income for most African rural populations, and agricultural techniques are tailored to the region's current environment. Climate change has the potential to affect the long-term viability of these systems, and they will change with little capability to adjust [13, 15].

In semi-arid Sub-Saharan Africa (SSA), water has long been thought to be the most limited resource for agricultural growth. Although water is scarce, crop development and yields are generally hampered by water distribution rather than a lack of total seasonal levels [13]. Rainfall displays great temporal variability in these areas, as seen by unpredictable onset windows (too early or late onsets), early cessation, and erratic mean seasonal and annual rainfall distribution patterns [4]. Higher seasonal rainfall variability, which results in critical and protracted intra-seasonal dry spells, has a significant impact on crop productivity.

Supplemental irrigation is the application of modest amounts of water to essentially rain-fed crops when rainfall fails to deliver sufficient moisture for normal plant growth, with the goal of improving and stabilizing yields [10]. Research results from the International Center for Agricultural Research in the Dry Areas (ICARDA) and other institutions in the dry areas, as well as harvest from farmers, showed substantial increases in rainfed crop yields in response to SI application in low as well as high rainfall regions [11].

When compared with the productivity of water in fully irrigated areas (rainfall effect is negligible), greater advantage is obtained with supplemental irrigation. In fully irrigated areas with good management, wheat grain yield is about 6 ton/ha using a total amount of 800 mm of water. This makes water productivity about 0.75 kg grain/m^3 of water, one-third of that under SI with similar management. Under purely rainfed conditions, the rainwater productivity, however, is only 0.5 kg grain/m^3 of rainwater [10]. The rainfall in this area is insufficient to supply the crop water requirements. As a result, additional watering should be provided. The purpose of this research was to see how varying levels of supplemental irrigation affected agricultural output and water use efficiency (WUE).

2. Material and Methods

2.1. Description of Study Area

The experiment was conducted at the Werer Agricultural Research Centre's in the Ethiopian region of Afar in 2018, 2019, and 2021. It's located at 9°16'8" latitude, 40°9'41" longitude, and 740 meters above sea level with an average annual rainfall of 590 mm; the area is classed as semi-arid. According to meteorological data collected at the experimental site's Agro meteorological observatory, the average minimum and maximum temperatures are 19°C and 40.8°C, respectively. Gradients are often relatively modest, typically in the 1-2 percent range.

The collected soil samples were composited into three samples based on the soil depth. The composite soil samples were collected and air-dried, thoroughly mixed. The samples were properly labelled, packed and transported to the laboratory. After that, the samples were dispersed after testing and for pH, and soil organic matter (SOM). Soil textures were analysed at Werer Agricultural research center Soil and plant Laboratory. The soil pH was measured in the supernatant suspension of a 1: 2: 5 using a Standard glass electrode pH meter [12]. The soil particle size distribution was determined using the Bouyoucos hydrometer method [6]. The water sample was taken from the site which was used for the irrigation application. Field capacity and permanent wilting point of the experimental site was done.

Table 1. Physical properties and soil texture of experimental field.

Soil depth (cm)	FC (%)	PWP (%)	Available water (mm/m)	Drainage rate (cm/hr)	BD (g/cm^3)	Texture			
						Sand	Clay	Silt	Class
0-30	42	30	147.9	26.9	1.19	5.1	58.2	36.7	Clay
30-60	42	30	152.9	24.4	1.23	9.1	52.9	38	Clay
60-90	41	27	156.8	26.4	1.22	6.5	51.5	42	Silty clay

FC= Field Capacity, PWP= Permanent Wilting Point, BD= Bulk density

The topsoil surface exhibited a slightly lower bulk density (1.19 g/cm^3) compared to the subsurface (1.22 g/cm^3), possibly due to higher organic matter content in the topsoil and increased compaction at lower depths. However, the average soil bulk density (1.21 g/cm^3) was generally suitable for crop root growth. Moisture content at the permanent wilting point varied with depth, increasing from the surface to lower depths. The total available water (TAW), which represents the amount of water a crop can extract from its root zone, is directly influenced by variations in field capacity (FC) and permanent wilting point (PWP) as well as root depth.

Organic Matter (OM) plays a crucial role in enhancing water-holding capacity, nutrient release, and soil structure. The composite soil sample provided exhibited a low level of soil OM, as indicated in Table 2. This finding aligns with previous research, which suggests that soils with OM values falling within the range of 0.86 - 2.59% are considered low in organic matter. Consequently, these soils require additional materials or nutrients to increase the organic matter content.

