Heliyon 11 (2025) e41618

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Soil fertility management on sesame (*Sesamum indicum* L.) production in Northern Ethiopia: A review

Fiseha Baraki [a,*], Fisseha Hadgu [b], Gebremedhin Berhe [b]

[a] *Tigray Agricultural Research Institute, Humera Agricultural Research Center, Humera, Tigray, Ethiopia*
[b] *Tigray Agricultural Research Institute, Mekelle Soil Research Center, Mekelle, Tigray, Ethiopia*

A R T I C L E I N F O

Keywords:
Fertilizer
Organic and inorganic fertilizers
Sesame
Sesame yield
Soil description
Soil fertility

A B S T R A C T

Sesame (*Sesamum indicum* L.) is an important cash crop and plays a vital role in many people's livelihoods in Ethiopia. However, its production is low due to many constraints, and low soil fertility is among the major. The previous fertilizer recommendation was a blanket recommendation regardless of the soil fertility status. Hence, the objective of this review is to synthesize the different recommendations and forward to the sesame growing areas. R statistical software and Python programming language used to analyze the chemical and physical soil properties, association among the chemical and physical soil properties and association with soil depth. The organic carbon, total N (Nitrogen), available P (Phosphorus), S (Sulfur) and Zn (Zinc) are below optimum value while K is sufficient in the soil and moderately alkaline soil. The soil particle size is dominantly clay (58.5 %). The clay particle size and pH increased while the sand and silt particle sizes, organic carbon, total N, available P and S decreased as the soil depth increased. 204,558.8 ton of sesame stack residue are burned every year, and from this, 7360.03 ton of NPK is lost every year in Western Tigray. The recommended N, P and S for sesame are: (i) 64 and 41 kg ha $^{-1}$ N for low N content areas and for medium N content areas respectively; 46 and 23 kg ha $^{-1}$ P_2O_5 for low and medium P content areas; (iii) 60 and 30 kg ha $^{-1}$ S for low medium S content areas may be recommended to boost sesame production.

1. Introduction

1.1. Sesame production and its importance

Sesame (*Sesamum indicum* L.) is an industrial crop that grows chiefly for its vital seed that contains about 50 % oil, 25 % protein [1] and 18.2–20.2 % carbohydrate [2]. The genus Sesamum is the oldest crop grown since 3500–3050 BC in the ancient Mesopotamia [3]. Sesame is often called the queen of oil seed crops because of its excellent quality of the edible oil it produces [4]. Sesame seed consists of major natural antioxidants like (+)-Sesamin, (+)-sesamolin and (+)-sesaminol [5]. These anti-oxidative compounds preserve the stability of sesame seed and oil. Sesame oil, has lower (<15 %) saturated fatty acids (SFAsa), which in turn has the health promoting effects such as lowering cholesterol levels and hypertension in humans [6]. Sesame is widely used as food, medicine, cosmetics, and health products and there are thousands of different types of sesame products in the world.

Sesame is well cultivated between 25° N and 25° S latitudes and it can be cultivated in humid, tropical and sub-tropical regions [7].

* Corresponding author.
E-mail address: fiseha.sbn@gmail.com (F. Baraki).

https://doi.org/10.1016/j.heliyon.2024.e41618
Received 25 July 2024; Received in revised form 20 November 2024; Accepted 31 December 2024
Available online 9 January 2025

Sesame grows best on medium to light well-drained soils that do not stand water. Good drainage is crucial, as sesame is very susceptible to short periods of waterlogging. It grows well on stored soil moisture with minimal irrigation or rainfall. It has been successfully produced on most soil types. The crop prefers slightly acid to alkaline soils but, intolerant of very acidic or saline soils. The crop has a deep taproot that grows best in deep non-compacted soils and maximum yields achieved when there is no soil compaction.

About 6.7 million ton of sesame seed produced from 12.8 million hectare worldwide in 2022. Africa is the largest sesame producer (59 %) followed by Asia (36 %) and America (5 %) [8]. In terms of yield in kg ha $^{-1}$, Ethiopia is in the fourth, with the productivity of 720 kg ha^{-1} from the top ten sesame producers in the world [8]. The sesame productivity in the lowlands of western Tigray is 396 kg ha^{-1}, and 825 kg ha $^{-1}$, without and with the use of improved technologies respectively [9]. This lower productivity is because of the poor agricultural production system. Among which, soil fertility management is obviously the most detrimental factor in lowering sesame productivity.

Tigray is the major sesame producer in the country and the crop occurs both as cultivated and wild, with incredible variability in the lowlands of Western Tigray. The Humera-type sesame is the reference for sesame grading in the international market and it has good aroma, sweet taste, and good demand in the world market [10]. It grows in the Humera areas and hence, these areas can be declared as best sesame growing areas in the world. During 2018/19 cropping season, 196,217 holders had grown oil crops in Tigray. Of whom, about 63 % of the holders (123,513 producers) had grown sesame. The area coverage, production and productivity of sesame was 95,943.72 ha (88.9 % of oil crops), 58,233.348 ton (79.3 % of oil crops production) and 0.607 ton ha^{-1}, respectively [11].

Different research studies investigated and recommended different fertilizer types rates and times and methods of applications for sesame production in the Northern Ethiopia, mainly in the Tigray state. The previously recommended rate, 41 kg ha^{-1}, Nitrogen (N) + 46 kg ha^{-1}, Phosphorus (P), is not adequate to boost sesame productivity and quality in the sesame growing areas of Tigray. Moreover, the previous recommendation was a blanket recommendation to all sesame-growing areas regardless of the soil fertility status. Hence, the objective of this review is to systematically synthesize the different recommendations and forward appropriate recommendations to the different sesame growing areas of Tigray, forwarding the future prospects of sesame fertilization rates and types and related issues.

1.2. Sesame production constraints

1.2.1. Biotic and abiotic stresses

Crop yield is the function of the interaction between genotype, environment and management: Yield = genotype (**G**) X environment (**E**) X management (**M**). Where: G: refers to crop variety or cultivar; E: refers to soil and agro-climate conditions in the particular location; and M: refers to any management or agricultural operation during the production period. Hence, the use of the right genotype, planting at the right environment and implementing the right management practices, including soil fertility management, are indispensable to boost productivity and quality. Hence, anything that affects the abovementioned factors (G, E and M) and/or their interactions adversely affects sesame productivity and quality.

Because of the conducive growing environment, immense genetic variability with many desirable traits, there is huge potential to produce quality sesame with higher productivity in Tigray. However, because of many intermingled constraints, the productivity and quality are below the crop's potential. The constraints can be because of the crop variety related limitations. Lack of widely adapting cultivars, shattering of capsules at maturity, non-synchronous maturity, poor stand establishment, the use of poor quality seeds, susceptibility to different biotic and abiotic stresses are among the major crop related constraints. On the other hand, the constraints might be because of the growing environment and management practices-abiotic stresses. This includes like inappropriate land preparation; inappropriate planting (time, rate and method) high post-harvest loss, agro-climatic stresses like moisture and temperature stress, edaphic stresses such as water logging and poor soil fertility and no/inappropriate fertilization and others. In addition to these abiotic stresses, insect pests [12,13]; diseases [14]; and weeds [15,16] are the major biotic stresses that significantly affects sesame productivity and quality.

1.2.2. Cultural practices

Most of the sesame growing areas in Tigray have been cultivated for many years continuously. Sesame is the major crop in Western Tigray, where the crop is grown year after year-mono-cropping. Moreover, sole sesame cultivation, without intercropping with any other crops is the common practice. Mono-cropping results in depletion of soil nutrients, damages soil structure, causes buildup of soil borne diseases and weed seeds. Mono-cropping, continuous cultivation, low soil organic matter, inappropriate land use practice, limited application of fertilizers and soil erosion, are among the major causes of soil fertility degradation [17,18]. Reduced yield, rocky outcrops, weed infestation, and crops wilting early in the growing cycle are the principal indicators used for identifying declining soil fertility or soil degradation [19]. In addition to mono-cropping, poor tillage practices (repeated shallow tillage with 5–10 cm deep) and the removal of sesame crop residues are also among the major problems that damage the soil structure and lowers soil organic matter.

2. Material and methods

Gathering of the available research outputs from different agricultural research centers, higher learning institutes and others was the starting of this review. Personal communications were also conducted to access the published and unpublished research outputs. Then, a detailed literature search was carried out using web of science, google scholars, Scopus and open access journals search engines. Papers selection was made through specific searches for appropriate articles on sesame soil fertility studies in different parts of the world. The selection process was based on appropriate criteria, including title, abstract, keywords and content.

From the collected literatures, descriptive statistics of soil physical and chemical properties and the box and whisker plot for sesame seed yield was analyzed using the "metan" package [20] of the R statistical software [21]. The correlation between the physical and chemical soil properties and relation of the soil physical and chemical properties with soil sampling depths is determined and sketched using Python programming language [22] version 3.12.4 of Matplotlib package [23] version 3.8.4, Pandas package [24] version 2.2.2 and Numpy package version 1.26.4 [25]. The exhaustive collection of literature materials and detailed analysis led us to make strong conclusions and future prospects.

3. Results and discussion

3.1. Estimation of annual NPS losses

Almost all of the farmers in the sesame growing areas clear their land by collecting and burning the crop residues, collecting for animal feed, and using as source of energy for cement industry. It implies that the nutrients have been burning and migrating from the farmland. Sesame biomass yield is estimated to be about 3.682 ton ha^{-1} [26] and sesame crop residue (stack residues and stand residue) is estimated to be 2.013 ton ha^{-1} in the sesame producing areas of western Tigray [27]. The findings on sesame stack residue and related values is described in (Table 1).

Based on the findings in (Table 1), the total macronutrient lost because of residue burning in the sesame growing areas of Western Tigray is presented in (Fig. 1). A total of 7360.03 ton nutrient concentration is lost every year in the sesame growing areas of Western Tigray from which, 5017.83 ton N is lost every year. The removal or burning of crop residue from a farmland can cause a loss of 98–100 % of N, 75 % of S, 21 % of P, and 35 % of K [30].

Most of the sesame fields are privately owned and poor soil fertility management production practices are implemented compared to smallholder farmers [9]. Sesame production in these areas is highly aggravating soil degradation results in low productivity and quality. Sesame production without fertilization and even inappropriate fertilization are among the major constraints of sesame production [31,32]. Therefore, the addition of the right type and rate of fertilizer at the right time with proper integrated soil fertility management is vital to boost sesame productivity and quality.

3.2. Soil description of the sesame growing areas

Fertilizer applications are important to increase crop productivity and agricultural sustainability [33]. The physical and chemical properties of a soil have a very high degree of association with crop production and have high influence on soil fertility and crop performance [34]. Many African soils show nutrient deficiency problems after only a short period of cultivation because of their nature as well as prevailing environmental conditions [35]. The major soil types in Kafta-Humera district are vertisols, cambisols, luvisols, leptosols, regosols, nitisols and fluvisols [36]. However, the dominant soil in the lowlands of Western Tigray is chromic Vertisols characterized by high contents of clay minerals [37]. The Vertisols in Ethiopia generally contain more than 40 % clay in their surface horizons [38] and this might be also true in the case of Vertisols of the sesame growing areas. Such Vertisols with high clay contents are susceptible to swelling and shrinking characteristics based on the moisture status of the soils [39]. The soils form many, narrow to wide sizes with shallow to deep depths cracks during the dry season that results in a difficulty to hold optimum moisture even from optimum shower and mainly for irrigation. The soils may also have poor drainage, which hold water in the above ground that causes logging effect on crops like sesame that are susceptible to water logging.

The soils in the lowlands of Western Tigray, are deficient in most of the macro and micro nutrients. Seven soil nutrients viz. total N, available P, exchangeable K, available S, extractable Fe, Zinc (Zn) and Boron (B) were found to be deficient at the Kafta Humera, Welkayt and Tsegede locations. As a result [40], recommended different blended fertilizers to the major sesame growing districts in the Western Tigray (Table 2). Accordingly, Kafta Humera requires seven types of blended fertilizers, of which three are the most dominant blends. Tsegede district requires four types of blended fertilizers, of which three of them are the most dominant blends. Similarly, six types of blended fertilizers are recommended for Welkayt district, and three of them are the most dominant blends though the method of application should not be as blended rather as elemental bases for macronutrients while foliar for those micronutrients. Hence, it is hardly possible to attain the potential yield in these areas without applying the abovementioned recommended fertilizer types

Table 1
Total sesame stack residue, burned sesame stack residue and nutrient concentration in sesame stack residue in Western Tigray, Northern Ethiopia.

