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Research Paper

Upholding Sunflower (*Helianthus annuus)* Yield and Profitability while Maintaining Soil Fertility Under Intercropping with Sunn Hemp and Mineral Fertilizer Application

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ABSTRACT

Sunflower (*Helianthus annuus* L.) is one of Tanzania's high-potential cash crops. Nonetheless, nutrient depletion, especially nitrogen (N), is limiting its productivity. The study was conducted in the semi-arid -Dodoma region in Tanzania where it adopted a randomized complete block design (RCBD) with six treatments each replicated four times. These treatments were T1; Control (sunflower pure stand) without mineral nitrogen (N) fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Data that were collected were sunflower growth, and yield parameters, economic returns (gross income, net income, benefit-cost ratio-BCR), and soil chemical properties. Regardless of the site, T6 and T3 showed the best performance based on the sunflower growth and yield. For instance, at Kongwa the sunflower leaf area was highest in T3 (285 cm^2) and T6 (282 cm^2) with T4 having the least value of 149 cm^2. Economically, Kongwa outperformed Bahi. Specifically, based on treatments, T3 had the highest gross income both at Kongwa (US$ 3412 ha^{-1}) and Bahi (US$ 1756 ha^{-1}). This translated into respective net income and BCR of US$ 1639 and 698, and 7.50 and 3.20. Except for soil pH, the other chemical soil properties tended to increase significantly ($p \leq 0.05$) under all the treatments containing integrated approaches like Sunn hemp and N fertilizer application relative to the sunflower pure stand. This study's findings will help rural poor farmers achieve their nutritional, social, and economic needs, hence reducing poverty, and increasing food security.

HIGHLIGHTS

- Sunflower is considered a high-potential cash crop in Tanzania, However, Nutrient depletion, particularly nitrogen (N), is hindering its productivity.
- The study aimed at improving soil properties, sunflower production, and economic returns using integrated approaches, such as Sunflower-Sunn hemp intercropping and the use of intercropping with mineral nitrogen (N) fertilizer.
- The study revealed that sunflower can achieve optimal growth, yield, and economic returns when intercropped with legumes like Sunn hemp and supplemented with nitrogenous fertilizer.

Keywords: Tanzania, Legume, Soil chemical properties, Economic returns

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Sunflower, which is botanically referred to as *Helianthus annuus* (L.) was introduced in Tanzania from Europe and America during the colonial era as one of the cash crops (Njiku, 2019). The country is ranked tenth worldwide and second in Africa among the major producers of sunflower seeds (FAOSTAT, 2022). In this country, the crop is produced in fifteen regions, among them being Singida, Iringa, Dodoma, Manyara, and Rukwa (URT, 2012). Sunflower is one of the main oil vegetable crops with high value worldwide whereby in 2015 it had a production of 39.62 million tons (FAOSTAT, 2022). This crop is very important and is mainly grown by poor smallholder farmers as one of the means of increasing employment (Njiku, 2019). The crop is regarded as a major contributor to the improved livelihood of the smallholder farmers residing in the central corridor regions of Tanzania (Salisali, 2012). Nonetheless, the farmers still experience low production, making it impossible to meet the international market demand (Njiku, 2019).

The decline in soil fertility status is the biggest problem in dryland areas of sub-Saharan Africa whereby it affects the production of crops including oilseed crops like the sunflower (Babec *et al.* 2020; Otieno *et al.* 2021; Ochieng *et al.* 2021). Most of the crops grown in dryland areas are produced under a low amount of nutrients like nitrogen and phosphorus leading to low yields (Swamila *et al.* 2022; Seleiman *et al.* 2021). Although there is constant upgrading of genetically improved varieties, currently sunflower-producing countries have continued to experience low yields of between 1.1 and 2.4 t ha^{-1}.

Dodoma is dominated by shallow soils originating from granite rocks and is generally referred to as Lithosol. All soils of Dodoma are of poor nutrient status and have a low amount of organic matter content, courtesy of the granitic parent materials, and low vegetation cover (Msanya *et al.* 2018). Most of the smallholder farmers in most parts of Tanzania including Dodoma do not apply inorganic fertilizers or any other technology to replenish the nutrients (Budotela, 1995). In that case, the nutrient status of the soil where sunflower is grown is generally poor. Because in dryland there is poor nutrient availability, various approaches must be adopted to replenish the nutrients.

One of the approaches to replenishing the nutrients in the soil is through the process of growing many crop species in a single field, a technique called intercropping (Babec *et al.* 2020; Maitra *et al.* 2021; Gitari *et al.* 2018a; Sahoo *et al*. 2023). The intercropping technique increases biodiversity in the field and increases the interactions between biotic components and abiotic factors. Bokan *et al.* (2016) and (Šeremešić *et al*. (2018) demonstrated that there are great benefits of intercropping in the sense of increasing yields per area, reducing the use of pesticides, and better utilization of available resources. Babec *et al*. (2020) and Nasar *et al*. (2022a) reported that intercropping crops with legumes can bring advantageous results on yield, also on other plant growth parameters at the same time while minimizing the cost of pesticides and nitrogenous fertilizer application, hence increasing profitability. Despite the numerous merits associated with intercropping, there is no documented work related to sunflower intercropping with Sunn hemp, which was the focus of the current study. Intercropping sunflower and Sunn hemp increase sunflower yields since Sunn hemp can fix a huge amount of nitrogen of up to 167 kg of nitrogen per hectare through its symbiotic association with Rhizobium bacteria.

MATERIALS AND METHODS

Site description

The study was conducted in two districts: Bahi and Kongwa, based in the semi-arid region of Dodoma in Tanzania. The site in Kongwa is located at 36.43° E, 6.17° S, 1125 m above sea level whereas the one in Bahi is situated at 35.19° E, 5.57° S, 900 m above sea level. Generally, Kongwa district receives annual rainfall ranging from 500 to 750 mm whereas the average rainfall for the Bahi district ranges between 530 and 640 mm. Rainfall distribution is mono-modal starting in late November, reaching a peak in December/January, and ending in April. The temperatures of the Dodoma region differ from season to season, with an average maximum and minimum of 29 and 17^{o}C, respectively.

The sites are dominated by shallow soils developed on granite rocks, classified as Lithosol. These soils have little organic matter and low nutrient status, due to low vegetation cover and the granitic parent materials (Msanya *et al.* 2018). In addition, they are dominated by deciduous trees (Baobab) as the main vegetation type with the agricultural farming systems being mixed cropping, monocropping, and livestock keeping. The two districts are mostly known for their agricultural production with the main cultivated crops being sunflower, maize, rice, beans, and cotton (MoA, 2015).

Treatments and experimental design

The study adopted a randomized complete block design (RCBD) with 24 plots each with a size of 5 m x 6 m. There were six treatments (Table 1) each replicated four times. A 0.5 m path separated the plots within blocks and the four blocks were set at 1 m apart. For the treatments that required fertilizer, urea fertilizer was applied to sunflowers only at planting and at the vegetative stage.

Crop establishment and agronomic practices

Before the onset of the rain, the land was cleared and well prepared by both plowing and harrowing to make an appropriate tilth for the crops. The sunflower was planted at an interplant spacing of 30 cm and between the row spacing of 75 cm. For 1:1 and 2:1 sunflower-Sunn hemp intercropping, the inter-row spacing of Sunn hemp was 75 and 35 cm, respectively. Two sunflower seeds were planted per hill, whereas Sunn hemp seeds were broadcasted following a straight line (for the intercropped plots). Routine management practices such as weeding, pest control, thinning, and gaping were performed accordingly throughout the crop-growing period.

Soil sampling and analysis

Soil sampling was done twice (before and after planting experimental trials) to a depth of 30 cm with the aid of an auger, by considering a random soil sampling technique. About 10-15 subsamples were obtained from each experimental site before establishing the experiment whereas, after crop harvest, the soil samples were taken separately from each of the 24 plots. Composite samples of roughly 500 g were drawn after mixing the sub-samples in a plastic bucket. The samples were delivered to the laboratory for chemical analysis and interpretation.

Soil pH was determined using a pH meter according to Ryan *et al*. (2001). Total nitrogen and organic carbon were analyzed using the Kjeldahl (Bremner, 1996) and the Walkey and Black (Nelson and Sommers, 1996) methods respectively. The exchangeable bases which included Na^+, K^+ Mg^{2+}, and Ca^{2+} were analyzed using a flame spectrophotometer method (Kalra and Maynard, 1991). Available phosphorus was extracted using the Mehlich-3 (M-3) technique (Bolland *et al.* 2003; Mehlich, 1984) and read in a spectrophotometer (Murphy and Riley, 1962).

Plant sampling and field measurements

From a net area of 2 m^2 taken from the middle of each plot, three plants were selected to determine the growth parameters: leaf area, plant height, and the number of leaves per plant, and yield indices: number of seeds per capitulum of sunflower, head diameter, the weight of seeds per plant and grain yield per ha. Measurements of the aforementioned growth parameter were considered at three phenological stages: vegetative, tasselling, and harvesting. Head diameter and height were determined using a tape measure, whereby the height was measured from the sunflower plant's ground to the sunflower's head. The number of leaves from each sample plant was counted from the first to the last visible leaf of the plant.

Nitrogen uptake was measured by plucking two leaves next to the sunflower head. These leaves were chopped and mixed after which 500 g composite samples were drawn per plot and packed in khaki bags. The samples in khaki bags were placed in an oven to dry at 65 °C to a constant weight after which they were ground using a Wiley mill to be ready for analyses. By following the micro-Kjeldahl procedures given by Yuen and Pollard (1953), the plant tissues were analyzed for total N concentration.

