

Land Suitability and Sustainability Evaluation for Sorghum (*Sorghum bicolor*) Production in Tula, Gombe State, Nigeria

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ABSTRACT

Land suitability and sustainability evaluation for crop production is important in the control of land degradation in a tropical environment. The current study aims to evaluate land suitability and sustainability for sorghum production in Tula, Gombe State, Nigeria. Soil samples were collected from upper, middle, and lower slope positions at 0-30 cm depth and analyzed in the laboratory. The results indicated that the soil texture was loamy sand and bulk density values were $<1.6 \text{ Mg m}^{-3}$, while the soil pH was slightly acid to neutral. SOC was rated medium in the upper and lower slopes ($>10 \text{ g kg}^{-1}$) and low ($<10 \text{ g kg}^{-1}$) in the middle slope. The exchangeable cations were medium to high in the upper and lower slopes, and medium on the middle slope. The suitability/sustainability assessment, cumulative rating index (CRI), was in order of upper > lower > middle slope. Soils in the upper and lower slopes were marginally suitable (S3) and sustainable S2 (CRI= 23 & 22), while those in the middle slope were marginally suitable (S3) and sustainable with high inputs S3 (CRI= 25) for sorghum production. The major agronomic constraints were soil texture, steep slope, low organic carbon, and total nitrogen, particularly in the middle slope, which may have affected sorghum production on a sustainable basis. Management practices such as the application of organic and inorganic fertilizer, technology adoption, effective irrigation, and agroforestry will enhance sorghum sustainability and impede land degradation.

Keywords: toposequence; sustainability; suitability; sorghum; land degradation.

1 INTRODUCTION

Sorghum (*Sorghum bicolor* [L.] Moench) is the fifth most important world cereal after maize, wheat, rice, and barley [1]. It is believed to have originated in Eastern Africa, most likely in Ethiopia, an area characterized by unpredictable and variable rainfall [2]. The crop spread across various African regions through the movement of local populations. Initially growing in the wild, sorghum was domesticated for use in Africa for approximately 2000 years [3]. The crops spread to Asia and parts of Western Europe, and can be attributed to the forced migration. It serves as a primary food source for around 750 million people residing in the semi-arid tropical regions of Africa, Asia, and Latin America [4]. Sorghum is mainly produced in countries such as, USA, Nigeria, Sudan, Mexico, and Ethiopia [5]. Sorghum production has an important impact on global food security, contributing directly to farmers' household incomes due to its industrial demand [6].

Sorghum provides food for man, livestock feed, biofuel, and forage [7]. In countries where sorghum is grown as a subsistence crop, the main food products prepared include thin and thick porridges,

fermented and unfermented breads, lactic and alcoholic beers and beverages, malted flours for brewing, and malted porridge mixes [8] [9]. In Kenya and South Africa, there is a small but growing market for pearled sorghum as an alternative to rice. In India, proposals have been made for the use of dehulled sorghum within feeding schedules for infants and children [8]. Globally, Nigeria is the second leading sorghum producer, with 6.9 million tons from 5.4 million hectares after the USA, with 8.7 million tons from 1.9 million hectares, and the highest in Africa [9]. Nigeria's bulk of sorghum production is derived from the Northern Guinea, Sudan, and Sahel Savanna ecological zones of the country. The northern region produces most of the sorghum in the country, with the northwest (48%) and northeast (32%) leading the scale [10]. The plant displays a great diversity in growth, development, and resource use efficiency, and has the potential to improve the productivity of resilient farming systems.

Sorghum is relatively tolerant to drought and waterlogging [11] and has a wide adaptation to varied soil conditions [12]. These characteristics make sorghum a staple choice in arid and semi-arid

regions of Africa. The plant can grow between 0-500 meters (m) above sea level. Planting distance is measured based on production purposes by farmers. However, environmental factors such as land degradation, water scarcity, climate variability, agricultural intensification, and environmental changes can have a negative impact on sustainable production [13] [14]. Extreme temperature >35 degrees Celsius (°C) can deter growth and crop yield [15]. Prolonged rainy seasons or excessive humidity would also have the potential to reduce productivity [16]. The increase in high cereal yield gaps in developing countries might be related to the above factors [17].

