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The association of mulch cover and organic fertilization improves the agronomic performance of millet under rainfed cultivation in a semi-arid environment

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A B S T R A C T

This study aimed to evaluate the agronomic performance of millet in response to the application of organic fertilizer combined with different levels of mulch cover on the soil. The research was carried out in the Brazilian semi-arid. The experimental design was randomized in blocks under split plots, with four replications. Five levels of mulch cover were applied (0, 1, 2, 3, and 4 Mg DM ha^{-1}), and tested combined with and without organic fertilization (30 Mg ha^{-1} of cattle manure). The agronomic characteristics of the millet cultivar were evaluated: stem length and diameter, number of tillers, inflorescence length, leaf area, leaf area index; gas exchange (photosynthesis, stomatal conductance, and instantaneous water use efficiency); and the dry mass yields. In general, morphological traits, CO_2 assimilation rate, stomatal conductance, and water use efficiency were improved by the use of organic fertilizer combined with the increasing levels of mulch cover. The greatest number of tillers per plant (5.75) was observed with organic fertilization combined with the application of 4 Mg DM ha^{-1} of mulch cover ($p<0.05$). The greatest level of mulch cover could increase photosynthesis by 79%. The application of mulch cover at the level of 4 Mg DM ha^{-1} favored better growth responses and yields of the millet. The use of mulch cover potentialized the effects of the organic fertilizer on the millet.

Keywords: Cattle manure; cover crop; CO_2 assimilation; forage production; *Pennisetum glaucum*.

A associação de cobertura morta e adubação orgânica melhora o desempenho agronômico do milheto sob cultivo de sequeiro no semiárido

R E S U M O

Este trabalho teve como objetivo avaliar o desempenho agronômico do milheto em resposta à aplicação de adubo orgânico combinado com diferentes coberturas mortas no solo. A pesquisa foi realizada no semiárido brasileiro. O delineamento experimental foi casualizado em blocos em parcelas subdivididas, com quatro repetições. Cinco níveis de cobertura morta foram aplicados (0, 1, 2, 3 e 4 Mg MS ha^{-1}), e testados combinados com e sem adubação orgânica (30 Mg ha^{-1} de esterco bovino). Foram avaliadas as características agronômicas da cultivar de milheto: comprimento e diâmetro do caule, número de perfilhos, comprimento da inflorescência, área foliar, índice de área foliar; trocas gasosas (fotossíntese, condutância estomática e eficiência instantânea do uso da água); e a produção de matéria seca. Em geral, as características morfológicas, a taxa de assimilação de CO_2, a condutância estomática e a eficiência do uso da água foram melhoradas pelo uso de fertilizante orgânico combinado com níveis crescentes de cobertura morta. O maior número de perfilhos por planta (5,75) foi observado com a adubação orgânica combinada com a aplicação de 4 Mg MS ha^{-1} de cobertura morta ($p<0,05$). O maior nível de cobertura morta poderia aumentar a fotossíntese em 79%. A aplicação de cobertura morta na dose de 4 Mg MS ha^{-1} favoreceu melhores respostas de crescimento e produtividade do milheto. A utilização de cobertura morta potencializou os efeitos da adubação orgânica sobre o milheto.

Palavras-chave: Assimilação de CO_2; cobertura morta; esterco bovino; *Pennisetum glaucum*; produção de forragem.

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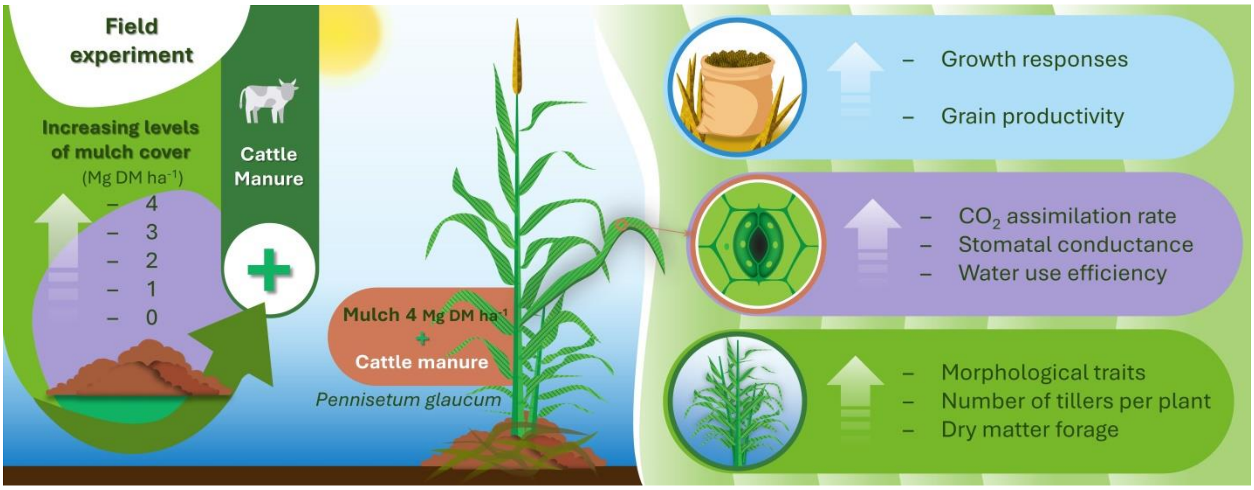

Graphic abstract: Effects of association of organic fertilization with different levels of mulch on structural characteristics, photosynthetic responses, and forage production in pearl millet.

Introduction

Water resources are scarce in several areas of the world, especially in arid and semi-arid regions, where it is a recurring problem that has negatively impacted the sustainability of agricultural production and food security (Kumar et al., 2021). The search for adapted crop species and improvement of the management practices in production systems of these areas has been the alternative currently explored to mitigate the problems associated with this variability in water supply, high temperatures, and soils with low fertility. These management practices are considered resilient actions available for the producers in rainfed regions (Araujo et al 2021).

In the Northeast region of Brazil, characterized by the predominance of a semi-arid climate, there is a lack and irregularity of rainfalls combined with high evapotranspiration (Silva et al., 2023; Jardim et al., 2023). These factors impact the biomass production of most crops and forage plants. Among the strategies to produce forage under semi-arid conditions, can be highlighted the use of forage species adapted to dry environments (Simões et al., 2022), controlled irrigation (Girma and Jemal, 2020), organic fertilization (Silva et al., 2023), and use of mulch cover (Souza et al., 2022).

Millet (*Pennisetum glaucum* L.) is a dual-purpose forage grass, its grain is used for human consumption and forage for feeding ruminants, mainly in silage and direct grazing. It is an important crop for agriculture and livestock production in semi-arid areas, especially under rainfed systems (Bijarnia et al., 2020). Millet potential is a consequence of its low water requirements (~350 mm), tolerance to high temperatures (42°C), low cost of cultivation and management, short growth cycle, high nutritional quality, and adaptation to semi-arid edaphoclimatic conditions (Bijarnia et al., 2020; Almeida et al., 2021; Kavya et al., 2023). India is the country responsible for approximately 42% of the global production of millet. India is the country responsible for approximately 42% of the global production of millet. On a productive scale, the millet cultivated area was 7.34 million hectares producing 10.86 million tons, representing a productivity of 1,436 kg ha-1 (Kavya et al., 2023).

Inefficient plant nutrition contributes to reduced soil fertility. The high price of inorganic fertilizers has increased the non-reposition of soil nutrients in agricultural areas, mostly under subsistence agriculture (Coulibaly et al., 2019). Currently, several studies have shown the benefits of using organic fertilizers, which include the availability of soil nutrients, improvements in soil structure and aggregates, increases in soil water holding capacity, and reduction of fertilization costs, among others (Assefa and Tadesse, 2019; Coelho et al., 2021; Liu et al., 2022; Pei et al., 2023). Even when the release of the nutrients from some organic fertilizers is slow (indigested or fresh manure), there are positive impacts on the yields of forage crops (Vital et al., 2020; Kumar et al., 2021; Zhai et al., 2022; Liu et al., 2023).

