Short-term effects of sunn hemp intercropping management in a maize-based system on the soil fertility of a Plinthic Cambisol in Free State, South Africa

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Research Article

Keywords: Soil fertility, Intercropping, Living mulch, In-field rainwater harvesting

Posted Date: February 6th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2483730/v1

Abstract

Intercropping is a promising strategy of improving soil fertility in no-till rainwater harvesting practices. However, the effect of intercropping forage legumes at various planting times and densities on soil fertility response under the in-field rainwater harvesting (IRWH) technique remains unknown in South Africa. The objective of this study was to determine the seasonal effect of sunn hemp (*Crotalaria juncea* L.) intercropping at different planting periods and densities into maize (*Zea mays* L.) after two growing seasons on selected soil fertility of a *Plinthic Cambisol* in Free State, South Africa. The experiment was a randomized complete block design with a factorial combination replicated thrice. The factorial combination consisted of three sunn hemp plantings dates viz., at maize planting, planting at V15 maize growth stage, and R1 maize growth stage, and three sunn hemp planting densities viz., 16.1 plants m^{-2}, 32.1 plants m^{-2}, and 48.1 plants m^{-2}. The results showed that the interaction of sunn hemp planting date and density was significant ($p < 0.05$) on soil organic matter (SOM) and Zinc (Zn). The growing season had a significant impact on changes in SOM, nitrogen (N), potassium (K), calcium (Ca), sodium (Na), manganese (Mn), and iron (Fe). Due to the intercropping periods and planting densities, the retention of sunn hemp residues with varying quantities and qualities may have influenced the soil nutrient dynamics in the short-term. Significant changes in soil fertility may take longer, and future research should be carried out in agricultural regions with different soil mineral matrices.

Introduction

Intercropping maize (*Zea mays* L.) with a subordinate companion crop for soil cover in the early, mid, or late growing season is a management practice known as live mulching (Liedgens et al. 2004; Sigdel et al. 2021). It is a sustainable climate-smart strategy for diversifying monocropping systems and improving agroecosystem services. Intercropping legumes with cereal food crops to improve soil health in rainfed smallholder and subsistence farming systems is gaining popularity (Tsubo et al. 2003; Cong et al. 2015; Garland et al. 2017). Several studies have been conducted to evaluate the feasibility of intercropping grain legumes like pigeon pea (*Cajanus cajan*), groundnuts (*Arachis hypogea*), cowpea (*Vigna unguiculata*), and beans (*Phaseolus vulgaris*) in maize-dominated cropping systems to improve food security (Mucheru-Muna et al. 2010). Other researchers have investigated forage legume, grass, and brassica intercropping to increase the quality and quantity of biomass production for livestock feed and residual soil fertility (Hassen et al. 2017; Javanmard et al. 2020; Kutamahufa et al. 2022). On the other hand, the latter is given low priority because living mulch growth is managed until vegetative, then terminated due to concerns that it will reduce dominant crop yield. Because subsistence farmers' primary goal is to increase harvestable grains, the scientific basis for intercropping for agroecosystem benefits is unknown. For example, grain legumes such as cowpea are commonly used in semiarid environments due to their adaptability and low fertility requirements, and nodulation can improve soil nitrogen (Jeranyama et al. 2000; Li et al. 2007). Sunn hemp (*Crotalaria juncea*) has the same adaptability characteristics as cowpea (Jeranyama et al. 2000). Still, few quantitative studies have been conducted to evaluate or optimize its intercropping for soil fertility improvement.

The advantages of intercropping include the provision of essential ecosystem services such as soil erosion and nutrient losses reduction, increased nutrient use efficiency, addition of soil N through N_2 symbiotic fixation with legume cover crops, and improved soil quality (Garland et al. 2017; Javanmard et al. 2020; Sigdel et al. 2021; Kutamahufa et al. 2022). Legume subordinate crops are most often selected for preventing N losses and for biological nitrogen (N_2) fixation, which may reduce N inputs required for the subsequent crop, such as maize (Jeranyama et al. 2000; Hartwig & Ammon 2002; Li et al. 2007; Liang et al. 2014). Legumes have the potential to fix nitrogen, a portion of which will be available for high-nitrogen-requiring crops such as maize (Jeranyama et al. 2000: Mucheru-Muna et al. 2010). In areas where excess nitrogen is already a problem, the use of ground covers may provide a sink to tie up some of this excess nitrogen and hold it until the next growing season, when a crop that can make use of the N might be planted (Hooda et al. 1998). These possibilities provide the incentive for looking at the effect of various crop species on soil erosion, nitrogen budgets, weed control, nutrient availability and other pest management and environmental problems (Hartwig & Ammon 2002). However, there is a need to evaluate the intercropping of leguminous subordinate crops on soil properties under rainwater harvesting.

In-field rainwater harvesting (IRWH) is a widely used adaptation technique to rainfall variability and fluctuations among South African smallholder farming homesteads for conserving soil moisture and extending crop water availability (Bothma et al. 2012; Botha et al. 2015). The technique is recommended for use on shallow duplex clay soils, particularly those with sloping topographies in semiarid areas (Hensley et al. 2000). This is because in-field rainwater harvesting is ineffective on coarse-textured soils with high hydraulic conductivity (Rockström 2000). Crop residue retention is not only one of the IRWH technique requirements for the mulching component, but it also has a significant impact on nutrient availability (Michael et al. 2021), in addition to improving soil structure, texture, and reducing hydraulic conductivity (Lampurlanés Castel and Cantero-Martínez 2006). In South Africa, farmers in arid and semiarid areas have arable lands with poor texture soils that retain little water. Therefore, organic mulch application becomes a priority for soil water retention while improving texture, structure, and nutrient availability. Moreover, the South African smallholder farming system is crop-livestock integrated (Dzvene et al. 2021), and the current management consists of continuous crop residue removal due to livestock feeding (Vanlauwe et al. 2014, Dzvene et al. 2019). Therefore, there is a need to evaluate the intercropping of forage legumes to increase biomass production, offset the effects of carbon (C) removal, and improve soil biochemical properties. Several studies have highlighted the positive impacts of IRWH on physical soil properties such as soil moisture (Dunkerley 2002, Al-Seekh and Mohammad 2009; Botha et al. 2015), bulk density and aggregate stability (Shreshtha et al. 2007). In these studies, mulching played an essential role in enhancing the soil's physical properties under IRWH.

There are contrasting reports on the effect of IRWH on soil fertility properties. A study by Singh et al. (2012) investigated the impact of rainwater harvesting combined with afforestation on soil properties, tree growth and restoration of degraded hills. After five years, there was an increase in soil pH, soil organic carbon, electric conductivity, ammonium nitrogen (NH_4^+), nitrate (NO_3^-N) and extractable phosphate (PO_4-P) down the slope of their study sites (Singh et al. 2012). The increases in these soil properties after five years were not attributed to rainwater harvesting but rather to a mass movement of material from the upper to lower slope. This resulted in the accumulation of salts and nutrients transported along with water from upper to lower slope positions (Singh et al. 2012). Similarly, Yong et al (2006) also observed similar trends of a nutrient accumulation from the upper slope to the lower slope due to the positive effects of IRWH, as it enabled soil water retention and nutrient mobilization that enhanced vegetation cover as the turnover of roots and litter. Another study by Liu et al. (2009) in semiarid China where mulching coupled with no-till practice was used as rainwater harvesting, observed an increase in soil organic carbon by 2.7% compared with the conventional tillage practice where a maize crop was planted. Al-Seekh and Mohammad (2009) reported a 5% increase in SOC because of harvesting rainwater on runoff, sediments and soil properties. A more recent study by Mduduzi (2017) in KwaZulu Natal and Eastern Cape provinces of South Africa observed no clear trend in the effect of IRWH on exchangeable bases, soil pH and micronutrients across all study sites. A short-term study by Posthumus and Stroosnijder (2010) showed no significant impact of rainwater harvesting on soil fertility. A rigorous review shows that the benefits of IRWH on crop yield increases and improved soil fertility can be realized when the technique is used in conjunction with soil conservation techniques such as living mulching with cover crops, minimum and zero tillage (no-till).