Table 2. *Experimental site soil chemical characterization.*

Depth (cm)	Ece (ds/m)	pH	Soluble cations			
			Ca$^+$Mg (meq/l)	meq/l (Na)	meq/l (k)	SAR
0-30	0.44	7.70	1.50	12.10	1.01	13.80
30-60	0.61	7.50	1.20	15.60	1.03	21.50
60-90	0.79	7.50	1.50	13.70	1.10	17.40

Depth (cm)	Exchangeable cations			OC (%)	TOC (%)	OM (%)	TN (%)	P (ppm)
	(Ca+Mg) cmol+/kg	K cmol+/kg	Na cmol+/kg					
0-30	46.3	5.8	18.5	0.77	0.95	1.64	0.08	14.73
30-60	44.7	4.3	16.2	0.61	0.8	1.38	0.07	16.63
60-90	43.3	2.6	14.3	0.52	0.69	1.19	0.06	17.06

OC= organic carbon, TOC= Total organic Carbon, OM= Organic matter, TN= Total nitrogen, SAR= Sodium Absorption Ratio

As indicated in Table 2, the salinity of the soil (ECe) at the experimental site was determined. Furthermore, the pH value of the experimental site was within safe levels. According to [7], soils having pH value in the ranges are considered neutral soils. The soil of the site categorized under clay soil texture.

2.2. Methods of Data Collection and Analyses

2.2.1. Reference Evapo-transpiration

Evapotranspiration refers to the combined processes of water loss from the soil surface through evaporation and from the crop through transpiration. Reference evapotranspiration (ETo) can be calculated using meteorological data following an expert consultation in May 1990, the FAO Penman-Monteith methodology is currently recommended as the sole standard method for defining and computing reference evapotranspiration. Data on radiation, air temperature, air humidity, and wind speed are required by the FAO Penman-Monteith technique [2]. The method indicated below was used to calculate crop water use throughout the irrigation period [8].

$$\mathrm{ET} = \mathrm{I} + \mathrm{P} - D_r - R_f \pm \Delta\mathrm{S} \tag{1}$$

Where, ET is evapotranspiration, I is irrigation water, P is effective rainfall plus capillary rise, D_r is drainage, R_f is runoff, and ΔS is change in the soil moisture content all in mm unit.

2.2.2. Treatment Design

The experiment was designed as a randomized complete block design with three replications and six supplemental irrigation treatments (Table 3). The treatments included supplemental irrigation and rain-fed with no supplemental irrigation as a control. The amount of irrigation water was calculated using Cropwat version 8.0 software, which considers climate, soil, and crop data. Input data for the CROPWAT software included the location (altitude, latitude, and longitude) of the meteorological station, daily maximum and minimum air temperatures, air humidity, sunshine duration, and wind speed from a meteorological station located at the experimental site. The amount of water applied at 100% ETc was calculated as the difference between crop water requirement and effective rainfall using the Cropwat model.

Table 3. *Treatment design.*

No	Treatment	Treatment description
1	T1	No supplemental irrigation
2	T2	Supplemental irrigation of 100% ETc
3	T3	Supplemental irrigation of 80% of ETc
4	T4	Supplemental irrigation of 60% ETc
5	T5	Supplemental irrigation of 40% ETc
6	T6	Supplemental irrigation of 20% ETc

T= Treatment, ETc= Evapotranspiration

There were a total of six treatments and three replications in the experiment. The irrigation treatments were applied by deducting from 100% ETc with respective percentages. The single plot area was 25 m^2. Each application of water was measured using a three-inch dimension Parshall flume. The spacing between furrows and plants was 0.9 m and 0.25 m, respectively.

Based on the meteorological data, the area received rainfall that was below the necessary amount for the crops. Figure 1 summarizes the monthly effective rainfall and the crop water requirement observed during the field study. There was a notable difference between the crop water requirements and the actual monthly rainfall. Effective amount of rainfall (figure 1) entering into the soil for plant use is small and not sufficient for the growth of crops like cotton, maize, sesame, and groundnut in this region.

