

Article

# Tillage, Crop Rotation and Crop Residue Management Effects on Nutrient Availability in a Sweet Sorghum-Based Cropping System in Marginal Soils of South Africa

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**Abstract:** The low soil fertility status of South African marginal soils threatens sustainable production of biofuel feedstock in smallholder farmers. It is therefore imperative to development sustainable and optimal management practices that improve soil fertility. The objective of this study was to determine the effect of tillage, rotation and crop residue management on nutrient availability in a bioenergy sweet sorghum-based cropping system in marginal soils. Two tillage levels, no-till (NT) and conventional tillage (CT); two crop rotations, sweet sorghum–grazing vetch–sweet sorghum (SVS) and sweet sorghum–fallow–sweet sorghum (SFS); and three crop residue retention levels, 0%, 15% and 30%, were tested. No-till enhanced total nitrogen, total organic nitrogen (TON), magnesium (Mg) and sodium (Na) by 3.19% to 45% compared to CT. SVS rotation increased ammonium (NH<sub>4</sub><sup>+</sup>-N) and nitrate (NO<sub>3</sub><sup>-</sup>-N) by 3.42% to 5.98% compared to SFS. A 30% crop residue retention increased NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, available phosphorus (Available P), cation exchange capacity (CEC), calcium (Ca), Mg and potassium (K) by 3.58% to 31.94% compared to crop residue removal. In the short term, a 30% crop residue retention was the main treatment that enhanced soil fertility. The application of NT–30% was a better practice to enhance soil fertility. However, research on inclusion of crop diversity/intercropping can add more value to the NT–30% practice in enhancing soil fertility.

Keywords: soil nitrogen; cation exchange capacity; extractable bases; fertility; conservation agriculture

#### 1. Introduction

The production of crops in African smallholder farming areas is affected by an inherent low soil fertility status [1–4] and low fertilizer application [5–7]; this is in addition to soil degradation, erosion and drought. Soil fertility is defined as the capacity of soil to supply essential nutrients to crops and is a major concern for agriculturalists [8]. Thus, the identification and recommendation of techniques that are both environmentally friendly and produce acceptable crop yields in a sustainable and profitable manner is important for crop production in Africa in order to meet the current increase in demand for food, fibre and fuel in the continent. Sustainable farming preserves soil quality, environment and water bodies, which ensures the production of good quality food for both humans and animals [9]. Management practices are the major drivers of sustainable farming because they can modify soil quality



through improvements in soil physical, chemical and hydrological properties [10]. Thus, agricultural practices that conserve natural resources without compromising yields and depend less on inorganic fertilizer are at the centre of sustainable agriculture.

Conservation agriculture (CA) built on minimum soil disturbance, crop rotation and crop residue retention as soil cover, is recommended as a technique for sustainable crop production that concurrently conserves soil and water resources while reducing input costs [11–15]. The application of no-till (NT) combined with crop rotation and crop residue retention enhances soil quality by reducing the physical breakdown of soil aggregates, protecting the soil against rain drops as well as enhancing the infiltration rate, nutrient cycling and soil organic carbon (SOC), which improves other soil properties while reducing soil erosion [13–15]. In addition, CA has a higher energy-use efficiency compared to conventional tillage (CT) [16]. The increase in SOC and aggregate stability after the implementation of CA are important in regulating water and gas movement, nutrient cycling and general soil behaviour [17]. Adoption of CA was reported to increase soil fertility and nutrient availability [15,18–20]. Consequently, nitrogen (N), phosphorus (P) and potassium (K) generally increase in the surface under CA compared to CT treatment [15,21–24].

The effect of CA on other exchangeable bases like magnesium (Mg), sodium (Na) and calcium (Ca) is not consistent in the literature. Their increase in the topsoil [10,25,26] and no significant difference [21,27] were all reported after adoption of CA. This is because the change in soil fertility due to tillage is site-specific and rests on the cropping systems, soil type, fertilizer management, other agronomic practices and climate [10]. In addition, the effect of CA on soil productivity is also site-specific and it depends on the cropping systems, additional agronomic management [12,28–30] and crop residue quality [31].