Descriptions related to sesame stack residue		Value	Reference
Total sesame stack residue (ton ha^{-1})		0.563	[28]
Sesame stack residue burned every year (ton ha^{-1})		0.381	
Sesame stack residue burned every year (%)		67.7	
Annual sesame production area (ha) in three woredas of Western Tigray	Welkayt,	64,160.25	[29]
	Tsegede	96,129	
	Kafta Humera	376,398	
Nutrient concentration in sesame residue on a dry weight basis (g kg^{-1})	Nitrogen	24.53	[27]
	Phosphorus	4.3	
	Sulfur	7.15	

Where: Stack residue is the residue obtained after threshing and locally called "*Jewjaw*".

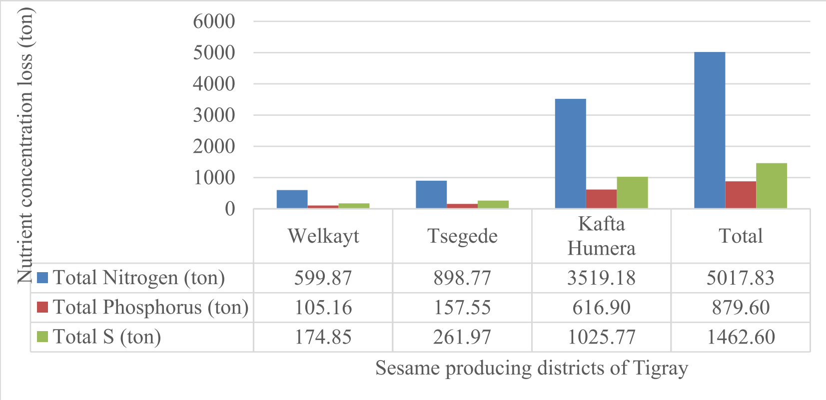

Fig. 1. Annual losses of N, P and S through residue burning in the sesame growing areas of western Tigray.

Table 2
The recommended blended fertilizers to the major sesame growing districts in the Western Tigray.

SNo	Blend Type	Formulation	Kafta Humera	Welkayt	Tsegede
1	NPKSB	13.7:27.4:14.4:5.1:0.54	¥	ÐÐ	
2	NPSB	18:36:7:0.71	¥	Ð	Ð
3	NPKSFeZnB	17:20:8:11:0.3:2.2:0.5	ÐÐ	ÐÐÐ	ÐÐÐ
4	NPKSZn	15:31:8:7:2.2	¥		
5	NPKSZnB	13:26.1:13.7:5.6:1.7:0.5	ÐÐÐ	¥	
6	NPSFeZnB	17:33:7:0.3:2.2:0.5	¥	¥	
7	NPSZnB	17:34:7:2.2:0.67	Ð	¥	ÐÐ
8	NPSFeZn	17:35:8:0.3:2.2			¥

Where: ¥: required blend type; D, DD and DDD: refers to the most, second and third dominantly required blends in the locations respectively.
Source [40].

accompanied by the right time and rate of application. The major problem with the blends is that, discrepancies between the labels and the actual chemical content of multi-nutrient fertilizers delivered to farmers are common. The variation observed has been quite small in some cases while it has been wider that reaches over 40 %. For example, NPS was 16N-18P_2O_5-7S suggesting 53 % less, which is not consistent with standard composition indicated in the fertilizer label: 19 N–38P_2O_5 + 7S [41].

The physical and chemical properties of the soils of different locations in Western Tigray is depicted in (Table 3). From which, descriptive statistics of the physical and chemical properties; the relationship between the physical and chemical properties and the soil sampling depth; and correlation analysis among the physical and chemical properties is analyzed using R version 4.3 statistical software [21]. Based on the mean values from the different locations, most of the soil chemical properties are out of the optimum range. Except K, the organic carbon, total N, available P, S and Zn are below the optimum value and the soil is moderately alkaline. This completely corroborates with the findings of [42,43]. The soils of the sesame growing areas are deficient in N and P [37,44,45]. Hence, fertilization is mandatory in these areas to amend the soil fertility thereby to boost crop productivity.

Soil quality assessments and managements should include the depth effects to provide a better understanding of the soil dynamics [56]. Hence, the relationship between the physical and chemical soil properties and soil sampling depths is shown in (Fig. 2). The clay particle size increased as the soil depth increased (Fig. 2A) while the sand (Fig. 2B) and silt (Fig. 2C) particle sizes decreased as the soil sampling depth increased. This completely accords to the findings of [57]. The pH of the soil (Fig. 2I) and CEC (Fig. 2J) increased while total N (Fig. 2D), available P (Fig. 2E), K (Fig. 2F). S (Fig. 2G) and organic carbon (Fig. 2H) decreased as the soil depth increased. This is in line with the findings of [57,58] who reported that the organic carbon and total N decreased while soil pH increased as the soil depth increased. Similarly [59], also found decrement of OC, total N and available P on the increment of soil profile while increment of clay content on the increment of soil profile. In contrast to this [60] reported that the soil organic carbon increases as the soil depth increases.

The descriptive statistics of the soil physical and chemical properties of the soil in Western Tigray is computed and described in (Table 4). The soil particle sizes and chemical properties except K, S and Zn are significantly ($P < 000$) different. This indicates that there is a variation in the soil characteristics of the sesame growing areas. This might be because of the actual soil variation, the cropping system and cropping history of the specific locations and the sampling and analysis related variations and others. The association among the physical and chemical properties of the soil is depicted in (Fig. 3). Accordingly, there is strong negative association of the clay particle size with the silt and sand particle sizes while it is positively associated with Zn, cation exchange capacity and organic carbon. Total N is positively associated with S, available P and K while negatively correlated with Zn. Similarly [61], reported that total N is positively correlated with available P.

Table 3
Physical and chemical properties of the soils of different locations in the lowlands of Western Tigray.

Location	Year	Depth	Sand (%)	Silt (%)	Clay (%)	pH (1:2.5H2O)	OC (%)	Total N (%)	Av. P (mg kg^{-1})	CEC (cmol (+) kg^{-1})	S (mg kg^{-1})	K (mg kg^{-1})	Zn (mg kg^{-1})	Reference
Humera	2020	0–20	24.9	28.2	46.9			0.115	10.9		13.97			[27]
Humera	2012	0–20				8.16	0.87	0.07	4			300		[43]
Maikadra	2012	0–20				7.8	0.49	0.06	4			225		
Adebay		0–20				8.31	0.98	0.06	4			346		
Rawyan		0–20				7.7	1.04	0.08	4			218		
Humera	2012–2013	0–20	25	22	53	8.48	0.53		3.02	24.85				[45]
Humera	2015		13	19	68	8.45	0.57	0.04	2.78	30		62.8		[46]
Humera	2015–2016	0–20	26	19	55	8.5	0.57	0.04	2.78	30				[44]
Humera		0–15	28	30	42	8.14	0.44	0.09	1.08	59.8	0.24			[26]
Humera		0–30	27	26	47	8.473	0.45	0.057	1.847	47.5	0.22			
Humera		30–60	29	21	50	8.95	0.38	0.035	0.59	67.9	0.14			
Humera		60–90	16	8	76	9.06	0.42	0.001	0.42	64	0.02			
Humera	2010–2011	0–30	39.1	29	31.9	8.38	0.46	0.046	7.6	56		290		[37]
Humera	2018–2019	0–15	18	31	51	7.4	0.73	0.02	3.7	40				[47]
Banat	2018–2019	0–15	18	26	56	6.91	0.7	0.04	4.6	40				
Kebabo	2018–2019	0–15	15	28	57	6.99	0.68	0.02	4.5	41				
Humera	2010	0–15	11.3	17.1	71.7	8	0.81			82.7				[39]
Humera	2010	0–30	13.5	14.8	71.8	8.05	0.78			80.55				
Humera		30–60	18	12.7	69.3	8.1	0.76			81.6				
Humera		60–90	20.6	8.8	70.6	8.3	0.72			80.2				
Humera		90–120	10.8	15.8	73.3	8.3	0.75			83.5				
Humera	2016	0–20	18	30	52	7.4	0.42	0.03	3.5	40	4.78			[48]
Humera						7.6		0.039	4.3					[49]
Maikadra						7.21		0.046	3.39					
Baeker	2016					6.69	0.86	0.03	4.03	69.66	9.02	319.4	0.25	[42]
Bereket	2016					7.32	0.97	0.03	1.8	65.83	11.55	263.6	0.25	
Maikadra	2016					7.05	0.76	0.04	1.39	63.84	8.73	346.6	1.51	
Maiwoyni	2016					6.74	1.03	0.04	1.09	70.12	7.77	393.1	1.7	
Humera	2016–2018	0–20	13	19	68	7.75	1.01	0.08	7.19	64.5	10.5			[50]
Mean			**20.3**	**21.3**	**58.5**	**7.86**	**0.70**	**0.05**	**3.60**	**58.34**	**6.09**	**276.5**	**0.93**	
Range						(7.4–8.0)[a]	(0.5–1.5)[a]	(0.05–0.12)[a]	(<5)[b]	(>40)[c]	(<0–10)[d]	(141–300)[e]	(0.5–1.0)[e]	[a] [51]; [b] [52]; [c] [53]; [d] [54]; [e] [55]
Rating						Moderately alkaline	Low	Low	Very Low	Very high	Very low	High	Medium	

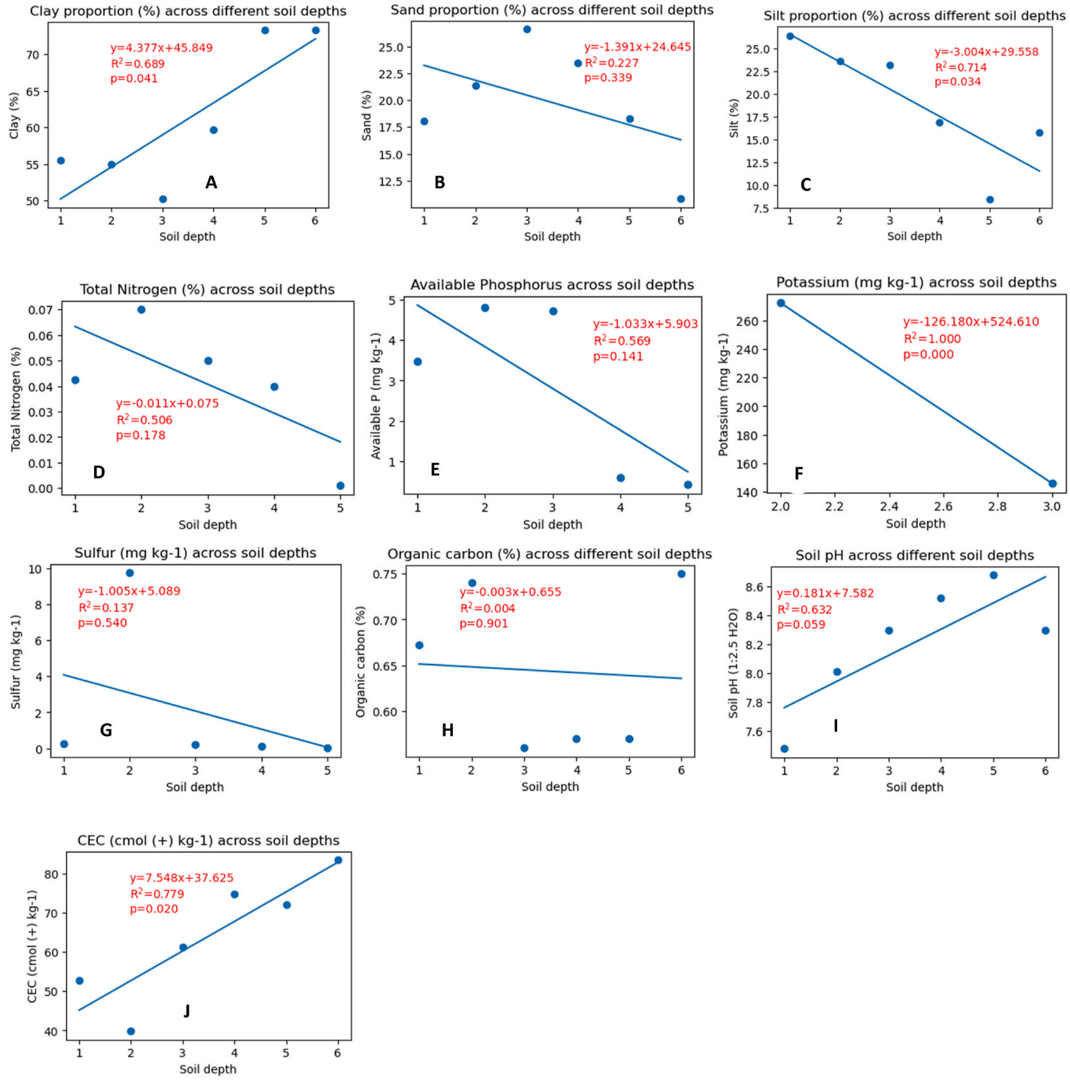

Fig. 2. Physical and chemical soil properties across different soil depths. Where; 1, 2, 3, 4, 5 and 6 in the abscissa, represents soil sampling depth of 0–15, 0–20, 0–30, 30–60, 60–90 and 90–120 cm respectively.