In sub-Saharan Africa, most farmers use suboptimal lands to cultivate sorghum for basic needs and livelihoods [18]. These include acid and nutrient-deficient wetlands with high risk of iron toxicity, unpredictable and frequent floods, acid and nutrient-deficient dry lands, and water-deficient dry lands [18]. Additionally, an increase in food demand because of population growth and the conversion of arable lands for uses in other sectors has led to an urgency for intensifying agricultural activities on suboptimal lands. Efforts to increase agricultural productivity in suboptimal lands should not jeopardize the sustainable function of ecosystems and limit the participation of local farmers [19]. Suitability and sustainability should be maintained while increasing productivity. Therefore, timely and reliable land resource information is required in developing countries for optimal utilization.

Nigeria is a developing country that produces 1.23 (t) of sorghum per hectare, which is relatively low compared with the world average of 1.45 (t) per hectare [9]. Sorghum cultivation in Nigeria is carried out using agroforestry or monoculture, but it is not as popular compared to corn and rice. The production in Nigeria has been very slow in recent times because farmers prefer to plant rice and corn. However, sorghum is more drought-resistant than corn, resulting in the development being directed at desert areas [20]. The plant is easier to cultivate depending on the crop variety, land preparation, maintenance, planting time, seed preparation, and pest and disease control. The plant needs water for optimal growth, after seedling establishment, and is relatively more resistant to pests and diseases compared to other crops [20]. The common pests include sorghum fly (*Atherigona varia Soccata*) [7] [20].

Land suitability evaluation is a scientific judgment on the degree of suitability of land for specific land use [21]. Accord suitability is a function of crop requirements and land features. Large areas of arable land in Tula, Gombe State, are under intense and unsustainable cultivation. In the past, the soils of Tula were not well studied in terms of their fertility, suitability, and productivity classes [22]. Evaluation of land resource suitability and sustainability for sorghum production is aimed at achieving the land suitability principle of "suitable planting and growth in the right place".

This principle has not been well-studied recently in Tula. Goals of sustainable agriculture would, however, be achieved when lands were categorized and utilized based on their different uses. The current study aims to evaluate the land suitability and sustainability of a toposequence for sorghum production in Tula, Gombe State, Nigeria. The objective of the study is to address the relevant issue of land degradation and sustainable sorghum production in a data-scarce region. While land suitability evaluations for sorghum exist, this study will add to the body of knowledge by focusing on a specific toposequence and integrating sustainability assessment using Lal's framework. This localized approach will provide valuable site-specific information for sustainable land management.

2 MATERIALS AND METHODS

2.1 Study Area

Tula is in Kaltungo Local Government Area of Gombe State, covering latitudes 11° 75' 55" to 19° 34' 48" N and longitudes 11° 59' 34" to 11° 34' 60" (Figure 1). Tula is situated within an upland area with an elevation of 645 m above sea level. Most of the settlements are used for agriculture and have high tourism potential in the Wange area. The climate of the study area, according to the Köppen climatic classification, is within the AW type of climate. It is seasonally wet and dry, having an average annual rainfall regime ranging from 850 to 1200 mm over a period of three decades (1953 to 1989). The rainfall is concentrated in the months of May and October, with a single maximum in July/August. The soils are developed on crystalline Basement Complex bedrock. Sedimentary formation underlies most of the area during the Late Cretaceous period, which has influenced the topography of the area. The soil and vegetation in Tula differ from other areas due to the undulating nature of the topography. The vegetation of the study area comprises shrubs and sparse growth of grasses. Major trees in the study area include *Acacia spp.*, *Anogeisus leiocarpus*, *Entanda africana*, *Prosopsis africana*, *Vitex doniana*, *Vitaleria paradoxum*, *Khaya senegalensis*, and *Parkia biglobosa*.

