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Asnath Shila Dolo [*] , Seome Michael Swafo [*] , Ramatlane Sydney Motsinoni

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Asnath Shila Dolo *, Seome Michael Swafo * and Ramatlane Sydney Motsinoni

School of Agriculture & Environmental Sciences, Department of Plant Production, Soil Science & Agricultural Engineering, University of Limpopo, Private Bag X1106, Sovenga 0727, Limpopo, South Africa

* Correspondence: shila.dolo@ul.ac.za (A.S.D.); seome.swafo@ul.ac.za (S.M.S)

Abstract: South Africa (SA) is grappling with a severe food insecurity crisis exacerbated by socioeconomic challenges. This resulted in the Department of Basic Education (DBE) advocating for the establishment of vegetable gardens at schools. However, information on the suitability of the soils in SA for sustainably growing Beetroot is unavailable. This study aimed to assess the suitability of soils for sustainable Beetroot production at various schools in the Kgakotlou circuit. Four Secondary Schools were selected: Mothimako, Madipoane, Klaas Mothapo and Phomolong. A detailed soil survey was carried out to study soils in vegetable gardens. Soil samples were collected for laboratory analysis of physicochemical properties. The soil suitability was evaluated using the physicochemical properties of the soils and optimal soil requirements for Beetroot production. We found various soils in the schools, including Cambisols (Hutton and Nkonkoni), Leptosol (Glenrosa), Plinthosol (Westleigh), and Acrisols (Tshiombo and Tubatse). Portions of the gardens on Hutton and Westleigh soil were moderately suitable (S2), limited by electrical conductivity (EC). Meanwhile, portions of Tshiombo, Tubatse, and Nkonkoni were marginally suitable (S3), limited by pH and EC. Portions on Glenrosa soil at Klaas Mothapo and Phomolong were not suitable (NS) and were limited by shallow depth, soil pH and EC. The results reveal the importance of considering soil suitability before establishing vegetable gardens in school settings. Indexing soil suitability using the physicochemical properties of soil resources for sustainable beetroot production is proposed for schools in the Kgakatlou circuit and other parts of SA.

Keywords: soil survey; land evaluation; soil information; soil suitability; sustainability; food insecurity

1. Introduction

South Africa faces challenges ranging from high unemployment and poverty to the ongoing energy crisis and rising living costs [1]. These negatively impact SA's state of food security by making food expensive and inaccessible to many [2]. An estimated 58 million people in SA are facing food insecurity, while almost 18.6 million children are stunted [3]. This incident resulted in the DBE advocating for vegetable garden establishment at schools [4]. The DBE is responsible for the National School Nutrition Program (NSNP). The NSNP has three pillars: (i) a feeding programme providing meals to learners, (ii) nutrition education promoting healthy lifestyles, and (iii) sustainable food production in schools, thereby promote food production and skills transfer to schools and communities aimed at food security [5].

Vegetables in SA play a central role in addressing food security and providing nutritional supplements and requirements to people [6,7]. Beetroot is a biennial plant grown annually for its storage root [6]. The roots are eaten grilled, boiled or roasted as a cooked vegetable or cold as a salad after cooking and adding oil and vinegar [7]. Beetroot is a rich source of carbohydrates and protein. It also has high essential vitamins, minerals and micronutrients [8]. The average beetroot consumption is approximately 57 794 tons per annum [7]. This shows that SA is self-sufficient regarding beetroot production. The central producing regions are the North West, Gauteng,

Mpumalanga, KwaZulu Natal and Western Cape [7]. The area planted for Beetroot each year in SA is determined by climatic and economic factors, neglecting the soil factor.

Soil is a crucial component of any successful agricultural operation. It serves as a medium for plant growth and provides water and essential nutrients [9]. Thus, it plays a critical role in the production of food. Nonetheless, soil is naturally different in space because of the way it is formed [10]. The various climates, parent materials, topography and organisms across space interact in time to create specific types of soil [11,12]. Therefore, the cultivation of crops needs to be guided by considering the location-specific inherent soil capacity [13]. Identification of the agricultural potential of soils is necessary for sustainable crop production [14].