Intercropping with a legume in a cereal-based system is critical to achieving the benefits of improved dominant crop yield and enhanced soil health. Legume intercropping can provide significant benefits through improvements of nutrient and water cycling efficiency, enhanced climate regulation, wildlife habitat and increased aesthetic, educational and recreational value opportunities (Franzluebbers et al. 2014). Many changes associated with soil properties under perennial crops are driven mainly by limited soil disturbance and increased organic matter inputs from roots and rhizodeposits compared to annual crops (Franzluebbers 2015). The main critical aspects of intercropping management are the selection of crop species and establishing an appropriate intercropping time (Sigdel et al. 2021). Berti et al. (2017) noted a 14% and 10% reduction in corn and soybean yields in response to intercropping camelina at V1-V3 of corn and V1-V2 of soybean growth stages, respectively. The choice of subordinate crop species may largely depend on the desired benefit and cost. Promoting a balance of favourable nutrient conditions and preventing competition for resources between the dominant crop and the intercropping subordinate crop species selected for live mulching is important. It is, therefore, essential to integrate sustainable and optimal practices under IRWH that will ensure improved soil moisture and soil health concurrently to ultimately achieve higher crop yield of arable land in the arid and semiarid regions of South Africa. This study's rationale for intercropping sunn hemp an annual crop species, by varying its planting times and densities, was to optimize its productivity for improving dominant crop yield. We hypothesized that optimal sunn hemp intercropping period and planting density management in a maize-based system would benefit the soil fertility properties of the *Plinthic Cambisol* in central Free State, South Africa. The objective of this study was to determine the seasonal effect of sunn hemp (*Crotalaria juncea* L.) intercropping at different planting periods (P) and densities (D) into maize (*Zea mays* L.) on selected soil fertility after two growing seasons.

Materials And Methods

Site description

The sunn hemp intercropping experiment was conducted at Kenilworth Experimental Farm (29°01'S, 26°09'E, 1354 m) near Bloemfontein (Kenilworth, Bainsvlei ecotope), Free State province, South Africa, during 2019/20 and 2020/21 summer growing seasons. The soil at the site is classified as Bainsvlei form (Soil Classification Working Group 2018), similar to Chromic Stagnic Plinthic Cambisol (WRB soil groups 2014). The experimental site is located in a semiarid agro-ecological zone with well-drained, red-brown soils with less than 1% topsoil organic matter with a very deep profile (> 2000 mm), sandy-loam soils with a soft plinthic B2 horizon (Soil Classification Working Group 2018). The soil had a clay, sand, and silt fraction of 8.5%, 85%, and 7%, respectively, at the start of the experiment (Table 1). The soil of the experimental site is also characterized as moderately acidic, with an average 0–30 cm depth of pH of 5.2, NH_4-N concentrations of 10.3 mg kg^{-1}, NO_3-N concentrations of 11.2 mg kg^{-1}, and available phosphorous concentrations of 7 mg kg^{-1} in the upper 300 mm horizons. The mean exchangeable base values for sodium, potassium, calcium, and magnesium were 22, 142, 336, and 100 mg kg^{-1}, respectively. The region receives 528 mm annual rainfall (± 155.6 mm), and annual mean minimum and maximum temperatures are 11.0°C and 25.5°C, respectively, with monthly standard deviations of ± 0.8–2.0°C and ± 1.2–3.1°C. The main rainy season lasts from October to April, with some rain falling during May, August and September.

Table 1
Soil physical and chemical properties at the experimental site at the beginning of the study.

Chemical properties		**Diagnostic Horizons**				
(0.00 -0.30 m) (mg kg^{-1})		**Depth (cm)**	**Color**	**Clay (%)**	**BD (gcm^{-3})**	**pH (KCl)**
NH_4-N	10.3	0.00-0.35	Red Brown	8.5	1.66	5.2
NO_3-N	11.2	0.35–1.18	Red Brown	14	1.68	5.1
P (Bray 1)	7.0	0.35–1.18	Brown	14	1.66	6.3
Na	22	1.18–1.80	Yellow orange	24	1.67	6.5
K	142	1.80-3.00	Yellow orange	24	1.68	6.6
Ca	336					
Mg	100					

Field management and experimental design

The experimental field was not used and has been a weedy fallow since June 2009. For this study, agronomic field activities were completed timeously before and during the maize growing season, which began during the previous summer in December 2018 with the establishment of in-field rainwater harvesting (IRWH) technique plots. The land was conventionally prepared with a ripper, mould plough, and disc, and a single sheer mouldboard plough with a basin implement was used to construct the basins in an E-W direction with an N-S slope. The runoff strips in the plots were manually raked to smooth the topsoil. The IRWH plots were established with a 2:1 basin to runoff strip (Tesfuhuney 2015). The subsequent tillage was minimized; no-till for maize sowing was planted in tramlines (1.1 m wide) adopted from previous IRWH techniques in the Free State, South Africa (Van Rensburg et al. 2012). The no-till runoff zone was used for intercropping sunn hemp. Planting of experimental treatments, including sole maize (SM), sole sunn hemp (SSH), and P1 sunn hemp, took place on 3 December, 2019, and 23 November, 2020 for the respective 2019/20 and 2020/21 growing seasons. The P1 and SSH treatments managed to grow for the entire growing season and therefore reached maturity and produced seeds for sustainability in subsistence farming systems. P2 sunn hemp treatments were planted on 16 January, 2020, and 8 January, 2021, for each growing season. In each growing season, the P2 sunn hemp treatments were terminated on 16 April, 2020 and 7 April, 2021. On 7 February 2020, and 1 February 2021, P3 treatment planting took place in each growing season.

Crops were planted at relatively high densities and thinned to the required densities two weeks after emergence. Rainfed maize fertilizer applications were based on a potential yield of 5000 kg ha^{-1} as determined by the Fertilizer Society of South Africa (FSSA 2007). Maize (cv. Pioneer P2432R) and sunn hemp (cv. local) was fertilized with 200 kg ha^{-1} 2:3:2 (22) NPK equivalent of 13 kg N ha^{-1}, 19 kg P ha^{-1}, and 13 kg K ha^{-1}). No topdressing was applied on the sunn hemp cover crop. To meet the N requirements, a top dressing of 250 kg ha^{-1} LAN (28% N, i.e., 70 kg ha^{-1} N) was split and applied to maize plots 4 and 7 weeks after emergence. Weeds were manually controlled throughout the season and spotted maize beetles (Astylus atromaculatus) at maize reproductive stage were controlled with Dursban 480 EC as needed. Crop harvesting was done by hand, and maize and sunn hemp stover was left in the field

A 3 × 3 factorial combination was used in a randomized complete block design with three replicates. The first factor was the planting period of sunn hemp intercrop. The standard maize developmental stage system was used to identify the vegetative stage (from seedling emergence VE to physiological maturity PM) (Ritchie et al. 1993). The planting period factor was at three-time levels: simultaneously with maize planting (P1), V15 maize growth stage (P2), and R1 maize growth stage (P3). The second factor was the sunn hemp plant density, which was evaluated at three levels: 16.1 plants m^{-2} (D1-low), 32.1 plants m^{-2} (D2-medium), and 48.1 plants m^{-2} (D3-high) to determine the optimum for intercropping. Sole maize and sole sunn hemp were included, whereas sole sunn hemp was also planted at the respective three plant densities only at P1 with intercrop maize densities fixed at 4 m^{-2}. The sunn hemp in both intercrop and sole was planted in five rows with a 30 cm row spacing in the runoff strip of the IRWH technique. In the sole sunn hemp treatment, there were no plants in the place where the maize was usually planted on the sides of the basin area. The main plots were 180 m^2 (12m width 15m length), and the subplots were 60 m^2 (12m width 5m length). The intercrop components were sown in an additive series in both seasons (Connolly et al. 2001). The schematic illustrations of the intercropping of sunn hemp at various plant densities under the IRWH technique are depicted in Fig. 1.

Soil sampling and analysis

From the experimental plot, three random samples were collected from A horizon in 1 m^2 area up 30 cm depth using a 5 cm corer for the basin and the runoff sections in each IRWH plot. The collected soil samples were homogenized to form a composite sample, representing the specific treatment for a particular sampling block. The samples were air dried, passed through 2 mm sieve after which they were stored for laboratory analysis. The samples were collected annually at the end of the growing season after harvesting maize and sunn hemp in both the 2019/2020 and 2020/2021 to take into account the impact of intercropping treatments' on soil organic matter decomposition and soil fertility. The soil samples were analysed following standard methods, i.e., soil pH was measured with a pH meter in a 1:2.5 (v/v) soil:water suspension as outlined in Agri Laboratory Association of Southern Africa (AgriLASA 2004). Exchangeable cations (K, Ca, Mg and Na), micronutrients (Cu, Mn, Zn, and Fe), and plant available phosphorus (P) in soil samples were extracted using a modified Ambic 2 procedure (Thompson 1995) and determined with an Inductively Coupled Plasma Emission Spectrograph (ICP-OES) (Varian 710-ES). Total nitrogen (N) was determined in the air-dried soil samples by dry combustion using the LECO (Truspec-CNS analyser) (LECO 2003). Soil organic matter (SOM) was determined using loss on ignition (LOI) as outlined by Okalebo et al. (2002).