2.2 Field Studies

An undulating terrain was selected for the purpose of assessing the impact of topography on land suitability and sustainability for sorghum production in the study area. The sampling area was marked adjacent to Wange and Yiri's topographic position (Figure 1). The upper, middle, and lower slope classes were located using ranging poles at intervals of 30 m along each slope position. Slope class was subdivided into two (2) subclasses, making a total of six (6) subclasses. Soil samples were collected from 0-15 cm and 15-30 cm in all six (6) subclasses, making a total of twelve (12) soil samples. The soil samples collected from each slope classes within 0-15 cm were mixed, as well as those collected within 15-30 cm, to obtain a composite sample. A total of six (6) samples were transported to the Gombe State University laboratory for analysis.

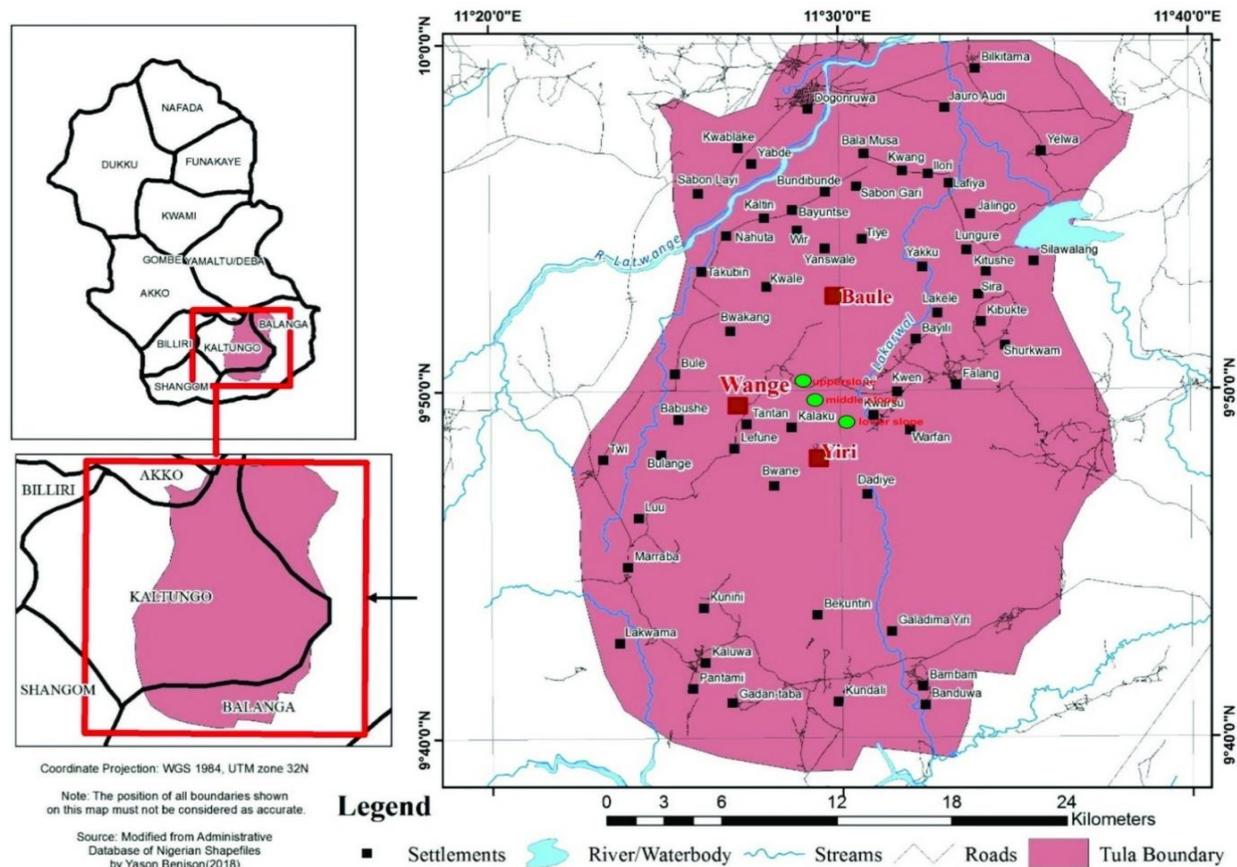


FIGURE 1: Map of the study area showing the sample points.
Source: Adapted from the administrative map of Gombe, Nigeria.