Table 4
Descriptive statistics of the soil physical and chemical properties.

variable	Min.	Max.	Range	Mean	No of Samples	SE	CV	P value
Clay (%)	31.9	76	44.1	57.88	20	2.79	21.58	P < 0.000
Sand (%)	10.8	39.1	28.3	20.82	20	1.75	37.53	P < 0.000
Silt (%)	8	32	24	21.32	20	1.818	38.15	P < 0.000
Total N (%)	0.001	0.115	0.12	0.047	24	0.005	54.48	P < 0.000
Av. P (mg kg^{-1})	0.3	10.9	10.6	3.47	25	0.48	69.34	P < 0.000
S (mg kg^{-1})	0.02	13.97	13.95	5.59	12	1.52	94.22	0.0037
Zn (mg kg^{-1})	0.25	1.7	1.45	0.93	4	0.39	84.75	0.099
K (mg kg^{-1})	0.15	393.1	392.95	184.73	15	39.65	83.13	0.0003
OC (%)	0.343	1.04	0.697	0.68	27	0.042	32.24	P < 0.000
pH (1:2.5H2O)	7	9	2	8	29	0.1269	8.633	P < 0.000
CEC (cmol (+) kg^{-1})	24.85	83.5	58.65	58.89	23	3.81	30.98	P < 0.000

Where; Min: Minimum, Max: Maximum, SE: Standard Error, CV: Coefficient of Variation.

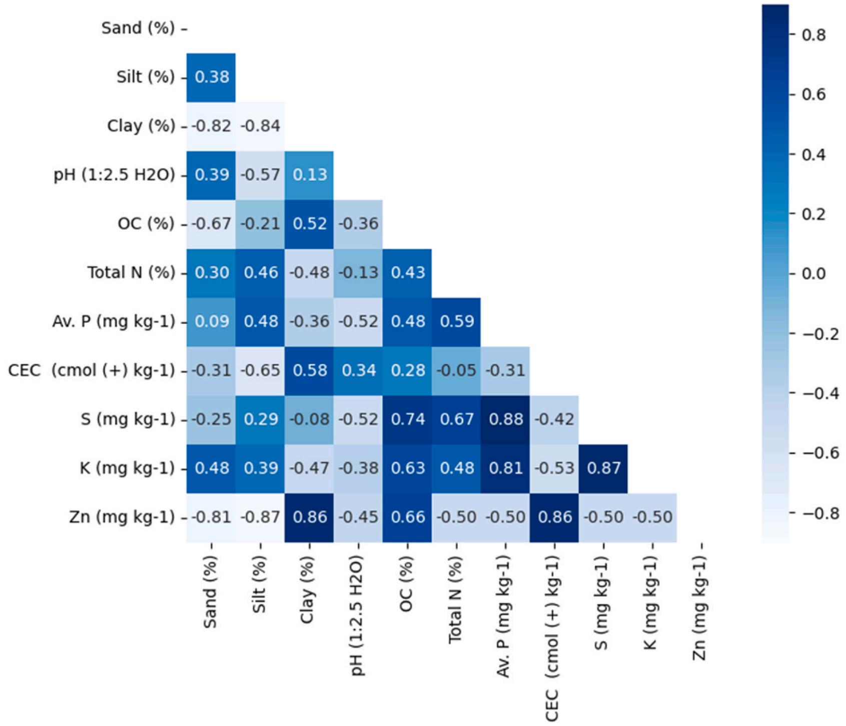

Fig. 3. Association among the soil physical and chemical properties.

3.3. *Response of sesame to different soil fertility management practices*

No fertilizer recommendations were available for many years in the sesame growing areas of Tigray and different fertilizer trials on sesame started in the late 2000's. Some results of sesame research works in Ethiopia suggested that sesame did not respond to fertilizer application [62]. However, most, if not all, of the experiments executed in sesame growing areas of Tigray showed significant

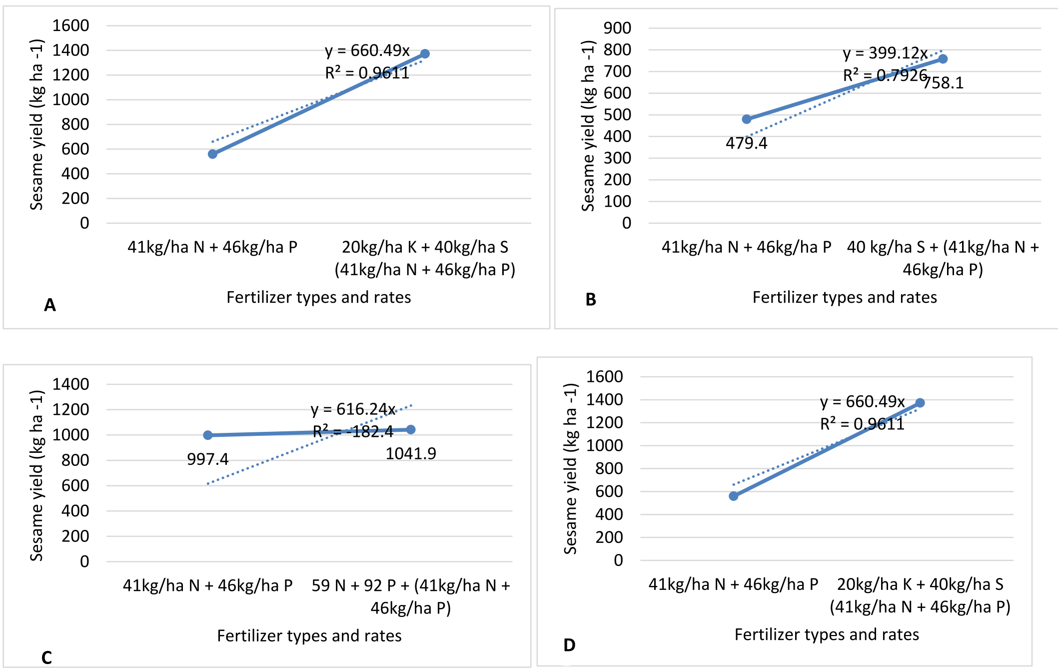

Fig. 4. Sesame yield (kg ha^{-1}) at the previously recommended and newly recommended fertilizer rates and types.

differences due to fertilizer application. Despite of the crop's responsiveness to fertilizer rates, there are no recommended fertilizer types and rates for the sesame growing environments (different soil types and agro-ecologies) which requires a due attention in the future and this review is expected to forward a clear recommendation and way forward.

41 kg ha^{-1}, Nitrogen (N) + 46 kg ha^{-1}, Phosphorus (P) was recommended about a decade before and this rate has been popularized and used by many sesame producers in Northern Ethiopia. From the different investigations, we have observed that it seems mandatory to add other fertilizer types and rates and to increase the previously recommended N and P rates to boost sesame productivity (Fig. 4). The addition of Sulfur (S) to the recommended rate enhanced sesame productivity (Fig. 4A and B). Moreover, increasing the previously recommended rates also enhanced the productivity (Fig. 4C and D). Hence, detailed summarization of the sesame fertilization researches and soil fertility status based fertilizer recommendation is vital and we believe this review will bring a solution in forwarding appropriate fertilizer type and rate according to the soil fertility status.

Different studies on sesame soil fertility management were conducted in the sesame growing areas of Western Tigray and from which, different recommendations were forwarded [9,26,31,37,43,44,46–50]. The summaries and synthesis of different results from different fertilizer rates and types with in western Tigray and vis-à-vis to other study areas is stated as follows.

3.3.1. Nitrogen application

Nitrogen is characterized as highly mobile nutrient and it can be easily lost through leaching, volatilization, denitrification and runoff after applied to soil. Among the three major nutrients (N, P and K), plants require N in higher amounts. Nitrogen has many functions comprising: increasing leaf sizes and quality, promotion of rapid growth, enhancing fruit and seed development; forms an essential component of different important components in plants including amino acids that are building blocks of proteins and enzymes, that are involved in catalyzing most biochemical processes [63]. Nitrogen application timing significantly affects the qualitative and quantitative yield; agronomic characteristics and N use efficiency. Hence, estimating the appropriate rate and time of N application in sesame is vital. Nitrogen fertilizer placement should be 3–5 cm deeper than the seeds and side dressing at 5–10 cm apart from the plant and maximum 20 cm distance from the plant. Under optimal environmental conditions, N fertilizer has no effect on phonological traits but it showed effect on growth parameters [64].

Optimum seed yield of sesame was obtained from application of 46–100 kg ha^{-1} N in most of the sesame-producing countries and lowering the N rate to less than 46 kg ha^{-1} N in marginal areas is economical [65]. Adequate N fertilization improved uptakes of other nutrients, particularly P and K and some micronutrients. Moreover, the authors also suggested that split N application at different growth stages of the crop increased productivity and this is in accordance to the findings of [31]. Highest sesame yield, at Humera, Western Tigray, was reported at 23 kg h^{-1} N at first branching stage and 23 kg ha^{-1} N at early flower initiation. However, currently N application may be affected by vigorousity of the crop, soil moisture, fertility status and many other factors.

An exhaustive research on N application on sesame was conducted in Humera for three production seasons (2016, 2017 and 2018) under rain-fed conditions [50]. The study consisted of 13 N rates (18–156 kg ha^{-1} N). The highest yield (1092 kg ha^{-1}) was obtained from the application of 75.5 kg ha^{-1} N. As the fertilizer rate increased, the yield started to decline and this might be because of higher vegetative growth of the plants which led to delayed seed setting. This delayed seed setting in turn results in low sesame yield. Regarding the profitability of the N fertilizer rates, the higher net profit (40320 ETB/ha), a marginal rate of return of 616.3 %, was gained from the application of 64 kg ha^{-1} N. This is about 5168 Ehiopian Birr/ha increment vis-à-vis the previously recommended N rate (41 kg ha^{-1} N). Furthermore, the higher agronomic use efficiency of N fertilizer (N-AUE) (5.9) was obtained from 64 kg ha^{-1} N and the lower (0.6) was from the higher N application rate (156 kg ha^{-1} N). Similarly the application of 60 kg ha −1 N [66–68]; 75 kg ha^{-1} N [69]; 80 kg ha^{-1} N [70,71] could result higher sesame yield. In addition to the sesame yield higher N application also increases sesame stover yield [71] which, is important to improve soil fertility and that can be used as a source of energy. The application higher (80 kg ha^{-1}) N fertilizer also increases the total N uptake by stover, by seed and by total plant parts [71]. However, some times, higher sesame productivity can be obtained from the application of higher level of N ranging from 105 to 150 kg ha^{-1} N fertilization [72–75]. Fertilization under irrigation condition also showed productivity increment. However, the productivity is lower 423.4 kg ha −1 from the application of 46 kg ha^{-1} N [76] and 894 kg ha^{-1} from the application of 75.5 N [50] vis-à-vis the rain fed sesame productivity. This might be because of the water quality or other production constraints under irrigation condition and this needs due attention in the future studies.