In SA, less attention has been paid to assessing the suitability of soils for agricultural production. Consequently, the need for reliable soil information to support agricultural decision-making has never been more significant [15]. Knowledge of soils and their properties is indispensable for agricultural development; it opens opportunities for a more rational management of land resources [16]. A soil survey describes the characteristics of soils, classifies, maps, and makes predictions about their behaviour [17]. It involves grouping soils with respect to their spatial location, profile characteristics, and relationships to one another, suitability for various purposes and needs for types of management [18]. Soil suitability assessment is estimating the potential of agricultural soil for specific use [19,20]. It matches the soil's inherent characteristics with the optimal crop requirements [19]. As a result, it helps choose crops to be grown suitable to location-specific soil units for optimising crop productivity [21]. The objective of this work was to (i) describe the characteristics of the soils and (ii) assess their suitability in various schools for Beetroot production.

2. Materials and Methods

2.1. Site Description

The research was conducted at Madipoane, Mothimako, Phomolong and Klaas Mothapo Secondary Schools of Kgakotlou Circuit in Capricorn District, Polokwane municipality in the Limpopo province of South Africa (Figure 1). Capricorn district has a semi-arid climate, with the highest precipitation occurring during the summer months from October to March. The annual rainfall ranges from 600 mm to 800 mm [22]. Mean annual temperatures range from 6°c to 29°c. All the selected schools' gardens are relatively flat. The altitude in all the gardens ranges from 1221 m to 1349 (Table 1).
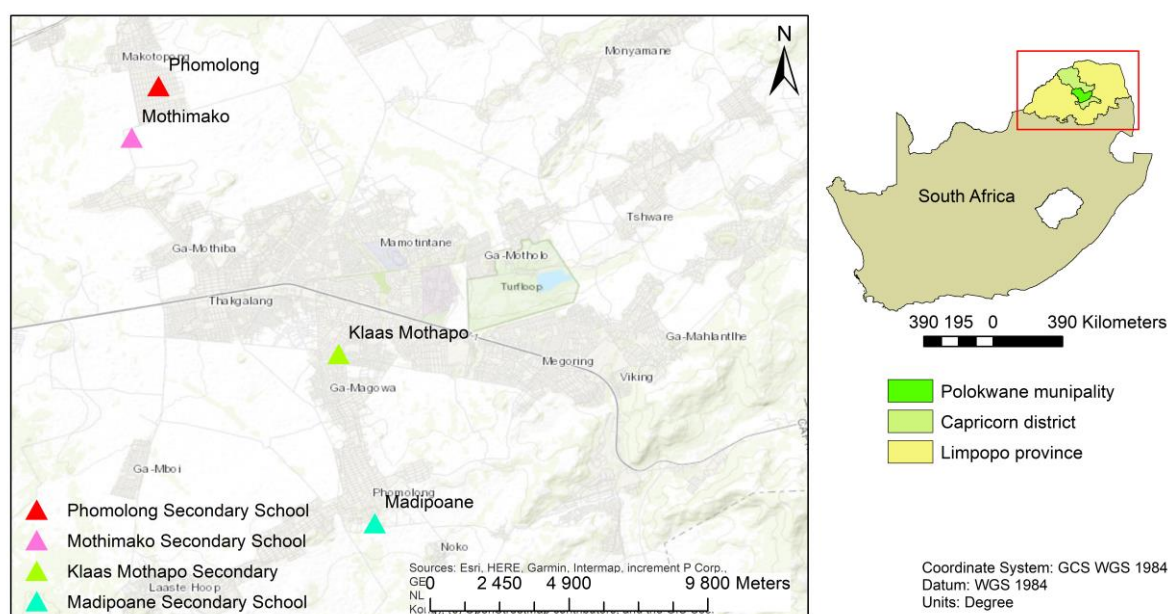

Figure 1. Location of Phomolong, Mothimako, Klaas Mothapo and Madipoane Secondary Schools of Kgakotlou circuit in Capricorn district, Limpopo province, South Africa.