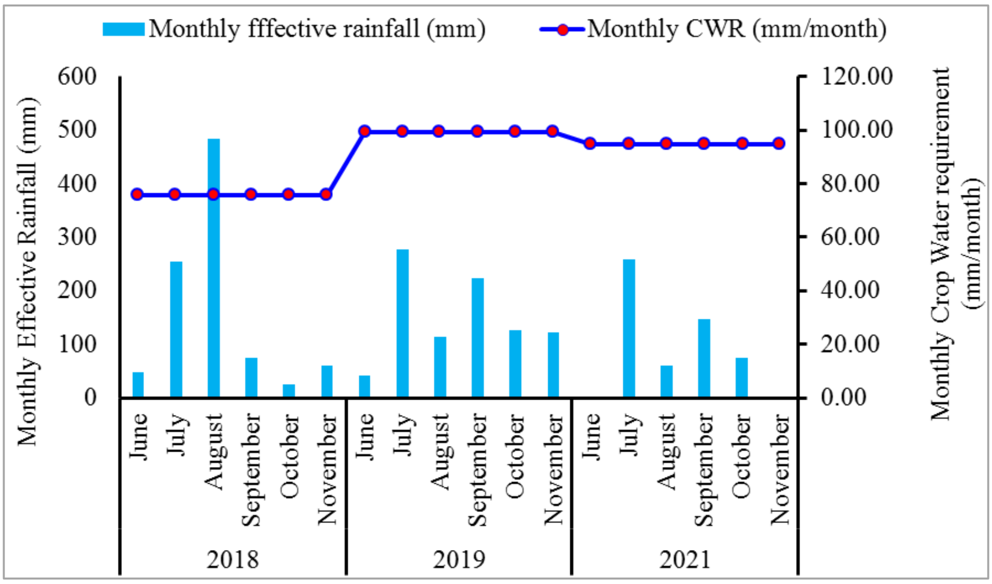

Figure 1. *The gap between monthly effective rainfall and crop water requirement.*

Hence, to meet the irrigation demand (water deficit) of the crop application of supplemental irrigation is necessary.

2.3. Supplemental Irrigation Water Requirement

The amount of water needed (CWR) to compensate the amount of water lost through evapotranspiration (ETc), requires reference evapotranspiration (ETo) and cotton crop coefficient (Kc) given by [2] 0.7 < Kc < 1.20 for the crop mid stage 1.15, for the end or late stage and 0.7 for the late-season stage. Calculation of crop water demand (ETc) using CROPWAT software over the growing season was from ETo and crop coefficient (Kc). The effective rainfall was estimated based on dependable rain (FAO/AGAW formula) on the method given by [2].

$$\left.\begin{aligned} P_{eff} &= 0.6 * P - 10 \text{ for month} \leq 70 \\ P_{eff} &= 0.8 * P - 24 \text{ for month } > 70 \end{aligned}\right\} \quad (2)$$

Estimating seasonal rainfall characteristics based on records is important to assess drought risk and to improve drought mitigation strategies such as supplementary irrigation. Rainfall inconsistency has been accounted to have a major effect on Ethiopia's economy and food production for the last three decades. There have been reported of rainfall variability and drought associated food shortage [5]. Relatively, high rainfall amount was received during 20 period (Figure 2).