The sesame yield in Humera revealed that there was a productivity increment. However, it decreased to 811 kg ha^{-1} when N was applied up to 156 kg ha^{-1}. Likewise, Yield was significantly decreased (from 934.5 to 788.22 kg ha^{-1}) when the N rate increased from 60 to 120 kg ha^{-1} [77] and yield was decreased from 1690 kg ha^{-1} to 1430 kg ha^{-1} when N rate increased from 69 to 92 kg ha^{-1} [32]. Moreover, different authors reported that continuous increase in N level decreases the productivity of sesame [73,74,78]. Generally, based on the above findings, sesame is highly responsive to N fertilization. However, yield decreased if the N level is excessive.

Higher oil content could be gained from the application of higher N fertilizer. On the other hand, low oil content and oil yield of sesame were recorded from the treatments received no N fertilizer. Whereas higher oil content and oil yield were obtained from treatments fertilized with N at the higher rate [79]. Oil contents of 45.88 % and 62.11 % were obtained from the application of 80 kg ha^{-1} N [80] and 108 kg ha^{-1} N [72], respectively.

3.3.2. Phosphorus application

P improves crop quality in a number of ways comprising: enhance sugar content, minimized grain moisture content, increased protein content, enhanced P content, and improved drought and disease resistance in some cereal crops like wheat and maize [81]. An experiment was conducted in 2018 and 2019 at farmer's field in Tsegede and Kafta Humera to investigate the response of sesame to the application of different rates of P under balanced fertilizer [82]. This balanced fertilizer was recommended for these areas based on the

[40]. Five P_2O_5 levels (0, 23, 46, 69 and 92 P_2O_5 kg ha^{-1}) were used in the experiment to evaluate the performance of sesame. Maximum sesame seed yield was recorded in plots receiving 69 kg ha^{-1}. However, it was reported that partial budget analysis revealed highest marginal rate of return from the application of 23 kg ha^{-1} P_2O_5. Based on these results, a verification trial was conducted with the objective to verify the previously recommendation of P (46 P_2O_5) with this finding. The results of the verification of 46 P_2O_5 and 23 P_2O_5 did not show significant variation, thus it is recommended to use the least cost fertilizer for setit-2 variety. Similarly, highest sesame yield was obtained from the application of 27.6 kg ha^{-1} P_2O_5 [83]. However, highest sesame yield was obtained from the application of even lower rate, 13.2 kg ha^{-1} of P_2O_5 [77]. This variation might be because of the difference on soil fertility status of the growing areas and hence, soil test based recommendations are highly advisable.

3.3.3. Sulfur application

Sulfur (S), which is the most abundant element in the earth's crust, is absorbed by plants as Sulphates ($SO4^{2-}$) [81]. Sulfur application increases oil and protein contents in seeds. It also increases the availability of other nutrients such as P, K, Zn and suppresses the uptake of sodium (Na) and chlorine [84], which are toxic to plant growth and development. Sulfur fertilization may increase the seed yields, oil yield and improve the oil quality by decreasing the concentrations of saturated fatty acids (palmitic and stearic acid) and such research works need due attention [85]. Moreover, the application of different levels of S significantly affected sesame oil content and oil yield, and nutrient (NPK) uptakes [86]. The response of sesame to different S rates on Hirhir and Abusufa sesame cultivars in Humera was studied [26] Based on this study, the authors declared that, 30 kg ha^{-1} S was recommended in the form of ammonium sulfate for higher sesame yield. Similarly, highest sesame seed yields of 1035.7 and 758.1 kg ha^{-1} were harvested during 2015 and 2016 cropping seasons, respectively from the applications of 40 kg ha^{-1} S in this study area [44]. In accordance to these findings, the application of 40 kg ha −1 S resulted in higher seed yield (1041 kg ha^{-1}) and oil content (43 %) [87] and 1210 kg ha^{-1} [68]. Generally, S fertilization significantly increased the seed yield, oil yield and the maximum oil yields were harvested from the application of 40 kg ha^{-1} S [79,85] and 50 kg ha^{-1} S [88]. Higher sesame yield, stover yield and oil content was also harvested from the application of 40 kg ha^{-1} S. Moreover, this S rate also resulted in higher NPK uptake of sesame [89]. In addition to S application, application of S combined with NPK [90] and S with P [91] could produce highest sesame yield. In contrast to this, the application of wider range of S rates (0–80 kg ha^{-1} S) resulted no significant difference on oil content [92]. In addition to the S application rates, the S application time should be further investigated to understand the right time of application and thereby to realize optimum S utilization.

3.3.4. Different fertilizers interactions

Nutrient elements do not bring the desired effect independently but if combined with different nutrients and management practices. As a balanced diet is required for a human body so it is required by the plant, and this has an implication on crop quality. The effect of different N rates in the form of urea (0, 25, 50, 100, 150, and 200 kg ha^{-1}) and P rates in the form of DAP (0, 25, 50, 100, 150, and 200 kg ha^{-1}) on sesame yield was investigated [37]. This study was performed on the Vertisols at Humera during 2010 and 2011 cropping seasons under rain fed condition. The highest sesame yield (1042.6 ha^{-1}) from this study was recorded from the application of 128 kg ha −1 N and 92 P_2O_5 kg ha^{-1} P (the highest rates). However, 41 kg ha^{-1} N and 46 kg ha^{-1} P_2O_5 resulted in a yield of 984.6 kg ha^{-1} was economically feasible. This rate was recommended and it has been used by many sesame growers in Tigray for about a decade. From research results conducted for three years (2016–2018), application of N and P fertilizers can double sesame yield and profitability provided that all of the other improved technologies are applied [9]. The combined yield showed that 825 kg ha^{-1} yield from application of 41 kg ha −1 N and 46 kg ha^{-1} P_2O_5 while 484 kg ha^{-1} yield was obtained from the non-fertilized treatments. The combined result showed that the application of fertilizer had a yield advantage of 70.4 % over non-fertilized. A net profit of 22,228 ETB and a Marginal Rate of Return (MRR) of 323 % could be gained from the fertilized sesame production accompanied by other improved technologies while 11,742 ETB and a MRR of 210 % could be gained from the non-fertilized. Hence, this study confirmed that the application N and P is mandatory to boost sesame productivity in the sesame growing areas of western Tigray. Higher sesame yield (1420 kg ha^{-1}) [93] and 738.6 kg ha^{-1} [94] was obtained from the application 120:90:60 kg ha^{-1} and 113:113:60 kg ha^{-1} NPK respectively. The application of higher NPK also significantly increased number of capsules per plant [95]. also reported that the application of 150 kg ha^{-1} NPK (15:15:15) enhanced sesame productivity vis-s-vis the control. These authors also reported that number of capsule per plant and number of seeds per capsule also increased from the application of combined 150 kg ha^{-1} NPK. Moreover, application of 50:25:30 kg ha^{-1} NPS increased the sesame yield, stover yield, oil content and oil yield of sesame [96].

An investigation on the response of sesame to urea and ammonium Sulfate on Vertisols of Kafta Humera during 2012/13 and 2013/14 cropping seasons was carried out [45]. The source of N was ammonium sulfate (NH_4SO_4) and urea. Highest sesame yield (830.7 kg ha^{-1}) was obtained from the application of 20 kg ha^{-1} N from urea +21 kg ha^{-1} N from NH4SO4 [24 kg ha^{-1} S] + 20 kg ha^{-1} which implies that 41N, 20 P and 24 S kg ha^{-1} is best performed. This might be due to the N and S nutrients from both urea and ammonium sulfate fertilizers. Moreover, the study area is characterized as a high pH soil and these fertilizers, especially S, have acidifying effect on this alkalinity property in addition to their importance as nutrient.

In accordance to the above findings, the application of combined N and P could boost sesame productivity [97, 98]. In addition to the application of combined N and P the addition of an organic fertilizer, 5 t/ha of farmyard manure could significantly increase sesame seed yield [99]. In addition to the ideal experimentations of different fertilizer rates and types, the use of models such as QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils), relating soil test values to actual nutrient uptake and crop yield is also found to be very important to meet the Ethiopian conditions [41]. Based on the recommendations using QUEFTS the use of 150 kg ha^{-1} urea and 50 kg ha^{-1} DAP is recommended to achieve 58 % of yield advantage [100]. However, such higher fertilizer use should be used if moisture content of the soil is favorable.

The effect of K and S on yield and yield components of sesame at Kafta Humera was investigated during 2016 cropping season [48]. Potassium and S were applied in the form of murate of potash (KCl) and calcium sulfate ($CaSO_4.2H_2O$), respectively. The full dose or recommended rates of N and P fertilizers were applied as basal to all plots based on the previously recommendation of 23 kg N and 46 kg ha^{-1} P_2O_5. Besides, 0.3 kg ha^{-1} of Borax ($Na_2B_4O_7.5H_2O$) and 1.72 kg ha^{-1} of Zinc Sulfate ($ZnSO_4.7H_2O$) adjusted to the amount of S required were applied as basal application for all treatments based on the [40] deficient nutrients report for the area. The authors reported highest yield (1371.67 kg ha^{-1}) from the application of 20 kg ha^{-1} K_2O and 40 kg ha^{-1} S while the lowest (559.13 kg ha^{-1}) yield was obtained from the control (no K and S). The reason for this may be due to enhancement of uptake of other nutrients by plants caused by the availability K and S. This might be because of these nutrients may enhance the uptake of other nutrients by the plants [101]. However, highest and economically feasible sesame yield could be obtained from the application of 40 kg ha −1 K_2O, which is twofold of the recommended rate in this study [67]. In contrast to this study, no significant variation of sesame yield was observed from the application of different K rates ranging from 0 to 45 kg ha^{-1} [69].

A study on identifying both organic and inorganic fertilizer placement methods, band and broadcast fertilizer placement was executed [102]. The study consisted of an inorganic fertilizer N at different levels (0, 50 and 80 kg ha^{-1} N) and organic phosphate (0, 23, 46 and 69 kg ha^{-1} Orga-p) at Humera. The author reported higher number of seeds per capsule and number of capsule per plant were recorded on band method of application. He indicated increment of seed yield per plant, seed weight per capsule and seed yield per hectare at the rate of 80 kg ha^{-1} N and 69 kg ha^{-1} orga-p. Based on the results, he concluded that band application method with 80 kg ha^{-1} N and 69 kg ha^{-1} orga-p showed higher seed yield of sesame.

3.3.5. *Blended fertilizers application*

N, P, K, S, Fe, Zn and B are found to be deficient in the soils of Western Tigray. Hence, to boost crop productivity in these areas it is mandatory to add nutrients in different ways. Hence, the application of blended fertilizer, physically mixing of three or more fertilizer ingredients in a factory to provide several nutrients, is found to be important to fulfill the multiple nutrient requirement of the soil in these sesame growing areas [40]. To estimate the appropriate blended fertilizer rate, a series of trials have been conducted in Western Tigray. A study comprised of five different rates of NPSZnB (50, 100,150, 200 and 250 kg ha^{-1}) and the previously recommended N and P rate (41 kg ha^{-1} N + 46 kg ha^{-1} P_2O_5) was conducted [47]. The NPSZnB constitutes 17 % N, 35 % P_2O_5, 7 % S, 2.2 % Zn and 0.1 % B. The application of different rates of NPSZnB was statistically significant compared with the results from plots where no fertilizer was added in three locations (Humera, Banat and Kebabo). The highest yield (773.8 kg ha^{-1}) was obtained from the application of 150 kg ha −1 NPSZnB while the lowest yield (501.9 kg ha^{-1}) was recorded from the treatments with no fertilizers in Humera. However, there was no statistically significant differences among the results from different rates of NPSZnB with the recommended N and P rate in the three study areas, Humera, Banat and Kebabo locations in Western Tigray. Hence, the lowest NPSZnB rate (50 kg ha^{-1}) or the previously recommended NP rates can be used in these sesame producing areas based on the economic feasibility, accessibility and other preferences. In contrast to this, the highest sesame yield, in Humera, was obtained from the application of 200 kg ha^{-1} NPSZnB and 100 kg ha^{-1} urea [49]. In accordance to this finding the application of 200 kg ha^{-1} NPSZnB could significantly boost Teff yield in Tigray [103]. Similarly, the application of 200 kg ha^{-1} NPSZnB together with the recommended Nitrogen rate could produce higher Maize yield [104]. Hence, the application of recommended Nitrogen rates in addition to the blended fertilizers looks to be beneficial.