Just like around the world, the use of marginal soils in South Africa is vital for bioenergy crop production, as outlined in the Biofuels Industrial Strategy of the Republic of South Africa [32]. This is because the use of arable soils to expand the production of bioenergy crops will lead into the use of less arable soils for food production, thus threatening food security [33,34]. The strategy mainly targets smallholder farmers with the aim to alleviate poverty [32]. Smallholder farmers are important in stimulating the rural economy and food security [35]. The strategy targets bioenergy crops such as sweet sorghum (Sorghum bicolor (L.) Moench), which is currently considered a leading bioenergy feedstock because it is adapted to marginal soils, uses less inputs and can yield higher bioethanol than most second-generation crops [36]. Sweet sorghum is ideal for dryland production because it requires less water and is tolerant to drought [37]. However, the inherent low fertility status in smallholder farmers' soils in South Africa, and the general inability to afford inorganic fertilizers [5,7], are major constraints for biomass production. Apart from the low fertility status, marginal soils are mainly dominated by low soil organic carbon (SOC), unstable and hardsetting soils, a low infiltration rate and water holding capacity as well as being highly erodible [33,38–40]. Resource-poor people mainly own marginal soils in South Africa and these soils constitute the largest proportion of underutilised soils in the country [41]. Thus, restoring marginal soils will not only expand the production of bioenergy crops, but it will also serve as a poverty alleviation strategy.

Conservation agriculture can serve as a suitable production system for conserving soil and enhancing soil fertility in South Africa under smallholder farming systems [12]. However, the effect of CA on soil fertility under biofuel feedstock production, like sweet sorghum, is still lacking, and not only in South Africa, but worldwide [36]. Most of the currently available literature on the benefits of CA in South Africa is mainly in maize production system under arable soils [42]. The benefits of CA are site specific and vary with crops [10,12]; thus, evidence from maize production system under arable soil cannot be extrapolated to bioenergy sweet sorghum under marginal soils. Arable soils have a higher SOC content than marginal soils [36]. The SOC content influences nutrient availability [5]. It was, therefore, deemed important that this study be carried out in soils with low SOC to ease extrapolation of the experimental findings. In addition, there is no clear agreement in the literature about the impact of CA on marginal soils, especially those with low fertility and hardsetting soils. According to the FAO [43], marginal soils with hardsetting properties may not be immediately suitable for CA implimentation while other authors have demonstrated the short-term benefits of CA on soil quality in hardsetting soils [44]. It has also been reported that hardsetting can be alleviated by increasing the SOC content, which in turn can be increased by crop residue retention [12]. However, there is paucity of information on the effects of sorghum residue retention on both soil fertility and biomass yield, especially in marginal soils. These inconsistencies in the literature highlight the need for more research on CA in marginal soils. The objective of this study was to determine the effect of tillage, rotation and crop residue management on nutrient availability as an indicator of soil fertility under a bioenergy sweet sorghum-based cropping system in marginal soils of South Africa. Our hypothesis was that the three components of CA combined will improve the soil conditions of low fertility hardsetting soils, thus increasing the nutrient availability in the topsoil in the short term.

#### 2. Materials and Methods

#### 2.1. Site Description and Experimental Design

#### 2.1.1. Study Site Description

The study was conducted at the University of Fort Hare experimental farm (latitude  $32^{\circ}46'$  S and longitude  $26^{\circ}50'$  E). Climatic conditions at the location is semi-arid and relatively mild, with a mean annual rainfall of about 575 mm, which is mainly received in summer, from October to April [44]. The main soil form at the farm is of alluvial origin, classified as Haplic Cambisol [45]. Soils in this region have an inherent low fertility status and farmers apply inadequate nutrient inputs [5]. In addition, soils from this region are known to be hardsetting with unstable aggregates [46]. Available P was at 71.87 mg kg<sup>-1</sup>, CEC at 13.86 cmol (+) kg<sup>-1</sup> and total N at 460 mg kg<sup>-1</sup> before establishment of the experiment. Some of the experimental site characteristics are listed in Table 1.