Sunflower yield and economic returns

At the harvesting stage, ten sunflower heads were taken randomly at the middle of each plot, sun-dried, and shelled manually. By use of an electronic weighing balance, the weight of the sunflower seeds was determined in kilograms then conversion into tonnes per hectare was made. For stover yield, sunflower leaves together with stalks were weighed together.

The cumulative cost of production was determined by adding all costs used in the production of the crop, which consisted of the costs of seeds, fertilizers, pesticides, labor, and farm leasing costs. The gross income was calculated based on the prevailing sunflower market price of US$ 0.66 kg^{-1}. Net income as well as a benefit: cost ratio were calculated using the two formulas given in Equations 1 and 2 (Cheptoek *et al.* 2021).

$$\text{Net income} = \text{Gross income} - \text{Total cost of production} \quad \ldots(1)$$

$$\text{Benefit: cost ratio} = \frac{\text{Net income}}{\text{Total cost of production}} \quad \ldots(2)$$

Data analysis

The data from this study were tabulated in Excel, then subjected to ANOVA using the statistical software, GenStat (GenStat, 2010). The significant means were distinguished by using the least significant difference (LSD) at a 95% confidence interval. The relationship among soil parameters as well as among the sunflower growth, yield, and economics parameters were determined by conducting a correlation analysis.

RESULTS

Rainfall and temperature patterns during the experimental period

At Kongwa, the highest (30.2 °C) maximum and minimum (19.1 °C) temperatures were noted with December 2021 having the lowest record for minimum (17.6 °C) temperature (Fig. 1). On the other hand, this site had January and February of 2022 receiving the highest amounts of rainfall of 314.1 mm and 299.4 mm, respectively.

Bahi was warmer and wetter than the Kongwa site with the highest maximum temperature of 31.8 °C in December 2021 and 30.3 °C in April 2022 whereas the highest minimum temperature was recorded in December (22.7 °C) and January (20.5 °C). January and February were distinguished to have received the highest amount of rainfall of 352.6 and 447.3 mm, respectively compared to December 2021 which was the driest month with 49.1 mm.

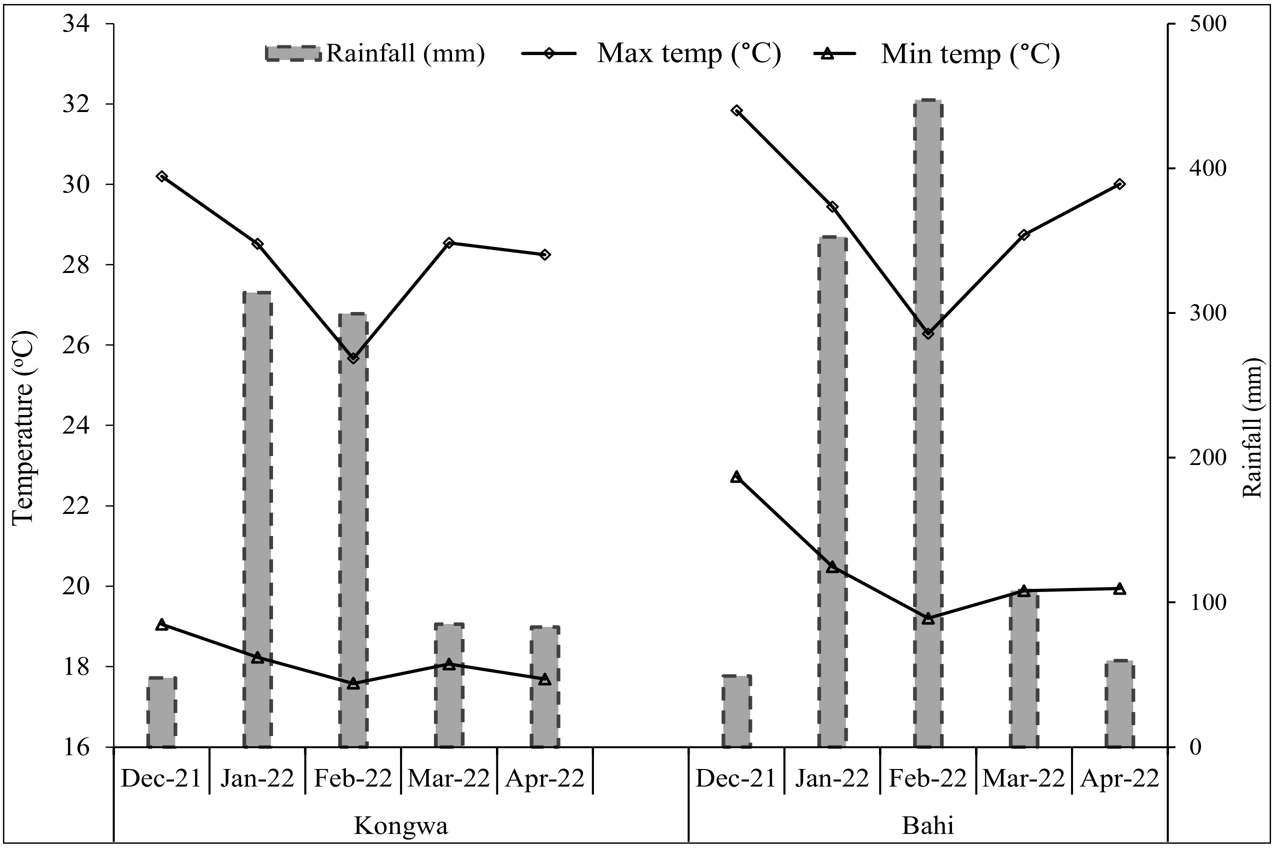

Fig. 1: Rainfall and temperature patterns during the experimental period

Effects of sunflower-Sunn hemp intercropping coupled with mineral nitrogen fertilizer on sunflower growth and yield parameters.

1. Effects on sunflower growth parameters

Plant height, leaf area, number of leaves per plant, sunflower head diameter, and nitrogen uptake were significantly ($p \leq 0.05$) affected by Sunn hemp intercropping coupled with mineral N fertilizer application with greater effects being noted in Kongwa than Bahi. For instance, in Kongwa at the vegetative stage, the highest sunflower plant height was recorded in T3 (88 cm) and T6 (83 cm) whereas intermediate values were noted in T4 (74 cm), T5 (73 cm), and T2 (60 cm), with control treatment (T1) having the least height of 34 cm (Fig. 2). At the tasseling stage, the sunflower plant height was such that T1 (85 cm) < T2 (102 cm) < T5 (121 cm) < T4 (133 cm) < T3 (155 cm) < T6 (157 cm). A similar scenario was depicted at maturity with plant height ranging from 125 cm in T1 to 169 cm in T6.

On the other hand, in Bahi, at the vegetative stage, plant height was 11, 15, 16, 17, and 19% lower in T1, T2, T4, T5, and T6, respectively compared to T3 (Fig. 2). At the tasseling stage, plant height was lowest in T1 (73 cm) and T5 (85 cm), and highest in T3 (109 cm) and T6 (104 cm). At maturity, sunflower plant height in T5, T2, T4, T6, and T3 was observed to be significantly higher by 16, 16, 17, 18, and 14%, respectively relative to T1.

Based on the sunflower leaf area, at Kongwa at the vegetative stage, the parameter was highest in T3 (285 cm^2) and T6 (282 cm^2) with T4 having the least value of 149 cm^2 (Fig. 3). At the tasselling stage, the leaf area decreased in the respective order of 567 > 497 > 393 > 339 > 294 > 218 cm^2 in T6, T3, T5, T4, T2, and T1, respectively. Similarly, at the maturity stage, the least leaf area (367 cm^2) was noted in T1, whereas the uppermost values were recorded in T6 (607 cm^2) and T3 (617 cm^2). At the vegetative stage in Bahi, the sunflower leaf area was such that T2 (133 cm^2) < T4 (134 cm^2) < T5 (147 cm^2) < T1 (155 cm^2) < T6 (186 cm^2) < T3 (253 cm^2) (Fig. 3). At the tasselling stage, the leaf area had a range of 222 cm^2 in T4 to 283 cm^2 in T6. A congruent observation was made at maturity where the parameter remained highest in T6 (208 cm^2) and T3 (196 cm^2) with the other treatments: T1, T2, T4, and T5 having respective values of 133, 173, 170, 165 cm^2.