Sesame yield and yield components' response to different rates of NPS was evaluated in Kafta Humera and Tsegede during 2018–2019 cropping seasons [105]. The treatments were five rates of NPS (50, 100, 150, 200 and 250 kg ha^{-1}) and two controls, one control with no fertilizer and the other control with the application of previously recommended NP rate (41 kg ha^{-1} N and 46 kg ha^{-1} P_2O_5). The study revealed that application of different rates of NPS gave statistically significant ($P < 0.001$) differences in yield and yield components compared with the non-fertilized treatment. Application of 50 kg ha^{-1} NPS produced 670.2 kg ha^{-1} while the non-fertilized treatment yielded 444.8 kg ha^{-1}. However, results due to the application of different rates of NPS (all rates) were statistically at par with that of the application of 41 kg ha^{-1} N and 46 kg ha^{-1} P_2O_5 (628.2 kg ha^{-1} yield). Hence, this study suggests that the application of 41 kg ha^{-1} N + 46 kg ha^{-1} P_2O_5 or 50 kg ha^{-1} NPS is advisable to be used in sesame production based on the economic feasibility, accessibility and other preferences. In contrast to this finding, highest sesame seed yield was obtained from the application of 150 kg ha^{-1} NPS [106] and 100 kg ha^{-1} NPS together with 46 kg ha^{-1} N [107]. However, these authors reported that a yield decrement was observed when the NPS rate increased from 10 to 200 kg ha^{-1} NPS. On the other hand, highest sesame seed yield could be obtained from the application of 300 kg ha^{-1} NPK [108]. Higher sesame yield (963.7 kg ha^{-1}), highest number of capsules per plant (74.6 capsules/plant and highest number of branches per plant (3.9 branches/plant) was obtained fron the application of 92 kg ha^{-1} N, 90 kg ha^{-1} P, 17 kg ha^{-1} S, and 1.7 kg ha^{-1} B [109]. Moreover, higher sesame seed yield could be obtained from the application of 100 kg ha −1 NPSB while the highest oil content was obtained from the application of 200 kg ha −1 NPSB [110]. On the other hand, the application of 50 kg ha^{-1} NPSB combined with 10 ton ha^{-1} FYM produced higher sesame yield. However, 100 kg ha^{-1} sole application of NPSB is required to harvest higher sesame yield [111]. From the above findings, many of the results from the application of different rates and types of fertilizers lack consistency. These variations might be because of the agro-climatic, edaphic and management practice variations of the testing sites. Hence, such variations should be taken into consideration during fertilizer trial.

A study consisted of seven treatments (recommended NP, NPSB, NPKSB, NPSZnB, NPKSZnB, NPSZn and NPKS) during 2014–2016 cropping seasons at Kafta Humera and Tsegede districts in Tigray State [112]. All the blend fertilizer types were applied at the rate of 100 kg ha^{-1} and Humera-1 and Setit-1 sesame varieties were used as planting materials. Combined analysis of 2014 and 2016 data showed that all the variables measured were not statistically different due to application of the fertilizer treatments at Tsegede. Similarly the combined analysis of the data over years (2014 and 2015) indicated that all the variables were not statistically different due to application of the fertilizer treatments at Kafta Humera. There were non-significant differences on sesame due to the blended fertilizers and recommended N and P fertilizers applied as treatments in most of the combined analyses done over cropping seasons.

3.3.6. Organic fertilizers application

In addition to the application of inorganic fertilizers, the use of organic fertilizers is becoming economically feasible and environmentally friendly. Organic fertilizer produced from plant parts like papaya fruit peel is a rich source of soil beneficial microbes and crop plant's nutrient that are important to enhance soil physical and chemical properties [113]. Moreover, since the plants produced from organic fertilizers can have adequate micronutrients organic fertilizer can be used as an alternative for the expensive and scarce inorganic fertilizer [114]. Green manure, compost, vermicomposting, liquid substances from plants' leaves extracts; byproducts from butcheries and different animals' droppings or dung are among the major organic fertilizers used to grow plants. Application of organic source of nutrients through 50 % of FYM and 50 % of vermicomposting + through rock phosphate (T2) resulted in maximum growth parameters, yield attributes and yield of sesame [115]. Hence, the use different sources may result in Nitrogen use efficiency and sesame productivity and quality, which may need further investigation. An experiment estimating optimum rates of two organic fertilizers (Eco-green and Orga) on sesame yield was conducted in Humera during 2016 and 2017 cropping seasons [116]. Eco green is a natural protein containing liquid fertilizer, with 24.7 % N, 23.4 % Mn, 14.3 % Zn, 12.1 % Fe and others. Orga is produced from slaughter factory and waste products and it contains 23.0 % P, 21 % Ca, 21 % organic matter and others. Eco-green was diluted in 1:8 of Eco-green to water and sprayed 2, 4, and 6 WAE (weeks after emergence), while orga was applied, once, during planting. The chemical fertilizer produced significantly ($P < 0.05$) higher yield from the organic fertilizers. The organic fertilizers (100 L/ha Eco-green and 300 kg ha^{-1} Orga) have scored higher sesame seed yield next to the mineral fertilizer. Hence, these rates may be recommended for organic sesame production. The application of an organic fertilizer, cow dung, sheep manure, increase sesame productivity [117]. In accordance to this study, the use of 5 ton ha^{-1} farm yard manure increased sesame seed yield [99]. The application of 10 ton ha^{-1} poultry manure can also give higher (900 kg ha^{-1}) sesame yield although the yield was decreased to 600 kg ha^{-1} from the application of higher (15 ton ha^{-1}) FYM and this was true for different sesame varieties [118]. In addition to the application of excess inorganic fertilizers, the application of excess organic fertilizer, an increase of poultry manure and sheep manure from 2.5 ton ha^{-1} to 5 ton ha^{-1} and lowered the sesame seed yield [117]. Similarly, an increase of farmyard manure from 5 ton ha^{-1} to 7 ton ha^{-1} decreased sesame seed yield [99]. In addition to the sesame yield higher number of branches (4.91), higher number of capsules per plant (106.87) and higher number of seeds per capsule (64.22) was also obtained from the application of 10 ton ha^{-1} FYM [119]. This is an indicator that enhancing soil fertility can also boosts other agronomic traits of sesame in addition to the seed yield.

3.3.7. Other soil fertility management practices

Crop rotation, deep ploughing, mulching, ploughing after crop harvesting and intercropping are among the major cultural practices that can enhance soil fertility. The major crops growing in the low lands of Western Tigray are sesame and sorghum. This practice has led to soil fertility depletion resulting in yield reduction and stagnation. Hence, different investigations on these cultural methods have been conducted. An experiment aiming to study the effect of organic mulches at 10 ton ha^{-1} and land preparation methods on sesame (Setit-1 variety) productivity and in-situ moisture conservation was conducted in Western Tigray, Humera, during 2015/2016 growing season [46]. Four types of organic mulches (rice straw, sorghum straw, sesame straw and Sudan's grass) were used by comparing them with control and three land preparation methods (ridge and furrow, raised bed and flat land preparation). The results indicated that land preparation methods and organic mulching had significant effect on soil moisture content at 0.4–0.6 m and grain yield. Ridge and furrow mulched with sesame straw showed 48 % soil moisture content increment than no mulch plots at 15 days after sowing. The highest yield (750 kg ha^{-1}) was recorded under flat land preparation with Sudan's grass and this is recommended in the sesame growing areas of western Tigray. The lowest yield (120 kg ha^{-1}) was recorded under no mulch with raised bed. This indicates mulching is highly advisable in these areas to promote soil moisture and thereby to enhance sesame productivity. Regarding the land preparation ridge and farrow land configuration methods is important to enhance soil water content and sesame seed yield [120]. This is in accordance to the findings of [121].

A research on ploughing frequency and depth was conducted in the lowlands of Western Tigray, Humera to estimate the optimum ploughing frequencies in the area [122]. The research recommended that to improve soil fertility and thereby to boost sesame productivity sesame field should be ploughed three times: Soon after harvesting the previous crop which is important to minimize weed seed bank, incorporate the green weeds and crop residues that helps to increase soil fertility; Soon after receiving the first shower is received which is important to pulverize the soil and; during sowing of the sesame seeds. Furthermore, it is also important to undertake a deep plough (20–30 cm deep) every three years, which is important to increase soil fertility and water holding capacity of the soil, which is in accordance with the reports of [122]. Moreover, shallow ploughing (2–5 cm) after harvest, after onset of rainfall, at planting and deep plough (25–30 cm) after crop harvest were evaluated to investigate the influences on the yield of sesame [123]. The research result showed that the highest yield (1228 kg ha^{-1}) was obtained when the farmlands were ploughed deep immediately after harvest. This is because of this deep plough incorporates the crop residue and other plant biomass into the soil. This crop residue incorporation increases soil organic matters and this in turn improve the fertility of the soil.

There are optional crops with interesting economic and nutritional contents like mungbean, soybean, sorghum and cotton that can be used as rotational crops and to be intercropped with sesame. Sesame is an important crop for intercropping, crop rotation and soil fertility improvement [124]. Sesame is important in intercropping which is mainly attributed to the allelopathy activity of sesame plants in which it inhibits the growth of weeds [,125,126]. A research was conducted to identify the appropriate rotational crop for two cropping seasons (2016 and 2017) [100]. The study reported that sesame grown after mungbean showed a yield advantage of 38, 22 and 14 % yield advantage over sesame grown after soybean, sorghum and sesame respectively. Intercropping contributes a significant role in sustainable agricultural system as it improves soil conservation, productivity and stability of yield [127]. Intercropping of sesame with mungbean and soybean enhances soil fertility and increases economic profitability as well as sustainability because of crop diversification. Specifically, intercropping sesame with half seed rate of mungbean is economically profitable and this practice is recommended in these area [128]. Intercropping of 50 % of the recommended seed rate of sesame with full seed rate of mungbean is suitable for obtaining maximum total productivity as well as economic return [129].

3.4. Sesame yield as affected by different fertilizer types and rates

Generally, the recommended fertilizer rates and types for sesame in the sesame growing areas are summarized in (Table 5). Different rates of different fertilizer types and sources are recommended by different researchers at different periods and hence, it is difficult to have single recommendation for the sesame growing areas. The box and whisker plot for sesame seed yield from different studies is described in (Fig. 5). A wider sesame grain yield distribution, with longer distance between the lower and upper quartiles, is observed from the field trial of W, D, J and Z respectively (Fig. 5). This might indicate that sesame is responsive to these different fertilizer rates and types and hence, farther investigations might be required. On the other hand, the sesame performance in some fertilizer trials like NPS and NPSZnB is almost similar indicating there is no sesame yield variation from the application of different rates of these fertilizer types. Since this is a blended fertilizer, the clear effect of the individual nutrients on sesame yield and yield components may not be clearly observed. Moreover, the highest sesame yield as the result of application of different fertilizer types and rates in the sesame growing areas of Western Tigray is depicted in (Fig. 6). Regardless of the agro-climatic and other management variations during execution of the research works the highest sesame yield (1371.67 kg ha^{-1}) was obtained in Humera from the application of 20 kg ha^{-1} K_2O and 40 kg ha^{-1} S topped to the recommended 41N and 46 P_2O_5 kg ha^{-1}. On the other hand, the lowest yield was obtained from the application of NPSZnB in Kebabo, Tsegede district. This indicates that the addition of macro and micronutrients to the recommended N and P can outsmart the recommended N and P alone.