2.3 Laboratory analyses

Soil samples collected were air-dried, crushed, and sieved through a 2 mm sieve, and < 2 mm fractions were used for laboratory analysis following methods described by [23]. Particle size distribution was determined by the hydrometer method. Bulk density was determined using the core method. Soil pH was measured in water (1:2.5 w/v) using a glass electrode pH meter. Organic carbon was determined by the dichromate wet oxidation method. Exchangeable sodium was extracted using ammonium acetate and determined using a flame photometer. The effective cation exchange capacity (ECEC) was determined by the summation method. Base saturation was calculated as a percentage of the sum of total exchangeable bases divided by effective cation exchange capacity, and electrical conductivity (ECe) was determined by the Wheatstone bridge method.

2.4 Land suitability evaluation

Land suitability evaluation for sorghum production was carried out using the National Bureau of Soil Survey and Land Use Planning method (Table 1). Key environmental factors considered in the evaluation were climate (annual rainfall, temperature), topography (slope), and soils [24]. The parameters employed for the evaluation of soils were soil depth, texture, drainage, pH, available P, organic carbon (OC), exchangeable K, CEC, and base saturation.

The identified soil units were placed in suitability classes by matching their characteristics with the land requirements of sorghum. The suitability of each factor for the respective soil units was classified as highly suitable (S1), moderately suitable (S2), marginally suitable (S3), or not suitable (N).

The overall land suitability classes were obtained using the principle of limiting conditions and multiplication methods [7]. The principle of limiting conditions uses the most extreme suitability limiting classes of individual qualities to produce the overall suitability class for each soil unit [7], while the multiplication method converts individual ratings to numerical factors and multiplies the values together. The numerical values are as follows: S1 = 1.0, S2 = 0.8, S3 = 0.5, and N = 0.0. According to [7], the numerical values for the overall suitability classes are as follows: 0.8 to 1.0 = S1, 0.4 to < 0.8 = S2, 0.2 to < 0.4 = S3, and 0.0 to < 0.2 = N.

2.5 Land sustainability evaluation

To determine the sustainability of land, indicators of soil sustainability such as root depth, soil texture, bulk density, soil structure, pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium were compared with the limits proposed by [25]. Table 2a and 2b show the critical levels and relative weighing factors (RWF) for soil properties.

TABLE 1: Land use requirement for sorghum production.

Land Characteristic / diagnostic factor	Highly suitable (S1)	Moderately Suitable (S2)	Marginal Suitable (S3)	Not Suitable (N)
Climatic regime				
Rainfall (mm)	650 – 850	550 – 650	450 – 550	< 450
Temperature (°C)	26 – 30	24-25,31-34	20-23, 35-40	<20, >40
Land quality				
Erosion Hazard - slope (%)	2 – 3	3-8	8-15	>15
Soil depth (cm)	100 – 75	50 - 75	30 - 50	<30
Soil Texture	C, CL, SiCl, SC	L, SiC, SiL	SL, LS	S, fragmental
Volume of coarse fragment	5 – 15	15 – 40	40 - 75	<75
Drainage	Well to moderate	Imperfectly	Poor and excessive	Very poor
Nutrient availability				
pH	6.0 - 8.0	5.5 - 5.9, 8.1 – 8.5	<5.5, 8.6 –9.0	> 9.0
Organic Carbon (g kg ⁻¹)	20 – 40	10 – 20	5.0 - 10	> 0.5
CEC (cmol kg ⁻¹)	30 – 20	20 – 10	10 – 5	< 5
Base Saturation (%)	80 -50	50 – 35	35 - 20	< 20
Soil toxicity				
Salinity EC (e)	2 – 4	4-8	8-10	> 10
Sodicity ESP	5 – 8	8-10	10-15	> 15

SiCl=Silt clay loam, SC=Sandy clay, CL=clay loam, L =loam, SL=sandy loam, LS=loam sand, SiL=Silt loam, SiC=Silt clay.