In Kongwa at the vegetative stage, the number of sunflower leaves per plant in T6, T3, T4 and T5, and T2, was higher by 18, 18, 17 and 16% compared to T1 plots (Fig. 4). At the tasselling stage, the average number of leaves were 27.6, 24.5, 31.1, 25.9, 26.3,

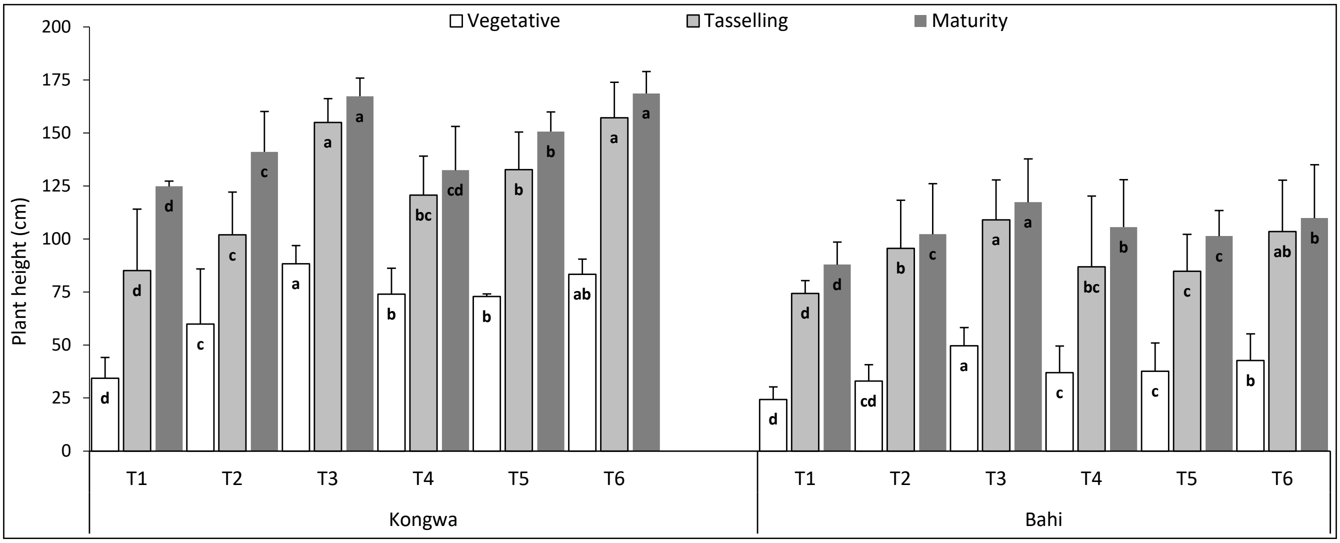

Fig. 2: Sunflower plant height at vegetative (white bars), tasseling (grey bars), and maturity (black bars) development stages in Kongwa and Bahi during the 2021/2022 crop growing season as influenced by mineral nitrogen (N) fertilizer under different sunflower-Sunn hemp planting patterns: T1; Control (sunflower pure stand) without fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer inputs, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Bars bearing similar alphabet letters within the same crop development stage and site represent means that do not differ significantly at p ≤0.05. Error bars indicate the standard error of the means

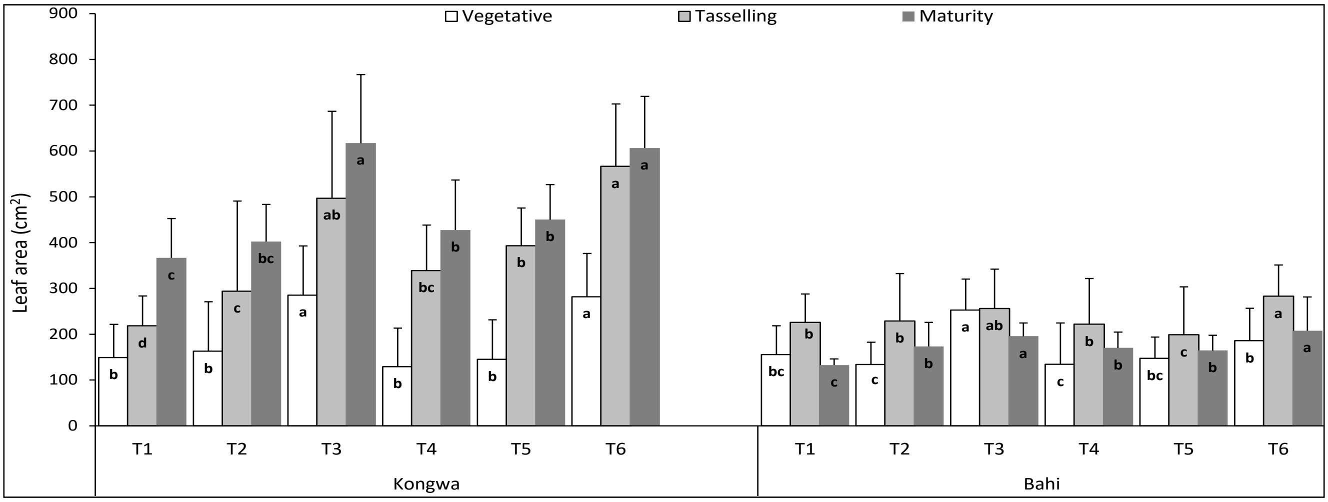

Fig. 3: Sunflower leaf area at vegetative (white bars), tasselling (grey bars), and maturity (black bars) development stages in Kongwa and Bahi during the 2021/2022 crop growing season as influenced by mineral nitrogen (N) fertilizer under different sunflower-Sunn hemp planting patterns: T1; Control (sunflower pure stand) without fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer inputs, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Bars bearing similar alphabet letters within the same crop development stage and site represent means that do not differ significantly at $p \leq 0.05$. Error bars indicate the standard error of the means

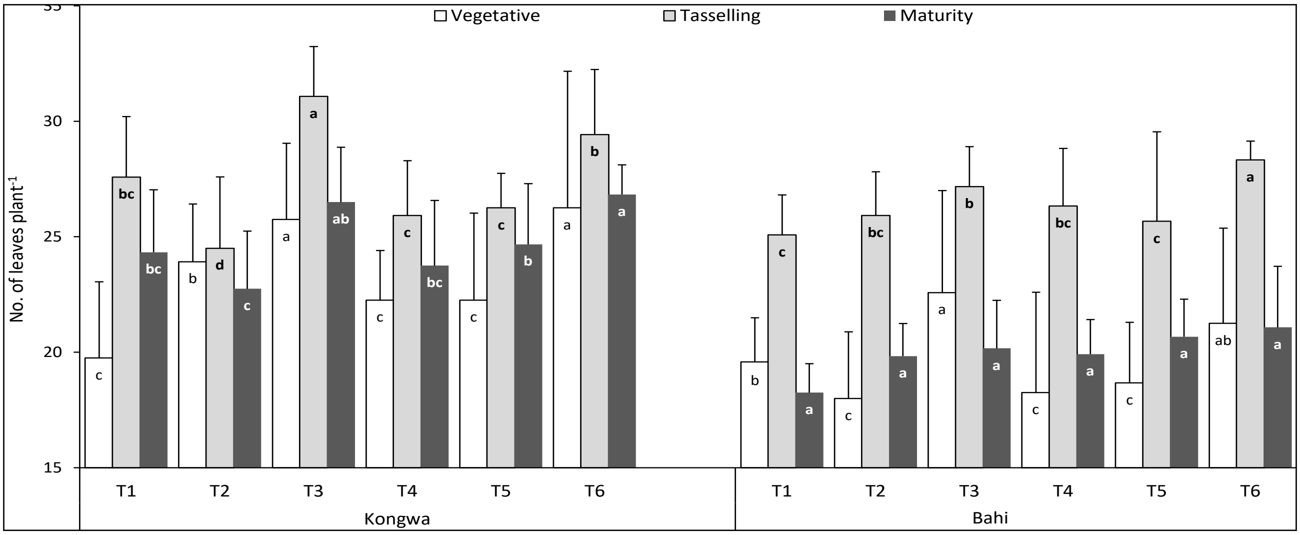

Fig. 4: Number of leaves per sunflower plant at vegetative (white bars), tasseling (grey bars), and maturity (black bars) development stages in Kongwa and Bahi during the 2021/2022 crop growing season as influenced by mineral nitrogen (N) fertilizer under different Sunflower-Sunn hemp planting patterns: T1; Control (sunflower pure stand) without fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Bars bearing similar alphabet letters within the same crop development stage and site represent means that do not differ significantly at $p \leq 0.05$. Error bars indicate the standard error of the means

and 29.4 for T1, T2, T3, T4, T5, and T6 respectively. However, at maturity, a slightly different order was noted and it was such that T6 (26.8) > T3 (26.5) > T5 (24.7) > T1 (24.3) > T4 (23.8) > T2 (22.1). On the other hand, in Bahi, at the vegetative stage, the average number of leaves ranged from 19.6 for T1 to 21.3 for T6 (Fig. 4). A comparable trend (T1 < T5 < T3 < T2 < T3 < T6) was noted at tasselling and maturity stages with respective ranges of 25–28 and 19–21 number of leaves per sunflower plant.