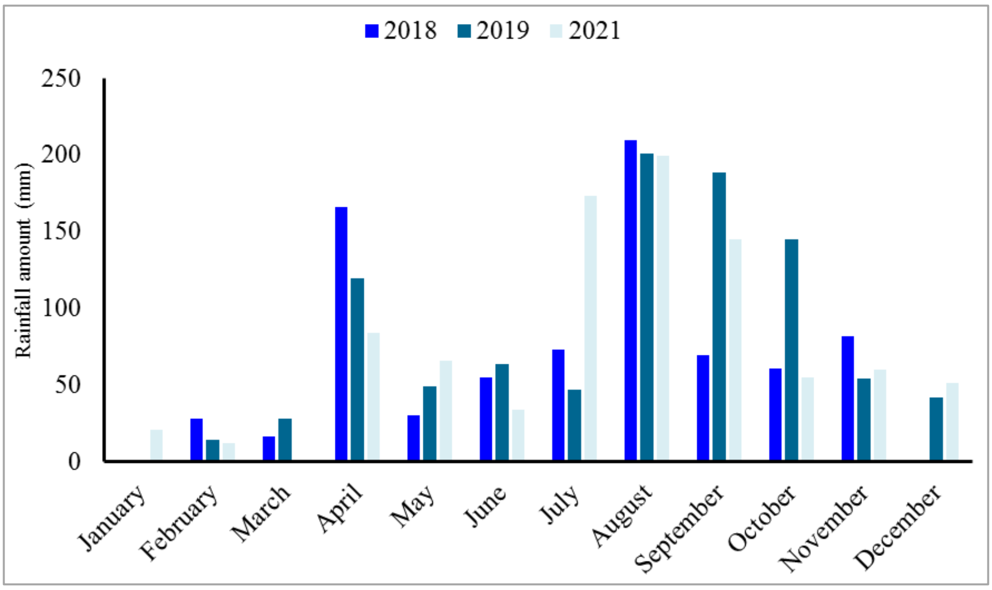

Figure 2. *Monthly rainfall distribution during field experiment.*

In semi-arid areas, the shortage of soil moisture typically occurs during the most critical stages of crop growth. This shortage is usually experienced in the summer but can occur at other stages as well due to the semi-arid climate. As a result of this stress, crops exhibit poor growth, leading to low yields. The management of supplemental irrigation is essentially the reverse of full irrigation. In full irrigation, the primary source of moisture is the fully controlled irrigation water, with limited and variable precipitation serving as a supplementary source. In contrast, supplemental irrigation management relies on irrigation as the primary source of water for crop production.

3. Result and Discussion

The results show more significant improvement in supplemental irrigation water use efficiency at supplemental irrigation application rates than at full irrigation. Highest water use efficiency (WUE) (0.87 kg/m^3) was achieved at application of 80% of evapotranspiration. The highest cotton seed yield on average (3,252 kg/ha) was achieved from 80% application of crop evapotranspiration to satisfy the crop water demand. From result described in the Table 4 supplementary irrigation is necessary in the areas where the monthly effective rainfall is less than the crop water requirement.

Table 4. *The average of measured parameters and statistical analysis results.*

Parameters	Years	Treatment							
		T1	T2	T3	T4	T5	T6	CV	LSD
TIA (mm)	2018	259.9	645.4	568.4	491.2	414.1	337		
	2019	402.9	788.1	711.1	633.9	556.8	479.7		
	2021	371.6	761.6	684.6	607.4	530.3	453.2		
PH (cm)	2018	96.5^b	126.6^a	111.8^{ab}	111.2^{ab}	125.6^a	103.8^b	8.65	17.7
	2019	96^b	126^a	112^{ab}	111^{ab}	125^a	103^{ab}	13.7	28.2
	2021	94.4^a	107^a	102^a	104^a	112^a	106^a	14.4	
SY (kg/ha)	2018	3601^a	3336^a	3369^a	4571^a	3900^a	4193^a	14.5	
	2019	1919^c	2905^a	3043^a	2182^{bc}	2224^{bc}	2749^{ab}	14.3	655.4
	2021	3006^a	2751^a	3344^a	3558^a	3058^a	3302^a	12.2	

Parameters	Years	Treatment							
		T1	T2	T3	T4	T5	T6	CV	LSD
Stand Count	2018	182,962[ab]	174073[ab]	193333[a]	202221[a]	184,444[ab]	156295[b]	10.8	35970
	2019	153,333[a]	153,333[a]	158518[a]	158518[a]	151110[a]	154814[a]	7.02	
	2021	38720[a]	39141[a]	40824[a]	42087[a]	37878[a]	36616[a]	11.3	
WUE (kg/m^3)	2018	0.64[a]	0.35[a]	0.39[a]	0.58[a]	0.55[a]	0.66[a]	9.2	
	2019	1.17[ab]	1.02[b]	1.13[ab]	0.89[b]	1.03[b]	1.43[a]	9.3	0.39
	2021	0.53[a]	0.28[b]	0.37[ab]	0.44[ab]	0.42[ab]	0.51[ab]	13.0	0.24

TIA= Total irrigation amount applied (mm), PH= plant height (cm), SY= Seed yield (kg/ha), WUE= Water Use Efficiency (kg/m^3)

In line with these findings, research results from ICARDA and other institutions in dry land areas, as well as data from farmers' fields, demonstrate substantial increases in crop yields in response to the application of relatively small amounts of supplemental irrigation. This increase is achievable in both low and high rainfall conditions. Generally, optimal supplemental irrigation ranges from 75 mm in areas with annual rainfall of 500 mm to 250 mm in areas receiving 250 mm of rain. With supplemental irrigation, the average grain yield rises to 3 t/ha. In 1996, over 40% of rainfed areas were under supplemental irrigation, and over half of the 4 million tonnes of national production was attributed to this practice [10].