Parameters	Units	Values
Sand	%	60.0
Silt	%	18.0
Clay	%	22.0
Texture	-	Sandy clay loam
pH (H <sub>2</sub> O)	-	6.98
Soil organic carbon (SOC)	$ m g  kg^{-1}$	11.5
Electrical conductivity	$mS m^{-1}$	62

Table 1. Some of the experimental site characteristics in the top 0.1 m soil depth (Source: [47]).

## 2.1.2. Treatments and Experimental Design

The experiment was initiated in October 2016 and terminated at the end of March 2019. A randomised complete block designed with a  $2 \times 2 \times 3$  split-split-plot treatment structure and three replications were used. The main plot was allocated to tillage at two levels (no-tillage (NT) and conventional tillage (CT)). The sub-plots were allocated to crop rotations with two levels (sweet sorghum–grazing vetch–sweet sorghum (SVS) and sweet sorghum–fallow–sweet sorghum (SFS)). Sub-sub-plots were allocated to crop residue retention at three levels, 0%, 15% and 30%, based on total harvested fresh biomass. Twelve treatment combinations were established. The main plots measured 12.8 m  $\times$  17 m, the sub-plots were 5.4 m  $\times$  5 m.

# 2.1.3. Management of Non-Experimental Variables

Before establishment the whole experimental field was ploughed with a mouldboard plough and harrowed to make a fine tilth. The 2016/2017 growing season was regarded as year zero and regenerated an average of 45-ton ha<sup>-1</sup> biomass yield, which was used to apply the first sweet sorghum residues retention levels. Thereafter, the CT plots were ploughed to a depth of 30 cm once at the beginning of each season, in April for winter planting and October for summer planting, using a tractor-drawn disk plough and then harrowed to make a fine tilth. In summer, sweet sorghum was planted in all the plots at 55,000 plants ha<sup>-1</sup>. Basal fertilizer was applied in all plots at planting at 300 kg ha<sup>-1</sup> of 2:3:4(30), while 400 kg ha<sup>-1</sup> of limestone ammonium nitrate fertilizer was applied as top dressing at 6 weeks after planting [48]. During the winter season, grazing vetch cover crop (*Vicia dasycarpa* cv. Max) was planted in the allocated plots at recommended seed rates of 35 kg ha<sup>-1</sup>. Basal fertiliser for the cover crop was applied as a compound at planting, at 10 kg P ha<sup>-1</sup> (6.7% N; 10% P; 13.3% K). The *Rhizobium leguminosarum* biovar viciae was used to inoculate the grazing vetch at planting. Glyphosate (N-(phosphono-methyl) glycine, 360 g L<sup>-1</sup>) was applied (5 L ha<sup>-1</sup>) to terminate the cover crop before it developed seeds at the end of the winter season. Cylam 50EC (Lambda-cyhalothrin (pyrethroid), 50 g L<sup>-1</sup>) was used to control pests in the sweet sorghum crop. Weeds were controlled by hand hoeing in all plots whenever it was necessary.

#### 2.2. Soil Sampling

In order to measure the effect of the treatments on nutrient availability after 3 years, soil samples were collected after harvesting the sweet sorghum in March 2019. Three random samples collected at a 0.1 m depth in each experimental plot were mixed into one composite sample. Visible plant residues and roots were removed from the composite sample. Composite samples were air-dried and passed through a 2 mm sieve before analysis.

#### 2.3. Analysis

#### 2.3.1. Electrical Conductivity and pH

Soil electrical conductivity (EC) and soil pH were measured in a 1:25 soil:water ratio using EC and pH electrode meters, respectively [49].

#### 2.3.2. Total N and Inorganic N

Total N was measured by dry combustion (Carlo Erba NA 1500 Elemental Analyzer). Inorganic N, ammonium ( $NH_4^+$ -N) and nitrate ( $NO_3^-$ -N) were extracted with 1 M KCl and determined with the colorimetric method using a continuous flow analyser [50]. Total organic N (TON) was calculated as the difference between the total N and inorganic N.

#### 2.3.3. Available P

Available P was determined using P-Bray1 [51]. The P concentration in the extracts was determined using a continuous flow analyser.

### 2.3.4. Cation Exchange Capacity (CEC) and Extractable Bases

The CEC and exchangeable bases, calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na), were determined by the ammonium acetate method [52].