Statistical analysis

The data were analyzed using SAS JMP® Pro 14 statistical software (SAS Institute Inc., Cary, NC). A three-way factorial analysis of variance (ANOVA) was performed for soil fertility parameters between the growing seasons, with planting period (P), plant density (D), and growing season (S) as variables. If significant, posthoc tests using the least significant difference at $p \leq 0.05$ tested for differences between means. Simple linear Pearson's correlation regression analysis of measured soil parameters was done at 95% confidence interval and prediction limits.

Results And Discussion

Table 2 shows the analysis of variance (ANOVA) results for the intercropping effect of sunn hemp into maize at different planting periods (P) and plant densities (D) during the two experimental growing seasons (S) on the measured soil fertility variables. The ANOVA results show that the growing season was the main factor influencing the sunn hemp intercropping effects on most of the measured variables (Table 2).

Table 2
Analysis of variance (ANOVA) results for the effect of sunn hemp intercropping period (P) and plant density (D) during the two growing seasons (S) on soil fertility properties of the *Plinthic Cambisol* in Free State, South Africa

Treatments	**pH**	**SOM**	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**Cu**	**Mn**	**Zn**	**Fe**
S	ns	***	**	ns	***	**	ns	***	ns	***	ns	***
P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
D	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
P x D	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
S x D	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
S x P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
S x P x D	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns

*, **, ***, ns Significant at $p < 0.05$; 0.01; 0.001; non-significant probability level respectively; ns indicates non-significant difference. S- growing season, P- planting period, D- plant density

Soil pH, SOM and macronutrients (N, P, K, Ca, Mg)

Sunn hemp intercropping at various maize growing stages and planting densities had no effect on pH between the growing seasons (Table 2). This is consistent with Kutamahufa et al. (2022) claim that the accumulation of different pools of organic matter during the early years of establishing interactive cropping systems is usually too low to affect fundamental soil chemical properties like pH. All the experimental plots' soils were acidic, with pH values ranging from 4.54 to 4.99. This pH range is not considered ideal for optimal nutrient availability for most crops, including maize (Kutamahufa et al. 2022). However, the pH of the soil in the experimental plots with sunn hemp residue retention increased from 4.66 in 2019/2020 growing season to 4.77 in the 2020/2021 growing season (Table 3). This observation may indicate the positive effects of using a legume in enhancing the soil's biochemical properties (Gura et al. 2022). At the end of the first season, planting sunn hemp at a density of 48.1 plants m^{-2} (D3) significantly enhanced soil pH (Fig. 1), further confirming legumes' positive effects on soil biochemical properties. After two seasons of treatment application, it should be noted that soil pH values were lower compared to their initial status, consistent with the acidifying effect of no-till adoption (Turmel et al. 2014) under the IRWH technique in this study. The increased acidity under no-till adoption is attributed to the more significant SOM accumulation from the decomposition of residues (Franzluebbers and Hons 1996). However, some additional acidifications could also be attributed to the nitrification effect of fertilizer N that was applied at the beginning of the trial.

Table 3
Growing season effect of sunn hemp intercropping period (P) and plant density (D) on soil fertility properties of the *Plinthic Cambisol*

	pH$_{CaCl}$	**SOM**	**N**	**P**	**Ca**	**Mg**	**K**	**Na**	**Cu**	**Fe**	**Mn**	**Zn**
Growing Season (S)		%		mg/kg								
2019/20 (S1)	4.66	0.214b	0.0124b	16.53	325.2a	104.9	178.3b	5.55a	1.05	65.23a	13.86b	1.83
2020/21 (S2)	4.77	0.299a	0.0153a	17.07	286.8b	107.9	225.6a	3.80b	0.80	36.64b	22.26a	1.04
P value	ns	***	*	ns	**	ns	***	***	ns	***	***	ns
CV (%)	5.28	20.51	31.90	26.30	15.12	17.63	20.12	29.11	59.82	12.40	38.91	55.04

*, **, ***, ns Significant at $p < 0.05$; 0.01; 0.001; non-significant probability level respectively; ns indicates non-significant difference.

Sunn hemp intercropping management had no significant effect ($p > 0.05$) on soil pH, SOM, N, P, Ca and Mg concentrations in the experimental plots between the growing seasons (Table 2). The non-significant effect of planting period and density associated with soil pH, SOM and macro-nutrients may be due to the short-term nature of the study. These observations suggest that soil fertility properties changes may require a longer time for subtle changes to be observed due to intercropping. Regarding the interaction effects, only the impact of planting period and density on SOM contents were significant (Table 2). The impact of the planting period of the sunn hemp seems to have a more substantial influence on the SOM accumulation, as shown by significantly different SOM contents. The outcome was more visible when sunn hemp was planted together with maize (P1) and when sunn hemp was planted at the R1 maize growth stage (P3) at a constant planting density of 16.1 plants m^{-2} (Table 4). Sunn hemp managed with P1 was allowed to mature, and at maturity, sunn hemp has a high biomass quantity of fibre content, which slows mineralization and results in a high SOM value. However, the short growing season and competition from maize hampered the growth of the P3 sunn hemp treatment, resulting in low biomass quantity. Between the seasons, early planting of sunn hemp probably resulted in higher biomass yield of the sunn hemp residues, which yielded significantly higher SOM contents. The significant SOM increase due to higher sunn hemp biomass demonstrates that crop mixtures can build resilient agricultural cropping systems by enhancing SOM stocks (Poeplau and Don 2015; Thapa et al. 2022).

Table 4
Sunn hemp intercropping period (P) and plant density (D) interaction effect on SOM and extractable Zn of the *Plinthic Cambisol*

Interaction	**SOM**			**Zn**		
	%			**mg/kg**		
	Planting density (D)					
Planting period (P)	1	2	3	1	2	3
1	0.294a	0.243ab	0.248ab	0.92b	1.07b	0.96b
2	0.261ab	0.278ab	0.224b	1.03b	4.74a	1.11b
3	0.222b	0.260ab	0.278ab	0.96b	1.01b	1.14b
P-value	0.050*			0.038*		
CV (%)	19.94			121.67		

*, **, *** Significant at $p < 0.05$; 0.01 and 0.001 probability level respectively; ns indicates non-significant difference. P1: simultaneous sunn hemp and maize planting; P2: sunn hemp planted at the V15 maize growth stage; P3: sunn hemp planted at R1 maize growth stage. ; D1-low: 16.1 plants m^{-2}; D2-medium: 32.1 plants m^{-2}; D3-high: 48.1 plants m^{-2}

When the data for the second season was analyzed separately, the interaction effect of planting period and sunn hemp density was significant soil N. The results showed that soil N's sunn hemp density was significant during the second and third planting periods (Fig. 3). During the second planting period, a higher planting density of sunn hemp seems to put more pressure on soil N than a lower density. This result can be explained by the interaction of quality and quantity of the retained sunn hemp biomass residue (Cong et al. 2015). P2 was terminated at flowering, resulting in high-quality residues faster at decomposition than P1, which was terminated at maturity. However, at the third planting period, a higher density of sunn hemp seems to have enhanced more soil N, probably due to more N being fixed by the *Rhizobia* into the soil. Sunn hemp intercropping also increased soil N through legume root excretion and leaf leachates. These observations confirm the complexity of field studies due to multiple variations and interactions that interfere with treatment applications.

When the growing seasons were compared, significant differences were noted in SOM, N, K and Ca concentrations across the two growing seasons (Table 3). Only Mg was not significantly different across the two growing seasons. Soil organic matter increased significantly from 0.214% in 2019/2020 to 0.299% in 2020/2021, while N and K increased significantly from 0.0124% and 178.3mg/kg in 2019/2020 to 0.0153% and 225.6mg/kg in 2020/2021 (Table 3). In contrast, Ca decreased significantly from 325.2 mg/kg in 2019/2020 to 286.8mg/kg in 2020/2021. A remarkable increase of SOM across the two seasons highlights the positive effects of no-till systems in conjunction with crop residue retention under IRWH. In conjunction with residue retention, several field studies have shown that no-till systems result in a more significant accumulation of SOM matter in the surface layers (Goverts et al. 2007). The significant increases noted with N and K across the two growing seasons were most probably associated with the decomposition of the sunn hemp residues that were retained on the soil surface. The residues of sunn hemp have a lower C:N ratio (Reicosky et al. 1995), which can be easily decomposed, returning a significant amount of nutrients in the soil, contributing to sustainable soil fertility management (Gura et al. 2022). Generally, crop residues with slow decomposition rates maintain a surface cover mulch over an extended period, which helps reduce weed pressure and conserve soil and water more effectively (Thapa et al. 2022).