4. Future prospects

Further fertilizer and soil fertility management studies on sesame should be carried out on:

- Pre and post experiment soil sampling and analysis of most soil physical and chemical properties
- Plant nutrient and quality analysis should be carried out after fertilization trials
- Agro-ecology, soil type and soil test based fertilizer studies and recommendations in the sesame growing areas of Tigray
- Elemental based nutrient optimization studies and method of application especially for those micronutrients should be conducted
- In the blended fertilizer, the specific nutrient effects are difficult to elucidate and hence, further nutrient based investigation is required
- Estimation of appropriate time of fertilizer applications (mainly N and S)
- Synergetic and antagonistic effects of different nutrients in sesame fertilization
- Detail studies on organic fertilizer trials (manufactured organic fertilizers, mulching, FYM, green manure, crop residue incorporation and others)
- Area specific soil fertility management studies (ploughing time, frequency and depth; drainage, crop rotation and others)

5. Conclusion and recommendation

Generally, the experiments carried out so far on sesame fertilization are negligible vis-à-vis the importance of the crop and macro and micro nutrients deficiency of the sesame growing areas. The fertilizer studies carried out so far are mainly on N, P and blended fertilizers and their effects on sesame yield and yield components. Obviously different macro and micronutrients significantly affects sesame oil content, oil yield and quality. However, such studies were missed and no/limited studies were conducted regarding the effect of fertilization on sesame seed quality. Furthermore, the fertilizer studies on sesame were concentrated around Humera area, not covering the whole sesame growing areas of Tigray and the fertilizer trials were not to specific soil type and agro-ecology.

Nitrogen was observed as the most important nutrient for growth and yield of sesame followed by P. Sesame had given response to different types of fertilizers as shown in (Table 5). Elemental calculations should be done from the different fertilizer types for each nutrient. Because of the limitations of the fertilizer experiments in covering all the environmental variability, it is quite difficult to recommend any fertilizer type and rate for specific sesame growing agro-ecologies and soil types in Tigray. The recommendations given in (Table 5) should be directly applied to the sites and soil types specified in the Table.

The recommended fertilizer rates for N, P and S are as follows: (i) 64 and 41 kg ha^{-1} N for low and medium N content areas respectively; 46 and 23 kg ha^{-1} P_2O_5 for low and medium P content areas respectively; (iii) 60 and 30 kg ha^{-1} S for low and medium S content areas respectively should be recommended. Moreover, the application of 100 L/ha Eco-green and 300 kg ha^{-1} Orga organic fertilizers is recommended for organic sesame production. Therefore, to enhance and sustain sesame productivity, improving soil fertility and health management is important.

CRediT authorship contribution statement

Fiseha Baraki: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Fisseha Hadgu:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **Gebremedhin Berhe:** Writing – review

Table 5
Fertilizer recommendations on sesame from different field trials.

Recommended fertilizer rate & type (kg ha −1)	Basal Application (type and rate)	Time of Application	Type of fertilizer/ source	Location	AEZ	Rain Fall (mm)	Temperature	Soil type	Georeference			Yield (kg ha^{-1})	References
									Lat. (°N)	Long. (°E)	Alt. (masl)		
40–100 N	NA	Urea and NH_4SO_4: 1/2 at planting and 1/2 before flower initiation; DAP, KCl, Orga and all blends: full dose at planting	Urea	Potential areas				All soil types					[65]
64 N	100 kg ha^{-1} NPS		Urea	H	SA1	576.4	28.3	Vertisols	14°15′	36°37′	609	1087	[50]
150 urea and 50 DAP	NA		Urea + DAP	H	SA1			All soil types				1050	[42]
41 N & 46 P_2O_5	NBA		Urea + DAP	H	SA1			Vertisols				984.6	[37]
41 N + 20 P+24 S	NBA		Urea + NH_4SO_4 +DAP	H	SA1			Vertisol				830.7	[45]
30–60 S under irrigation	41 N & 46 kg ha^{-1} P2O5		NH4SO4	H	SA1			Vertisols				2066	[26]
20 K_2O and 40 S	41 N & 46P_2O_5; 0.3 $Na_2B_4O_7.5H_2O$ & 1.72 kg ha^{-1} $ZnSO_4.7H_2O$		KCl and $CaSO_4.2H_2O$	H	SA1			Vertisols				1371.67	[48]
50NPS	NBA		NPS	H, B, K	SA1		28.5 [B]	Vertisols[B]	13°48′[B]	36°30 [B]	619 [B]	670.2	[105]
50NPSZnB	NBA		NPSZnB	H	SA1			Vertisols				607.2	[47]
100	NBA		NPSB & NPKSB	K & M	SA1	888.4 [K]	27.6 [K]	Vertisols†	13°36′ [K]	36°41′ [K]	696 [K]	577.8 [K] 693.6[M]	[112]
200 NPSZnB	46 kg ha^{-1} N		NPSZnB	M	SA1			Vertisols	13°20′	36°34′		1183.6	[49]
80 Urea & 69 P	NBA		Urea and orga-p	H	SA1			Vertisols				493	[102]
300 Orga	NBA		Orga	H	SA1			Vertisols				1187	[116]
100 Litter/ha	NBA	2,4,6 WEA	Eco-green	H	SA1			Vertisols				1054	[116]

H: Humera; B: Banat; K: Kebabo; M: Maikadra; NA: Not available; NBA: no basal application; SA1: hot to warm semi-arid lowlands; WEA: weeks after seedling emergence; [B]: Agro-climatic data for Banat; [K]: Agro-climatic and yield data for Kebabo; [M:] Yield data for Maikadra.

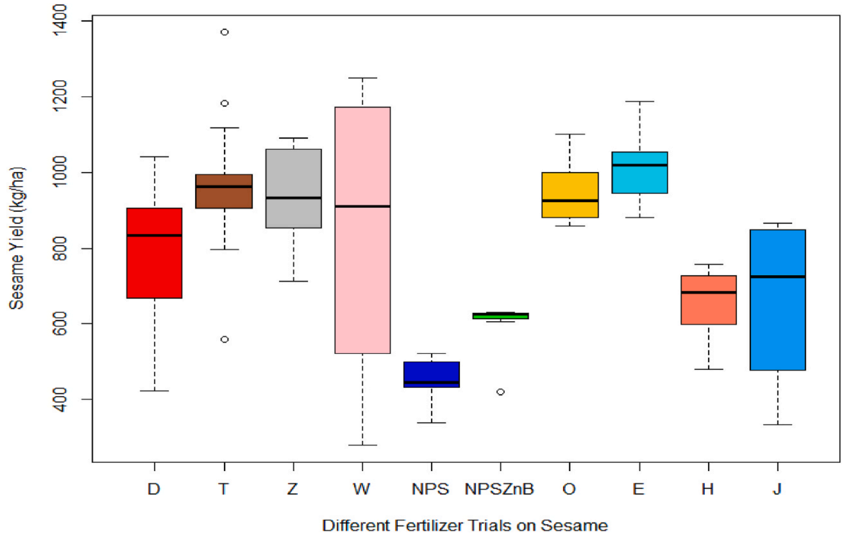

Fig. 5. The box and whisker plot for sesame yield as affected by different fertilizer rates and types. Where: D: [37]; T: [48]; Z: [50]; W: [49]; NPS: [105]; NPSZnB: [47]; O: [116]; E: [116]; H [44]: and J: [45]. The names/letters in the abscissa represent different fertilizer type and rates trials on sesame and details are in supplementary information 1.

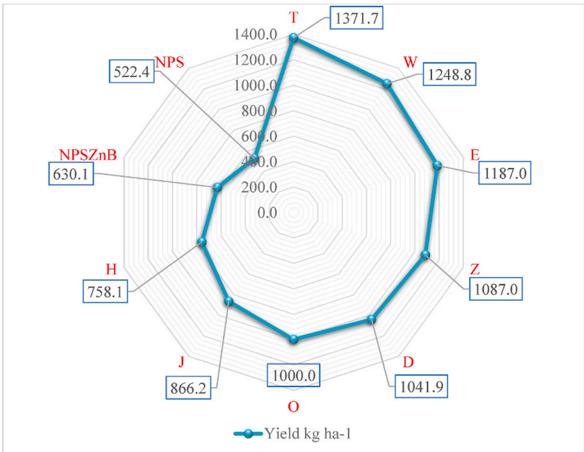

Fig. 6. Spider chart showing highest sesame yield from different trials as affected by different fertilizer type and rates (Details for treatments is described in the supplementary information 1).

& editing, Supervision, Software, Methodology, Conceptualization.

Data availability

The data used in the article are sourced from different studies and are available upon the request.

Ethics approval and consent to participate

Not applicable.

Permissions to collect the plants/plant parts

Not applicable.

Consent for publication

This review is done from synthesizing different findings on soil fertility management on sesame.

Funding

No funding was received to assist with the preparation of this manuscript.

Declaration of competing interest

This review comprised of agronomist, soil researcher and geo-informatics researcher. These authors contributed in different parts of the research planning, collecting materials for the review, gathering different data from different manuscripts, data analysis, manuscript drafting and editing. Every member contributed in the research is included in this manuscript. Hence, the authors declare that there are no conflicts of interest. Furthermore, this investigation received no specific fund from any funding agency, commercial or not-for-profit sectors and this research was done in Ethiopia.

Acknowledgments

The authors would like to sincerely acknowledge to Tigray Agricultural Research Institute and to Humera Agricultural Research Center Researchers for their commitment during implementing the experiment.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e41618.

References

[1] D. Burden, Sesame profile, Organic Farming 2005 (2014) cited.
[2] M. Adegunwa, A. Adebowale, E. Solano, Effect of Thermal Processing on the Biochemical Composition, Anti-nutritional Factors and Functional Properties of Beniseed (Sesamum indicum) Flour, 2012.
[3] I. Bisht, et al., Diversity in Indian sesame collection and stratification of germplasm accessions in different diversity groups, Genet. Resour. Crop Evol. 45 (4) (1998) 325–335.
[4] T. Tunde-Akintunde, M. Oke, B. Akintunde, Sesame seed, in: Akpan Uduak G (Ed.), Oilseeds, Intech, 2012, 978-953-51-0665-4.
[5] J. Murata, et al., Oxidative rearrangement of (+)-sesamin by CYP92B14 co-generates twin dietary lignans in sesame, Nat. Commun. 8 (1) (2017) 1–10.
[6] D. Sankar, et al., Modulation of blood pressure, lipid profiles and redox status in hypertensive patients taking different edible oils, Clin. Chim. Acta 355 (1–2) (2005) 97–104.
[7] E. Naturland, Organic Farming in the Tropics and Subtropics: Sesame, Special Section: Organic Cultivation of Sesame, 2002.
[8] FAOSTAT, Food and Agriculture organization of the United Nations (2024).
[9] T. Schrader, et al., Agricultural Sector Transformation Is Teamwork: Experiences of the Sesame Business Network Support Programme in Northwest Ethiopia, Wageningen Centre for Development Innovation, 2020.
[10] J. Wijnands, J. Biersteker, E. van Loo, Oilseeds Business Opportunities in Rthiopia 2009: Opportunities to Increase Export and to Serve the Domestic Edible Oil Market, 2009.
[11] CSA, Agricultural sample survey of 2018/19: report on area and production of major crops, Stat. Bull. I (589) (2019).
[12] M. Berhe, et al., Insect species dynamics and associated losses in on-farm stored sesame (Sesamum indicum L.) seeds in major sesame growing areas in Ethiopia, Int. J. Trop. Insect Sci. (2024) 1–17.
[13] Z. Gebregergis, D. Assefa, I. Fitwy, Assessment of incidence of sesame webworm antigastra catalaunalis (duponchel) in western Tigray, north Ethiopia, J. Agric. Ecol. Res. Int 9 (2016) 1–9.
[14] A.A. Kebede, W.N. Golla, Y.B. Kindeya, Screening of Sesame Genotypes Resistance to Fusarium Wilt Disease (Fusarium Oxysporum F. Sp. Sesumi) in Western Tigray, Ethiopia, 2020.
[15] F. Baraki, et al., Efficacy of Diuron on the Management of Broad-Leaf Weeds in Sesame (Sesamum indicum L.) Fields in Tigray, 2023. Ethiopia.
[16] G. Zenawi, T. Goitom, B. Fiseha, Assessment of an invasive weed, in: Maimaio" Commelina Foecunda in the Sesame Fields of Western Zone of Tigray, Northern Ethiopia, vol. 2018, International journal of agronomy, 2018.
[17] G. Agegnehu, P.N. Nelson, M.I. Bird, Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols, Soil Tillage Res. 160 (2016) 1–13.
[18] T. Mulualem, B. Yebo, Review on integrated soil fertility management for better crop production in Ethiopia, Sky J. Agricultural Research 4 (1) (2015) 21–32.
[19] M. Corbeels, A. Shiferaw, M. Haile, Farmers' Knowledge of Soil Fertility and Local Management Strategies in Tigray, Ethiopia, 2000.
[20] T. Olivoto, A.D.C. Lúcio, metan: an R package for multi-environment trial analysis, Methods Ecol. Evol. 11 (6) (2020) 783–789.
[21] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2024. https://www.rproject.org/.
[22] G. Van Rossum, F. Drake, Python 3 Reference Manual, 2009 cotts Valley, CA: reateSpace.
[23] J.D. Hunter, Matplotlib: a 2D graphics environment, Comput. Sci. Eng. 9 (3) (2007) 90–95.
[24] W. McKinney, Data structures for statistical computing in Python, in: SciPy, 2010.
[25] C.R. Harris, et al., Array programming with NumPy, Nature 585 (7825) (2020) 357–362.
[26] K. Kelali, Effect of different rates of sulfur fertilizer on yield, yield components and seed quality of sesame (sesame indicum L.) varieties grown under irrigated condition on the vertisols of setit Humera, Tigray, Ethiopia, Mekelle University, College of Dryland Agriculture and Natural Resources: Mekelle, Tigray, Ethiopia (2012).
[27] Y. Desta, et al., Potential, quality and quantity assessment of sesame plant residue in dry land vertisols of Tigrai, Ethiopia; Approach for sustainability of dry-land farming, Heliyon 6 (10) (2020) e05234.