#### 2.3.5. Statistical Analysis

Analysis of variance (ANOVA) was performed using JMP<sup>®</sup> 14. Mean separations were done using the least significant difference method at  $p \le 0.05$ .

#### 3. Results

Table 2 shows the effect of tillage, rotation, crop residue management and their interaction on the measured variables. Crop residue management was the main factor of management practice to influence most of the measured variables.

**Table 2.** Analysis of variance (ANOVA) results of electrical conductivity (EC), pH, total nitrogen, total organic nitrogen (TON), ammonium ( $NH_4^+$ -N), nitrate ( $NO_3^-$ -N), available phosphorus (available P), cation exchange capacity (CEC), calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) as influenced by tillage, rotation, crop residue management and their interaction.

	EC	pН	Total N	TON	NH4 <sup>+</sup> -N	NO <sub>3</sub> N	Available P	CEC	Ca	Mg	К	Na
Till.	0.080	0.330	< 0.0001	< 0.0001	0.132	0.054	0.399	0.191	0.366	0.029	0.088	0.008
Rot.	0.371	0.112	0.945	0.980	0.004	0.033	0.886	0.340	0.111	0.317	0.300	0.147
Res. man.	0.490	0.901	0.273	0.371	< 0.0001	< 0.0001	0.008	< 0.0001	0.0004	0.0002	0.018	0.325
Till. $\times$ Rot.	0.155	0.531	0.227	0.227	0.790	0.686	0.567	0.301	0.595	0.751	0.221	0.092
Till. $\times$ Res. Man.	0.652	0.301	0.824	0.824	0.047	0.911	0.625	0.752	0.748	0.466	0.042	0.549
Rot. $\times$ Res. Man.	0.611	0.391	0.703	0.713	0.331	0.277	0.406	0.816	0.923	0.373	0.505	0.463
Till. $\times$ Rot. $\times$ Res. Man	0.702	0.901	0.541	0.540	0.680	0.526	0.216	0.6785	0.903	0.933	0.209	0.413

Till.: tillage; Rot.: Rotation; Res. Man.: crop residue management.

#### 3.1. pH and Electrical Conductivity (EC)

Tillage, crop rotation, crop residue management and their interactions had no effects on pH and EC (p > 0.05) (Table 2). The soils from all the experimental plots were slightly acidic, with the pH values ranging from 6.44 to 6.55 (Table 3), whilst the EC ranged from 143.81 to 167.79 µS cm<sup>-1</sup> (Table 3).

**Table 3.** Mean separation results of electrical conductivity (EC), pH, total nitrogen, total organic nitrogen (TON), ammonium ( $NH_4^+$ -N), nitrate ( $NO_3^-$ -N) and available phosphorus (available P) as influenced by tillage, rotation, crop residue management and the tillage × crop residue interaction.