In contrast, crop species such as sunn hemp with higher decomposition rates release nutrients, especially N, quickly and help to meet all or part of the N requirements of the subsequent crops (Poffenbarger et al. 2015; Thapa et al. 2018; 2022). Moreover, in the long-term, due to their faster decomposition rates, sunn hemp residues will stabilize greater proportions of residue-derived C and N into soil organic matter due to greater microbial efficiency, thereby enhancing agricultural sustainability (Cotrufo et al. 2013). The non-significant effect of residues associated with P and Mg may also indicate that some nutrients may require a longer time to be affected, depending on the management system employed (Govaerts et al. 2007). Overall, after two seasons of treatment application, P, K and Mg increased whereas Ca decreased. A decrease associated with Ca may be due to higher net removal of Ca by the growing maize and sun hemp crops and lack of sufficient replenishments through decomposition of crop residues.

Micronutrients (Na, Cu, Mn, Zn, Fe)

Sunn hemp intercropping at various maize growing stages and planting densities had no effect on most of the micronutrients across the growing seasons ($p > 0.05$) except Zn (Table 2). Extractable Zn was the most affected soil fertility property by the management of sunn hemp. Across the two seasons, significantly higher Zn accumulated when sunn hemp was planted at the V15 maize growth stage (P2) (Fig. 4). Furthermore, the interaction of the planting period with both the plant density and season was significant on the extractable Zn (Table 2). Planting sunn hemp at V15 maize growth stage with a plant density of 32.1 plants m^{-2} registered significantly higher Zn contents than other combinations across the two seasons (Table 4). Higher Zn concentrations were recorded at the end of the first season (S1) when sunn hemp was planted at early maize vegetative growth (P2) (Fig. 5). The combination of all the treatment factors shows that planting sunn hemp at V15 maize growth stage with a planting density of 32.1 plants m^{-2} during the first season resulted in significantly higher Zn contents (Table 5). These significant observations on extractable Zn seem to have been triggered by the planting of the sunn hemp at V15 maize growth stage (P2). Significantly higher concentrations of Fe were registered across different sunn hemp density treatments at the end of the first season compared to the second season (Fig. 6). This may be due to nutrient harvest, which significantly decreased the amount of Fe at the end of the second season. This observation was also confirmed when the data for the first season was separately analyzed.

Table 5
Sunn hemp intercropping growing season (S), planting period (P) and plant density (D) interaction effect on extractable Zn (mg/kg) of the *Plinthic Cambisol*

Interaction	**Growing season (S)**					
	1			**2**		
	Planting period (P)					
Plant density (D)	1	2	3	1	2	3
1	0.80b	1.10b	0.89b	1.05b	1.05b	1.02b
2	1.06b	8.35a	0.93b	1.02b	1.13b	1.09b
3	1.05b	1.24b	1.07b	0.83b	0.97b	1.21b
P-value		0.029*			ns	
CV (%)		133.28			19.63	

*, **, *** Significant at $p < 0.05$; 0.01 and 0.001 probability level respectively; ns indicates non-significant difference.

The results confirmed the significant effect of higher cover crop densities on net Fe removal due to crop harvest (Fig. 7). The concentrations of Na, Fe and Mn were significantly ($p < 0.05$) affected by the growing seasons (Table 2). Na and Fe concentrations were significantly reduced from 5.55 to 3.80 and 65.23 to 36.64 mg/kg, respectively, from 2019/2020 to the 2020/2021 growing season, while concentrations of Mn were significantly increased from 13.86 to 22.26mg/kg during the same period (Table 3). The significant reduction in the concentrations of Na and Fe at the end of the second season may be due to the overall net nutrient removal through the crop harvest. The significant increase in Mn after two seasons was possibly caused by crop residue decomposition, adding more Mn into the soil. Overall, a net decrease in Na was noted after two seasons of treatment application. At the end of the first and second seasons, the initial extractable Na content at the beginning of the trial was significantly reduced by 74.8% and 82.7%, respectively. This significant observation may confirm the usefulness of a forage legume crop in reducing salinity levels. This agrees with an observation made by Gura and Mnkeni (2019), who discovered that incorporating soybean crop in the crop rotation sequence significantly reduced salinity levels.

Correlation analysis

Pearson's correlation analysis of the evaluated soil fertility parameters revealed linear positive and negative relationships that were mostly significant at $p < 0.05$ (Table 6). The positive relationship between the properties pH vs. Ca; pH vs. Mg; pH vs. K; SOM vs. N; SOM vs. K; SOM vs. Mn; Ca vs. Mg; and Mg vs. K was strong, with R^2 ranging = 0.51–0.77 ($p < 0.05$). Other related study detected similar correlation coefficient between SOM and N of $R^2 = 0.59–0.81$ (Thinh et al. 2019, Xu et al. 2021).

Table 6
Bivariate correlation matrix for soil fertility properties

	Pearson Correlation Coefficients										
	Prob > |r| under H0: Rho = 0										
	pH	**SOM**	**N**	**P**	**Ca**	**Mg**	**K**	**Na**	**Cu**	**Fe**	**Mn**
pH	1	0.3022*	0.4203**	-0.1274	0.5656***	0.6443***	0.5662***	0.1466	-0.1886	-0.4190**	-0.2487
SOM	0.3022*	1	0.6062***	0.2655	0.0991	0.4096**	0.6096***	-0.3506**	-0.1663	-0.5567***	0.5144***
N	0.4203**	0.6062***	1	0.1265	0.2587	0.4581***	0.3950**	-0.2311	0.0045	-0.2543	0.0746
P	-0.1274	0.2655	0.1265	1	-0.0981	-0.1365	0.3484**	-0.1967	-0.0865	0.1746	0.4855***
Ca	0.5656***	0.0991	0.2587	-0.0981	1	0.7702***	0.3619**	0.4021**	-0.0549	0.2237	-0.3926**
Mg	0.6443***	0.4096**	0.4581***	-0.1365	0.7702***	1	0.5238***	0.0859	-0.2288	-0.2512	-0.1945
K	0.5662***	0.6096***	0.3950**	0.3484**	0.3619**	0.5238***	1	-0.1285	-0.1192	-0.4836***	0.3398*
Na	0.1466	-0.3506**	-0.2311	-0.1967	0.4021**	0.0859	-0.1285	1	0.1853	0.4156**	-0.2935*
Cu	-0.1886	-0.1663	0.0045	-0.0865	-0.0549	-0.2288	-0.1192	0.1853	1	0.1811	-0.1023
Fe	-0.4190**	-0.5567***	-0.2543	0.1746	0.2237	-0.2512	-0.4836***	0.4153**	0.1811	1	-0.2731*
Mn	-0.2487	0.5144***	0.1746	0.4855***	-0.3926**	-0.1945	0.3398*	-0.2935*	-0.1023	-0.2731*	1
Zn	-0.2468	-0.0551	-0.0986	-0.0202	-0.0875	-0.1962	-0.0857	0.2261	0.6195***	0.1817	0.2377

Top number showing R2 value and below, *, **, *** Significant at $p < 0.05$; 0.01 and 0.001 probability level respectively.

Conclusion

Sunn hemp planting date and planting density had no significant effect on most measured soil fertility properties between the two growing seasons. Extractable Zn was the most affected soil fertility property by the management of sunn hemp, as indicated by the significant interaction effects of the sunn hemp planting period and density. However, the growing season was the main factor influencing the effects of sunn hemp intercropping on most of the measured soil fertility properties. When the growing seasons were compared, significant differences were noted in SOM, N, K, Ca, Na, Mn and Fe concentrations. The significant increases reported with SOM, N, K and Mn between the two growing seasons were most probably associated with the decomposition of the sunn hemp residues with varying qualities and quantities that were retained on the soil surface. A decrease associated with Ca and Fe may be due to higher net removal of these nutrients by the growing maize and sunn hemp crops and subsequent lack of sufficient replenishments through decomposition of crop residues. The retention of sunn hemp residues with varying quantities and qualities due to the planting periods and densities influenced short nutrient dynamics. Significant changes in soil fertility properties may take longer, and future research should be carried out in agricultural regions with different soil mineral matrices.

Declarations

Technical assistance and Funding

The authors thank Mr Elias Yokwane and Mrs Nozindaba Radebe, Department of Soil, Crop, and Climate Sciences, University of the Free State, Bloemfontein, for technical assistance during field trials. The Water Research Commission (WRC), the National Research Foundation (NRF), and the Food and Beverages Manufacturing Sector Education and Training Authority (FoodBev SETA) are acknowledged for their financial contributions to for the research study.