[28] T. Aregawi, G. Animut, H. Kassa, Utilization and nutritive value of sesame (Sesamum indicum L.) straw as feed for livestock in the North western lowlands of Ethiopia, Livest. Res. Rural Dev. 25 (7) (2013).
[29] K. Kelali, M. Misker, A.G. Kormelinck, Sesame yields and (post-)harvest losses in Ethiopia: evidence from the field, Sesame Business Network Ethiopia: Humera, Tigray, Ethiopia (2014).
[30] R. Gelderman, Estimating Nutrient Loss from Crop Residue Fires, 2009.
[31] G. Gebrelibanos, Growth, yield and yield component of sesame (Sesamum indicum L.) as affected by timing of nitrogen application, Journal of Biology, Agriculture and Healthcare 5 (5) (2015) 165–169.
[32] S.B. Mekonnen, J. Sharma, N. Dechassa, Effects of nitrogen fertilizer rates on yield and yield components of sesame (Sesamum indicum L.) varieties under irrigation in Gode, South-Eastern Ethiopia, International Journal of Plant Breeding and Crop Science 3 (1) (2016) 71–78.
[33] O.O. Agbede, Understanding Soil and Plant Nutrition, Petra Digital Press, 2009.
[34] N. Onwudiwe, et al., Municipal Solid Waste and NPK Fertilizer Effects on Soil Physical Properties and Maize Performance in Nsukka, Southeast Nigeria, 2014.
[35] M. Usman, A. Ali, O. Olatunji, Effect of fertilizer application on soil properties and yield of sesame (Sesamum indicum L.) varieties in Southern Guinea and Sudan Savanna Agro-Ecological Zone of Nigeria, African Journal of Agriculture and Food Science 4 (1) (2020) 89–108.
[36] Haile, M., et al., Survey of the Agricultural Soils of Kafta-Humera Woreda, Western Tigray, Ethiopia. CASCAPE. 2019, Mekelle University, Capacity Building for Scaling up of Evidence Based Practices in Agricultural Production in Ethiopia: Mekelle, Tigray, Ethiopia.
[37] M. Amare, D. Fisseha, C. Andreasen, The effect of N and P fertilizers on yield and yield components of sesame (Sesamum indicum L.) in low-fertile soil of north-western Ethiopia, Agriculture 9 (10) (2019) 227.
[38] B. Debele, 6.3 the vertisols OF Ethiopia their properties, classification and management, in: Fifth Meeting of the Eastern African Sub-committee for Soil Correlation and Land Evaluation, Wad Medani, Sudan, 5-10 December 1983, Food & Agriculture Org, 1985.
[39] I. Shabtai, et al., Effects of land use on structure and hydraulic properties of Vertisols containing a sodic horizon in northern Ethiopia, Soil Tillage Res. 136 (2014) 19–27.
[40] MoA and ATA, ATA (Ethiopian Agricultural Transformation Agency) and MOA (Ministry of Agriculture), Soil Fertility Status and Fertilizer Recommendation Atlas for Tigray Regional State, ATA (Ethiopian Agricultural Transformation Agency) and MOA (Ministry of Agriculture), Addis Ababa, Ethiopia, 2014, 2014.
[41] M. Haile, ECherishing Ethiopian soils for sustainable agricultural production: healthy soils for healthy and productive people, in: National Workshop on: the Role of Blended Fertilizers in Enhancing Productivity and Quality of Crops in Ethiopia, Axum Hotel, Mekelle Ethiopia, 2019.
[42] W. Gebrehiwot, et al., Best fit manual for improved sesame production in Tigray region, Ethiopia, in: Mekelle University, Capacity Building for Scaling up of Evidence-Based Practices in Agricultural Production in Ethiopia (CASCAPE), 2020, pp. 1–34. Mekelle, Ethiopia.
[43] B. Haileselassie, Y. Weldegebriel, Status survey of total plant and total DTPA extractable soil copper, Zinc, iron and manganese in different agro ecological zones, soils and districts of Tigray, Ethiopia, Tigray Agricultural Research Institute, Regional Agricultural Research Fund Mekelle, Tigray, Ethiopia (2012).
[44] H. Abrha, 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) (2018) 1–15.
[45] G. Berhe, H. Abraha, W. Haftu, Evaluation of urea and ammonium sulfate on yield and yield components of sesame (Sesamum indicum L.) under high pH vertisol of Western Tigray, Northern Ethiopia, Cogent Food Agric. 5 (1) (2019) 1600461.
[46] G. Teame, A. Tsegay, B. Abrha, Effect of organic mulching on soil moisture, yield, and yield contributing components of sesame (Sesamum indicum L.), International journal of agronomy 2017 (2017).
[47] T. Shimgabr, et al., Evaluation of sesame yield and yield component under different NPSZnB fertilizer rates in western Tigray, Ethiopia, Asian Soil Research Journal 3 (1) (2020) 7–16.
[48] T. Shimgabr, L. Wogi, A. Argaw, Response of sesame (Sesamum indicum L.) to potassium and sulfur application at Kafta Humera district, western Tigray, northern Ethiopia, Asian Soil Research Journal 2 (4) (2020) 1–14.
[49] W. Haftu, Site Specific Blended Fertilizer Rates for Sesame (Sesamum indicum L.) Yield in Vertisols of Kafta Humera District Western Zone of Tigray Ethiopia, Mekelle University, College of Dryland Agriculture and Natural Resources, Mekelle, Tigray,Ethiopia, 2019.
[50] Z. Gebregergis, F. Baraki, G. Teame, Optimizing N fertilizer use for sesame under rain fed and irrigation conditions in Northern Ethiopia, Oil Crop Science 8 (4) (2023) 252–258.
[51] T. Tadesse, I. Haque, E. Aduayi, Soil, Plant, Water, Fertilizer, Animal Manure and Compost Analysis Manual, 1991.
[52] A. Cottenie, Soil and Plant Testing as a Basis of Fertilizer Recommendations, 1980.
[53] P. Hazelton, B. Murphy, Interpreting Soil Test Results: what Do All the Numbers Mean? CSIRO publishing, 2016.
[54] I.I. Bashour, A.H. Sayegh, Methods of Analysis for Soils of Arid and Semi-arid Regions, 2007.
[55] J. Jones, Agronomic Handbook: Management of Crops, Soils and Their Fertility, CRC Press, Boca Raton, FL, USA, 2002.
[56] T. Weldmichael, et al., The influence of depth on soil chemical properties and microbial respiration in the upper soil horizons, Eurasian Soil Sci. 53 (6) (2020) 780–786.
[57] N. Abate, K. Kibret, Effects of land use, soil depth and topography on soil physicochemical properties along the toposequence at the Wadla Delanta Massif, Northcentral Highlands of Ethiopia, Environ. Pollut. 5 (2) (2016) 57–71.
[58] M. de Deus, A.Z. Miller, N.T. Jiménez-Morillo, Molecular characterization of burned organic matter at different soil depths and its relationship with soil water repellency: a preliminary result, Agronomy 11 (12) (2021) 2560.
[59] M. Tumayro, D. Tesgaye, Impact of land use types and soil depths on selected soil physicochemical properties in Fasha District, Konso Zone, Southern Ethiopia, J. Soil Sci. Environ. Manag. 12 (1) (2021) 10–16.
[60] Q. Feng, K. Endo, C. Guodong, Soil carbon in desertified land in relation to site characteristics, Geoderma 106 (1–2) (2002) 21–43.
[61] M.L. Waskom, Seaborn: statistical data visualization, J. Open Source Softw. 6 (60) (2021) 3021.
[62] K. Padalia, K. Bargali, S.S. Bargali, Present scenario of agriculture and its allied occupation in a typical hill village of Central Himalaya, India, Indian J. Agric. Sci. 87 (1) (2017) 132–141.
[63] G. Terefe, et al., Sesame Production Manual. Ethiopia: Ethiopian Institute of Agricultural Research Embassy of the Kingdom of the Netherlands, 2012.
[64] N.C. Brady, R.R. Weil, R.R. Weil, The Nature and Properties of Soils, vol. 13, Prentice Hall, Upper Saddle River, NJ, 2008.
[65] A.R. Nemati, R.S. Sharifi, Effects of rates and nitrogen application timing on yield, in: Agronomic Characteristics and Nitrogen Use Efficiency in Corn, 2012.
[66] G. Zenawi, A. Mizan, Effect of nitrogen fertilization on the growth and seed yield of sesame (Sesamum indicum L.), International journal of Agronomy 2019 (2019).
[67] M. Shamsuzzoha, et al., Effect of combined application of nitrogen and boron on yield contributing characters and yield of sesame (Sesamum indicum L.), Annual Research & Review in Biology 31 (5) (2019) 1–12.
[68] A. Bijarnia, et al., Effect of nitrogen and potassium on growth, yield and nutrient uptake of sesame (Sesamum indicum L.) under loamy sand soil of Rajasthan, J. Pharmacogn. Phytochem. 8 (3) (2019) 566–570.
[69] S. Shilpi, et al., Effect of nitrogen and sulfur on the growth and yield of sesame, International Journal of Bio-resource and stress Management 3 (Jun, 2) (2012) 177–182.
[70] H. Shehu, J.D. Kwari, M. Sandabe, Effects of N, P and K Fertilizers on Yield, Content and Uptake of N, P and K by Sesame (Sesamum indicum), 2010.
[71] S.M. Shahidullah, et al., Determination of optimum doses of nitrogen for higher growth and yield of Sesame, International Journal of Applied Research 2 (1) (2016) 10–15.
[72] M.S. Mandviwala, et al., Optimizing nitrogen efficiency, partitioning and balance using different ratios of organic and inorganic fertilizers in summer sesame, Indian Journal of Fertilisers 20 (7) (2024) 678–684.
[73] E. Abd El Lateef, A.M. Wali, M. Abd El-Salam, Effect of manure sources and rates on nitrogen replacement value, sesame yield and nutrient content under drip irrigation system, Bull. Natl. Res. Cent. 45 (2021) 1–11.