Treatment	рН	EC (μS cm <sup>-1</sup> )	Total N (mg kg <sup>−1</sup> )	TON (mg kg <sup>-1</sup> )	NH4 <sup>+</sup> -N (mg kg <sup>-1</sup> )	NO3 <sup>-</sup> -N (mg kg <sup>-1</sup> )	Available P (mg kg <sup>-1</sup> )
Tillage							
NT	6.46 <sup>a</sup>	167.79 <sup>a</sup>	1064.56 <sup>a</sup>	1037.25 <sup>a</sup>	12.29 <sup>a</sup>	15.01 <sup>a</sup>	66.48 <sup>a</sup>
СТ	6.53 <sup>a</sup>	143.81 <sup>a</sup>	918.89 <sup>b</sup>	892.56 <sup>b</sup>	12.08 <sup>a</sup>	14.24 <sup>a</sup>	65.12 <sup>a</sup>
	NS	NS	p < 0.001	p < 0.001	NS	NS	NS
Rotation							
SVS	6.44 <sup>a</sup>	161.72 <sup>a</sup>	992.61 <sup>a</sup>	965.16 <sup>a</sup>	12.39 <sup>a</sup>	15.05 <sup>a</sup>	65.92 <sup>a</sup>
SFS	6.55 <sup>a</sup>	149.87 <sup>a</sup>	990.83 <sup>a</sup>	964.65 <sup>a</sup>	11.98 <sup>b</sup>	14.20 <sup>b</sup>	65.69 <sup>a</sup>
	NS	NS	NS	NS	p < 0.01	p < 0.05	NS
Crop residue management							
0%	6.50 <sup>a</sup>	147.53 <sup>a</sup>	972.33 <sup>a</sup>	948.23 <sup>a</sup>	11.14 <sup>c</sup>	12.96 <sup>b</sup>	63.03 <sup>b</sup>
15%	6.51 <sup>a</sup>	153.30 <sup>a</sup>	982.83 <sup>a</sup>	956.94 <sup>a</sup>	12.08 <sup>b</sup>	13.80 <sup>b</sup>	64.84 <sup>b</sup>
30%	6.47 <sup>a</sup>	166.56 <sup>a</sup>	1020.00 <sup>a</sup>	989.55 <sup>a</sup>	13.34 <sup>a</sup>	17.10 <sup>a</sup>	69.53 <sup>a</sup>
	NS	NS	NS	NS	p < 0.001	p < 0.001	p < 0.01
Tillage × crop residue interaction							
NT-30%	6.39 <sup>a</sup>	153.12 <sup>a</sup>	1053.70 <sup>a</sup>	1022.80 <sup>a</sup>	13.47 <sup>a</sup>	17.43 <sup>a</sup>	70.38 <sup>a</sup>
CT-30%	6.50 <sup>a</sup>	141.95 <sup>a</sup>	936.83 <sup>a</sup>	906.84 <sup>a</sup>	13.21 <sup>a</sup>	16.78 <sup>a</sup>	68.68 <sup>a</sup>
NT-15%	6.48 <sup>a</sup>	163.55 <sup>a</sup>	1036.83 <sup>a</sup>	1010.32 <sup>a</sup>	12.38 <sup>b</sup>	14.13 <sup>a</sup>	66.38 <sup>a</sup>
CT-15%	6.47 <sup>a</sup>	143.05 <sup>a</sup>	911.83 <sup>a</sup>	886.57 <sup>a</sup>	11.78 <sup>bc</sup>	13.48 <sup>a</sup>	63.30 <sup>a</sup>
CT-0%	6.61 <sup>a</sup>	146.42 <sup>a</sup>	908.00 <sup>a</sup>	884.27 <sup>a</sup>	11.26 <sup>cd</sup>	12.47 <sup>a</sup>	63.38 <sup>a</sup>
NT-0%	6.51 <sup>a</sup>	186.70 <sup>a</sup>	1031.67 <sup>a</sup>	1007.19 <sup>a</sup>	11.02 <sup>d</sup>	13.46 <sup>a</sup>	62.69 <sup>a</sup>
	NS	NS	NS	NS	p < 0.05	NS	NS

NS: no significant difference; NT: no-till; CT: conventional tillage; SVS: sweet sorghum–grazing vetch–sweet sorghum; SFS: sweet sorghum–fallow–sweet sorghum. Different letters in the same column show significant variation among treatments.