2. Effects on sunflower yield parameters and nitrogen uptake

Sunflower grain yield, number of seeds per plant, the weight of seed per plant, and sunflower stover yield were significantly ($p \leq 0.05$) affected by Sunn

Table 1: Treatments and their Description

Treatment code	Treatment's descriptions
T1	Control (sunflower pure stand) without mineral nitrogen (N) fertilizer
T2	Intercrop (Sunflower + Sunn hemp) under a 1:1 row ratio without N fertilizer
T3	Intercrop (Sunflower + Sunn hemp) under a 1:1 row ratio with N fertilizer
T4	Intercrop (Sunflower + Sunn hemp) under a 2:1 row ratio without N fertilizer
T5	Intercrop (Sunflower + Sunn hemp) under a 2:1 row ratio with N fertilizer
T6	Sunflower pure stand with N fertilizer

Table 2: Sunflower yield parameters as influenced by mineral nitrogen fertilizer under different Sunflower-Sunn hemp planting patterns at Kongwa and Bahi sites in the 2021/2022 crop growing season

Site	Treatment	Weight of seeds plant^{-1} (g)	Grain yield (t ha^{-1})	Number of seeds plant^{-1}	Stover yield (t ha^{-1})
Kongwa	TI	63.33 ± 29^{d}	2.81 ± 1.29^{d}	1026.75 ± 50^{d}	17.38 ± 6.33^{d}
	T2	77.54 ± 19^{c}	3.45 ± 0.84^{c}	1252.08 ± 30^{c}	25.43 ± 7.11^{d}
	T3	116.33 ± 4^{a}	5.17 ± 0.19^{a}	1879.25 ± 70^{a}	69.38 ± 26.37^{a}
	T4	91.17 ± 17^{b}	4.05 ± 0.76^{bc}	1479.33 ± 285^{bc}	26.14 ± 15.21^{cd}
	T5	106.33 ± 3^{a}	4.73 ± 0.12^{b}	1726.92 ± 34^{b}	38.78 ± 3.12^{bc}
	T6	113.42 ± 5^{a}	5.04 ± 0.22^{ab}	1827.17 ± 83^{ab}	49.44 ± 25.67^{b}
LSD		12.37	0.55	206.00	12.82
p value		<.001	<.001	<.001	<.001
Bahi	T1	31.25 ± 5^{c}	1.39 ± 0.21^{c}	485.08 ± 83^{c}	6.86 ± 0.52^{d}
	T2	48.21 ± 17^{b}	2.14 ± 0.77^{b}	779.25 ± 281^{b}	10.56 ± 4.67^{b}
	T3	59.86 ± 16^{a}	2.66 ± 0.71^{a}	967.92 ± 258^{a}	13.34 ± 5.21^{a}
	T4	48.43 ± 13^{b}	2.15 ± 0.60^{b}	785.25 ± 212^{b}	10.60 ± 4.75^{b}
	T5	43.32 ± 6^{b}	1.93 ± 0.27^{b}	708.75 ± 93^{b}	8.16 ± 0.73^{c}
	T6	58.17 ± 17^{a}	2.59 ± 0.75^{a}	949.17 ± 270^{a}	13.26 ± 5.33^{a}
LSD		7.01	2.43	108	2.43
p value		<.001	<.001	<.001	<.001

T1; Control (sunflower pure stand) without mineral nitrogen (N) fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Down the column and within the same site, means followed by different letters diverge significantly at $p \leq 0.05$.

hemp intercropping coupled with N fertilizer application with the greater effect noted in Kongwa than Bahi. For instance, at the Kongwa site, the sunflower yield differed between treatments where it increased in the order of T1 (2.8 t ha^{-1} < T2 (3.5 t ha^{-1}) < T4 (4.1 t ha^{-1}) < T5 (4.7 t ha^{-1}) < T6 (5.0 t ha^{-1}) < T3 (5.2 t ha^{-1}) (Table 2). A congruent trend was observed in Bahi with grain yield ranging from 1.39 t ha^{-1} in T1 to 2.7 t ha^{-1} in T3.

The highest number of sunflower seeds per plant (in Kongwa) was observed in T3 (1879) whereas T1 had the least value at 1027 (Table 2). In Bahi, the highest record of sunflower seeds per plant was made from T3 (968) and T6 (949), followed by T2, T4, and T5 with intermediate values of 779, 785, and 708, respectively, while the least value of 485 was recorded in T1.

The highest weight of seeds per plant was observed at the Kongwa in T3 (106 g), T6 (113 g), and T5 (107 g) followed by T4 (91 g) and T2 (78 g) whereas the least value was recorded in T1 (63 g) (Table 2). For Bahi, the heaviest seeds were noted in T3 (60 g) and T6 (58 g), whereas T1 had the lightest seeds (31 g). At Kongwa, stover yield (in t ha^{-1}) increased in the order of T1 (17) < T2 (25) < T4 (26) < T5 (39) < T6 (49) < T3 (69) (Table 2). The stover yield at Bahi was highest in T3 and T6 with a mean of 13 t ha^{-1} and least in T1 (8 t ha^{-1}).

Concerning sunflower head diameter, at Kongwa, T6, T3, T5, T2, and T4 had higher values by 20,19, 17, 16, and 15%, respectively compared to T1 (Fig. 5). Lower values were noted for this parameter in Bahi whereby in comparison to control the other

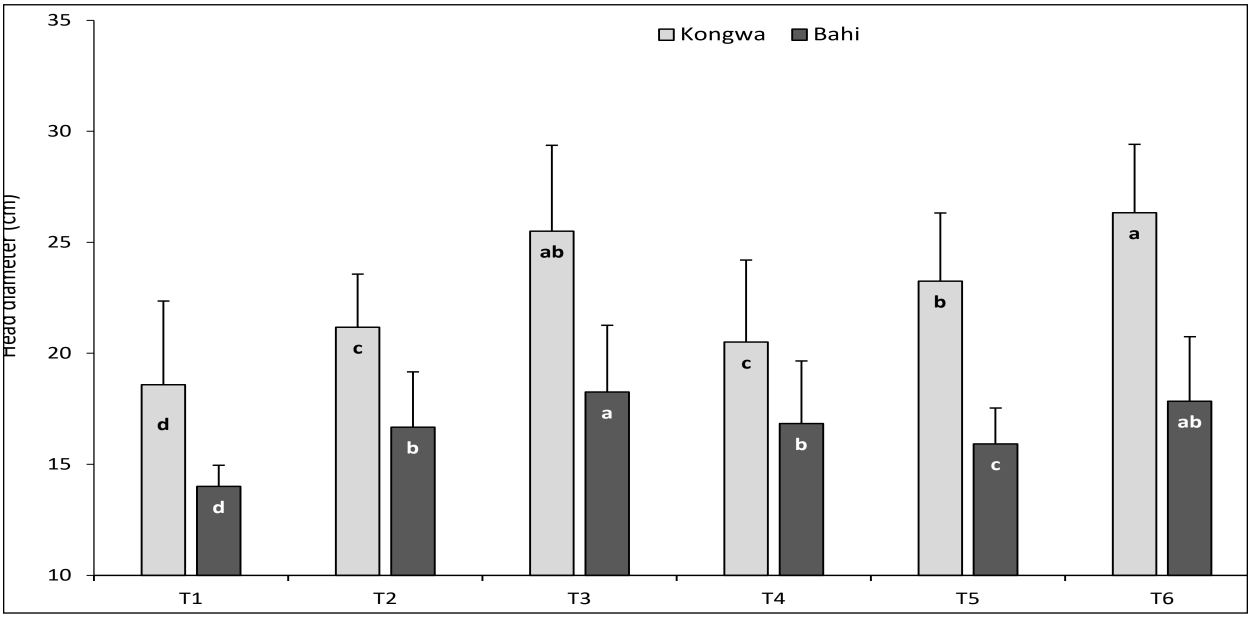

Fig. 5: Sunflower head diameter in Kongwa and Bahi sites during the 2021/2022 crop growing season as affected by mineral N fertilizer under different sunflower-Sunn hemp planting patterns: T1; Control (sunflower pure stand) without fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Bars bearing similar alphabet letters within the same site represent means that do not diverge significantly at $p \leq 0.05$. Error bars indicate the standard error of the means

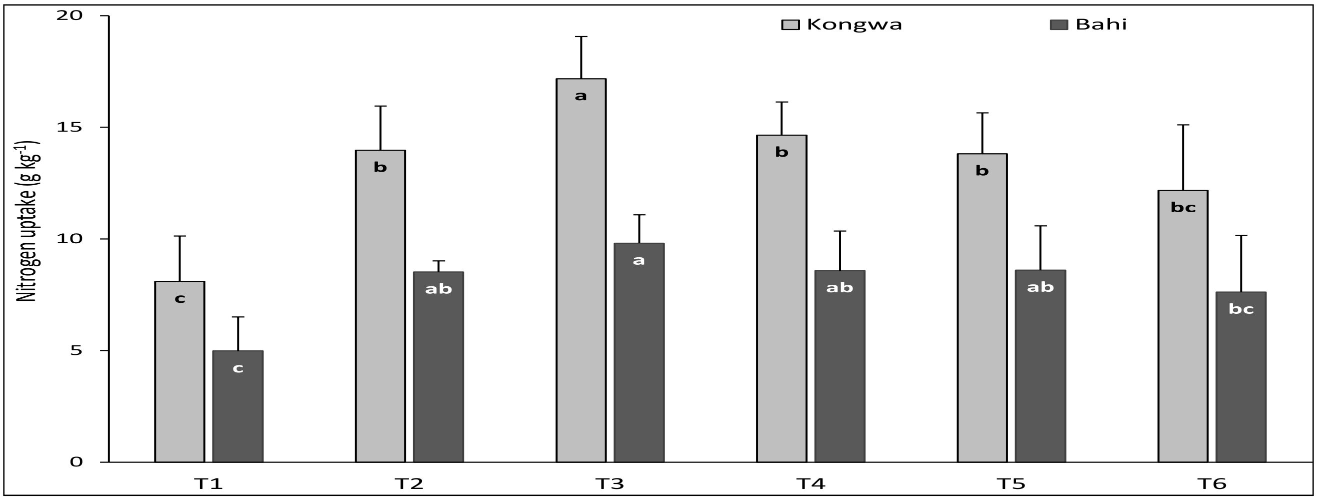

Fig. 6: Sunflower nitrogen uptake in Kongwa and Bahi sites during the 2021/2022 crop growing season as influenced by mineral N fertilizer under different sunflower-Sunn hemp planting patterns: T1; Control (sunflower pure stand) without fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer

treatments had head diameters that were longer by 14–18%.