The use of mulch cover has been suggested as an alternative agricultural management for reducing the impacts of the absence of water or high evapotranspiration in semi-arid regions (Tuure et al., 2021; Chai et al., 2022; Souza et al., 2022; Dantas et al., 2023). Several benefits of using mulch cover can be highlighted including the retention of soil moisture, less variation in soil temperature, greater microbial activity, reduction of erosion and surface runoff, and better soil aeration (Souza et al., 2022). In addition, mulch cover also plays other important roles as a source of nutrients due to the decomposition of its biomass, and suppression of weeds (Kader et al., 2017; Webber et al., 2022).

Previous studies evaluated the effects of organic fertilization (Vital et al., 2020; Kavya et al., 2023), mulch cover associated with the intercropping of millet with cactus (Souza et al., 2022), and the use of wastewater on millet gas exchange in a greenhouse (Silva et al., 2021). However, no study has investigated the interactions of organic fertilization associated with different levels of mulch cover in millet cultivation in semi-arid areas. Furthermore, the present study brings newer investigating the association of these management practices with growth characteristics, forage production, and gas exchange of millet in rainfed cultivation in a semi-arid environment.

The objective of this study was to evaluate the agronomic characteristics, forage production, and gas exchange of millet under organic fertilization combined with different levels of mulch cover in rainfed cultivation in the semi-arid region. We hypothesize that organic fertilization and the use of increasing levels of mulch can improve the morphophysiological and productive characteristics of millet.

Material and methods

The experiment was carried out from March to May 2019, at Lagoinha Farm, located in the city of Serra Talhada-PE, Pajeú microregion, 496 m a.s.l, latitude: 7º 55'48” S and longitude: 38º 17' 8” W (Figure 1). According to the Köppen classification, the climate of the region is BShw' type, semi-arid, hot, and dry. The rainy period occurs between December to May, and March is the rainiest month. The annual average precipitation is 642 mm year^{-1} (Alvares et al., 2013).

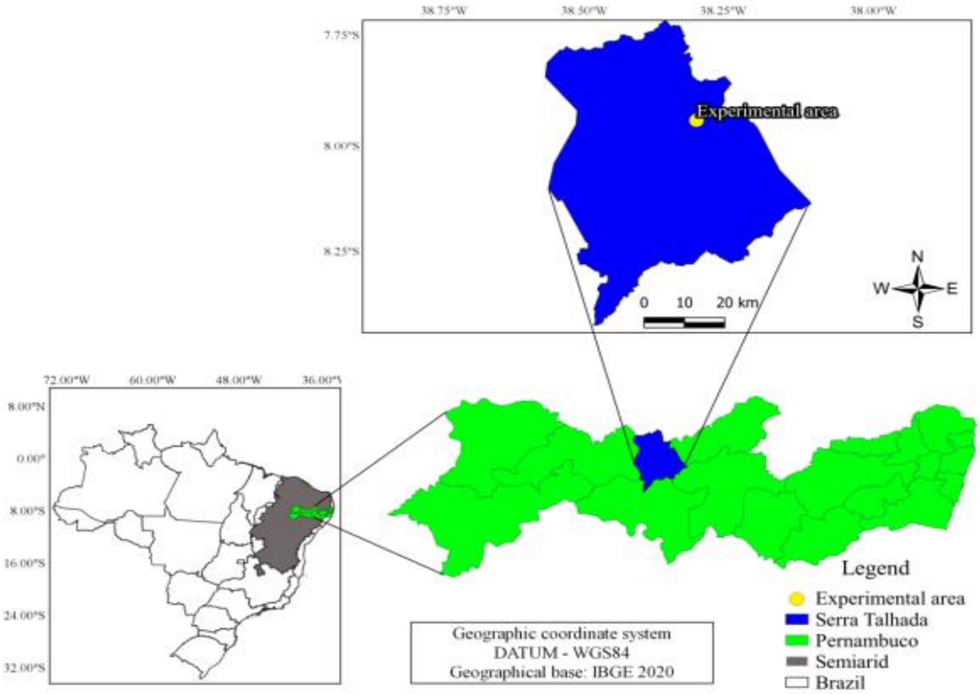

Figure 1. Location of the experimental area, Lagoinha Farm, Serra Talhada-PE, Brazil.

The meteorological variables (precipitation, air temperature, evapotranspiration, and air humidity, Figure 2) were measured at an automatic station of the National Institute of Meteorology (INMET), located in Serra Talhada city, Pernambuco, Brazil. Reference evapotranspiration was calculated using the Penman-Monteith method available in the FAO-56 bulletin (Allen et al., 1998). During the experimental period, the accumulated rainfall was 365.6 mm. The soil chemical analysis and physical of the experimental area in millet values were in (Table 1) and (Table 2), respectively.

The millet (*Pennisetum glaucum* (L.) R. Br.) cultivar IPA BULK 1 BF was planted on January 4th 2019, at 4.0 cm depth, with 0.70 m planting spacing between rows. After seven days, a standardization removal of plants was performed, leaving 15 plants per linear meter, resulting in an average population of 214,000 plants ha^{-1}. On March 15th 2019, a standardization cut was carried out at 10 cm height above the ground. After the standardization, the plants began to be monitored and evaluated.

The experimental design was randomized in blocks, with split plots. The main plots were composed of two conditions of organic fertilization (absence and fertilization with 30 Mg OM ha^{-1}), and the subplots by five mulch cover levels (0, 1, 2, 3, and 4 Mg DM ha^{-1}), with four replications. The plots had dimensions of 112 m^2 (14.0 x 8.0 m) and the subplots of 11.2 m^2 (2.8 x 4.0 m). The sampling area of each subplot comprised the two central rows, with experimental borders of 1.0 m at each side, totaling a 2.8 m^2 area per plot.

The source of organic fertilizer was matured cattle manure. This manure was produced by the herd of the experimental station. The manure was manually surface applied at a rate of 3.4 kg OM m^2, on January 3rd 2019, based on the recommendation of Cavalcanti et al. (2008). The chemical characteristics of cattle manure were 24.74 g kg^{-1} of nitrogen, 3.16 g kg^{-1} of phosphorus, 28.50 g kg^{-1} potassium, 37.31 g kg^{-1} calcium, 7.58 g kg^{-1} of magnesium, 695.03 g kg^{-1} of organic matter, 347.51 g kg^{-1} of carbon, and a carbon:nitrogen ratio of 14.

During the trial, manual weeding was carried out eventually. The mulch cover was applied on March 14th 2019, using the straw of the native pasture present in the experimental station, which was mostly composed of *Urochloa mosambicensis* (Hack.) Dandy. The levels of mulch cover applied were 0, 1, 2, 3, and 4 Mg DM ha^{-1}.

Two plants were evaluated in the sampling area of each subplot. Among the morphological variables measured included: stem length – measured from the base of the stem to the insertion of the flag leaf; stem diameter – measured at the base of the stem at 5 cm from the ground; the number of tillers – counted manually; panicle inflorescence length – from the insertion to the apex of the panicle; leaf blade length – measured from the ligule to the end of the leaf blade; and leaf blade width – measured from the middle region of the leaf blade. A digital caliper, measuring tape, and a millimeter ruler were used in the measurements taken 60 days after the standardization cut. The leaf area was estimated at 30 days of regrowth, based on measurements of the length and width of the leaf blade according to Leite et al. (2019). The leaf area index (LAI) was recorded using the light meter device AccuPAR LP - 80, Decagon Devices, Pullman, USA. Readings were taken at 30 days of regrowth, between 11:00 am and 12:00 pm, in the useful area of each subplot.