Table 1. Geographical information of the schools in the Kgakotlou circuit and the garden extent.

Name of school	Longitude	Latitude	Altitude (m)	Slope	Garden extent (m²)
Klaas Mothapo	29°42'24.18"	23°54'01.37"	1349	Gentle	1671
Madipoane	29°43'4.9"	23°57'44.58"	1353	Gentle	750,4
Mothimako	29°38'19.76"	23°50'24.18"	1225	Gentle	3190
Phomolong	29°38'57.5"	23°49'24.7"	1221	Gentle/	946

2.2. Soil Survey and Classification

A detailed soil survey was conducted in each garden to study the soils [23]. Soil descriptions were based on the FAO guidelines [24]. In each garden, a profile pit (1.5 m wide x 1.5 m long, depth was defined to the limiting layer) was dug using a pick and a spade to aid soil classification. For each soil profile, the following soil attributes and site characteristics were collected: top, sub and total depth; effective rooting depth; colour of the A and B horizon; soil permeability; slope percentage; surface cover type (rock, boulder, stone, gravel and grit). The soils were classified using SA taxonomy (SAT) [25]. The soils were correlated with the World Reference Base for Soil Resources (WRB) [18] using [26].

Each profile pit was georeferenced using a portable handheld global positioning system (GPS) (Model Garmin 12 L). To assist soil mapping, the boundaries of each soil were established using an auger across the gardens and georeferenced using GPS.

2.3. Soil Sampling

Soil samples were collected from the dug profile pits. At each profile pit, soil samples were collected from the A horizon (top soil) and B horizon (sub soil) on three faces. Three soil samples were collected from each pit from the A horizon and three from the B horizon. In total, the soil profile had six samples for laboratory analysis. The samples were then labelled according to the school, profile pit number, and horizon and replicate number. From there, they were carefully handled and taken to the laboratory for preparation and analysis.

2.4. Soil Preparation and Analysis

Soil samples were air-dried, crushed and sieved before analysis. Particle size distribution of sand, silt and clay was determined using the hydrometer method [27]. Soil organic carbon (OC) was determined using the Walkley and Black method [28]. Soil boron (B), phosphorus (P), total nitrogen (N) and potassium (K) were determined using ICP-OES [29]. Soil pH H_2O in 1:2.5 suspension of soil and water was determined using the pH meter [29]. Soil EC was determined in 1:2.5 suspension of soil and water using an EC meter [29].

2.5. Land Suitability Assessment for Beetroot Production

We used the principles and concepts of the FAO Framework for Land Evaluation [19] and the FAO guidelines for land evaluation for rainfed agriculture [30] modified by [31] and [21] to assess the suitability of the soils for Beetroot production. Ten important soil parameters i.e. soil depth, soil texture, soil reaction (pH), soil organic carbon (SOC), EC, nitrogen (N), potassium (K), phosphorus (P), and Boron (B) for Beetroot growth and yielding [6,7] were used in the suitability assessment. Rainfall, temperature, and slope were homogenous across the schools and thus excluded from the evaluation. The soil suitability was determined for four suitability classes: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (NS) and suborder (indicating limitations) using the maximum limitation method [19,21,30,31].

2.6. Soil and Suitability Mapping

We used soil surveys and laboratory data to develop soil mapping units in the vegetable gardens. The units were spatially explicitly mapped by developing polygons utilising Google Earth

Pro (Google earth, 2024, Keyhole, Inc., Mountain View, CA, USA) and ArcGIS 10.8.1 (ESRI, Redlands, CA, USA) software following the method outlined by [32]. We adopted the procedure outlined by [32,33] to develop the suitability maps of the gardens for Beetroot production.