Disclosure statement

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Admire Dzvene, Isaac Gura, and Weldemichael Tesfuhuney. The first draft of the manuscript was written by Isaac Gura and Admire Dzvene. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

1. Al-Seekh SH, and Mohammad AG. 2009. The effect of water harvesting techniques on runoff, sedimentation, and soil properties. *Environmental management* 44(1): 37-45. https://doi.org/10.1007/s00267-009-9310-z
2. Berti M, Samarappuli D, Johnson BL, Gesch RW. 2017. Integrating winter camelina into maize and soybean cropping systems. *Industrial crops and Products* 107: 595-601. https://doi.org/10.1016/j.indcrop.2017.06.014
3. Botha JJ, Anderson JJ, Van Staden PP. 2015. Rainwater harvesting and conservation tillage increase maize yields in South Africa. *Water resources and rural development* 6: 66-77. https://doi.org/10.1016/j.wrr.2015.04.001
4. Bothma CB, Van Rensburg LD, Le Roux PAL. 2012. Rainfall intensity and soil physical properties influence on infiltration and runoff under in-field rainwater harvesting conditions. *Irrigation and Drainage* 61: 41-49. https://doi.org/10.1002/ird.1680
5. Cong WF, Hoffland E, Li L, Janssen BH, van der Werf W. 2015. Intercropping affects the rate of decomposition of soil organic matter and root litter. *Plant and Soil* 391(1): 399-411. https://doi.org/10.1007/s11104-015-2433-5
6. Connolly J, Goma HC, Rahim K. 2001. The information content of indicators in intercropping research. *Agriculture, ecosystems & environment* 87(2): 191-207. https://doi.org/10.1016/S0167-8809(01)00278-X
7. Cotrufo MF, Wallenstein MD, Boot CM, Denef K., Paul E. 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Global change biology* 19(4): 988-995. https://doi.org/10.1111/gcb.12113
8. Dzvene AR, Chiduza C, Mnkeni PNS, Peter PC. 2019. Characterization of livestock biochars and their effect on selected soil properties and maize early growth stage in soils of Eastern Cape province, South Africa. *South African Journal of Plant and Soil* 36(3): 199-209. https://doi.org/10.1080/02571862.2018.1536930
9. Dzvene AR, Tesfuhuney W, Walker S, Fourie A, Botha C, Ceronio G. 2021. Farmers' knowledge, attitudes, and perceptions for the adoption of in-field rainwater harvesting (IRWH) technique in Thaba Nchu, South Africa. *African Journal of Science, Technology, Innovation and Development* 14 (6): 1458–1475. https://doi.org/10.1080/20421338.2021.1960542
10. Fertilizer Society of South Africa (FSSA). 2007. FSSA Fertilizer Handbook. Fertilizer Society of South Africa, Pretoria, South Africa
11. Franzluebbers AJ, Hons FM. 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. *Soil and Tillage Research* 39(3-4): 229-239. https://doi.org/10.1016/S0167-1987(96)01056-2
12. Franzluebbers AJ. 2015. Farming strategies to fuel bioenergy demands and facilitate essential soil services. Geoderma 259: 251–258. https://doi.org/10.1016/j.geoderma.2015.06.007
13. Franzluebbers AJ, Sawchik J, Taboada MA. 2014. Agronomic and environmental impacts of pasture–crop rotations in temperate North and South America. *Agriculture, Ecosystems & Environment* 190: 18-26. https://doi.org/10.1016/j.agee.2013.09.017

14. Garland G, Bünemann EK, Oberson A, Frossard E, Six J. 2017. Plant-mediated rhizospheric interactions in maize-pigeon pea intercropping enhance soil aggregation and organic phosphorus storage. *Plant and Soil* 415(1): 37-55. https://doi.org/10.1007/s11104-016-3145-1
15. Govaerts B, Sayre KD, Lichter K, Dendooven L, Deckers J. 2007. Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. *Plant and Soil* 291(1): 39-54. https://doi.org/10.1007/s11104-006-9172-6
16. Gura I, Mnkeni PNS. 2019. Crop rotation and residue management effects under no till on the soil quality of a Haplic Cambisol in Alice, Eastern Cape, South Africa. *Geoderma* 337: 927-934. https://doi.org/10.1016/j.geoderma.2018.10.042
17. Gura I, Mnkeni PNS, Du Preez CC, Barnard JH. 2022. Short-term effects of conservation agriculture strategies on the soil quality of a Haplic Plinthosol in Eastern Cape, South Africa. *Soil and Tillage Research* 220: 105378. https://doi.org/10.1016/j.still.2022.105378
18. Hartwig NL, Ammon HU. 2002. Cover Crops and Living Mulches. *Weed Science* 50 (6): 688-699. https://doi.org/10.1614/0043-1745(2002)050[0688:AIACCA]2.0.CO,2
19. Hassen A, Talore DG, Tesfamariam EH, Friend MA, Mpanza TDE. 2017. Potential use of forage-legume intercropping technologies to adapt to climate-change impacts on mixed crop-livestock systems in Africa: a review. *Regional Environmental Change* 17(6): 1713-1724. https://doi.org/10.1007/s10113-017-1131-7
20. Hensley M, Botha JJ, Anderson JJ, Van Staden PP, Du Toit A. 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water (No. 878/1, p. 00). WRC report.
21. Hooda PS, Moynagh M, Svoboda IF, Anderson HA. 1998. A comparative study of nitrate leaching from intensively managed monoculture grass and grass–clover pastures. *The Journal of Agricultural Science* 131(3): 267-275. https://doi.org/10.1017/S0021859698005863
22. Javanmard A, Machiani MA, Lithourgidis A, Morshedloo MR, Ostadi A. 2020. Intercropping of maize with legumes: A cleaner strategy for improving the quantity and quality of forage. *Cleaner Engineering and Technology* 1: 100003. https://doi.org/10.1016/j.clet.2020.100003
23. Jeranyama P, Hesterman OB, Waddington SR, Harwood RR. 2000. Relay-intercropping of sunnhemp and cowpea into a smallholder maize system in Zimbabwe. Agronomy Journal 92(2): 239-244. https://doi.org/10.2134/agronj2000.922239x
24. Kutamahufa M, Matare L, Soropa G, Mashavakure N, Svotwa E. Mashingaidze AB. 2022. Forage legumes exhibit a differential potential to compete against maize and weeds and to restore soil fertility in a maize-forage legume intercrop. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science* 72(1): 127-141. https://doi.org/10.1080/09064710.2021.1998593
25. Lampurlanés J, Cantero-Martínez C. 2006. Hydraulic conductivity, residue cover and soil surface roughness under different tillage systems in semiarid conditions. *Soil and Tillage Research* 85(1-2): 13-26. https://doi.org/10.1016/j.still.2004.11.006
26. Li L, Li SM, Sun JH, Zhou LL, Bao XG, Zhang HG, Zhang FS. 2007. Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. *Proceedings of the National Academy of Sciences* 104(27): 11192-11196. https://doi.org/10.1073/pnas.0704591104
27. Liedgens M, Soldati A, Stamp P. 2004. Interactions of maize and Italian ryegrass in a living mulch system: (1) Shoot growth and rooting patterns. *Plant and Soil* 262(1): 191-203. https://doi.org/10.1023/B:PLSO.0000037041.24789.67
28. Liu CA, Jin SL, Zhou LM, Jia Y, Li FM, Xiong YC, Li XG. 2009. Effects of plastic film mulch and tillage on maize productivity and soil parameters. *European Journal of Agronomy* 31(4): 241-249. https://doi.org/10.1016/j.eja.2009.08.004
29. Mduduzi K. 2015. Assessing the effect of in-field rainwater harvesting on soil physico-chemical properties and crop yield in comparison with the traditional farmers' practice. Master's thesis, School of Agricultural, Earth and Environmental Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
30. Michael K, Monicah MM, Peter B, Job K. 2021. Optimizing interaction between crop residues and inorganic N under zero tillage systems in sub-humid region of Kenya. *Heliyon* 7(9): e07908. https://doi.org/10.1016/j.heliyon.2021.e07908
31. Mucheru-Muna M, Pypers P, Mugendi D, Kung'u J, Mugwe J, Merckx R, Vanlauwe B. 2010. A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. *Field Crops Research* 115(2): 132-139. https://doi.org/10.1016/j.fcr.2009.10.013
32. Okalebo JR, Gathua KW, Woomer PL. 2002. Laboratory methods of soil and plant analysis: a working manual second edition. Sacred Africa, Nairobi, 21, 25-26.
33. Poeplau C, Don A. 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. *Agriculture, Ecosystems & Environment* 200: 33-41. https://doi.org/10.1016/j.agee.2014.10.024
34. Poffenbarger HJ, Mirsky SB, Weil RR, Kramer M, Spargo JT, Cavigelli MA. 2015. Legume proportion, poultry litter, and tillage effects on cover crop decomposition. *Agronomy Journal* 107(6): 2083-2096. https://doi.org/10.2134/agronj15.0065
35. Posthumus H, Stroosnijder L. 2010. To terrace or not: the short-term impact of bench terraces on soil properties and crop response in the Peruvian Andes. *Environment, Development and Sustainability* 12(2): 263-276. https://doi.org/10.1007/s10668-009-9193-4
36. Reicosky DC, Kemper WD, Langdale G, Douglas CL, Rasmussen PE. 1995. Soil organic matter changes resulting from tillage and biomass production. *Journal of soil and water conservation* 50(3): 253-261.
37. Ritchie SW, Hanway JJ, Benson GO. 1993. How a Corn Plant Develops. Iowa State University of Science and Technology Cooperative Extension Service
38. Rockstrom J. 2000. Water resources management in smallholder farms in Eastern and Southern Africa: An overview. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 25(3): 275-283. https://doi.org/10.1016/S1464-1909(00)00015-0
39. Sigdel S, Chatterjee A, Berti M, Wick A, Gasch C. 2021. Interseeding cover crops in sugar beet. *Field Crops Research* 263, 108079. https://doi.org/10.1016/j.fcr.2021.108079