Source: NBSS & LUP (1994).

The critical levels were assigned based on limitations to crop production [26]. Table 2 presented the range from no limitation to extreme limitations on a scale of 1 to 5 for the relative weighting factor. The data were combined into a cumulative rating index and weighting factors. The indicators were used to determine the sustainability class in accordance with [25].

The lower limit of “1” for a soil property indicates no limitation (excellent soil quality), and the upper limit of “5” reflects a severe constraint. To obtain the overall sustainability rating for each land use, the summation of the data obtained from the critical weight factors derived from Table 2 was compared with the overall cumulative rating of the land (Table 3) to determine the degree of sustainability for each land use as outlined by [25].

TABLE 2a: Critical levels and relative weighing factors (RWF) for soil properties.

Limitation	ERD (cm)	Structure	Const.	BD (Mg.cm ⁻³)	pH	SOC (g.kg ⁻¹)	Total N (g.kg ⁻¹)	Avail. P (mg.kg ⁻¹)	SAR (%)
None	> 150	Sub angular, crumb/ granular	Loose	<1.3	6-7	> 10	>4	>25	<3
Slight	100-150	Sub angular blocky	Very friable	1.3-1.4	5.8-6, 7-7.4	5-10	2-4	20-25	3-6
Moderate	50 -100	moderate sub angular blocky	Friable	1.4-1.5	5.4-5.8, 7.4-7.8	2.5-5	1-2	15-20	6-12
Severe	25 – 50	weak sub-angular blocky	Hard	1.5-1.6	5.0-5.4, 7.8-8.2	1-2.5	0.5-1	10-5	12-20
Extreme	< 25	Massive, single grain	Hard	>1.6	<5.0, >8.2	< 1.0	<0.5	<5	>20

Key RW = Relative weight, BD: bulk density; SAR: sodium adsorption ratio; SOC: soil organic carbon, ERD: Effective rooting depth.

Source: Lal (1994).

TABLE 2b: Critical levels and relative weighing factor (RWF) for soil properties.

Sustainability	Soil sustainability class	Cumulative rating index
Highly sustainable	S ₁	<20
Sustainable	S ₂	20-25
Sustainable with high input	S ₃	25-30
Sustainable with another land use	S ₄	30-40
Unsustainable	US	>40

Source: Lal (1994).

3 RESULTS AND DISCUSSION

3.1 Qualitative land suitability classification for sorghum production

The availability of suitable land for cultivation impacts food security and a sustainable environment, highlighting the importance of increasing productivity. Evaluating soil quality and field characteristics can help maximize sorghum production [27]. The summary of land characteristics of the study area is presented in Table 4, and the assessment ratings resulting from matching land qualities and requirements for sorghum are presented in Table 1 using the [24] suitability ratings. The mean annual rainfall was considered highly suitable (S₁), while the mean temperature was moderately suitable (S₂) for the upper, middle, and lower slope positions (Table 5).

Water use in the study area was very efficient, with the sources being rainwater and irrigation practices. Irrigation is an effective method used by farmers to increase water use efficiency in plant cultivation, including sorghum. The use of techniques such as drip or sensor-based irrigation that accurately measure soil moisture to determine plants' water needs will improve water use efficiency. Using these methods, farmers can avoid wasting water and provide an accurate amount based on plant requirements. Furthermore, sorghum is tolerant to aridity [28] and has a greater ability to maintain water compared to maize, as stated by [22]. This makes the plant suitable for areas experiencing drought or having limited water availability. Sorghum has a 20% greater water use efficiency in arid areas compared to maize and rice, resulting in good prospects for wide-scale cultivation in arid and semi-arid environments [29].

TABLE 4: Land characteristics of the toposequence in the study area.