Plant gas exchange was recorded at 45 and 60 days of regrowth. The measurements were taken at the leaf level: net CO_2 assimilation, stomatal conductance, and water use efficiency (net CO_2 assimilation/transpiration). To measure these variables, a Portable Infrared Gas Analyzer model Licor 6400XT was used, operating using artificial light of 1000 µmol of photons m^{-2} s^{-1}. The readings were performed on the third fully expanded leaf, from top to bottom, between 8:00 am and 11:00 am. These measurements were recorded in one plant per subplot.

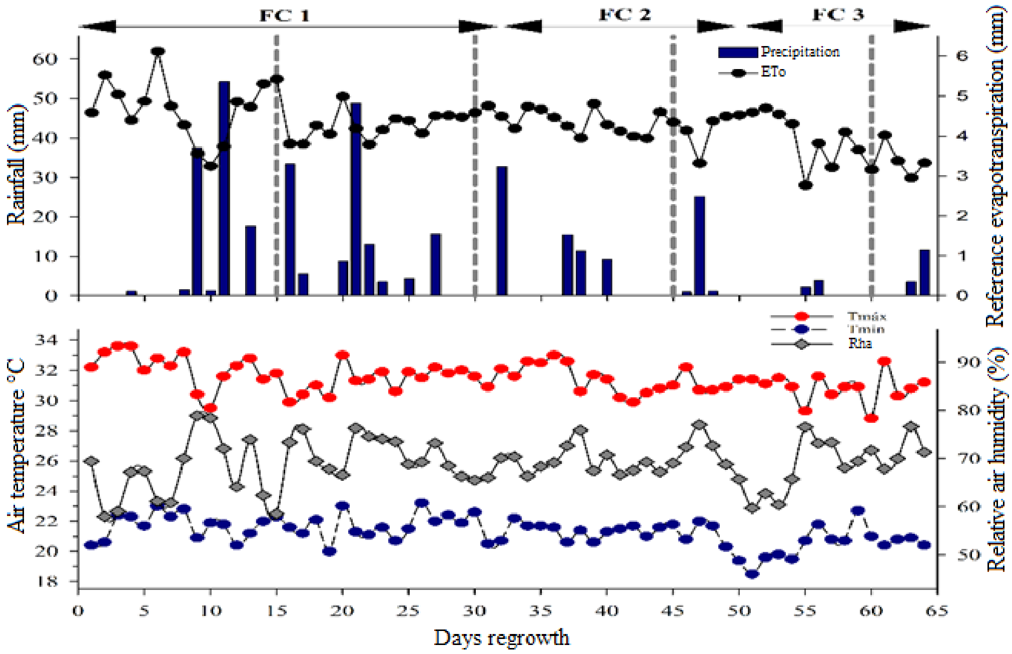

Figure 2. Precipitation and rainfall distribution, reference evapotranspiration (ETo), maximum (Tmax) and minimum (Tmin) air temperature, and relative air humidity during the experimental period, Serra Talhada-PE, Brazil. The dashed lines indicate the evaluation period and the millet phenophases (FC1 – vegetative, FC2 – inflorescence formation, and FC3 – grain phase).

Table 1. Soil chemical analysis in millet with different levels of mulch and organic fertilization.

L	P	pH	K	Al	Ca	Mg	Na
	mg/dm^3	(H_2O)	cmol$_c$/dm^3				
0-10	28	7.90	0.80	0.00	11.50	1.50	0.70
20-30	8	7.90	0.15	0.00	8.70	1.80	1.11

L = layer; P = phosphorus; K = potassium; Al = aluminum; Ca = calcium; Mg = magnesium; Na = sodium.

Table 2. Soil physical analysis in millet with different levels of mulch and organic fertilization.

L	D	Granulometry (%)			NC (%)	F (%)	T (%)	AW	
		Sand	Silt	Clay				(%)	(mm/cm)
0-10	2.52	28	22	10	4	78	SA	20.46	2.93
20-30	2.52	29	21	10	6	67	SA	14.08	2.01

L = layer; D = density; NC = natural clay; F = flocculation; SA = Sandy loam; T = texture; AD = available water.

The harvesting occurred on May 17th 2019, and all plants in the useful area of the plots were harvested. They were cut at the ground level, and they were weighed to estimate the green mass production (GMP). Then, the following morphological components were separated and weighed on a precision scale: live leaves (sheath, ligule, and leaf blade); stem, panicle inflorescence, and dead material. After this procedure, the subsamples were dried in an oven at 65 °C until they reached constant weight. Dry matter production (DMP) was estimated based on the total dry mass (Detmann et al., 2012). Rainfall use efficiency (RUE) was estimated by dividing the DMP by the accumulated rainfall during the experimental period (365.6 mm^{-1}) (Perazzo et al., 2013).

The data were subjected to the Shapiro-Wilk normality test and Bartlett's homoscedasticity test. Once the assumptions of these tests were met, the analysis of variance (Test F) and Tukey's test were performed to compare means ($p<0.05$). The interaction effect between organic fertilization and mulch cover ($p<0.05$) was tested. When the level of mulch cover was significant, regression analyses were performed. The software used for processing the statistical analyzes was the R statistical software (Team Core R, 2022), and the graphs were produced in SigmaPlot 14.0.

Results

The organic fertilization showed no significant influence on the morphological variables stem length and diameter, and also, inflorescence length ($p>0.05$). However, these variables showed a significant influence from the level of mulch cover applied ($p<0.05$). The stem length showed a quadratic behavior to the level of mulch cover, while stem diameter and inflorescence length showed a linear response (Figure 3).

The shorter stem lengths were recorded at the lowest levels of mulch cover applied 0 and 1 Mg DM ha^{-1}, with average values of 116.66 and 137.87 cm, respectively. On the other hand, plants developing under intermediate levels of mulch cover on the soil (2 and 3 Mg DM ha^{-1}), displayed longer stem lengths ($p<0.05$), 142.91 and 150.03 cm, respectively. At the level of 4 Mg DM ha^{-1} stem length was 140.03 cm. Plants growing under bare soil also displayed the shortest stem diameter (6.86 mm), while plants under the highest level of mulch cover, showed a stem diameter of 8.85 mm, 29% greater than the plants under bare soil. Increasing levels of mulch cover increased the length of the inflorescence ($p<0.05$). The inflorescence length in plants on soils with 4 Mg DM ha^{-1} of mulch cover was 35.38 cm, greater than those without mulch cover (28.68 cm), representing an increment of 23%.

There was an interaction between organic fertilization and mulch cover on the number of tillers at 60 days of regrowth (Table 3) ($p<0.05$). The greatest number of tillers per plant was observed when combining organic fertilization of 30 t Mg ha^{-1} with the application of 4 Mg DM ha^{-1} of mulch cover ($p<0.05$). When no organic fertilizer was applied, the use of mulch cover above 3 Mg DM ha^{-1} was shown to increase the number of tillers. The plants displayed greater leaf area (120.92 cm^2) at 30 days of regrowth when the mulch cover was applied at the highest level of 4 Mg DM ha^{-1} (Figure 4). This superiority represented an increase of 49% in the leaf area compared to the plants under bare soil (80.92 cm^2).