[74] F.S. El-Nakhlawy, M.A. Shaheen, Response of seed yield, yield components and oil content to the sesame cultivar and nitrogen fertilizer rate diversity, Meteorology, Environment and Arid Land Agriculture Sciences 20 (2) (2009).
[75] N.S. El-Khouly, H. Saudy, A. El-Momen, Varietal variations of sesame in nitrogen utilization efficacy, Arab Universities Journal of Agricultural Sciences 26 (2018) 1819–1826. Special issue (2C).
[76] Z. Nahar, et al., Response of Nitrogen Levels on Yield of Sesame (Sesamum indicum L.), 2008.
[77] A.B. Girma, Performance of sesame (Sesamum indicum L.) under different supplementary irrigation and nitrogen fertilizer levels in Humera, northern Ethiopia, Modern Concepts & Developments in Agronomy 5 (1) (2019).
[78] I.M. Haruna, L. Aliyu, Seed yield and economic returns of sesame (Sesamum indicum L.) as influenced by poultry manure, nitrogen and phosphorus fertilization at Samaru, Nigeria, Rev. Científica UDO Agrícola 12 (1) (2012) 153–157.
[79] A. Siddik, et al., Combined effect of nitrogen and NAA on the yield of Sesame (Sesamum indicum L.), Scientia 13 (1) (2016) 1–9.
[80] J. Ahmad, et al., Growth and oil yield of sesame as influenced by sulphur and nitrogen, Open Access journal of agricultural research 3 (7) (2018) 2474–8846.
[81] M.A. Malik, et al., Influence of different nitrogen levels on productivity of sesame (Sesamum indicum L.) under varying planting patterns, Int. J. Agric. Biol. 5 (4) (2003) 490–492.
[82] J. Havlin, et al., Soil Fertility and Fertilizers: an Introduction to Nutrient Management, 1999.
[83] HuARC-NRM, The response of sesame to the application of different rates of P under balanced fertilizer in Kafta Humera and Tsegede woredas of the Western Tigray, Annual Report of Department of Natural Resources and Management of the Humera Agricultural Research (2020).
[84] H.B. Umata, A.H. Dabalo, Effect of fertilizer rate on the yield and yield component of sesame (Sesamum indicum) in moisture stress of Eastern Hareghe Zone, Agric. Res. Technol. Open Access J. 8 (3) (2017) 555738.
[85] O.T. Coomes, et al., Farmer seed networks make a limited contribution to agriculture? Four common misconceptions, Food Pol. 56 (2015) 41–50.
[86] M.A. Raza, et al., Sulphur application increases seed yield and oil content in sesame seeds under rainfed conditions, Field Crops Res. 218 (2018) 51–58.
[87] A. Raja, et al., Sulphur levels on nutrient uptake and yield of sesame varieties and nutrient availability, Int. J. Soil Sci. 2 (4) (2007) 278–285.
[88] A. Puste, et al., Effect of Irrigation and Sulphur on Growth, Yield and Water Use of Summer Sesame (Sesamum indicum L.) in New Alluvial Zone of West Bengal, 2015.
[89] F. Ahmad, et al., Influence of sulphur and potassium levels on yield and yield attribute of sesame (Sesamum indicum L.), Research in Agriculture Livestock and Fisheries 5 (2) (2018) 147–150.
[90] M. Prusty, et al., Effect of different sources and levels of sulphur in sesame on yield, nutrient uptake and soil fertility in acid alfisols of odisha, India, Int. J. Phys. Soc. Sci. 36 (6) (2024) 669–677.
[91] C. Kundu, et al., Effect of doses and time of sulphur application on yield and oil content of sesame (Sesamum indicum L.), Environ. Ecol. 28 (4A) (2010) 2629–2631.
[92] A. Mishra, et al., Evaluation of interaction effect of phosphorus and sulphur on growth, yield and yield components of sesame (Sesamum indicum L.) under rainfed condition of Chitrakoot area, Pharm. Innov. 11 (1) (2022) 1866–1870.
[93] D. Bunphan, et al., Growth, yield and oil content of sesame ('Sesamum indicum'L.) as influenced by sulphur levels under infertile soil, Aust. J. Crop. Sci. 15 (10) (2021).
[94] G. Diyarov, et al., Acceptable planting periods and fertilizing methods of sesame (Sesamum L.) in the western province of Zarafshan oasis, Uzbekistan, in: E3S Web of Conferences, EDP Sciences, 2024.
[95] S. Hanif, et al., Enhancing sesame yield in arid conditions through NPK fertilizer optimization, Asian Plant Research Journal 12 (3) (2024) 1–11.
[96] M. Yusuf, U. Musa, Evaluation of five sesame (sesamum indicum L.) varieties under varying fertilizer rates and establishment methods for growth and yield in Anyigba, Kogi state, Nigeria, International Journal of Precision Farming 2 (1) (2024) 1–14.
[97] M. Vaishnav, et al., Effect of mineral fertilizer on yield, quality and nutrient uptake of black sesame [sesamum radiatum (L.)], Int. J. Phys. Soc. Sci. 36 (6) (2024) 282–287.
[98] T. Adisu, B. Anbesse, D. Tamene, Effect of nitrogen and phosphorus on yield and yield components of sesame (Sesamum indicum L, in: At Kamashi Zone of Benshangul Gumuz under Balanced Fertilizer, 2020.
[99] A. Isa, et al., Effect of nitrogen and phosphorus fertilizer on the performance of sesame (Sesamum indicum L.) varieties in Sudan savannah, Journal of Agripreneurship and Sustainable Development 5 (3) (2022) 42–48.
[100] T. Teshome, Effects of nitrogen, phosphorous (inorganic fertilizers) and farm yard manure on growth, yield, yield components and oil contents of sesame (Sesamum indicum L.) at Assosa district, Beneshangul Gumuze Region, Ethiopia, Nat. Sci. 14 (12) (2016) 19–28.
[101] W. Gebrehiwot, et al., Best fit manual for improved sesame production in Tigray region, Ethiopia, in: CASCAPE (Capacity Building for Scaling up of Evidence-Based Practices in Agricultural Production in Ethiopia) Project, Mekelle University, Mekelle, Tigray, Ethiopia, 2020, pp. 1–34.
[102] D. Haile, D. Nigussie, A. Ayana, Nitrogen use efficiency of bread wheat: effects of nitrogen rate and time of application, J. Soil Sci. Plant Nutr. 12 (3) (2012) 389–410.
[103] D. Tafere, The response of sesame (sesame indicum L.) to different levels of nitrogen and organic phosphate (orga) fertilizers in semiarid northern Ethiopia of Kafta Humera, in: Land Resources Management and Environmental Protection, College of Dryland Agriculture and Natural Resources, Mekelle University, Mekelle, Tigray, Ethiopia, 2010.
[104] T. Berhe, et al., Evaluating the Response of NPSZnB Fertilizer on Yield and Yield Components of Teff at North Western Zone of Tigray, 2023. Ethiopia.
[105] B. Anbessa, G. Abera, S. Kassas, Effect of blended fertilizer on yield, nutrient uptake and economy of maize (Zea mays L.) in Assosa District, western Ethiopia (2022).
[106] T. Shimgabr, et al., Evaluation of NPS fertilizer on yield and yield components of sesame under rain-fed condition in western zone of Tigray, Ethiopia, in: National Workshop on: the Role of Blended Fertilizers in Enhancing Productivity and Quality of Crops in Ethiopia, Axum Hotel, Mekelle Ethiopia, 2019.
[107] K. Zebene, N. Geleta, Effect of NPS fertilizer rates on yield and yield components of Sesame (Sesamum indicum L.) varieties at Uke, Western Ethiopia, J. Plant Sci. 10 (3) (2022) 96–105.
[108] T. Gutu, C. Debela, Effect of NPS and N fertilizer rates on growth and yield of sesame (Sesamum indicum L.) at western Oromiya, Ethiopia, American Journal of Plant Biology 8 (2) (2023) 43–48.
[109] E. Eifediyi, et al., Performance of Sesame (Sesamum indicum L.) as Influenced by 2, 4–dichlorophenoxyacetic Acid and NPK Fertilizer, 2019.
[110] Z.A. Musse, S.B. Ambaye, Effect of different blended fertilizers formulae for the productivity of sesame at bench maji zone, south Ethiopia, Journal of Tropical Crop Science 11 (2) (2024).
[111] G.G. Geserto, Z.M. Adare, Blended NPSB Fertilizer Rates Effect on Growth, Yield and Yield Components of Sesame (Sesamum indicum L.) Varieties at Konso, 2022. Southern Ethiopia.
[112] F. Alemu, T. Lishan, Managing integrated NPSB fertilizers and farmyard manure to improve the sesame (Sesamum indicum L.) yield in Guraferda districts, southwest Ethiopia, Russ. Agric. Sci. 50 (2) (2024) 131–141.
[113] F. Hadgu, et al., Evaluation of new blended and micro-nutrient fertilizers on sesame grown on soils of western lowlands of Tigray, Humera Agricultural Research Ceneter: Humera, Tigray (2019).
[114] S. Dahunsi, et al., Crop performance and soil fertility improvement using organic fertilizer produced from valorization of Carica papaya fruit peel, Sci. Rep. 11 (1) (2021) 4696.
[115] A.O. Adekiya, et al., Organic and in-organic fertilizers effects on the performance of tomato (Solanum lycopersicum) and cucumber (Cucumis sativus) grown on soilless medium, Sci. Rep. 12 (1) (2022) 12212.
[116] A. Pattnayak, et al., Effect of different organic nutrient sources on the growth and yield of summer sesamum (Sesamum indicum L.), Journal of Advances in Biology & Biotechnology 27 (7) (2024) 400–407.
[117] HuARC-CROP, *Estimating optimum rates of Eco-green and Orga organic fertilizers on sesame yield in Humera, Western Tigray* 2020, Humera Agricultural Research Center: Humera, Tigray, Ethiopia.

[118] I. Haruna, M. Abimiku, Yield of sesame (Sesamum indicum L.) as influenced by organic fertilizers in the southern Guinea Savanna of Nigeria, Sustain. Agric. Res. 1 (1) (2012).
[119] O. Nnebue, et al., Preliminary investigation of growth and yield of four sesame varieties (sesamum indicum) using cured poultry manure in Owerri, Nigeria, Agrosearch 22 (2) (2024) 62–77.
[120] G. Teame, A. Tsegay, D. Weldeareagy, Effect of land configuration ways on soil moisture and sesame seed yield in Ethiopia, Turkish Journal of Food and Agriculture Sciences 3 (1) (2021) 1–6.
[121] M. Navrange, et al., Effect of Land Configuration and Weed Management Practices on Yield and Economics of Sesame, 2022.
[122] HuARC-CROP, Estimating optimum ploughing frequency and depth to enhance soil fertility and sesame productivity in Humera, Western Tigray, Humera Agricultural Research Center: Humera, Tigray, Ethiopia (2014).
[123] G. Gebresamuel, A. Gebretsadik, Agricultural best practices: evidences from CASCAPE project in Tigray, in: CASCAPE (Capacity Building for Scaling up of Evidence Based Best Practices in Agricultural Production in Ethiopia), Mekelle University, Mekelle, Ethiopia, 2020, pp. 1–62.
[124] A. Couch, et al., Non-dehiscent sesame (Sesamum indicum L.): its unique production potential and expansion into the southeastern USA, J. Crop Improv. 31 (2) (2017) 101–172.
[125] A.N. Shah, et al., Allelopathic potential of oil seed crops in production of crops: a review, Environ. Sci. Pollut. Control Ser. 23 (2016) 14854–14867.
[126] I. Hussain, et al., Allelopathic potential of sesame plant leachate against Cyperus rotundus L, Annals of Agrarian Science 15 (1) (2017) 141–147.
[127] P. Banik, et al., Wheat and chickpea intercropping systems in an additive series experiment: advantages and weed smothering, Eur. J. Agron. 24 (4) (2006) 325–332.
[128] F. Baraki, et al., Augmenting productivity and profitability through Sesame–Legume intercropping, Heliyon 9 (7) (2023) e18333.
[129] M.M. Islam, et al., Intercropping of sesame with mungbean increased system productivity and farm profit in coastal region of Bangladesh, Journal of the Indian Society of the Coastal Agricultural Research 42 (1) (2024) 147524.