Climate regime	Upper	Middle	Lower
Rainfall (mm)	1025	1025	1025
Temperature (°C)	32	32	32
Land quality			
Slope (%)	2 – 4	4 – 8	2 – 4
Soil depth (cm)	80	50 -60	100
Soil Texture	LS	LS	LS
Volume of coarse fragment	46.1	47.2	47.2
Drainage	Well drained	Well drained	Moderately drained
Bulk density (Mg.cm ⁻³)	1.02	1.12	1.19
Nutrient availability			
pH	6.29	6.23	6.49
Organic Carbon (g kg ⁻¹)	13.6	8.85	10.5
Available p (mgkg ⁻¹)	58.8	34.7	102
Total Nitrogen (g kg ⁻¹)	0.74	0.56	0.88
Exchangeable K (cmol kg ⁻¹)	0.2	0.12	0.22
ECEC (cmol kg ⁻¹)	15.4	15.2	13.51
Base Saturation (%)	95.5	97.4	94.1
Salinity and Sodicity			
Salinity EC (e)	0.2	0.16	0.27
Sodicity ESP	2.47	2.77	3.18

*CL = clay loam, L = loam, SL = sandy loam, LS = loam sand, S = sand LCM = loam coarse sand.

Soil management in sorghum production involves practices that maintain or improve soil health and fertility. Soil sustainability for sorghum cultivation has previously been shown to improve soil conditions [30]. Topography is the major factor that

influences most processes taking place in the environment, especially on agricultural land. Different geochemical conditions are experienced on different landscape positions (upper, middle slope, and lower slope), depending upon the influence of

topography on the drainage and hydrology of the soil cover [22]. The result of the suitability of sorghum along a toposequence in Tula indicated that the upper and lower slope positions with a slope of 2–4% are classified as highly suitable (S1), while the middle slope with a slope of 4–8 % was moderately suitable (S2). An effective soil depth of 75–100 cm classified the upper and lower slopes as highly suitable (S1), while the middle slope with a soil depth of 75–50 cm was moderately suitable (S2) for sorghum cultivation.

Based on soil texture, all three slope classes (upper, middle, and lower) were marginally suitable (S3) due to the sandy loam textural class. The volume of coarse fragments in all slope classes fell within 40–75%, therefore are classified as marginally suitable (S3). Furthermore, all the slope classes were well to moderately drained and thus classified as highly suitable (S1) for sorghum production. In terms of soil reaction (pH), all slope classes were highly suitable (S1). The upper and lower slopes were moderately suitable (S2), while the middle slope was marginally suitable (S3) in terms of organic

carbon concentration. Considering nutrient retention (ECEC), all slope positions were within an ECEC range of 20–10 cmol/kg and accordingly, classified as moderately suitable (S2). All slope classes were >90% in base saturation, <2 dSm⁻¹, and <5 % in EC and ESP, respectively, and thus classified as highly suitable (S1) for sorghum production. These findings agree with the study of [25] on the assessment of global sorghum production, tolerance, and climate risk. The study highlights opportunities for the sustainability of sorghum cultivation in the future with climate change. Sorghum yield seems to increase persistently despite global warming due to an improved inputs approach, offering hope that similar adaptation approaches can be fruitful, especially in sub-Saharan Africa. A combination of interventions, including adequate use of fertilizers and technology adoption (e.g., tolerant cultivars), effective management (e.g., improved irrigation), and improved agronomic practices, is the key to enhancing sorghum yield and ensuring the sustainability of this important crop under a warmer climate.

TABLE 5: Land suitability of the toposequence for sorghum production.

Climate regime	Upper	Middle	Lower
Rainfall (mm)	S1 (1.0)	S1 (1.0)	S1 (1.0)
Temperature (°C)	S2 (0.8)	S2 (0.8)	S2 (0.8)
Land quality			
Slope (%)	S1 (1.0)	S2 (0.8)	S1 (1.0)
Soil depth (cm)	S1 (1.0)	S2 (0.8)	S1 (1.0)
Soil Texture	S3 (0.5)	S3 (0.5)	S3 (0.5)
Volume of coarse fragment	S3 (0.5)	S3 (0.5)	S3 (0.5)
Drainage	S1 (1.0)	S1 (1.0)	S1 (1.0)
Nutrient availability			
pH	S1 (1.0)	S1 (1.0)	S1 (1.0)
Organic carbon (g kg ⁻¹)	S2 (0.8)	S3 (0.5)	S2 (0.8)
ECEC (cmol kg ⁻¹)	S2 (0.8)	S2 (0.8)	S2 (0.8)
Base saturation (%)	S1 (1.0)	S1 (1.0)	S1 (1.0)
Salinity and Sodicty			
Salinity EC (e)	S1 (1.0)	S1 (1.0)	S1 (1.0)
Sodicty ESP	S1 (1.0)	S1 (1.0)	S1 (1.0)
Limiting factor	S3F-1	S3F-2	S3F-1
Multiplication	N (0.128)	N (0.051)	N (0.128)