3. Results

3.1. Morphological Characteristics of the Soils

Morphological characteristics of the soils in vegetable gardens of Secondary Schools in the Kgakotlou circuit are shown in Table 2. Two soils were found at Klaas Mothapo Secondary School: Nkonkoni (Cambisol) and Glenrosa (Leptosol). An Orthic A horizon marks both soils. They are distinguishable by the subsoil soil horizon, with Nkonkoni as red apedal B/Lithic and Glenrosa as Lithic B. The presence of Lithic B makes Glenrosa a shallow soil, whereas Nkonkoni is a deeper soil. The colour varies from 2.5YR 3/3 dark reddish brown to 2.5YR 4/3 reddish brown on their topsoils. The subsoils have the same colour as dark reddish brown. The soils were well drained. The area covered by Glenrosa is 1103 m^2, while Nkonkoni is 568 m^2 out of the total vegetable garden area (1671 $m^{2)}$ (Figure 2a).

At Madipoane Secondary School, we found two soils (Tshiombo and Tubatse) covering the vegetable garden area. The soils are broadly known as Acrisols.   They are marked by an Orthic A horizon. Tshiombo was distinguished by Neocutanic B underlain by unspecified material showing signs of wetness in the subsoil. Whereas Tubatse was distinguished by Neocutanic B underlain by Lithic material. Both soils were deep. Tshiombo had a similar colour (5YR 5/6 Yellowish red) in the topsoil and subsoil. Tubatse was marked by a 2.5YR 3/3 dark reddish brown colour in the topsoil and 5YR 4/3 reddish brown in the subsoil. Out of the vegetable garden's total area (750.4 m^2), 672 m^2 and 78.4 m^2 was covered by Tshiombo and Tubatse respectively (Figure 2b).

We found only one soil type at Mothimako Secondary School. Hutton (Cambisol) soil was distinguishable by a red Orthic A horizon underlain by a red apedal B horizon. The top horizon of the soil was 7.7 cm, while the subsoil was 53 cm. Hutton soil covered 3190 m^2, the total area of the vegetable garden (Figure 2c).

We found two soils at Phomolong Secondary School, namely Glenrosa and Westleigh soil. Westleigh soil is chiefly known as Plinthosol, while Glenrosa is known as Leptosol. The two soils have the same Orthic A horizon. They are distinguished by the subsoil, with Glenrosa having a Lithic B and Westleigh having a soft plinthic B. The colour of Glenrosa was 5YR Reddish brown in the top soil and subsoil. Westleigh soil was marked by a 7.5YR 5/3 Brown colour. Westleigh and Glenrosa covered 368 m^2 and 578 m^2 respectively, with total area of the vegetable garden being 946 m^2 (Figure 2d).

Table 2. Morphological characteristics of the soils in varying schools.

School	Pit	SAT	Horizon	Thickness (cm)	Colour	WRB
Klaas Mothapo	1	Nkonkoni	Orthic A	14	2.5YR 3/3 Dark reddish brown	Cambisol
			Red apedal/Lithic	23	5YR 3/4 Dark reddish brown	
	2	Glenrosa	Orthic A	23	2.5YR 4/3 Reddish brown	Leptosol
			Lithic	21	2.5YR 3/3 Dark reddish brown	
Madipoane	1	Tshiombo	Orthic A	21	5YR 5/6 Yellowish red	Acrisol
			Neocutanic B/Unspecified material showing signs of wetness	21	5YR 5/6 Yellowish red	
	2	Tubatse	Orthic A	21	2.5YR 3/3 Dark reddish brown	Acrisol
			Neocutanic B/Lithic	51	5YR 4/3 Reddish brown	
Mothimako	1	Hutton	Orthic A	7.7	2.5YR 4/6 Red	Cambisol
			Red apedal B	53	2.5YR 4/8 Red	
Phomolong	1	Glenrosa	Orthic A	12	5YR 4/4 Reddish brown	Leptosol
			Lithic	17	5YR 4/4 Reddish brown	
	2	Westleigh	Orthic A	16	7.5YR 5/3 Brown	Plinthosol
			Soft plinthic B/Gleyic	20	7.5YR 5/3 Brown	