#### 3.2. Total, Organic and Inorganic (Ammonium ( $NH_4^+$ -N) and Nitrate ( $NO_3^-$ -N)) Nitrogen

Total and organic N were highly and significantly (p < 0.001) affected by tillage (Table 2). The application of NT increased both total N and TON compared to CT (Table 3). Total N and TON were 15.85% and 16.21% higher in the NT compared to CT treatment, respectively. The tillage × crop residue management interaction significantly (p < 0.05) influenced NH<sub>4</sub><sup>+</sup>-N (Table 2). In addition, NH<sub>4</sub><sup>+</sup>-N was highly and significantly influenced by crop rotation (p < 0.01) and crop residue management (p < 0.001) (Table 2). Irrespective of tillage practice, the application of 30% crop residue retention resulted in the highest NH<sub>4</sub><sup>+</sup>-N (Table 3). NH<sub>4</sub><sup>+</sup>-N was 19.63% higher in NT–30% compared to CT–0%, which is regarded as common practice in conventional farming. It is also important to note that under NT, an increase in crop residue retention from 0 to 15% resulted in a significant increase in N, which further increased at 30%, whereas under CT, meaningful increases in N were only observed at the highest crop residue level (Table 3). SVS had significantly higher NH<sub>4</sub><sup>+</sup>-N compared to the SFS treatment (Table 3). NH<sub>4</sub><sup>+</sup>-N compared to crop residue retention significantly higher NH<sub>4</sub><sup>+</sup>-N was 3.42% higher in the SVS than the SFS treatment. The increase in crop residue retention significantly higher NH<sub>4</sub><sup>+</sup>-N compared to the SFS treatment (Table 3). NH<sub>4</sub><sup>+</sup>-N was 3.42% higher in the SVS than the SFS treatment. The increase in crop residue retention significantly increased NH<sub>4</sub><sup>+</sup>-N compared to crop residue removal (Table 3). The 30% crop residue retention significantly increased NH<sub>4</sub><sup>+</sup>-N compared to crop residue removal, while NH<sub>4</sub><sup>+</sup>-N was

8.44% higher in 15% crop residue retention compared to crop residue removal.  $NH_4^+$ -N was 10.43% higher in 30% crop residue retention compared to 15% crop residue retention.

The amount of  $NO_3^-$ -N was influenced by crop rotation (p < 0.05) and crop residue management (p < 0.001) (Table 2). SVS increased  $NO_3^-$ -N by 5.98% compared to SFS (Table 3), whilst the application of 30% crop residue retention significantly increased  $NO_3^-$ -N compared to 15% crop residue retention and crop residue removal (Table 3). A 30% crop residue retention had 31.94% higher  $NO_3^-$ -N compared to crop residue removal.

#### 3.3. P-Bray1 (Available P)

Available P was highly and significantly (p < 0.01) influenced by crop residue management (Table 2). Available P was statistically higher under 30% crop residue retention compared to both 15% crop residue retention and crop residue removal (Table 3). The application of 30% crop residue retention had 10.31% higher available P compared to the crop residue removal treatment.

#### 3.4. Cation Exchange Capacity (CEC) and Extractable Bases

Crop residue management highly and significantly (p < 0.001) influenced CEC and Ca (Table 2), which increased with an increase in crop residue retention (Table 4). A 30% crop residue retention had 11.30% and 27.32% higher CEC compared to 15% crop residue retention and crop residue removal, respectively. Ca was 2.12% and 3.58% higher in 30% crop residue retention than in 15% crop residue retention and crop residue removal, separately.

Treatment	CEC (cmol (+) kg <sup>-1</sup> )	Ca (cmol (+) kg <sup>-1</sup> )	Mg (cmol (+) kg <sup>-1</sup> )	K (cmol (+) kg <sup>-1</sup> )	Na (cmol (+) kg <sup>-1</sup> )
Tillage					
NT	13.36 <sup>a</sup>	7.12 <sup>a</sup>	2.91 <sup>a</sup>	0.34 <sup>a</sup>	0.29 <sup>a</sup>
CT	12.91 <sup>a</sup>	7.08 <sup>a</sup>	2.82 <sup>b</sup>	0.31 <sup>a</sup>	0.20 <sup>b</sup>
	NS	NS	p < 0.05	NS	p < 0.01
Rotation					
SVS	13.30 <sup>a</sup>	7.13 <sup>a</sup>	2.85 <sup>a</sup>	0.32 <sup>a</sup>	0.22 <sup>a</sup>
SFS	12.97 <sup>a</sup>	7.06 <sup>a</sup>	2.88 <sup>a</sup>	0.33 <sup>a</sup>	0.27 <sup>a</sup>
	NS	NS	NS	NS	NS
Crop residue management					
0%	11.53 <sup>c</sup>	6.98 <sup>c</sup>	2.78 <sup>b</sup>	0.30 <sup>b</sup>	0.28 <sup>a</sup>
15%	13.19 <sup>b</sup>	7.08 <sup>b</sup>	2.81 <sup>b</sup>	0.33 <sup>b</sup>	0.23 <sup>a</sup>
30%	14.68 <sup>a</sup>	7.23 <sup>a</sup>	3.01 <sup>a</sup>	0.35 <sup>a</sup>	0.23 <sup>a</sup>
	p < 0.001	p < 0.001	p < 0.01	p < 0.05	NS
Tillage × crop residue interaction					
NT-30%	15.06 <sup>a</sup>	7.27 <sup>a</sup>	3.08 <sup>a</sup>	0.38 <sup>a</sup>	0.26 <sup>a</sup>
CT-15%	13.13 <sup>a</sup>	7.07 <sup>a</sup>	2.77 <sup>a</sup>	0.33 <sup>ab</sup>	0.19 <sup>a</sup>
NT-15%	13.26 <sup>a</sup>	7.10 <sup>a</sup>	2.85 <sup>a</sup>	0.32 <sup>ab</sup>	0.26 <sup>a</sup>
CT-30%	14.31 <sup>a</sup>	7.18 <sup>a</sup>	2.93 <sup>a</sup>	0.31 <sup>ab</sup>	0.20 <sup>a</sup>
NT-0%	11.76 <sup>a</sup>	6.98 <sup>a</sup>	2.80 <sup>a</sup>	0.30 <sup>b</sup>	0.35 <sup>a</sup>
CT-0%	11.30 <sup>a</sup>	6.97 <sup>a</sup>	2.77 <sup>a</sup>	0.29 <sup>b</sup>	0.21 <sup>a</sup>
	NS	NS	NS	p < 0.05	NS