The upper and lower slope positions of the study area were marginally suitable (S3) due to the loamy sand soil texture and high number of coarse fragments. Additionally, the middle slope position was also marginally suitable (S3) due to loamy sand texture, high number of coarse fragments, and low organic carbon. Generally, the major limitations of these soils were texture, coarse fragments, and organic carbon. The overall suitability of Tula soils for sorghum was classified as S_{3f}, while the land suitability units were f-1 and f-2 (fertility) (S_{3f}-1 and S_{3f}-2). The soils in the upper and lower slopes were classified as S_{3s}-1 and characterized by soil texture and coarse fragment limitations, while the middle slope was classified as S_{3fs}-2, which represents

limitations of slope, soil texture, coarse fragment, and organic carbon for sorghum production at the unit level of classification based on limiting conditions. With the limitations, production for animal feed may have higher sustainability in terms of resource use efficiency because sorghum can grow in areas that are less fertile or areas with low water availability [30].

Based on the multiplication method, the rating of the slope positions for sorghum production showed that physical properties (coarse fragments, soil texture) and nutrient availability (low organic carbon) lowered the slope position suitability to currently not suitable (N₁) for all slope classes, which implies

implies that it rates all slope positions lower than the limiting condition (Table 5). Generally, none of the slope positions were highly suitable (S_1) for sorghum. This may be attributed to the low fertility status resulting from soil degradation, as indicated by low organic matter. Several land evaluation studies have also reported that soils of the Nigerian savanna region are mostly not rated highly suitable (S_1) [31] and [32]. Most of the soil is associated with a high rate of degradation affecting soil quality due to unsustainable management practices such as overgrazing, bush burning, and continuous cultivation. This agrees with [33] and [34] studies, which reported slope gradients, total nitrogen, available phosphorus, and organic carbon among the major limitations of soils in the semi-arid region of Ethiopia. The low fertility status can be improved by the application of organic matter from crop residues and animal manure [32]. Additionally, incorporating inorganic fertilizer based on the recommended rate would add more nutrients into the soil.

Sorghum cultivation aligns with sustainable agricultural practices. Its deep root system helps with soil conservation, decreasing erosion, and improving soil structure. Furthermore, studies like those by [35] have highlighted how sorghum positively impacts microbial biomass carbon and enzyme activities, which are critical for soil health. Essentially, the combined perceptions from research studies, including those by [36] and [37], present a compelling case for the various advantages of sorghum, not just as an agronomic crop but also as a socio-economic tool to support food security, improve nutrition, and enhance sustainable agricultural practices in various regions. Therefore, incorporating sorghum in the study area will help to reduce the effect of soil degradation and enhance soil productivity.

3.2 Land Sustainability Evaluation and Management

After comparing different indicators of soil sustainability using the criteria and scoring proposed by [25], it is observed that the cumulative rating index (weighting factors) calculated for different slope positions varied from 23 to 26 (Table 6).

TABLE 6: Critical and relative weighing factors for soil properties.

Toposequence	ERD (cm)	Text	Const	Struct	BD	pH	SOC	Total N	Avail. P	SAR	CRI	SSC
Upper Slope	3	4	4	3	1	1	1	4	1	1	23	S_2
Middle Slope	3	5	4	4	1	1	2	4	1	1	26	S_3
Lower Slope	2	5	4	4	1	1	1	4	1	1	24	S_2

Key: SMU = Soil Mapping Unit, ERD = Effective root depth, SSC = soil sustainability class, Const. = Consistency, CRI = cumulative rating index, Text. = Soil texture, SOC = soil organic carbon, BD= bulk density, SAR= sodium absorption ratio.