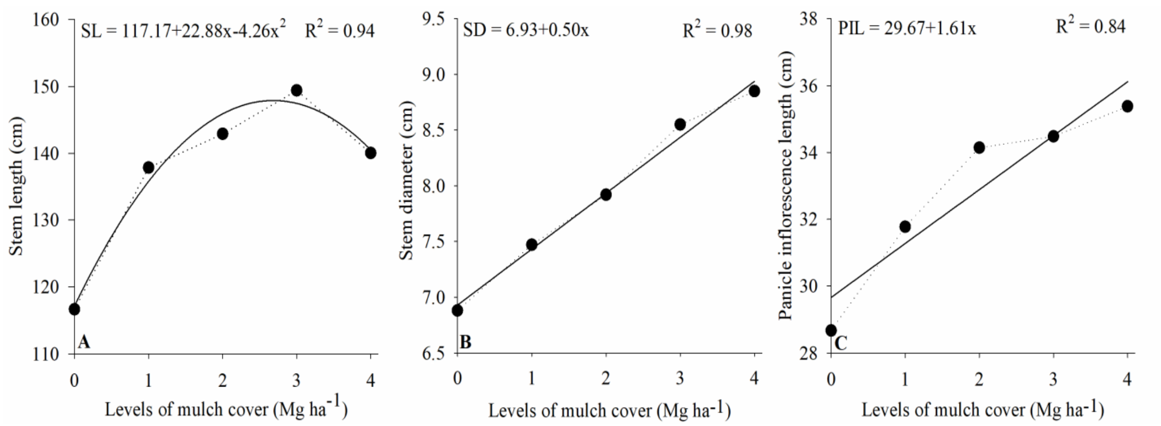

Figure 3**.** Structural characteristics of millet at 60 days regrowth, stem length (SL) (a), stem diameter (SD) – (b) panicle inflorescence length (PL) (c), as a function of different levels of mulch cover applied to the soil.

Regarding the mulch cover levels of 1, 2, and 3 Mg DM ha^{-1}, there was a linear increase in leaf area of 23, 28, and 41%, when compared to plants under bare soil. The greatest LAI value (2.11) was observed in the plants growing on the soil that received 3 Mg DM ha^{-1} of mulch cover ($p<0.05$), while the lowest (1.69) in the plants growing without mulch cover. The plants cultivated on the soil that received 1, 2, and 4 Mg DM ha^{-1} of mulch cover, displayed LAI values of 2.00, 1.98, and 2.05, respectively, none of them differed among themselves ($p>0.05$).

Table 3. Number of tillers per plant of millet in response to organic fertilization and soil mulch cover at 60 days regrowth.

Organic fertilization (Mg ha^{-1})	**Levels of mulch cover (Mg DM ha^{-1})**					p-valor
	0	1	2	3	4	
0	0.62 Ab	1.37 Ab	1.62 Ab	4.25 Aa	2.62 Bab	<0.001
30	1.62 Ab	2.87 Ab	5.00 Ab	3.0 Ab	5.75 Aa	<0.001
p-valor	0.1521	0.0340	0.2090	0.0752	<0.001	

Means followed by equal letters, uppercase in columns and lowercase in rows, did not differ statistically based on Tukey's test ($p<0.01$).

In general, the net CO_2 assimilation rate and stomatal conductance, and water use efficiency of the millet were shown to be improved by the increasing levels of mulch cover on the soil (Figure 5). The presence of mulch cover on the soil increased photosynthesis by 79 and 69% at 45 and 60 days of regrowth, respectively, when compared to the plants growing on bare soil. Notably, CO_2 assimilation was higher at 45 days for all levels of mulch cover applied. The stomatal conductance showed greater results at 45 days for the plants growing on the soil that received 4 Mg DM ha^{-1}. As occurred for CO_2 assimilation, the stomatal conductance was higher at 45 days compared to 60 days of regrowth. The water use efficiency showed positive responses to the use of mulch cover, especially at the highest application rate (4 Mg DM ha^{-1}), however, at 45 days of regrowth the use of 1, 2, and 3 Mg DM ha^{-1}, showed comparable results to the bare soil.

The regression analysis showed linear effects of the increasing levels of the use of mulch cover on the biomass of leaves (R^2=0.89), stems (R^2=0.87), inflorescence (R^2=0.83), and total dry mass (R^2=0.86) ($p<0.05$) (Figure 6). As expected, the use of organic fertilization significantly improved the dry mass production of the millet compared to no fertilization, however, it could be noticed that the use of mulch cover potentialized the effects of the organic fertilizer for all components (leaf, stems, inflorescence and total dry mass). The regression line regarding the dry mass production of the plants without fertilization, except for the leaves, had their angular coefficients reduced due to the absence of fertilization. The use of mulch cover significantly increased the total dry mass production in the plants that received organic fertilizer, the use of 4 Mg DM ha^{-1} could provide dry mass production of around 9.4 Mg ha^{-1} at 60 days of regrowth, while the plants that received organic fertilizer but grew on bare soil only produced around 4 Mg DM ha^{-1}.

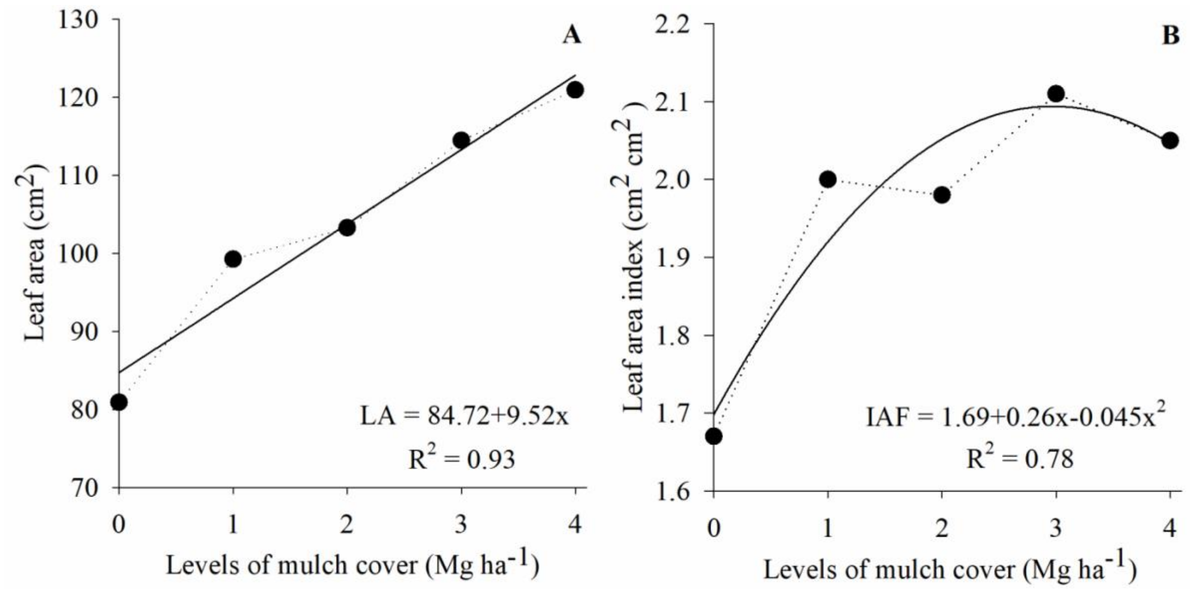

Figure 4. Leaf area (A) and leaf area index – LAI (B) of millet at 30 days regrowth, as a function of different levels of mulch cover applied to the soil.

The use of 4 Mg DM ha^{-1} combined with fertilization significantly improved the biomass of the stems above 4.5 Mg DM ha^{-1}, which was also associated with a greater number of tillers (table 3). Plants growing without mulch cover showed stem production inferior to 2.5 Mg DM ha^{-1}.

The biomass of the inflorescence displayed linear results to the levels of mulch cover applied. The use of mulch cover of 4 Mg DM ha^{-1} increased the inflorescence production (2.2 Mg DM ha^{-1}), it was almost three times greater than the plants growing on bare soil (0.71 Mg DM ha^{-1}).