40. Singh G, Khan AU, Kumar A, Bala N, Tomar UK. 2012. Effects of rainwater harvesting and afforestation on soil properties and growth of Emblica officinalis while restoring degraded hills in western India. *African Journal of Environmental Science and Technology* 6(8): 300-311. https://doi.org/10.5897/AJEST11.040
41. Soil Classification Working Group, 2018. Soil classification: A taxonomic system for South Africa. Department of Agricultural Development, Pretoria
42. Tesfuhuney WA, van Rensburg LD, Walker S, Allemann J. 2015. Quantifying and predicting soil water evaporation as influenced by runoff strip lengths and mulch cover. *Agricultural Water Management* 152: 7-16. https://doi.org/10.1016/j.agwat.2014.11.018
43. Thapa R, Poffenbarger H, Tully KL, Ackroyd VJ, Kramer M, Mirsky SB. 2018. Biomass production and nitrogen accumulation by hairy vetch–cereal rye mixtures: A meta-analysis. *Agronomy Journal* 110(4): 1197-1208. https://doi.org/10.2134/agronj2017.09.0544
44. Thapa R, Tully KL, Reberg-Horton C, Cabrera M, Davis BW, Fleisher D, Gaskin J, Hitchcock R, Poncet A, Schomberg HH, Seehaver SA. 2022. Cover crop residue decomposition in no-till cropping systems: Insights from multi-state on-farm litter bag studies. *Agriculture, Ecosystems & Environment* 326: 107823. https://doi.org/10.1016/j.agee.2021.107823
45. Thinh NTH, Hoai V, Anh HL, Anh VT, Chau TV, Van Giap T, Tien TM. 2019. Study the changes in soil organic carbon of rice-maize cropping system in the top layer of Alluvisol soil in Dan Phuong: A study of C-13 stable isotope composition (δ13C). *Journal of Environmental Protection* 10(10): 1361-1372. https://doi.org/10.4236/jep.2019.1010080
46. Thompson GR. 1995. A comparison of methods used for the extraction of K in soils of the Western Cape. *South African journal of plant and soil* 12(1): 20-26. https://doi.org/10.1080/02571862.1995.10634329
47. Tsubo M, Mukhala E, Ogindo HO, Walker S. 2003. Productivity of maize-bean intercropping in a semiarid region of South Africa. *Water SA* 29(4): 381-388. https://doi.org/10.4314/wsa.v29i4.5038
48. Turmel M, Speratti A, Baudron F, Verhulst N, Govaerts B. 2014. Crop residue management and soil health: A systems analysis. *Agricultural Systems* 134: 6–16. https://doi.org/10.1016/j.agsy.2014.05.009
49. Van Rensburg LD, Bothma CB, Fraenkel CH, Le Roux PAL, Hensley M. 2012. In-field rainwater harvesting: mechanical tillage implements and scope for upscaling. *Irrigation and drainage* 61: 138-147. https://doi.org/10.1002/ird.1682
50. Vanlauwe B, Wendt J, Giller KE, Corbeels M, Gerard B, Nolte C. 2014. A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. *Field Crops Research* 155: 10-13. https://doi.org/10.1016/j.fcr.2013.10.002
51. World Reference Base for Soil Resources (WRB), 2014. International soil classification system for naming soils and creating legends for soil maps. World soil resources reports. 0488 Food and Agriculture Organization of the United Nations 106. ISSN 0532- Rome.
52. Xu Q, Xiong K, Chi Y, Song S. 2021. Effects of Crop and Grass Intercropping on the Soil Environment in the Karst Area. *Sustainability* 13(10): 5484. https://doi.org/10.3390/su13105484

Figures

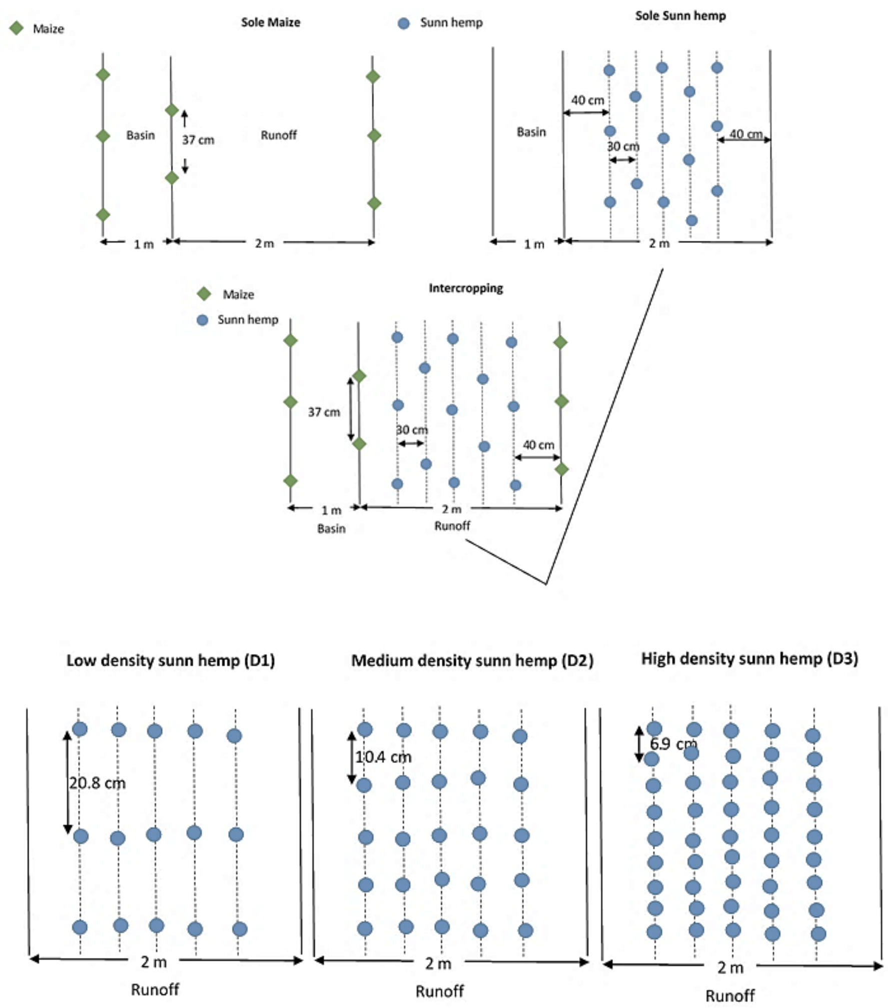

Figure 1

The spatial arrangement for sunn hemp intercropping at various planting densities under the in-field rainwater harvesting (IRWH) technique