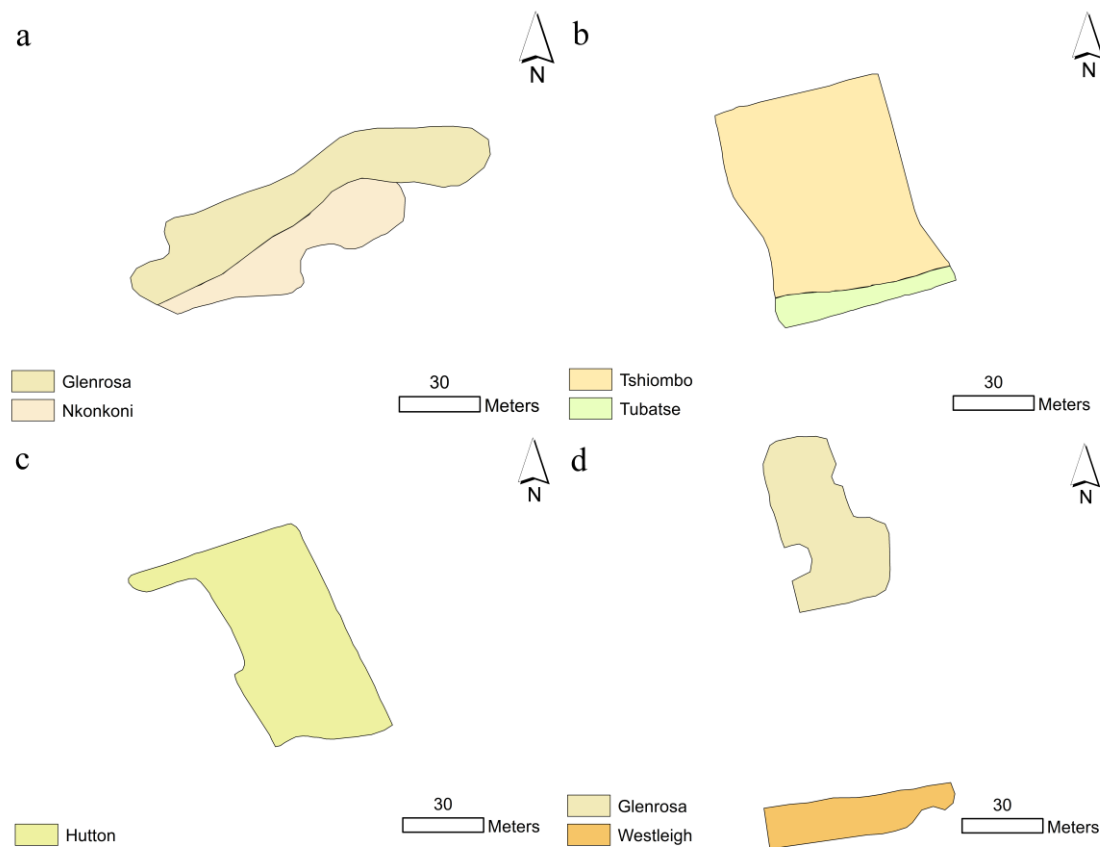SAT, South African Taxonomy; WRB, World Reference Base for Soil Resource.

Figure 2. Spatial distribution of soils at (a) Klaas Mothapo, (b) Madipoane, (c) Mothimako and (d) Phomolong Secondary School Garden.