**Table 4.** Mean separation results of cation exchange capacity (CEC), calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) as influenced by tillage, rotation, crop residue management and the tillage  $\times$  crop residue interaction.

NT: no-till; CT: conventional tillage; SVS: sweet sorghum–grazing vetch–sweet sorghum; SFS: sweet sorghum–fallow–sweet sorghum. Different letters in the same column show significant variation among treatments.

Magnesium (Mg) was significantly influenced by tillage (p < 0.05) and crop residue management (p < 0.001) (Table 2). Mg was higher in both NT compared to CT and 30% crop residue retention compared to 15% crop residue retention and crop residue removal (Table 4). In this study, NT had 3.19% higher Mg compared to the CT treatment while 30% crop residue retention had 8.27% higher Mg compared to crop residue removal.

The tillage × crop residue management interaction significantly (p < 0.05) influenced K (Table 2). NT–30% had significantly higher K than NT–0% and CT–0% (Table 4). Compared to CT–0%, NT–30% had 30.72% higher K. Crop residue management also significantly (p < 0.05) influenced K (Table 2). A 30% crop residue retention had statistically higher K than crop residue removal (Table 4). K was 16.67% higher in 30% crop residue retention compared to crop residue removal. Tillage highly and significantly (p < 0.01) influenced Na (Table 2). NT had higher Na compared to the CT treatment (Table 4). Na was 45% higher in the NT compared to the CT treatment.

#### 4. Discussion

The enhancement and conservation of soil fertility in marginal soils of South Africa is vital for farm productivity among smallholder farmers [5]. Soil fertility is a consequence of the soil chemical, physical and biological properties that work together to offer nutrients, aeration, water and stability for plant growth [53]. The effect of tillage, rotation, crop residue management and their interaction on EC, pH, total N, TON,  $NH_4^+$ -N,  $NO_3^-$ -N, available P, CEC, calcium Ca, Mg, K and Na were studied. The results of this study are of importance to the low-input smallholder farmers in marginal soil areas, and who are the main target for biofuel feedstock production in South Africa. Thus, the present findings confirm the benefits of CA in enhancing soil nutrient availability.

The results from this study suggest that tillage, crop rotation and crop residue retention of up to 30% of fresh bioenergy sweet sorghum biomass may not affect soil acidity in the topsoil of marginal soils in the short term. Previous studies completed in similar soil conditions also found no significant difference in pH and EC after implementation of a NT and crop residue retention treatment compared to CT and crop residue removal treatment [54–56]. Despite no significant difference, pH was lower under NT treatment, supporting previous studies [10,55]. The lower pH in NT might be due to accumulation of SOM under NT and soil with crop residue, increasing the number of electrolytes then decreasing pH [10]. In this study, both the pH and EC were within the ideal range for optimum soil productivity and plant growth—a pH of 5.5 to 7.0 and EC of less than 2000 µS/cm [10,57,58].