Nitrogen uptake at the Kongwa site was noted to have increased in the order of T1 (8.1 g kg^{-1}) < T6 (12.2) < T5 (13.8 g kg^{-1}) < T2 (14.0 g kg^{-1}) < T4 (14.6 g kg^{-1}) < T3 (17.2) (Fig. 6). On the other hand, at Bahi it increased in the order of T1 (5.0 g kg^{-1}) < T6 (7.6 g kg^{-1}) < T2 (8.5 g kg^{-1}) < T4 and T5 (8.6 g kg^{-1}) < T3 (9.8 g kg^{-1}).

Effects of Sunflower-Sunn hemp intercropping coupled with mineral nitrogen fertilizer on economic returns

The gross income, net income, and benefit-cost ratio (BCR) differed among the treatments with significantly $p \leq 0.05$) higher economic returns recorded in the Kongwa compared with the Bahi site. The highest (US$ 278 ha^{-1} and the least (US$ 205 ha^{-1}) cost of production were recorded in T5 and T2, respectively with intermediate values being noted in T3 (US$ 248 ha^{-1}) and T4 (US$ 235 ha^{-1}) (Table 3). At the Kongwa site, the highest gross income was recorded in T3 (US$ 3412 ha^{-1}), and T6 (US$ 3327 ha^{-1}), whereas the least value (US$ 1858 ha^{-1}) was recorded in T1 (Table 4). On the other hand, at the Bahi site, the utmost gross income of US$ 1756 ha^{-1} and US$ 1706 ha^{-1} was recorded in T3 and T6, respectively, with intermediate values being noted in T2 (US$ 1414 ha^{-1}), T4 (US$ 1421 ha^{-1}) and T5 (US$ 1271 ha^{-1}). T1 had the least record of gross income of US$ 917 ha^{-1}. Across the sites, the lowest net income was recorded in the control treatment. That is, Kongwa had a net income of US$ 1639 with a BCR of 7.50 while the counterpart treatment at Bahi had respective values of US$ 698 and 3.20 (Table 4).

Relationship among the assessed sunflower growth, yield, and economic parameters

Sunflower plant height, significantly and positively correlated with head diameter, number of seeds per plant, sunflower leaf area, nitrogen uptake, the weight of seeds per plant, grain yield, stover yield, gross income, and net income (r = 0.85 – 0.98) (Table 5). Similarly, sunflower leaf area had direct correlations with the number of leaves and sunflower head diameters, the number of seeds per plant, the weight of seeds per plant, nitrogen uptake, sunflower yields, stover yields, gross and net income (r = 0.83-0.98).

On the other hand, there were strong and positive relationships between sunflower head diameter and the number of seeds per plant, the weight of seeds per plant, nitrogen uptake, sunflower grain yield, stover yields, as well as with gross and net income (r = 0.86 - 0.99) (Table 5). Similarly, the number of seeds per plant exhibited positive relationships with the weight of seeds per plant, grain yield, gross income, net income, and stover yields (r = 0.86- 0.99). Nevertheless, the correlation between the number of seeds per plant and N uptake was observed to be weak. The weight of seeds per plant had positive correlations with sunflower stover yield, yield, net income, and gross income (r = 0.98 - 1.00).

Initial soil chemical properties for the experimental sites

Before the establishment of the experiment, the soil at the Kongwa site had total nitrogen of 0.4 g kg^{-1}, organic carbon of 5.2 g kg^{-1}, and available phosphorus of 62 mg kg^{-1} with a neutral pH of 7.2 (Table 1). It was also found to contain 0.27, 1.65, 0.20, 0.23, and 0.03 cmol kg^{-1} of potassium, calcium, magnesium, and sodium, respectively. On the

Table 3: Variable cost for different treatments at Kongwa and Bahi sites in the 2021/2022 crop-growing season

Site	Treatment	Land preparation	Land lease	Sunflower seeds	Sunn hemp seeds	Planting	Weeding	Pesticides	Fertilizers	Harvesting	Total
					(US$ ha^{-1})						
Kongwa	TI	17.4	54.3	32.6	0.0	13.0	34.8	33.7	0.0	32.6	218.4
	T2	17.4	54.3	32.6	14.8	17.4	23.9	3.5	0.0	41.3	205.2
	T3	17.4	54.3	32.6	14.8	17.4	23.9	3.5	42.8	41.3	248.0
	T4	17.4	54.3	32.6	29.6	21.7	28.2	3.5	0.0	47.5	234.8
	T5	17.4	54.3	32.6	29.6	21.7	28.2	3.5	42.8	47.5	277.6
	T6	17.4	54.3	32.6	0.0	13.0	34.8	33.7	42.8	32.6	261.2
Bahi	T1	17.4	54.3	32.6	0.0	13.0	34.8	33.7	0.0	32.6	218.4
	T2	17.4	54.3	32.6	14.8	17.4	23.9	3.5	0.0	41.3	205.2
	T3	17.4	54.3	32.6	14.8	17.4	23.9	3.5	42.8	41.3	248
	T4	17.4	54.3	32.6	29.6	21.7	28.2	3.5	0.0	47.5	234.8
	T5	17.4	54.3	32.6	29.6	21.7	28.2	3.5	42.8	47.5	277.6
	T6	17.4	54.3	32.6	0.0	13.0	34.8	33.7	42.8	32.6	261.2

T1; Control (sunflower pure stand) without mineral nitrogen (N) fertilizer, T2; Sunn hemp-sunflower intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer.

Table 4: Gross income, net income, and benefit-cost ratio as influenced by mineral nitrogen fertilizer under different Sunflower-Sunn hemp planting patterns at Kongwa and Bahi sites in the 2021/2022 crop growing season

Site	Treatment	Gross income (US$ ha^{-1})	Net income (US$ ha^{-1})	Benefit-cost ratio
Kongwa	TI	1857.78 ± 854^{d}	1639.32 ± 854^{d}	7.50 ± 3.91^{d}
	T2	2274.58 ± 554^{c}	2069.29 ± 554^{c}	10.08 ± 2.70^{c}
	T3	3412.20 ± 123^{a}	3164.08 ± 123^{a}	12.75 ± 0.50^{a}
	T4	2674.22 ± 504^{b}	2439.33 ± 504^{b}	10.38 ± 2.15^{bc}
	T5	3119.11 ± 82^{a}	2841.39 ± 82^{a}	10.23 ± 0.30^{bc}
	T6	3326.89 ±148^{a}	3065.60 ± 148^{a}	11.73 ± 0.57^{ab}
LSD		363.0	363.0	1.64
p value		<.001	<.001	<.001
Bahi	T1	916.67 ± 135^{c}	698.21 ± 135^{d}	3.20 ± 0.62^{c}
	T2	1414.11 ± 508^{b}	1208.82 ± 508^{b}	5.89 ± 2.47^{ab}
	T3	1755.84 ± 472^{a}	1507.72 ± 472^{a}	6.08 ± 1.90^{a}
	T4	1420.71 ± 395^{b}	1185.82 ± 395b^{c}	5.05 ± 1.68^{b}
	T5	1270.62 ± 181^{b}	992.90 ± 181^{c}	3.58 ± 0.65^{c}
	T6	1706.22 ± 495^{a}	1444.93 ± 495^{a}	5.53 ± 1.89^{ab}
LSD		205.6	205.6	0.91
p value		<.001	<.001	<.001

T1; Control (sunflower pure stand) without mineral nitrogen (N) fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Down the column and within the same site, means followed by different letters diverge significantly at p ≤ 0.05.

Table 5: Correlation (Pearson) relationships among the growth (plant height, leaf area, no of leaves $plant^{-1}$, head diameter, and nitrogen uptake) and yield (No. of seeds $plant^{-1}$, the weight of seeds $plant^{-1}$, grain yield, and stover yield), economic (gross income and net income) parameters

Parameter	Plant height	Leaf area	No of leaves $plant^{-1}$	Head diameter	No. of seeds $plant^{-1}$	Weight of seeds $plant^{-1}$	Grain yield	Nitrogen uptake	Stover yields	Gross income
Leaf area	0.912***									
No of leaves $plant^{-1}$	0.733**	0.834**								
Head diameter	0.979***	0.959***	0.768**							
No. of seeds $plant^{-1}$	0.972***	0.980***	0.794**	0.996***						
Weight of seeds $plant^{-1}$	0.972***	0.977***	0.769**	0.995***	0.999***					
Grain yield	0.972**	0.978***	0.772**	0.995***	0.999***	0.999***				
Nitrogen uptake	0.851**	0.662*	0.678*	0.810**	0.672*	0.761*	0.760*			
Stover yields	0.921***	0.953***	0.645*	0.963***	0.967***	0.975***	0.975***	0.635*		
Gross income	0.972***	0.977***	0.769**	0.995***	0.999***	0.997***	1.000***	0.761*	0.975**	
Net income	0.963***	0.966***	0.725**	0.993***	0.993***	0.996***	0.996***	0.752*	0.985***	0.996***

Significant at p < 0.01 (***), p = 0.01 (**) and p ≤ 0.05 (*).

other hand, the Bahi site was slightly acidic with a pH of 6.3, lower total nitrogen (0.4 g kg^{-1}), and organic carbon (4 g kg^{-1}) with available phosphorus of 12 mg kg^{-1}. Nonetheless, besides having lower exchangeable potassium (0.13 cmol kg^{-1}) and sodium (0.22 cmol kg^{-1}) than the Kongwa site, Bahi exhibited higher exchangeable magnesium (2.22 cmol kg^{-1}) and calcium (2.23 cmol kg^{-1}).