3.2. Physical and Chemical Characteristics of the Soils

The chemical and physical characteristics of the soils are shown in Table 3. Almost all the soils had a pH above 7.0, indicating alkaline conditions, except for Westleigh soil at Phomolong Secondary School with a pH of 5.95. The EC content of the soils varied from 4.64 us/cm to 221.6 us/cm. The lowest EC content was observed at Phomolong under Westleigh soil, while the highest was at Mothimako in Hutton soil. The OC content of the soils varied from 0.05% to 0.81%. The lowest content was found in Nkonkoni and Glenrosa soil at KlaasMothapo and Phomolong Secondary School. The N content of the soils varied from 8.90 mg/kg to 25.97 mg/kg. Both soils at Phomolong had low N content. The highest N content was at Madipoane in Tshiombo soil, followed by Glenrosa at Klaas Mothapo. The K content of the soils ranged from 149 mg/kg to 351.33 mg/kg. The low P content was found in Tubatse soil at Madipoane while the highest was at Phomolong in Glenrosa soil. The K content of the soils ranged from 30.18 mg/kg to 94.57 mg/kg. There was a slight difference in the K content of soils except for Nkonkoni, Tshiombo, Westleigh and Glenrosa at Phomolong Secondary School. Boron content of the soils ranged from 245.33 mg/kg to 543.67 mg/kg. The highest B content was found at Phomolong under Glenrosa soil, while the lowest was found at Madipoane under Tubatse soil. Soil texture was slightly different. Except for Glenrosa soil with Sandy loam texture, the textures of the soils varied sand and loamy sand in all the schools.

Table 3. Chemical and physical characteristics of the soils.

School	Soil Type	pH (H₂O)	EC (us/cm)	OC (%)	N	P	K	B	Clay	Silt	Sand	Texture class
						…………(mg/kg)…………				…………...(%)………		
Klaas Mothapo	Nk	8.47	24.64	0.05	18.91	263	44	423	1.33	16.85	81.81	Loamy sand
	Gs	7.90	14.41	0.81	22.34	195.87	30.17	322.23	6.67	38.56	54.77	Sandy loam
Madipoane	Tsh	9.60	110.03	0.10	25.97	254.33	60.77	362.33	5.71	1.44	92.85	Sand
Mothimako	Tu	7.35	22.83	0.47	17.98	149	32.93	245.33	4.37	9.81	85.81	Loamy sand
	Hu	7.27	221.6	0.84	21.34	282.5	30.18	467.75	8.29	10.62	81.09	Loamy sand
Phomolong	Gs	8.75	134.97	0.05	9.76	351.33	94.57	543.67	8	2.4	89.6	Sand
	We	5.95	4.64	0.55	8.90	326.67	74.63	466	9.55	2.29	88.16	Loamy sand

Nk, Nkonkoni; Gs, Glenrosa; Tsh, Tshiombo; Tu, Tubatse; Hu, Hutton; We, Westleigh; EC, Electrical conductivity; OC, Organic carbon; N, nitrogen; P, Phosphorus; K, Potassium; B, Boron.