The general mean score of the weighted factors of the three positions was in the order of middle slope (26) > lower slope (24) > upper slope (23). Soils on the upper and lower slopes were sustainable with present land use (S_2) with minimal limitation of soil texture, structure, and low total nitrogen. To maintain and upgrade the sustainability of the slope classes, the use of organic manures along with balanced fertilization and conservation tillage should be adopted. The middle slope soil class was sustainable but with high input/management (S_3) on account of major limitations such as poor soil fertility (low total nitrogen and organic carbon) and unfavorable soil texture and structure (Table 5). The use of organic manure along with inorganic fertilizers should be adopted to upgrade the unit to a highly sustainable one and to improve the land quality [38]. Generally, the study revealed two classes of sustainability, which include: sustainable (S_2) and sustainable with high input/management (S_3). This finding confirms the report of previous researchers [39] [40] who submitted that most land uses fall within sustainable (S_2) to sustainable with alternative land use (S_4). Thus, this information is vital for farmers for sustainable management practices and improved productivity.

CONCLUSION

In conclusion, all the slope classes assessed were rated low to medium based on nutrient status. In terms of suitability, all the slope classes were highly suitable in climate, they were marginally suitable based on limiting factors, and currently not suitable based on multiplication methods for sorghum production. The soil slope classes were sustainable (S_2) to sustainable with high inputs (S_3) due to slope gradients, unsuitable texture, high amounts of coarse fragments, low organic carbon, and total nitrogen. However, for optimum performance and to upgrade the suitability and sustainability of the area to be highly suitable and sustainable, the recommended rate of mineral fertilizer, manure application, and management practices, which will encourage the return of plants/crop residues into this soil to improve the soil's quality, should be applied. The results of this study provide notable information for soil scientists and policy planners.

In essence, achieving sustainable sorghum farming in Tula relies on a comprehensive strategy that includes enhancing climate resilience in sorghum production through genetic improvements and technological innovations to address the multifaceted challenges posed by climate change.

Genetic advancements will enable the development of sorghum varieties that are more tolerant to drought and heat, laying a critical foundation for resilience. Employment of agronomic practices such as soil and water management and integrated pest and disease control will optimize the growing environment and bolster the plant's defenses against stressors. Technological innovations, including precision agriculture and climate forecasting, offer tools for precise management and prediction of climatic impacts, enabling more informed decision-making. The synergy between these strategies is key to enhancing sorghum's resilience, ensuring sustainable production, and securing food supplies in vulnerable regions. Applying organic or inorganic mulches on the soil surface can notably reduce evaporation, suppress weed growth, moderate soil temperature, and increase water infiltration.

Further study on soil suitability and sustainability should integrate the socioeconomic factors that influence land use decisions and sustainability, such as farmer perceptions, market access, and policy environment. Additionally, the current research used NBSS and LUP methods as the criteria for weighting factors. Therefore, different approaches or methods, such as the applications of GIS and spatial analysis through selection of the criteria, which were weighted through Multi-Criteria Evaluation, can be employed in future studies to assess the suitability of sorghum for sustainable agriculture.

Limitations of the research

The study focuses on a single toposequence, limiting the generalizability of the findings to other areas. Further research needs to widen the scope of the study area to include the semi-arid areas of the north-western and north-eastern regions of Nigeria.

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Author contributions

Jimoh, I. A. Yahqub, M. Ofem, K. I., and Gambo, A designed the study, and the methodologies used. Jimoh, I. A. performed the fieldwork survey presented in the study. All four authors were involved in data analysis and, initial draft of the manuscript. I. A. Jimoh and A. Gambo edited and revised the manuscript. All four authors reviewed the final draft of the manuscript.

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Consent for publication

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Declarations Competing interests

The authors declare no competing interests.

Ethics declaration

Not required.

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