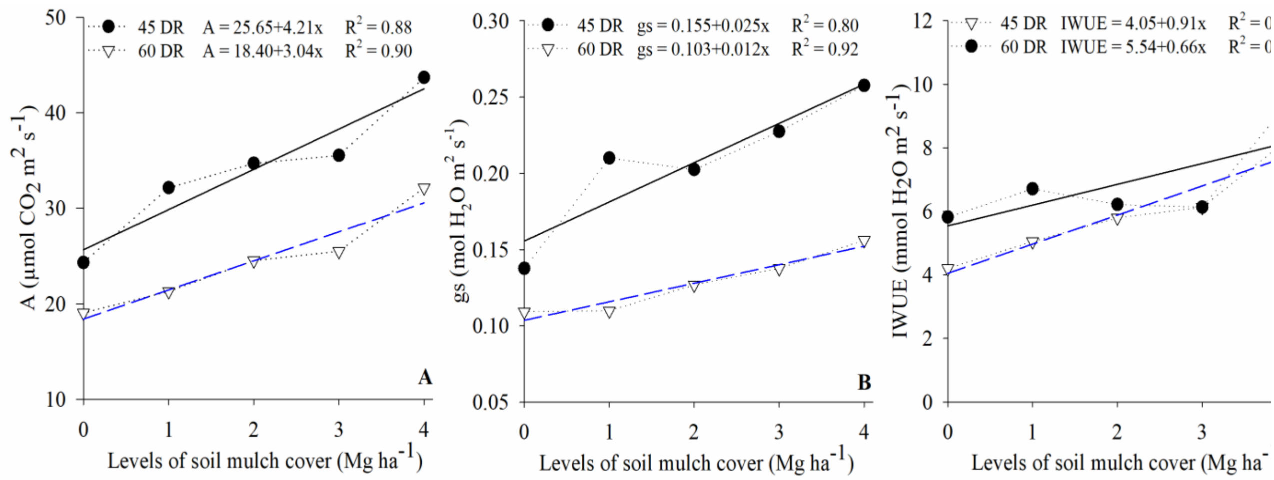

Figure 5. Gas exchange in millet as a function of different levels of soil mulch cover, net CO_2 assimilation rate (a) and stomatal conductance (b), and instantaneous water use efficiency (WUE) (c) at 45 and 60 days of regrowth (DR).

Plants that received organic fertilizer showed higher values of rainwater use efficiency ($p<0.05$). There was no difference in the rainwater use efficiency among the levels of mulch cover 0, 1, and 2 Mg DM ha^{-1}, with or without organic fertilization ($p>0.05$).

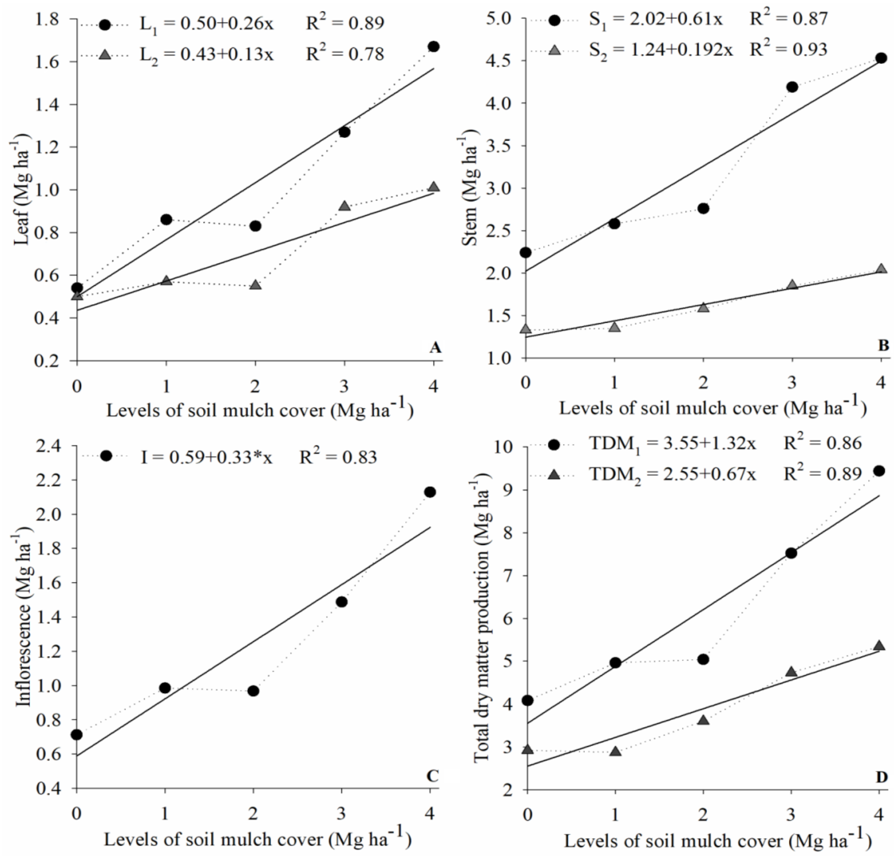

Figure 6. Leaf (A), stem (B), inflorescence (C), and total dry matter production (D) Mg DM ha^{-1} of millet at 60 days of regrowth, in response to the use or absence of organic fertilization combined with different levels of soil mulch cover. 1 = fertilization and 2 = no fertilization.

The highest rainwater use efficiency was observed when there was an application of 4 Mg DM ha^{-1} of mulch cover ($p<0.05$), especially when combined with organic fertilization (Figure 7).

The application of 3 Mg DM ha^{-1} showed intermediate rainwater use efficiency, not differing from any level of mulch cover, including the bare soil.

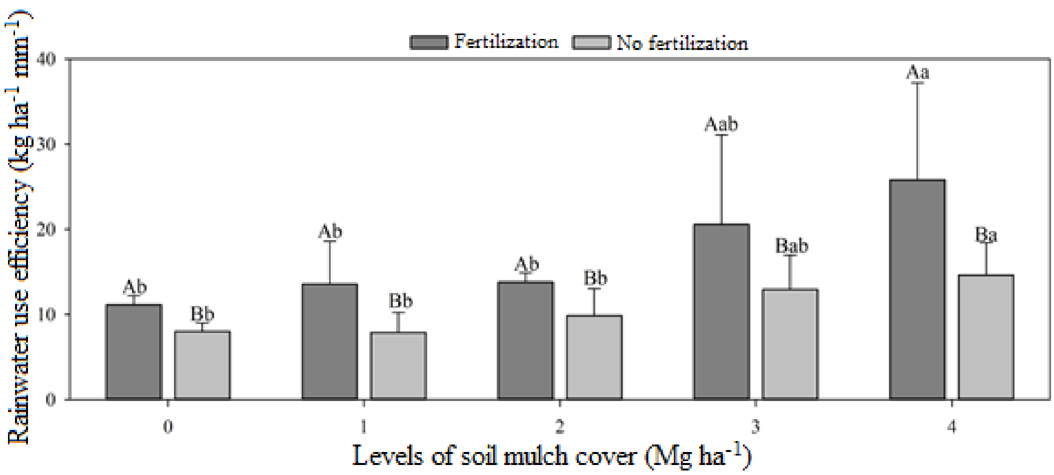

Figure 7. Rainwater use efficiency of millet under organic fertilization or not, combined with different levels of mulch cover. Means followed by equal uppercase (fertilization), and lowercase (mulch cover) letters did not differ statistically based on Tukey's test ($p<0.01$).