3.3. Soil Suitability Classification for Beetroot Production

Soil suitability assessment revealed varied suitability classes for Beetroot production in the Kgakotlou (Figure 3). At Klaas Mothapo Secondary School, the portion of the vegetable garden underlain by Glenrosa soil was not suitable (NS) for Beetroot production (Figure 3a). A shallow depth, and high EC and pH limited the soil. In the same school, the portion belonging to Nkonkoni soil was marginally suitable (S3), limited by high pH and EC. Similarly, the garden at Madipoane Secondary School was marginally suitable under Hutton (S3) (Figure 3a). All the soils in the school were limited by a high pH and EC (Figure 3b). The vegetable garden area at Mothimako Secondary School was moderately suitable (S2) for Beetroot production, limited by a slightly high pH (Figure 3c). The portion of the Phomolong Secondary School Garden was unsuitable (NS) for beetroot production limited by a shallow depth, high pH and EC (Figure 3d). On the other side of the school, there was a moderately suitable (S2) portion for Beetroot production limited by a low pH (Figure 3c).
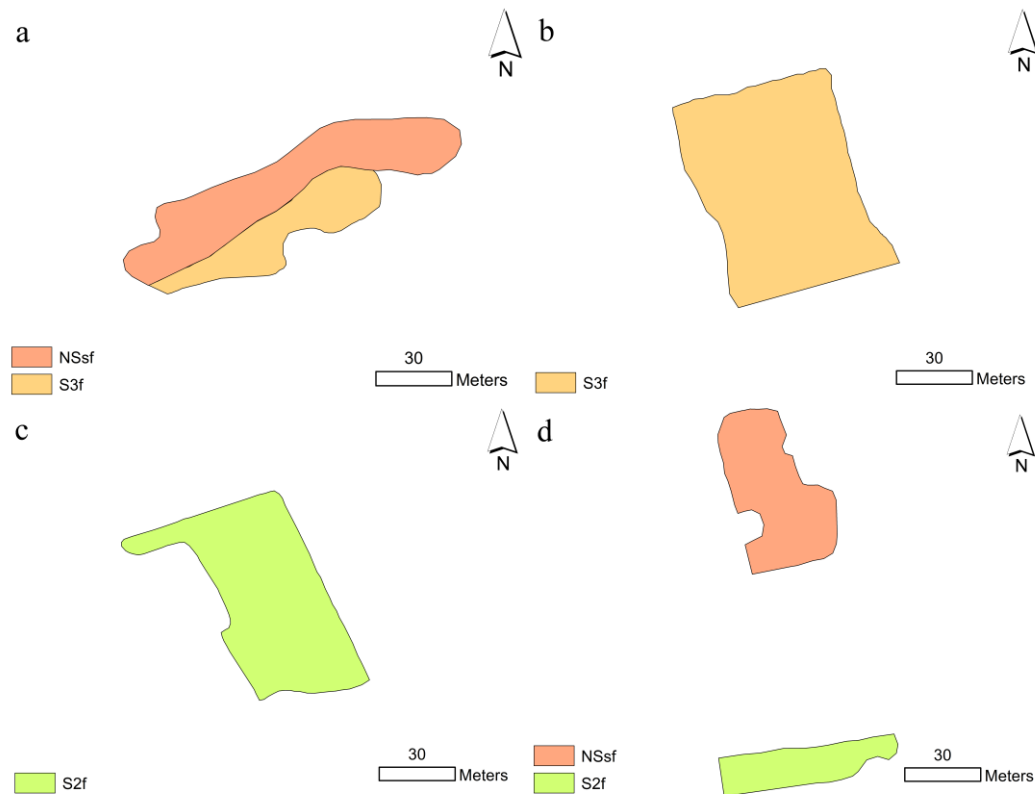
Figure 3. Soil suitability for Beetroot production at (a) Klaas Mothapo, (b) Madipoane, (c) Mothimako and Phomolong Secondary School Garden. The limiting factors are indicated by s and f alongside the suitability class. Where s shows limiting factors imposed by soil physical properties such depth and clay. f shows limiting factors introduced by soil fertility, such organic carbon, electrical conductivity and pH.

4. Discussion

We generally found moderate, marginal and unsuitable soils for Beetroot production in the Kgakotlou circuit schools. Hutton soil occupying the total vegetable garden area at Mothimako was moderately suitable (S2) for beetroot production. Likewise, Westleigh soil which was occupying 39% at Phomolong was moderately suitable (S2). At Klass Mothapo Secondary School, 34% on Nkonkoni was marginally suitable, while 66% under Glenrosa soil was not suitable for beetroot production. Like Nkonkoni soil at Klaas Mothapo, all the soils (Tshiombo and Tubatse) at Madipoane Secondary School were marginally suitable for beetroot production. Glenrosa soil at Phomolong occupying 61% of the vegetable garden area was not suitable for beetroot production.