Effects of intercropping sunflower with Sunn hemp coupled with the application of mineral N fertilizer on soil chemical properties

Compared with the sunflower pure stand treatment, all the other treatments containing integrated approaches like Sunn hemp and N fertilizer application were found to have an increase in nutrient levels. The soil of the Kongwa site was observed to have a high percentage of nutrient increase (changes) compared to the Bahi site. For instance, at Kongwa, the soil pH dropped from 7.12 (Table 6) to 6.85, 6.92, and 6.90 (Table 6) in the treatments supplied with N fertilizers: T3, T5, and T6, respectively. The soil pH remained almost unchanged in the non-fertilized treatment. Similar results were obtained at the Bahi site, where the soil pH dropped from 6.26 (Table 6) to 6.18, 6.17, and 6.17 (Table 7) in T3, T5, and T6, respectively.

With reference to the baseline value of 5.2 g kg^{-1} for organic carbon at the Kongwa site, there were increases of 8% in T2, 10% in T3, 3% in T4, and 2% in T5, and decreases of 3 and 4% in T6 and T1, respectively (Table 7). At the Bahi site, the organic carbon was higher by 0.2, 0.8, 0.9, 1.2, and 0.2 g kg^{-1} for T6, T2, T3, T4, and T5, respectively, compared to the amount of carbon before the establishment. At the Kongwa site, the total nitrogen values noted in T2 (2.1 g kg^{-1}), T3 (0.6 g kg^{-1}), T4 (0.5g kg^{-1}), and T5 (0.5 g kg^{-1}) were higher by 1.7, 0.2, 0.1, and 0.1 g kg^{-1} relative to the control (T1) (Table 7). Similarly, at the Bahi site, the total nitrogen indicated a positive trajectory with increases of 0.3, 0.4, 0.5, 0.5, 0.5, and 0.6 g kg^{-1} in T1, T6, T3, T2, T5, and T4, respectively,

Table 6: Soil chemical properties at Kongwa and Bahi sites (at 0–0.3 m depth) before the establishment of the experiment in November 2021

Site	Block	pH	Carbon (g kg^{-1})	Nitrogen (g kg^{-1})	Phosphorus (mg kg^{-1})	Potassium (cmol kg^{-1})	Calcium (cmol kg^{-1})	Magnesium (cmol kg^{-1})	Sodium (cmol kg^{-1})
Kongwa	1	7.02	4.72	0.35	67.25	0.28	1.81	0.15	0.22
	2	7.14	4.21	0.52	55.15	0.25	1.42	0.23	0.24
	3	7.15	6.82	0.42	64.03	0.29	2.05	0.23	0.24
	4	7.17	5.20	0.43	62.21	0.27	1.44	0.18	0.22
Bahi	1	6.26	4.20	0.38	13.0	0.11	2.62	0.22	0.24
	2	6.38	3.80	0.38	12.2	0.13	2.82	0.25	0.22
	3	6.28	4.40	0.42	12.6	0.14	1.60	0.23	0.21
	4	6.12	3.60	0.33	10.2	0.14	1.94	0.21	0.22

Table 7: Soil chemical properties for Kongwa and Bahi sites (at 0–0.3 m depth) at the end of the experiment in April 2022

Site	Treatment	pH	Carbon (g kg^{-1})	Nitrogen (g kg^{-1})	Phosphorus (mg kg^{-1})	Potassium (cmol kg^{-1})	Calcium (cmol kg^{-1})	Magnesium (cmol kg^{-1})	Sodium (cmol kg^{-1})
Kongwa	TI	7.13 ± 0.06^{a}	4.8 ± 0.11^{c}	0.4 ± 0.01^{a}	62.35 ± 8.33^{c}	0.33 ± 0.04^{c}	1.70 ± 0.26^{a}	0.22 ± 0.102^{a}	0.22 ± 0.000^{a}
	T2	7.12 ± 0.07^{a}	6.0 ± 0.07^{a}	2.1 ± 0.02^{a}	68.56 ± 8.15^{a}	0.39 ± 0.07^{ab}	1.98 ± 0.17^{a}	0.24 ± 0.131^{a}	0.29 ± 0.056^{a}
	T3	6.85 ± 0.06^{b}	6.2 ± 0.07^{a}	0.6 ± 0.00^{a}	66.96 ± 9.18^{a}	0.41 ± 0.05^{a}	1.85 ± 0.19^{a}	0.22 ± 0.114^{a}	0.26 ± 0.021^{a}
	T4	7.11 ± 0.06^{a}	5.5 ± 0.09^{b}	0.5 ± 0.00^{a}	69.00 ± 8.48^{a}	0.40 ± 0.07^{a}	1.85 ± 0.30^{a}	0.22 ± 0.109^{a}	0.25 ± 0.025^{a}
	T5	6.92 ± 0.06^{b}	5.4 ± 0.09^{b}	0.5 ± 0.01^{a}	66.09 ± 8.81^{ab}	0.40 ± 0.05^{a}	1.80 ± 0.16^{a}	0.22 ± 0.112^{a}	0.25 ± 0.026^{a}
	T6	6.90 ± 0.02^{b}	4.9 ± 0.11^{bc}	0.4 ± 0.00^{a}	63.41 ± 10.84^{bc}	0.35 ± 0.05^{bc}	1.68 ± 0.15^{a}	0.21 ± 0.090^{a}	0.24 ± 0.033^{a}
LSD		0.08	0.5	0.14	3.15	0.05	0.1	0.033	0.042
p value		<.001	<.001	0.38	0.002	0.02	0.099	0.486	0.07
Bahi	T1	6.26 ± 0.01^{a}	4.2 ± 0.05^{b}	0.3 ± 0.01^{c}	11.82 ± 1.25^{a}	0.12 ± 0.01^{b}	2.20 ± 0.469^{a}	0.22 ± 0.020^{c}	0.20 ± 0.017^{a}
	T2	6.26 ± 0.11^{a}	4.8 ± 0.04^{a}	0.5 ± 0.01^{ab}	13.10 ± 0.64^{a}	0.14 ± 0.01^{a}	2.60 ± 0.748^{a}	0.26 ± 0.030^{bc}	0.22 ± 0.016^{a}
	T3	6.18 ± 0.08^{b}	4.9 ± 0.07^{a}	0.5 ± 0.01^{b}	11.90 ± 0.81^{a}	0.14 ± 0.00^{a}	2.70 ± 0.476^{a}	0.28 ± 0.027^{a}	0.26 ± 0.030^{a}
	T4	6.26 ± 0.09^{a}	5.2 ± 0.03^{a}	0.6 ± 0.00^{a}	13.21 ± 0.97^{a}	0.12 ± 0.01^{b}	2.48 ± 0.724^{a}	0.27 ± 0.059^{ab}	0.23 ± 0.044^{a}
	T5	6.17 ± 0.09^{b}	4.8 ± 0.00^{a}	0.5 ± 0.01^{ab}	11.93 ± 1.13^{a}	0.12 ± 0.01^{b}	2.60 ± 0.440^{a}	0.25 ± 0.029^{bc}	0.22 ± 0.016^{a}
	T6	6.17 ± 0.08^{b}	4.2 ± 0.04^{b}	0.4 ± 0.00^{bc}	11.90 ± 1.49^{a}	0.12 ± 0.01^{b}	2.18 ± 0.498^{a}	0.23 ± 0.011^{bc}	0.23 ± 0.025^{a}
LSD		0.031	0.5	0.09	0.715	0.012	0.395	0.038	0.032
p value		<.001	0.003	0.004	<.001	0.002	0.054	0.043	0.061

T1; Control (sunflower pure stand) without mineral nitrogen (N) fertilizer, T2; Sunflower-Sunn hemp intercrop under 1:1 row ratio without fertilizer, T3; Sunflower-Sunn hemp intercrop under 1:1 row ratio with fertilizer, T4; Sunflower-Sunn hemp intercrop under 2:1 row ratio without fertilizer, T5; Sunflower-Sunn hemp intercrop under 2:1 row ratio with fertilizer and T6; Sunflower pure stand with fertilizer. Down the column and within the same site, means followed by different letters diverge significantly at p ≤ 0.05.

compared to the former value (0.4 g kg^{-1}). Total nitrogen decreased by 0.1 g kg^{-1} in the T1 (Table 7).

The highest amount of phosphorus of 69 mg kg^{-1} was measured at Kongwa in T4 and T2, which were noted to have the uppermost increase relative to the baseline value (62 mg kg^{-1}). The smallest change in P was recorded in T3 (0.19 mg kg^{-1}) and T5 (1.25 mg kg^{-1}). At Bahi the results show that available phosphorus dropped by 0.07 mg kg^{-1} in T3, 0.1 mg kg^{-1} in T5 and T6 as well as by 0.18 mg kg^{-1} in T1. In contrast, it increased by 1.21 mg kg^{-1} and 1.10 mg kg^{-1} in T4 and T2, respectively (Table 7).