Discussion

The results of this study showed that the millet had its agronomic performance improved by the combined application of organic fertilizer (cattle manure) with the increasing levels of mulch cover. Generally, the application of organic fertilizers is reported to improve soil conditioning and plant growth. Among the benefits of the use of organic fertilizer can include the release of macro (e.g., N, P, K, Mg, Ca, S) and micronutrients (e.g., Fe, Zn, Cu, Mn, B), increments in the water holding capacity and organic matter content in the soil, presence of some beneficial microorganisms (e.g., plant-growth-promoting bacteria), availability of organic C for feeding soil microbes, improvement of the soil structure (e.g. aeration and aggregates), nutrient recycling, and reduction in the fertilization costs (Assefa & Tadesse, 2019; Coelho et al., 2021; Liu et al., 2022; Pei et al., 2023). In our study, even though the organic fertilizer was surface applied, and the growth period of the millet was short (60 days), the agronomical benefits of using the organic fertilizer were significant. We applied matured cattle manure as the source of organic fertilizer, possibly, the maturation process helped to improve the breakdown of some of the fiber components in the manure, increasing the release of nutrients present in the organic material. Fresh cattle slurry/manure (non-digested organic matter), generally displays a slow release of nutrients to the soil (Samara et al., 2020; Rayne & Aula, 2020; Prado et al., 2022).

Some of the structural characteristics (stem length and diameter, and inflorescence length) were not significantly affected by the organic fertilization. Nevertheless, the number of tillers and the biomass (leaves, stems, inflorescence) were positively influenced by the use of organic fertilizer, in comparison to unfertilized plants. As the number of tillers and the proportion of stems and leaves play a very important role in the structural characteristics of the millet, the use of organic fertilization (undigested cattle manure) could improve these traits. Fewer studies reported no influence of organic fertilization on the structural characteristics of the millet (Vital et al., 2020). Stem elongation and diameter, as well as the inflorescence length, were positively favored by the increasing levels of mulch cover. Generally, stem elongation occurs at an accelerated rate in grasses with a bunch-like (cespitose) growth habit such as millet, requiring adequate levels of water and nutrients availability (e.g., nitrogen) (Tounkara et al., 2020; Aboelgoud & Rajab, 2021). Possibly, the presence of mulch cover especially at higher doses, helped to retain more water and humidity in the soil, favoring the water uptake by the plants (Farzi et al., 2017; Leger et al., 2022; Pedroza-Parga et al., 2022). Also, it probably accelerated the decomposition of the organic matter (manure and straw), helping to release more nutrients into the soil (Hallama et al, 2019; Nyabami et al., 2023).

The increase in CO_2 assimilation and biomass conversion in response to the increasing levels of mulch cover can be associated with the environmental conditions during the trial. The plants growing on the bare soils possibly faced more water stress (Farzi et al., 2017). These plants growing on the bare soil, or at lower doses of mulch cover applied, possibly tried to avoid water loss by initially reducing their stomatal opening and conductance, leading to decreases in photosynthesis (Chaves et al., 2016; Mashilo et al., 2017; Wahab et al., 2022). This was consequently reflected in their lower yields at the harvesting. Millets can display diverse mechanisms to overcome temporary water stress, which can include stomatal closure, reduction in stomatal conductance, reduction of the leaf area, restriction of the internal CO_2 concentration, and reduction in the rubisco activity (Vijayalakshmi et al., 2012, Shrestha et al., 2023).

The smaller leaf area index (LAI) values in the plants growing on bare soils are a response of the plants to mitigate water loss due to transpiration. The larger the leaf area, the greater the number of stomata per plant. Also, the reduction of the LAI under water stress is a physiological mechanism to keep most of the remaining cells and tissues turgid and active. Cell and tissue expansion are directly related to the water content in the plants (Osakabe et al., 2014; Gupta et al., 2020). Low leaf area index is directly associated with decreases in light interception in grass species (Coelho et al., 2020). Also, considering the stomatal closure, the growth development and yields of the plants under water stress (bare soil or low level of mulch cover applied) were severely affected.

The millet is reported to display different responses to the negative effects of drought or water stress, however, the principal decline in productivity can happen when it coincides with the reproductive stage (Vijayalakshmi et al., 2012; Shrestha et al., 2023). At 60 days of regrowth, the plants of all treatments considerably reduced their stomatal conductance, this can be explained because the plants were in their flowering phase (grain filling). At this phase, the plants prioritize utilizing the water to maintain their cell turgor, and to keep their physiological processes, which can reflect in a higher water use efficiency. Water use efficiency is a combination of diverse physiological adaptation mechanisms that enhances plant productivity under conditions of water restriction (Medrano et al., 2015). The fact that the inflorescence was mostly affected by the mulch cover than the fertilization, might be related to the dynamics of biomass accumulation in millet. The millet concentrates its biomass accumulation in the stems, especially stem elongation, followed by leaves, and then in the inflorescence (Scheffer-Basso et al., 2004).

This study verified some of the benefits of the combined use of organic fertilization and mulch cover on the production of millet under rainfed conditions in the Brazilian semi-arid region. Most of the positive results were attributed to the nutrients released by the organic fertilizer, retention of the humidity in the soil, and the reduction of the water stress in millet plants. Although the highest level of mulch cover applied required a greater amount of straw, the productivity of the millet was doubled compared to the plants under bare soil. We suggest the use of mulch cover is a feasible alternative to increase millet productivity under rainfed conditions in semi-arid regions.

Conclusions

The combined use of organic fertilizer and mulch cover, increased the net CO_2 assimilation rate, stomatal conductance, and water use efficiency, and also, positively impacted the morphological development and yields of millet. The application of mulch cover at the level of 4 Mg DM ha^{-1} favored better growth responses and yields of the millet. The use of mulch cover potentialized the organic fertilizer, possibly due to increments in the water content and activity in the soil. It is suggested cultivation systems that combine organic fertilization with the application of mulch cover as a sustainable practice for millet production under rainfed conditions in semi-arid.

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References

Almeida, M. C. R. D., Leite, M. L. D. M. V., Souza, L. S. B. D., Simões, V. J. L. P., Pessoa, L. G. M., Lucena, L. R. R. D., Cruz, M. G & Sá Júnior, E. H. D. 2020. Agronomic characteristics of the Pennisetum glaucum submitted to water and saline stresses. Acta Scientiarum. Animal Sciences, 43. https://doi.org/10.4025/actascianimsci.v43i1.50468

Aboelgoud, S. A., & Rajab, M. 2021. Performance of Two Fodder Pearl Millet Varieties under Different Seeding and Nitrogen Fertilizer Rates. Journal of Plant Production, 12(10), 1069-1076. https://doi.org/10.21608/jpp.2021.205709

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. D. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22(6), 711-728.

Araújo, Y. P. D., Souza, L. S. B. D., Silva, T. G. F. D., & Moura, M. S. B. D. 2020. Water and Radiation Use Efficiencies by Erythrina velutina and Enterolobium contortisiliquum Under Different Water Conditions. Floresta e Ambiente, 28. https://doi.org/10.1590/2179-8087-FLORAM-2019-0080

Assefa, S., Tadesse, S. 2019. The principal role of organic fertilizer on soil properties and agricultural productivity-a review. Agri Res and Tech: Open Access J , 22 (2), 556192. http://dx.doi.org/10.19080/ARTOAJ.2019.22.556192

Bijarnia, A. L., Singh, U., & Sutaliya, R. 2020. Influence of integrated nutrient management on fodder pearl millet in transitional plain of Luni Basin. International Journal of Economic Plants, 7(4), 193-196.

Cavalcanti, F. D. A., Santos, J. C. P., Pereira, J. R., Leite, J. P., Silva, M. C. L., Freire, F. J., ... & Lima, J. F. V. F. 2008. Recomendações de adubação para o Estado de Pernambuco: 2. aproximação. Recife: IPA.