The limitations associated with Glenrosa (Leptosol) soil at Klaas Mothapo and Phomolong include a shallow depth, pH and EC. Soil depth determines rooting, moisture and nutrient storage, mineral reserve, anchorage, and various plant growth conditions [34]. Glenrosa soil has a restrictive limiting layer (Lithic B) that impedes water and air movement through the soil or restricts roots or otherwise provides an unfavorable root environment [35]. The roots of the plant will remain confined to a small volume of soil that cannot provide adequate anchorage, water and nutrients [35,36]. Nutrient and water absorption capacity of the restricted roots is also low. Shallow soils cannot store enough water to support the plants, and the soils are droughty in the dry season [36]. Glenrosa soils have excessive internal drainage naturally (in our case it is evident by low clay and OC contents) which can cause drought despite the soil receiving sufficient water either from rain or irrigation [35]. The Glenrosa soils are at a low stage of weathering and development, and most of the ions are held in the form of primary minerals [37]. Subsequently, they have low exchangeable cations and exchangeable capacity to sustain crop production. As such, Beetroot grown on this soil will suffer from a lack of water and nutrients, and restricted root growth will affect the anchorage of the crop.

All the soils in this study, their suitability was affected by EC. Soil salinity is simply the salt content in the soil. The significant limitations of salt-affected soils include their low osmotic potential due to the high soluble salt contents and low contents of micronutrients such as Fe, Mn, Zn, Cu and B, which is vital for Beetroot [6,38]. A continuous osmotic phase inhibits water uptake by plants due to osmotic pressure of saline soil solution lowering its potential energy; and a slower ionic phase when the accumulation of specific ions in the plant over a period leads to ion toxicity or ion imbalance [38].

Westleigh soil suitability was limited by a low pH, indicating acidic conditions. Soil acidity affects emergence, survival, root growth, and microbial growth [39]. Under acidic conditions, aluminium and manganese become more soluble and toxic in most soils, and deficiencies of essential plant nutrients such as P, Ca, K, Mg, and Mo occur [39]. Increased solubility of toxic metals (Al and Mn) in soil restricts the plant's access to water and nutrients, thereby causing severe injury to roots, a reduction in crop yield, and an increase in plant susceptibility to pathogens.

A soft plinthic material characterises Westleigh soil in the subsoil. Soft plinthite is dense and obstructs deep percolation of water and penetration of plant roots [35]. Even though plinthite is initially formed below the soil surface and remains soft, it is often exposed to the surface through erosion. It hardens irreversibility to iron pan making the land quite unusable for agriculture [40,41]. In addition to the limitation imposed by salinity on Tshiombo and Tubatse. These soils naturally have poor chemical properties. Levels of plant nutrients are low, and aluminium toxicity and P-sorption have substantial limitations [35].

5. Conclusions

This study was undertaken to describe the characteristics of the soils and assess their suitability for Beetroot production in various schools in the Kgakotlou circuit. We found that Klaas Mothapo Secondary School Garden was characterised by Nkonkoni and Glenrosa soil. Tshiombo and Tubatse soils were found at Madipoane Secondary School. Mothimako Secondary School Garden was marked by Hutton soil. At Phomolong Secondary School we found Glenrosa and Westleigh soils. The soils in the study were mostly loamy sand, with some having sandy loam and sand texture. The soils varied highly in terms of their chemical properties.

Soil suitability assessment revealed that Hutton soil occupying the total vegetable garden area at Mothimako was moderately suitable (S2) for beetroot production. Likewise, Westleigh soil which was occupying 39% at Phomolong was moderately suitable (S2). At Klaas Mothapo Secondary School, 34% on Nkonkoni was marginally suitable, while 66% under Glenrosa soil was not suitable for beetroot pro-duction. Like Nkonkoni soil at Klaas Mothapo, all the soils (Tshiombo and Tubatse) at Madipoane Secondary School were marginally suitable for beetroot production. Glenrosa soil at Phomolong occupying 61% of the garden was not suitable for beetroot production. The major limitations in this work were soil depth, EC and pH.

The areas occupied by Glenrosa at Klaas Mothapo and Phomolong Secondary School should not be used for cultivation of Beetroot. Application of lime should be done on soil Westleigh to increase the soil suitability for Beetroot, while on the other soils gypsum should be applied. The EC can be managed through adequate irrigation, leaching and draining.

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