At the Kongwa site the highest amount of potassium in cmol kg^{-1} was measured in the Sun hemp-Sunflower intercropped plots: T3 (0.41), T5, and T4 (0.40), whereas T1 recorded the least K value of 0.33 cmol kg^{-1}. On the other hand, at Bahi, a higher amount of K of 0.14 cmol kg^{-1} was recorded in T3, and T2 compared to the other treatments where a value of 0.12 cmol kg^{-1} was noted. Based on calcium, at the Kongwa site, T3 recorded the highest percentage increase of 18% relative to the baseline value, followed by T5, T2, and T4 which recorded a 17% increase, whereas at Bahi the percentage increase was 15% in T6 and T1, 17% in T4, and 18% in T2, T5 and T3 (Table 7).

At the Kongwa site, 0.02 cmol kg^{-1} of magnesium in T1, T3, T4, and T5, 0.04 cmol kg^{-1} in T2, and 0.01 cmol kg^{-1} in T6 were found to have been added to the soil compared to its initial amount (0.20 cmol kg^{-1}) before the start of the experiment. On the other hand, at the Bahi site, 0.04, 0.06, 0.05, 0.03, 0.01 cmol Mg kg^{-1} in T1, T2, T3, T4, and T5 respectively were added to the soil relative to the baseline value of 0.22 cmol Mg kg^{-1}. At Kongwa, sodium was found to have decreased in the order of T1 (0.22 cmol Na kg^{-1}) < T6 (0.24 cmol Na kg^{-1}) < T4 and T5 (0.25 Na cmol kg^{-1}) < T3 (0.26 Na cmol kg^{-1}) < T2 (0.29 Na cmol kg^{-1}). On the other hand, at Bahi, Na was in the order T1 (0.20 cmol Na kg^{-1}) < T2 and T5 (0.22 cmol Na kg^{-1}) < T4 and T6 (0.230 cmol Na kg^{-1}) < T3 (0.29 cmol Na kg^{-1}).

DISCUSSION

Effects of Sunn hemp combined with mineral fertilizer on sunflower growth parameters and yield under mono and inter-cropping systems

There was measurable evidence that the treatments that contained Sunn hemp alone, mineral fertilizers alone, or combined Sunn hemp and N fertilizers, showed improvements in the plant height, leaf area, number of leaves, sunflower head diameter, number of seeds per plant, the weight of seeds per plant, sunflower yield, nitrogen uptake, and sunflower stover yields. Under intercropping of Sunflower and Sunn's hemp coupled with the application of nitrogenous there was improved growth and yield of sunflower. This could be attributed to the addition of nitrogen nutrients through the supplied nitrogenous fertilizers as well as by the Sunn hemp, through its process of nitrogen fixation.

Again, all the treatments that contained Sunn hemp and nitrogenous fertilizers outperformed the control treatments in terms of sunflower plant height. Such could be attributed to the nitrogen nutrient supplied by the legume plant as well as the additional supply from the fertilizer. Similar results were reported by Solemani *et al.* (2013), who confirmed that increasing nitrogen in the soil also increases the sunflower height. In addition, the results of this study agree with the findings of Abu-Alrub *et al*. (2014), who found that the use of nitrogen fertilizers in the soil led to a considerable rise in the height of buffel grass in contrast to the unfertilized soil. Sunn hemp could as well have helped in increasing the availability of nutrients to Sunflower due to its deep extensive root system that takes the nutrients beyond the root zone and pumps them to the topsoil layer. Sunn hemp provided additional benefits to sunflower such as conserving soil moisture (through its extensive crop cover) and suppressing pests, weeds, and diseases.

Regarding the sunflower leaf area, the results showed that in both locations, at all three sunflower growth phases, T6 and T3 had particularly large leaf areas. This could be because these treatments contained nutrients such as N from nutrients cycling by Sunn hemp which allowed the sunflower leaves to expand in width and length resulting in greater leaf area. These findings are consistent with the ones of Nasar *et al*. (2021, 2022b), who found that nitrogen increased the photosynthetic activities of maize plants which improved the leaves' characteristics including leaf area and the number of leaves. Similarly, Iqbal *et al*. (2001) reported that some of the phenological sunflower parameters such as leaf area, the number of leaves per plant, head diameter, and height of the plant were maximized at the N level of 120 kg ha^{-1}. Furthermore, the results are in line with those of Moghimi and Maghsoudi (2015) and Sher *et al*. (2016), who discovered that sorghum cultivars with higher nitrogen rates produced more leaves and a big leaf area. The small leaf area in the other treatments like in the 2:1 intercropped treatment could be because of the spatial arrangements of the crops which did not support the full expansion of leaves. The same could be attributed to poor nutrients and moisture availability to support sunflower growth.

Concerning the number of leaves, the results showed that, there was a noticeable variation in the total number of leaves per plant between treatments and across all sunflower developmental phases. The highest number of leaves recorded in the fertilized Sunflower-Sunn hemp intercrop plots could be attributed to the nutrients that had been added to the soil, which supported the plant to bear a greater number of leaves. Analogous results have been published by Ochieng' *et al*. (2021), Raza *et al*. (2022), and Chandler (2015) who observed that supplying plants with nitrogen increases their number of leaves and plant height. The greatest variation in the number of leaves per plant observed during the three stages could be attributed to the fact that the leaves are actively created during the vegetative stage, fully produced and active during the flowering stage, and drying up during the harvesting stage (De la Haba *et al.* 2014).

Sunflower head diameter, number of seeds $plant^{-1}$, the weight of seeds per plant, and grain yields were noted to be significantly high in the plots of Sunflower-Sunn hemp intercropping under a 1:1 row ratio with fertilizer. This could have resulted from the release of nutrients by biological nitrogen fixation and nutrient cycling by Sunn hemp, and/or N fertilizer application that helped the sunflower to perform better in the mentioned parameters. In their field study, Olalde *et al*. (2000) presented similar results, where they reported that increasing nitrogen levels help in increasing the production of biomass, seed yields, the number of achenes per capitulum, and head diameter. The results are also in agreement with Singh *et al*. (2000) who observed that increasing nitrogen application leads to an increase in oil contents, head diameter, as well as the number of seeds. A big head diameter leads to more number seeds (Babec *et al.* 2020), then a high weight of seeds which finally achieves the highest sunflower grain yield.

In addition to the added nutrients, another probable explanation for improved yield parameters under intercropping coupled with N application is the spatial arrangement of the crops. For instance, in the 2:1 Sunn hemp-sunflower arrangement there was competition for some natural resources like light and space (Jeranyama *et al.* 2000; Gitari *et al.* 2018b). On the other hand, in the control plots, the performance in the mentioned parameter was poor compared to all the treatments with N probably because of the limited nutrients and moisture. It was noted that all the treatments with the highest plant height had good sunflower yields. This agrees with Kaya (2016) who confirmed that plant height indirectly affects seed yield through leaf area and petiole length, for that case sunflower yields depend on the performance of other sunflower growth parameters.

With regards to nitrogen uptake, it was observed to be high in T6 and T3 compared to other treatments. This could be attributed to the N fertilizers supplied in the soil as well as the biological nitrogen fixation performed by the Sunn hemp legume. Under such cases, the released nitrogen could have been taken up by the sunflower hence the highest nitrogen concentration in the leaves. This agrees with the article published by Hooks *et al*. (2007) who observed a high nitrogen content in the cucumber leaves, grown under the Sunn hemp-cucumber intercropping system.

Based on the results obtained, T6 and T3 recorded the highest sunflower stover yields, which could be attributed to the nutrients supplied by the combination of N fertilizers and BNF by Sunn hemp. Similar results were reported by Dzvene *et al*. (2022) who confirmed that intercropping Sunn hemp with maize has substantial positive impacts on the amount of biomass produced by maize in terms of the yield. As documented by Cheptoek *et al*. (2021), Chandler (2015), and Ochieng' *et al*. (2021), supplying plants with nitrogen increases their leaf number, plant height, stem diameter, leaf area, internode length, and the number of internodes hence high yield. The results show that the treatments that performed better in other parameters also had good performance in sunflower stover yields.

Across the sites, the Kongwa site showed good performance in sunflower growth parameters and yields, this could be because of the low temperature recorded at Kongwa which did not affect the availability of the limited soil moisture. This contrasts with the Bahi site, which was observed to have a high amount of temperature, which affected the availability of the limited soil moisture by evapotranspiration, leading to poor performance of the crops. Similar results have been published by Bhatt and Hossain (2019) whereby they observed that higher daytime temperatures cause a greater daily increase in the evaporative demand and consequently higher evapotranspiration rate. Drought stress, especially high temperature significantly reduces many aspects of yield, including 1000-achene weight, capitulum diameter, achene weight per capitulum, and achene number per capitulum (Tyagi and Dhillon, 2015; Seleiman *et al.* 2021; Goher *et al.* 2023).

Effects of Sunn hemp combined with mineral fertilizer on Sunflower profitability under Mono and intercropping systems

High crop yield is the most important result of crop production since it leads to greater benefit-cost ratios and economic returns. This research showed that different factors had significant effects on sunflower crop performance in the field, which in turn affected sunflower yield and the crop's economic worth. Poor economic return was noted in the control treatment. The reason behind this could be the limited nutrients and moisture to support sunflower yield, which resulted in low economic returns. The treatments that had an integrated approach, including intercropped ones showed high economic returns compared to the control. Similar results were published by Ahmed and Hefzy (2020), who agreed that the intercropped sunflower and legume beans resulted in high economic returns compared to pure stand sunflower. The results also concur with those of Hooks *et al.* (2007) who reported that intercropping cucumber and Sunn hemp, resulted in high cucumber yields hence high economic returns. Similarly, Olalde *et al.* (2000) in their article they reported that increasing nitrogen levels help in increasing sunflower seed yields which also increases economic return.