Coelho, J. J., Hennessy, A., Casey, I., Bragança, C. R. S., Woodcock, T., & Kennedy, N. (2020). Biofertilisation with anaerobic digestates: a field study of effects on soil microbial abundance and diversity. Applied Soil Ecology, 147, 103403. https://doi.org/10.1016/j.apsoil.2019.103403

Coelho, J.J., da Silva Santos, E.R., da Cunha, M.V., dos Santos, M.V.F., Júnior, J.C.B.D., & Mello, A.C.L. 2020. Correlations between plant height and light interception in grasses by different light meter devices. Revista Brasileira de Ciências Agrárias, 15(4), pp.1-6. https://doi.org/10.5039/agraria.v15i4a8494

Chai, Y., Chai, Q., Yang, C., Chen, Y., Li, R., Li, Y., Chang, L., Lan, X., Cheng, H., & Chai, S. 2022. Plastic film mulching increases yield, water productivity, and net income of rain-fed winter wheat compared with no mulching in semiarid Northwest China. Agricultural Water Management, 262, 107420. https://doi.org/10.1016/j.agwat.2021.107420

Chaves, M. M., Costa, J. M., Zarrouk, O., Pinheiro, C., Lopes, C. M., & Pereira, J. S. 2016. Controlling stomatal aperture in semi-arid regions—the dilemma of saving water or being cool?. Plant Science, 251, 54-64. https://doi.org/10.1016/j.plantsci.2016.06.015

Coulibaly, A., Woumou, K., & Aune, J. B. 2019. Sustainable intensification of sorghum and pearl millet production by seed priming, seed treatment and fertilizer microdosing under different rainfall regimes in Mali. Agronomy, 9(10), 664. https://doi.org/10.3390/agronomy9100664

Dantas, F. D. G., Santos, M. V. F. D., Lima, G. F. D. C., Coêlho, J. J., Medeiros, J. F. D., & Cunha, M. V. D. 2023. Drip irrigation with saline water combined with mulch cover as strategies for forage cactus production in semi-arid zones. Irrigation Science, 41(2), 295-308. https://doi.org/10.1007/s00271-022-00841-8

Detmann E, Souza MA, Valadares Filho SC, Queiroz AC, Berchielli TT, Saliba EOS, Cabral LS, Pina DS, Ladeira MM, Azevedo JAG. 2012. Métodos para Análise de Alimentos. Visconde do Rio Branco: Suprema.

Farzi, R., Gholami, M., Baninasab, B. and Gheysari, M., 2017. Evaluation of different mulch materials for reducing soil surface evaporation in semi-arid region. Soil Use and Management, 33(1), pp.120-128. https://doi.org/10.1111/sum.12325

Girma, M., & Jemal, A. 2015. Irrigation system in Israel: A review. International Journal of water resources and environmental engineering, 7(3), pp.29-37.

Gupta, A., Rico-Medina, A., & Caño-Delgado, A.I. 2020. The physiology of plant responses to drought. Science, 368(6488), pp.266-269. https://doi.org/10.1126/science.aaz7614

Hallama, M., Pekrun, C., Lambers, H., & Kandeler, E. 2019. Hidden miners–the roles of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. Plant and soil, 434(1), pp.7-45. https://doi.org/10.1007/s11104-018-3810-7

Jardim, A. M. D. R. F., de Morais, J. E. F., de Souza, L. S. B., Marin, F. R., de Moura, M. S. B., Morellato, L. P. C., Montenegro, A. A. A., Ometto, J. P. H. B., Lima, J. L., Dubeux Júnior, J. C. B., & da Silva, T. G. F. 2023. Sink or carbon source? How the Opuntia cactus agroecosystem interacts in the use of carbon, nutrients and radiation in the Brazilian semi-arid region. Journal of Hydrology, 130121. https://doi.org/10.1016/j.jhydrol.2023.130121

Kader, M. A., Senge, M., Mojid, M. A., & Ito, K. 2017. Recent advances in mulching materials and methods for modifying soil environment. Soil and Tillage Research, 168, 155-166. https://doi.org/10.1016/j.still.2017.01.001

Kavya, L., Debbarma, V., & Vaishnavi, N. 2023. Influence of Organic Manures and Zinc on Growth, Yield and Economics of Pearl Millet (Pennisetum glaucum L.). International Journal of Environment and Climate Change, 13(7), 160–167. https://doi.org/10.9734/ijecc/2023/v13i71862

Kumar, P., Kumar, R., Sewhag, M., Sharma, K. D., Chugh, L. K., & Rajanna, G. A. (2021). Physiological attributes, productivity, micronutrient and heavy metal content in pearl millet (Pennisetum glaucum L.) as influenced by treated sewage and canal irrigation water under different nutrient sources. Cereal Research Communications, 49(3), 393-399. https://doi.org/10.1007/s42976-020-00127-9

Leite, M. L. D. M. V., Lucena, L. R. R. D., Cruz, M. G. D., Sá, E. H. D., & Simões, V. J. L. P. 2019. Leaf area estimate of Pennisetum glaucum by linear dimensions. Acta Scientiarum. Animal Sciences, 41.

https://doi.org/10.4025/actascianimsci.v41i1.42808

Leger, A. M., Ball, K. R., Rathke, S. J., & Blankinship, J. C. 2022. Mulch more so than compost improves soil health to reestablish vegetation in a semiarid rangeland. Restoration Ecology, e13698. https://doi.org/10.1111/rec.13698

Li, S., Li, Y., Lin, H., Feng, H., & Dyck, M. 2018. Effects of different mulching technologies on evapotranspiration and summer maize growth. Agricultural Water Management, 201, 309-318. https://doi.org/10.1016/j.agwat.2017.10.025

Liu, F; Tian, H; Zhang, C; Chen, Y; Li, X; Zhang, X; Cai, Y; Chen, H. 2022. Effects of partial replacement of nitrogen fertilizer with organic fertilizer on maize yield and soil physical and chemical properties under straw returning. Journal of Shanxi Agricultural Sciences, 50, p. 78-83.

Liu, P., Guo, X., Zhou, D., Zhang, Q., Ren, X., Wang, R., ... & Li, J. 2023. Quantify the effect of manure fertilizer addition and optimal nitrogen input on rainfed wheat yield and nitrogen requirement using nitrogen nutrition index. Agriculture, Ecosystems & Environment, 345, 108319. https://doi.org/10.1016/j.agee.2022.108319

Marques, T. V., Mendes, K., Mutti, P., Medeiros, S., Silva, L., Perez-Marin, A. M., ... & Bezerra, B. 2020. Environmental and biophysical controls of evapotranspiration from Seasonally Dry Tropical Forests (Caatinga) in the Brazilian Semiarid. Agricultural and Forest Meteorology, 287, 107957. https://doi.org/10.1016/j.agrformet.2020.107957

Mashilo, J., Odindo, A. O., Shimelis, H. A., Musenge, P., Tesfay, S. Z., & Magwaza, L. S. 2017. Drought tolerance of selected bottle gourd [Lagenaria siceraria (Molina) Standl.] landraces assessed by leaf gas exchange and photosynthetic efficiency. Plant physiology and biochemistry, 120, 75-87. https://doi.org/10.1016/j.plaphy.2017.09.022

Medrano, H., Tomás, M., Martorell, S., Escalona, J. M., Pou, A., Fuentes, S., ... & Bota, J. (2015). Improving water use efficiency of vineyards in semi-arid regions. A review. Agronomy for Sustainable Development, 35(2), 499-517.