Maximizing farmers' profits may not always lead to maximum water use efficiency (WUE). In situations where the cost of irrigation water is low and the available water resource is brackish, farmers may not be incentivized to maximize WUE; instead, they might apply water to meet the full crop water needs to achieve near-maximum yield and decrease the effect of soil salinity and sodicity. However, in scenarios where irrigation water is highly saline achieving maximum yield may not impossible. In such cases, proper management of irrigation water should consider soil characteristics for the long-term sustainability of the resource. Additionally, it should also take into account the value of water at both the national and farmer levels. Therefore, application of over irrigation water aggravate the expansion of soil salinity and sodicity which disturbs the chemical and physical properties (infiltration and water holding capacity) of soil.

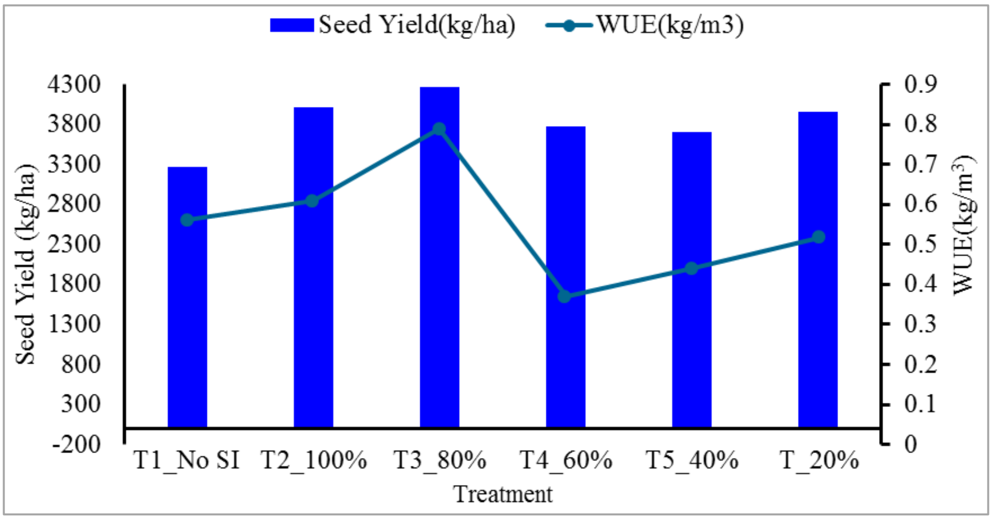

Figure 3. Effect supplemental irrigation on WUE and lint yield of cotton.

As indicated in the (Figure 3) the maximum seed yield was obtained from application 654.7 mm irrigation water. The maximum water use efficiency (0.87 m^3/kg) had recorded from application of 80% evapotranspiration need from supplemental irrigation and the 20% fulfilled by rainfall. The lower water use efficiency had recorded from application of 60% evapotranspiration requirement by supplemental irrigation. The trend of water use efficiency increases as the application of supplemental irrigation decreases.

The results of 2018 to 2021 indicated that plant height and water use efficiency statistically significant (Table 4).

Table 5. Effect of Supplemental irrigation on WUE.

Treatment	PH (cm)	Stand count	WUE (m^3/kg)
T1	88.8[b]	130892.1[a]	0.78[ab]
T2	100.7[ab]	122182.8[ab]	0.55[c]
T3	94.9[ab]	130892.1[a]	0.87[a]
T4	98.5[ab]	134275.8[a]	0.63[bc]
T5	103.8[a]	125005.5[ab]	0.67[bc]
T6	95.4[ab]	115908.8[b]	0.63[bc]
Lsd	13.11	12819.49	0.18
CV	22.9	15	13

PH= plant height, T1-T6= Treatment Number, and WUE= water use efficiency

The result supplementing the cotton with the treatment application of 80% ETc of irrigation obtained better lint and seed yield and water use efficiency as compared to other treatments.

4. Conclusion

Highest water use efficiency (WUE) (0.87 kg/m^3) was achieved at rates 80% of water requirement of crop application of effective rainfall amount. The highest cotton seed yield on average (3,252 kg/ha) was achieved from 80% application of supplementary irrigation to effective rainfall to satisfy the crop water demand of cotton. Therefore, application of 80% (654.7 mm) of supplementary irrigation has been recommended for farmers due to substantial increment of seed and lint yield.

Abbreviations

ETC	Crop Evapotranspiration
ETo	Reference Evapotranspiration
SI	Supplemental Irrigation
WUE	Water Use Efficiency

Author Contributions

Fikadu Robi: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Jemal Mohammed: Conceptualization, Data curation, Investigation, Supervision, Visualization, Writing – review & editing

Wondimu Tolcha: Investigation, Supervision, Writing – review & editing

Tesema Mitiku: Supervision, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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