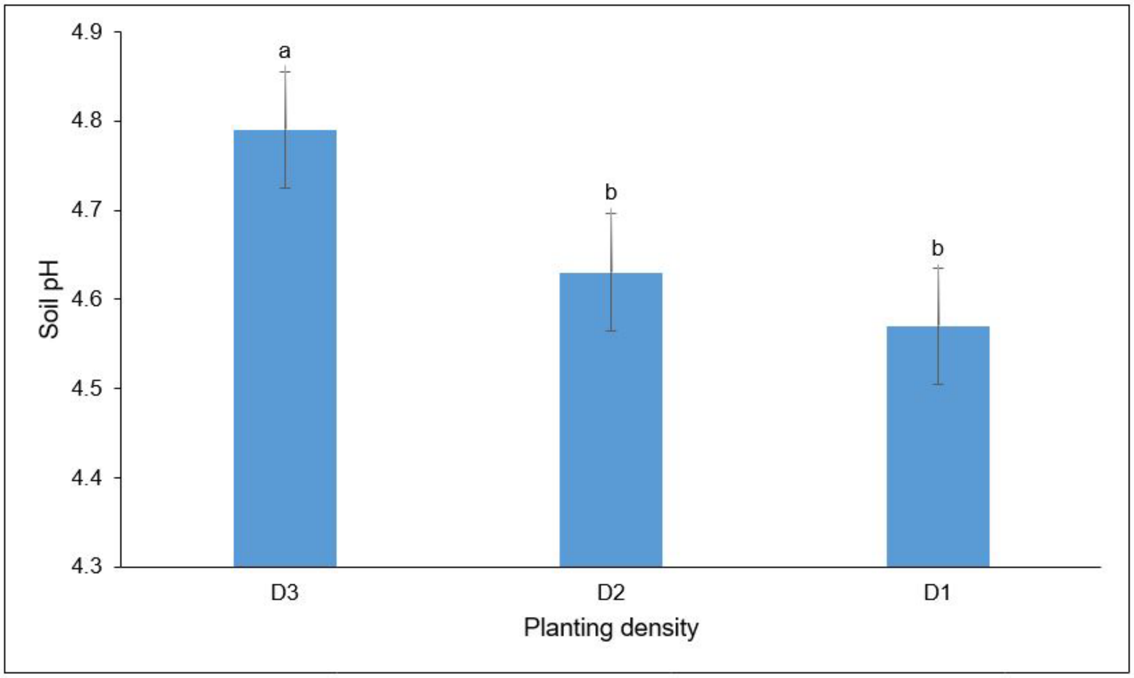

Figure 2

The effect of sunn hemp intercropping density (D) on soil pH of the *Plinthic Cambisol* at the end of the 2019/20 growing season after harvest. (D1-low: 16.1 plants m^{-2}, D2-medium: 32.1 plants m^{-2}, D3-high: 48.1 plants m^{-2}). Different letters on the bars indicate the statistical significance at LSD $_{(0.05)}$.

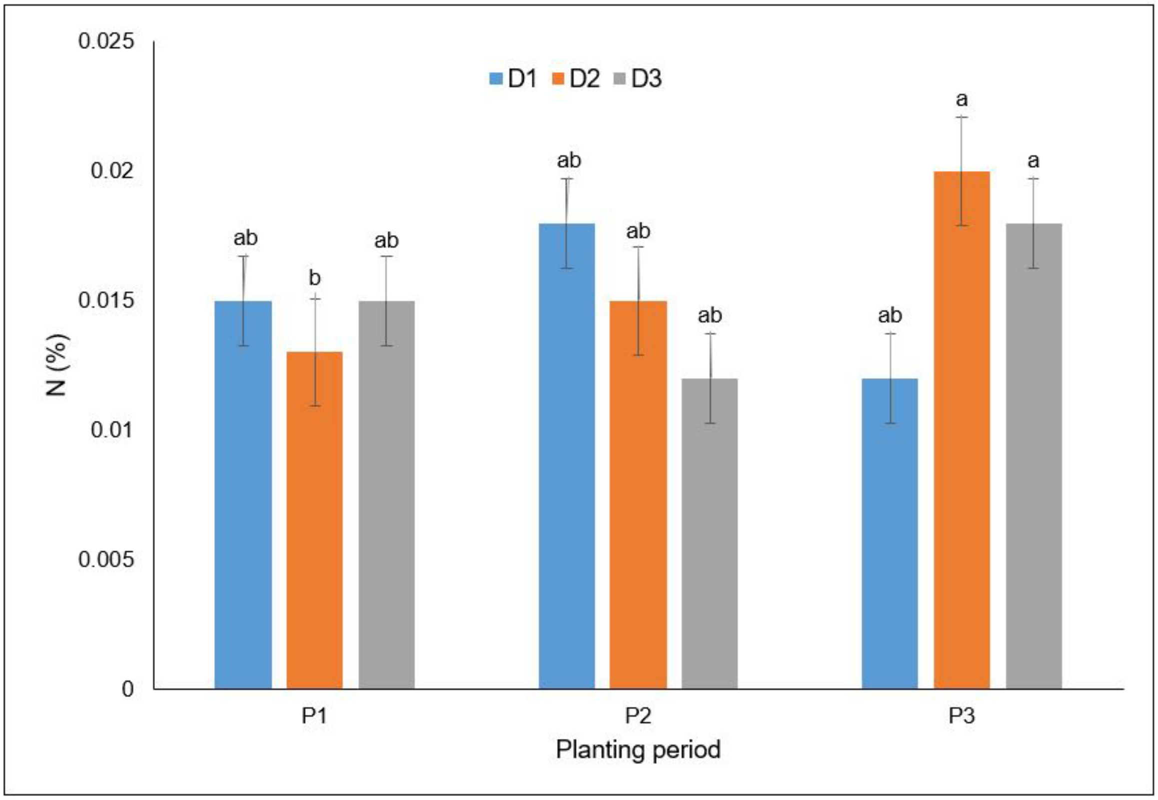

Figure 3

The interaction effect of sunn hemp intercropping period (P) and plant density (D) on N (%) of the *Plinthic Cambisol* at the end of the 2020/21 growing season after harvest. (P1: simultaneous sunn hemp and maize planting, P2: sunn hemp planted at the V15 maize growth stage, P3: sunn hemp planted at R1 maize growth stage, D1-low: 16.1 plants m^{-2}, D2-medium: 32.1 plants m^{-2}, D3-high: 48.1 plants m^{-2}). Different letters on the bars indicate the statistical significance at LSD $_{(0.05)}$.

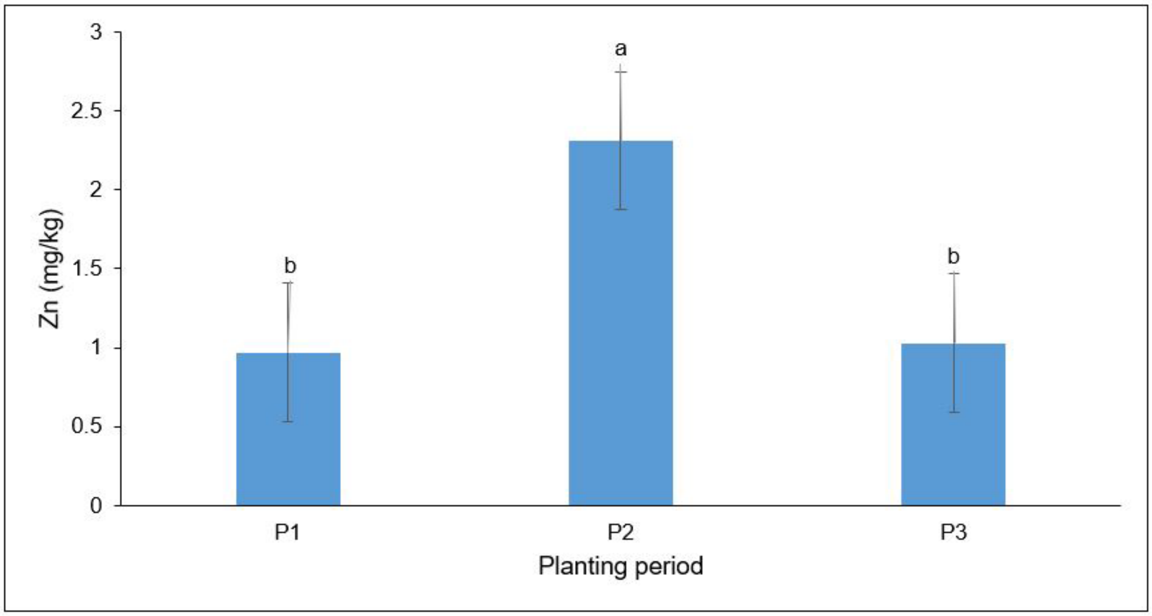

Figure 4

The effect of sunn hemp intercropping period (P) on Zn (mg/kg) of the *Plinthic Cambisol* between the two growing seasons. (P1: simultaneous sunn hemp and maize planting, P2: sunn hemp planted at the V15 maize growth stage, P3: sunn hemp planted at R1 maize growth stage). Different letters on the bars indicate statistical significance at LSD $_{(0.05)}$.