Nyabami, P., Maltais-Landry, G., & Lin, Y. 2023. Nitrogen release dynamics of cover crop mixtures in a subtropical agroecosystem were rapid and species-specific. Plant and Soil, 1-14. https://doi.org/10.1007/s11104-023-06183-4

Osakabe, Y., Osakabe, K., Shinozaki, K., & Tran, L. S. P. 2014. Response of plants to water stress. Frontiers in plant science, 5, 86. https://doi.org/10.3389/fpls.2014.00086

Pei, Y., Chen, X., Niu, Z., Su, X., Wang, Y., & Wang, X. 2023. Effects of nitrogen fertilizer substitution by cow manure on yield, net GHG emissions, carbon and nitrogen footprints in sweet maize farmland in the Pearl River Delta in China. Journal of Cleaner Production, 399, 136676. https://doi.org/10.1016/j.jclepro.2023.136676

Pedroza-Parga, E. H., Pedroza-Sandoval, A., Velásquez-Valle, M. A., Sánchez-Cohen, I., Trejo-Calzada, R., & Samaniego-Gaxiola, J. A. 2022. Effect of soil cover on the growth and productivity of buffel grass (Cenchrus ciliaris L.) in degraded soils of arid zones. Revista Mexicana de Ciências Pecuárias, 13(4), 866-878. https://doi.org/10.22319/rmcp.v13i4.5963

Perazzo, A. F., Santos, E. M., Pinho, R. M. A., Campos, F. S., Ramos, J. P. D. F., Aquino, M. M. D., ... & Bezerra, H. F. C. 2013. Características agronômicas e eficiência do uso da chuva em cultivares de sorgo no semiárido. Ciência Rural, 43, 1771-1776. https://doi.org/10.1590/S0103847820130010000007

Prado, J., Ribeiro, H., Alvarenga, P., & Fangueiro, D. 2022. A step towards the production of manure-based fertilizers: Disclosing the effects of animal species and slurry treatment on their nutrients content and availability. Journal of Cleaner Production, 337, 130369. https://doi.org/10.1016/j.jclepro.2022.130369

Rayne, N., & Aula, L. 2020. Esterco pecuário e os impactos na saúde do solo: Uma revisão. Sistemas de solo , 4 (4), 64. https://doi.org/10.3390/soilsystems4040064

Rossato, L., Alvala, R. C. D. S., Marengo, J. A., Zeri, M., Cunha, A. P. D. A., Pires, L. B., & Barbosa, H. A. 2017. Impact of soil moisture on crop yields over Brazilian semiarid. Frontiers in Environmental Science, 5, 73. https://doi.org/10.3389/fenvs.2017.00073

Sá Júnior, E. H., Cruz, M. G., Leite, M. L. D. M. V., & de Lucena, L. R. R. 2018. Características agronômicas de capim-corrente (Urochloa mosambicensis) adubado com esterco suíno e submetido a duas alturas de corte. Revista Ciência Agrícola, 16(1), 1-9. https://doi.org/10.28998/rca.v16i1.3303

Samara, E., Matsi, T., Barbayiannis, N., & Lithourgidis, A. 2020. Liquid cattle manure effect on corn yield and nutrients' uptake and soil fertility, in comparison to the common and recommended inorganic fertilization. Journal of Soil Science and Plant Nutrition, 20(4), 2283-2293. https://doi.org/10.1007/s42729-020-00294-y

Simões, V. J. L. P., Leite, M. L. D. M. V., de Lucena, L. R. R., Silva, J. R. I., Izidro, J. L. P. S., & de Souza, E. S. 2022. Use of biostimulants in millet as strategies for tolerance to salinity of irrigation water. Acta Scientiarum. Technology, 44, e59126-e59126. https://doi.org/10.4025/actascitechnol.v44i1.59126

Scheffer-Basso, S. M., Agranionik, H., & Fonteli, R. 2004. Acúmulo de biomassa e composição bromatológica de milhetos das cultivares comum e africano. Current Agricultural Science and Technology, 10(4).

Shrestha, N., Hu, H., Shrestha, K., & Doust, A. N. 2023. Pearl millet response to drought: A review. Frontiers in Plant Science, 14, 1059574. https://doi.org/10.3389/fpls.2023.1059574

Silva, L. F., da Silva, E. F., Morais, F. M. S., Portela, J. C., de Oliveira, F. H. T., de Freitas, D. F., ... & Antunes, L. F. S. 2023. Potential of vermicomposting with mixtures of animal manure and vegetable leaves in the development of Eisenia foetida, microbial biomass, and enzymatic activity under semi-arid conditions. Journal of Environmental Management, 330, 117169. https://doi.org/10.1016/j.jenvman.2022.117169

Souza, M. D. S., Freire da Silva, T. G., de Souza, L. S. B., Alves, H. K. M. N., Leite, R. M. C., de Souza, C. A. A., ... & de Souza, P. J. D. O. P. 2022. Growth, phenology and harvesting time of cactus-millet intercropping system under biotic mulching. Archives of Agronomy and Soil Science, 68(6), 764-778. https://doi.org/10.1080/03650340.2020.1852553

Pei, Y., Chen, X., Niu, Z., Su, X., Wang, Y., & Wang, X. 2023. Effects of nitrogen fertilizer substitution by cow manure on yield, net GHG emissions, carbon and nitrogen footprints in sweet maize farmland in the Pearl River Delta in China. Journal of Cleaner Production, 399, 136676. https://doi.org/10.1016/j.jclepro.2023.136676

Team, R. C. (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Tounkara, A., Clermont-Dauphin, C., Affholder, F., Ndiaye, S., Masse, D., & Cournac, L. 2020. Inorganic fertilizer use efficiency of millet crop increased with organic fertilizer application in rainfed agriculture on smallholdings in central Senegal. Agriculture, Ecosystems & Environment, 294, 106878. https://doi.org/10.1016/j.agee.2020.106878

Tuure, J., Räsänen, M., Hautala, M., Pellikka, P., Mäkelä, P. S. A., & Alakukku, L. 2021. Plant residue mulch increases measured and modelled soil moisture content in the effective root zone of maize in semi-arid Kenya. Soil and Tillage Research, 209, 104945.

Vijayalakshmi, T., Varalaxmi, Y., Jainender, S., Yadav, S. K., Vanaja, M., Jyothilakshmi, N., & Maheswari, M. 2012. Physiological and biochemical basis of water-deficit stress tolerance in pearl millet hybrid and parents. http://www.scirp.org/journal/PaperInformation.aspx?PaperID=25793

Vital, A. D. F. M., Souza, T., da Silva, L. J. R., dos Santos, R. V., da Silva, S. I. A., dos Santos Nascimento, G., & Santos, D. 2020. Biomass production and macronutrient content in Pennisetum glaucum (L.) R. Brown as affected by organic fertilization and irrigation. Revista Brasileira de Ciências Agrárias, 15(4), 1-8. https://doi.org/10.5039/agraria.v15i4a8576

Wang, L., Li, X. G., Guan, Z. H., Jia, B., Turner, N. C., & Li, F. M. 2018. The effects of plastic-film mulch on the grain yield and root biomass of maize vary with cultivar in a cold semiarid environment. Field Crops Research, 216, 89-99. https://doi.org/10.1016/j.fcr.2017.11.010

Wahab, A., Abdi, G., Saleem, M. H., Ali, B., Ullah, S., Shah, W., ... & Marc, R. A. 2022. Plants' physio-biochemical and phyto-hormonal responses to alleviate the adverse effects of drought stress: A comprehensive review.

Plants, 11(13), 1620. https://doi.org/10.3390/plants11131620

Webber, S. M., Bailey, A. P., Huxley, T., Potts, S. G., & Lukac, M. 2022. Traditional and cover crop-derived mulches enhance soil ecosystem services in apple orchards. Applied Soil Ecology, 178, 104569. https://doi.org/10.1016/j.apsoil.2022.104569

Zhai, L., Wang, Z., Zhaic, Y., Zhang, L., Zheng, M., Yao, H., Lv, L., Shen, H., Zhang, J., Yao, Y., & Jia, X. 2022. Partial substitution of chemical fertilizer by organic fertilizer benefits grain yield, water use efficiency, and economic return of summer maize. Soil and Tillage Research, 217, 105287. https://doi.org/10.1016/j.still.2021.105287