The net income was higher and almost the same in fertilized sole sunflower treatments and the treatments of fertilized 1:1 Sunn hemp + sunflower. This was because the income of Sunn hemp was not factored in as an immediate economic return (Dzvene *et al.* 2022). Otherwise, by putting the Sunn hemp income, all the intercropped treatments would have shown high profit compared to sole sunflower treatments.

At Kongwa, the generally better good performance in terms of yields and economic returns than at Bahi could be ascribed to the low temperature recorded at Kongwa, which probably did not affect the availability of the limited soil moisture. In contrast, the Bahi site was observed to have a high ambient temperature, which must have affected the availability of the limited soil moisture by evapotranspiration, leading to poor performance of the crop and hence poor yield which resulted in poor sunflower economic returns. Flower anthesis and initiation are critical growth stages in sunflower production (Göksoy *et al.* 2004; Hussain *et al.* 2015) because the number of florets and the fertile flowers determines the achene yield. The high temperature at this stage of development reduces pollen viability, causing smaller heads, and reducing yields (Khalilvand *et al.* 2007; Benlloch-González *et al.* 2015; Göksoy *et al.* 2004; Elsheikh *et al.* 2015). Many aspects of yield, such as head diameter, number of achenes per head, the weight of seed per capitulum, and 1000-achene weight, are drastically reduced by drought stress (Tyagi and Dhillon, 2015).

Relationship among the assessed sunflower growth, yield, and economic parameter

Sunflower plant height strongly correlated with sunflower head diameter, the number of seeds per plant, sunflower leaf area, nitrogen uptake, the weight of seeds per plant, grain yield, stover yield, gross income, and net income. This indicated that the higher the plant height the more the leaves which lead to a high rate of photosynthetic activities hence good performance of the plant in other parameters. It was noted that all the plants with high plant height performed better in other growth parameters and economic returns. Kaya (2016) confirmed that plant height indirectly affects seed yield through leaf area and petiole length, for that case sunflower yields depend on the performance of other sunflower growth parameters. Tyagi and

Dhillon (2015) also observed that sunflower plant height has a strong relationship with head diameter, which also affects other parameters like the number of seeds, gross income, the weight of seeds, yields, and net income.

The direct correlations of the Sunflower leaf area with the number of leaves and sunflower head diameters, the number of seeds plant^{-1}, the weight of seeds plant^{-1}, nitrogen uptake, sunflower yields, stover yields, gross and net income could be due to the big the leaf area. With a large leaf area, it is expected that there are more photosynthetic activities which ultimately results in high growth and finally affects the yield parameters as well as economic return. Earlier studies by Tyagi and Dhillon (2015) reported similar results, that sunflower leaf area had indirect impacts on sunflower growth parameters, yields as well as economic return.

The positive strong relationships between sunflower head diameter and the number of seeds plant^{-1}, the weight of seeds plant^{-1}, sunflower grain yield, and stover yields, as well as with gross and net income, are associated with the size of the sunflower head. Consequently, this impacts the number of seeds, the weight of seeds, and grain yield (Babec *et al.* 2020), as well as gross and net incomes. Similarly, as noted by Balalić (2016), sunflower seed yield is equally affected by head size, which determines both the number of seeds per head and the average size of those seeds.

The number of seeds per plant exhibited positive relationships with the weight of seeds per plant, grain yield, gross income, net income, and stover yields. This was an indication that the more the number of seeds the higher the grain yields and the higher the gross and net income. Earlier, Tyagi and Dhillon (2015) confirmed that the number of seeds per plant leads to positive impacts on other parameters. Nevertheless, the correlation between the number of seeds per plant and N uptake was observed to be weak. Such an observation was not a surprise since N uptake was analyzed from the leaves and not from the seeds. The observed positive correlations between the weight of seeds per plant and sunflower stover yield, yield, net income, and gross income could be ascribed to the higher weight of the seeds (Hladni *et al.* 2016). This translated into high net income and gross income.

Effects of Sunn hemp combined with mineral fertilizer on soil chemical properties under mono and inter-cropping systems

Soil samples from the fields revealed statistically significant evidence of soil modification in all the plots where Sunn hemp was planted alongside sunflowers. Nutrients were noted to increase in the treatments containing Sunn hemp legume. Probably this is because Sunn hemp has a long taproot. Such a deep rooting system might have facilitated Sunn hemp to take the nutrients beyond the root zone of Sunflower. Hence this reduced the nutrients lost through the process of leaching and fixation (Hopkins *et al.* 2014; Gitari *et al.* 2018a; Fernandes and Soratto, 2012). *Crotalaria juncea* is the most popularly utilized legume as green manure under intercropping due to its rapid development, robust annual structure, upright stem, large biomass output, and ability to fix atmospheric N_2 and recycle various soil nutrients (Vargas *et al.* 2011). Moura *et al*. (2005) noted that any legume takes around 50 days to break down and release approximately 30% of N present in the plant material.

Total soil nitrogen was found to increase slightly in plots that contained Sunn hemp. This could be because Sunn hemp undergoes biological nitrogen fixation thereby adding some amount of nitrogen to the soil. These findings are in agreement with the earlier reports by Perin *et al*. (2006) who found that in the maize-sunn hemp intercropping system, the Sunn hemp accumulated about 144 kg N ha^{-1}. The nitrogen contents were reported to be much higher in the treatments with Sunn hemp, which could be beneficial to the subsequent crop in the field (Vargas *et al.* 2011). These results concur with those of Rotar and Joy (1983) and Mansoer *et al*. (1997) whereby Sunn hemp was reported to have added about 160 and 143 kg of N per ha, respectively after 60 to 70 days of its growth. Similar results were obtained by Ramos *et al*. (2001), which showed that Sunn hemp accumulated about 150 kg N ha^{-1} under Maize-Sunn hemp intercropping. The results are also in agreement with Chappa *et al*. (2022), who revealed that the inclusion of legumes like Sunn hemp in an intercropping system could result in symbiotic N fixation and ultimately higher yield. Approximately, 38% of the N in biomass continued to be available for maize that was planted 16 weeks after mowing the Sunn hemp (Mansoer *et al.* 1997).

The soil organic carbon in all the treatments containing Sunn hemp increased, compared to the other treatments. This could be ascribed to the ability of Sunn hemp to produce high biomass which after decomposition increases the soil's organic carbon. These findings corroborate those of Freidenreich *et al.* (2022) in which Sunn hemp was reported to speed up the release of organic matter in cropping systems. Similarly, Bhayal *et al*. (2018) observed that intercropping Sunn hem and soybeans resulted in increased soil organic carbon. When intercropped with maize, Winter legume (Sunn hemp) offers many benefits, such as soil erosion control, enhanced water infiltration, increased organic C contents, as well as cooling the soil temperatures (Reeves, 1994; Heydarzadeh *et al*. 2023). Sole sunflower treatments supplied with N fertilizers also showed a positive increase in soil organic carbon. This could be because of the nitrogen supplied, which supported the biomass yield of the crops, in turn, increased the soil's organic carbon. Such results are also supported by Jin (2018), who confirmed that N fertilization increases the organic carbon of the soil profile. In the treatments without Sunn hemp, the organic carbon was confirmed to be low. Such an observation could be attributed to the low amount of biomass, as well as poor soil moisture which does not support organic matter decomposition.

It was observed that all the plots with the integrated approach had high available phosphorus compared to the control. This could be due to the deep extensive roots of Sunn hemp which take residual phosphorus beyond the root zone. More so it could be associated with increased biomass production, which released nutrients into the soil. These results also corroborate with those of Wang *et al*. (2011) who reported that Sunn hemp (*Crotalaria juncea*) accumulates a high amount of P and N because of its high production of biomass.

Exchangeable bases increased in all the treatments containing Sunn hemp after crop harvest. This could be because of the long tap rooting system of Sunn hemp, which enabled it to take the residual exchangeable bases below the root zone. Such a phenomenon agrees with the results published by Dzvene *et al.* (2022) who demonstrated that Sunn hemp encourages the cycling of nutrients by boosting the activity of microbes hence the release of the nutrients. The soil pH was observed to be unaffected in the non-fertilized treatments, but some slight changes in the treatments that contained N fertilizers were observed. This could be attributed to the use of urea fertilizers which could have released protons that affected the soil reaction. Similar results have been reported by Shetty *et al*. (2019) who demonstrated that urea adds bicarbonate to the soil which reacts with soil H^+ ions hence lowering soil pH. In summary, the utilization of an integrated approach, such as the combination of Sunn hemp and mineral fertilizer, demonstrated a good effect on the chemical characteristics of the soil.

CONCLUSION

This study sought to improve soil chemical properties, sunflower production, and economic returns using integrated approaches (Sunflower-Sunn hemp intercropping or Sunflower-Sunn hemp intercropping in combination with mineral N fertilizer). It intended to find out the most ideal approach in sunflower production that would improve its growth, yield, and profitability. The study showed that sunflower can grow and produce optimally besides giving higher economic returns, particularly when it is intercropped with legumes such as Sunn hemp coupled with the application of nitrogenous fertilizer. It is anticipated that the increased production of sunflower would help in improving the nutritional needs and the social economics of the impoverished smallholder farmers, hence reducing poverty, and increasing food security.

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