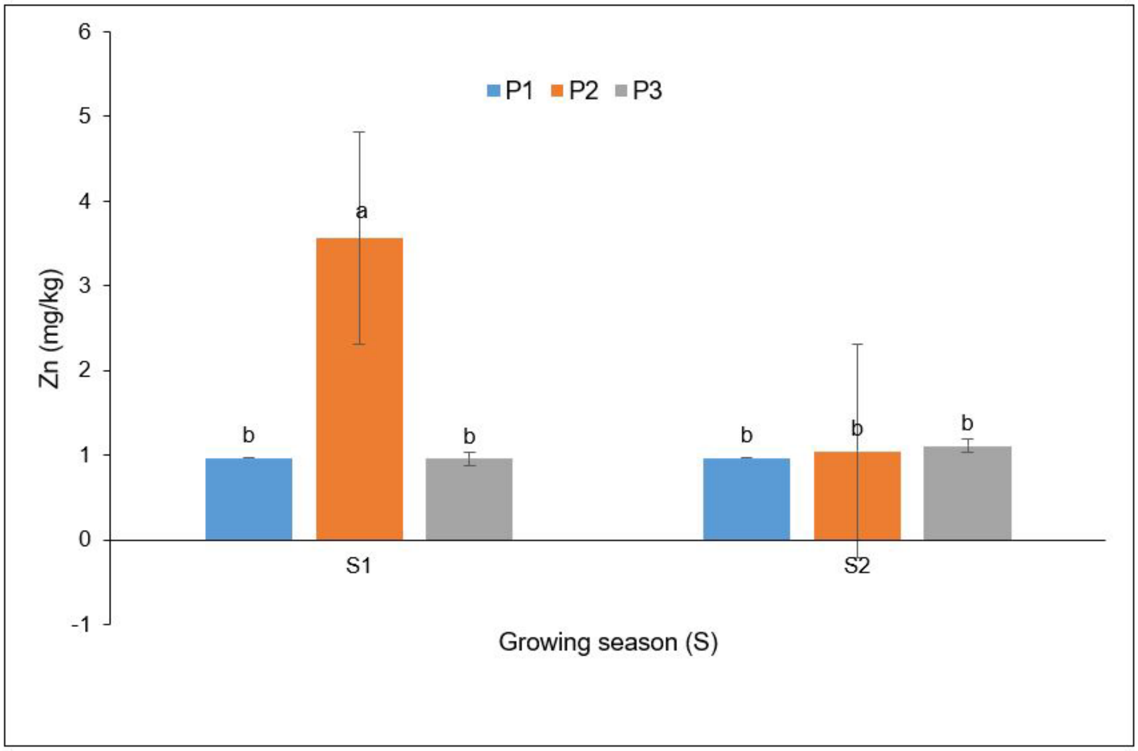

Figure 5

The interaction effect of sunn hemp intercropping period (P) changes with growing seasons on the Plinthic Cambisol's extractable Zn (mg/kg). (S1-growing season 1: 2019/20, S2-growing season 2: 2020/21, D1-low: 16.1 plants m^{-2}, D2-medium: 32.1 plants m^{-2}, D3-high: 48.1 plants m^{-2}). Different letters on the bars indicate the statistical significance at LSD $_{(0.05)}$.

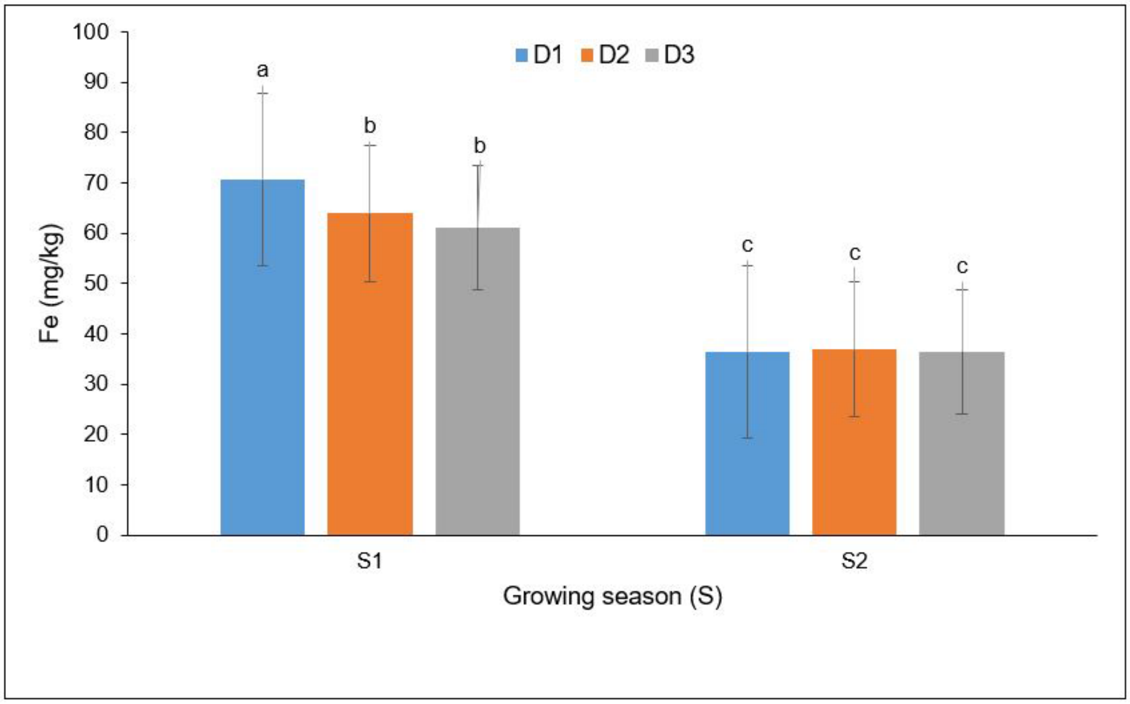

Figure 6

The interaction effect of sunn hemp intercropping density (D) changes with growing seasons on the Plinthic Cambisol's extractable Fe (mg/kg). (S1-growing season 1: 2019/20, S2-growing season 2: 2020/21, D1-low: 16.1 plants m^{-2}, D2-medium: 32.1 plants m^{-2}, D3-high: 48.1 plants m^{-2}). Different letters on the bars indicate the statistical significance at LSD $_{(0.05)}$.

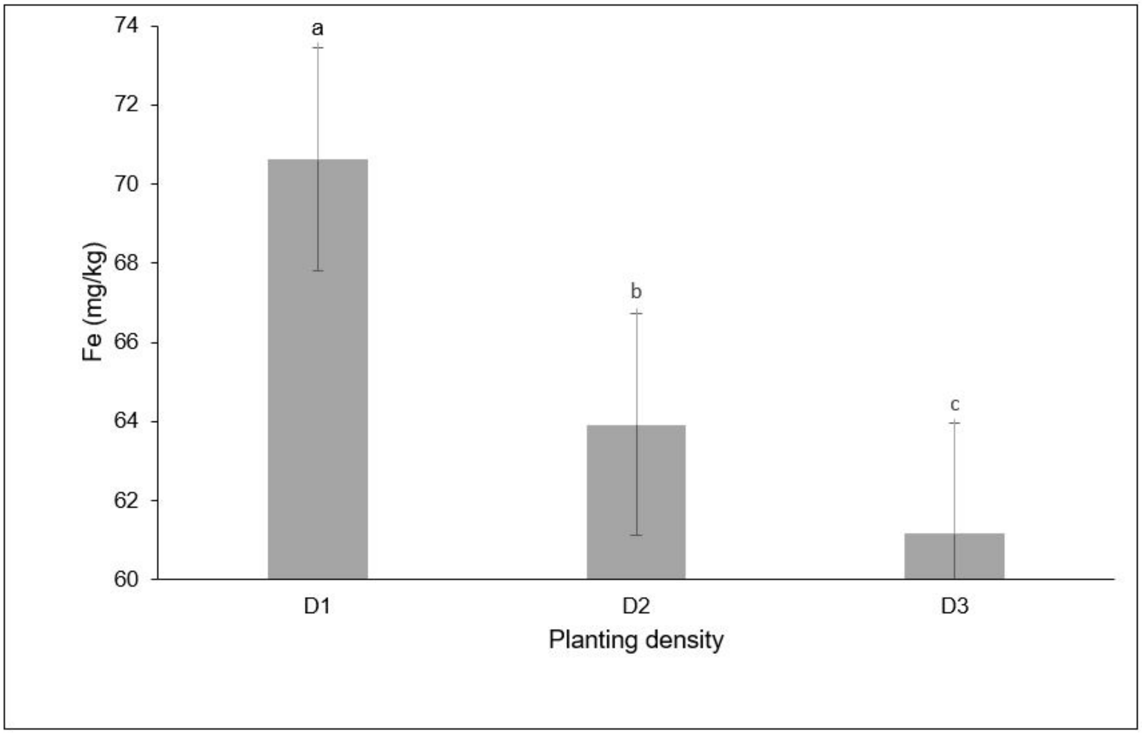

Figure 7

The effect of sunn hemp intercropping density (D) on the Plinthic Cambisol's Fe (mg/kg) at the end of the 2019/20 season after harvest. (D1-low: 16.1 plants m^{-2}, D2-medium: 32.1 plants m^{-2}, D3-high: 48.1 plants m^{-2}). Different letters on the bars indicate the statistical significance at LSD $_{(0.05)}$.