Total organic nitrogen formed up to 97% of the total N, which will later be available to plants through mineralization [59]. The increase in total N under the NT compared to CT treatment was previously reported [15,60–63], which is thus supported by this study. The increase in total N in NT is generally due to the absence of soil disturbance and to crop residue retention, which increases the SOM and microbial activity linked to nitrogen fixation [24,62–64]. Crop residue retention of up to 30% of sweet sorghum fresh biomass and crop rotation had no statistically significant effect on total N in the short term, which contradicts findings of previous research [15,65,66]. The lack of a significant increase in total N in this study after crop residue retention might be because of the short study duration. The importance of duration was demonstrated by Li et al. [64], who found an increase in total N from the fifth year of their 11-year study. This is because the increase in total N depends on the crop residue retention duration [59,64]. In addition, the difference in findings in this study compared to previous studies might be due to the different crop residue retention loads and low biomass in crop rotation due to dry spells, which were experienced during the study. Moreover, the change in soil properties after implementation of CA is influenced by initial SOC and climate conditions [67], and such changes are slow in soils with low SOC in arid and semi-arid conditions [68]. The findings suggest that marginal soils under bioenergy sweet sorghum will require more crop residue retention and/or a longer implementation period before a meaningful increase in the amount of total N can be observed.

Available N (NH<sub>4</sub><sup>+</sup>-N; NO<sub>3</sub><sup>-</sup>-N) was significantly enhanced by crop residue retention, rotation and NT with crop residue retention. The increase in available N was previously reported due to crop residue retention and rotation [55,69,70]. NT with crop residue retention was also reported to increase inorganic N [55]. A 30% crop residue retention was found to enhance NH<sub>4</sub><sup>+</sup>-N better, regardless of the tillage system (Table 3). In this study, the increase in crop residue retention resulted in a direct increment in the amount of NH<sub>4</sub><sup>+</sup>-N, while a 30% crop residue retention was required to improve NO<sub>3</sub><sup>-</sup>-N. This demonstrate that NH<sub>4</sub><sup>+</sup>-N is more sensitive to changes in the amount of crop residue retention than NO<sub>3</sub><sup>-</sup>-N in marginal soils. The increase in available N is mainly due to the build-up of organic material in systems with crop residue retention [56,71].

Crop residue retention was the main component of the treatments to enhance CEC and available P, Mg, K and Ca in this short-term study. The increase in available P, CEC [69,72,73], Mg, K and Ca after crop residue retention was previously reported [74–76]. Crop residue retention enhances available P by decreasing the adsorption of P to mineral surfaces [56]. The enhancement in available Mg and K was also reported under NT with crop residue retention compared to the CT treatment [55,63,76], which is supported by this study. The increase in CEC and availability of P, Mg, K and Ca is due to the increase in SOM after crop residue retention [69,73,74,77]. This study suggests that CEC and Ca are also more sensitive to changes in crop residue retention than available P, Mg and K in marginal soils. Availability of Na was higher under NT than in CT, supporting previous studies [78]. The results from this study demonstrate that crop residue retention is a vital source for soil nutrient cycling [79], even under soils with low SOC [55,56]. The study also concurs with Mupambwa and Wakindiki [44], who reported that CA enhances soil properties under hardsetting soils, even in the short term.

#### 5. Conclusions

Results from this short-term study demonstrated that crop residue retention is critical in improving the soil fertility status in soils with low natural fertility, such as those in some parts of the Eastern Cape province of South Africa, in the short term. The application of crop residue retention as high as 30% of the bioenergy sweet sorghum fresh biomass was found to be ideal in improving soil fertility in South African marginal soils in the short term. In addition, the application of NT with 30% crop residue retention can enhance soil fertility in South Africa in areas with below average winter rainfall. More research on the implementation of crop diversity/intercropping under NT with 30% crop residue retention during summer rainy seasons are needed in order to enhance the soil fertility status in South African marginal soils.

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