Industrial Crops & Products 184 (2022) 115059

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

How to enhance the agronomic performance of cactus-sorghum intercropped system: planting configurations, density and orientation

Cleber Pereira Alves [a,b,*], Alexandre Maniçoba da Rosa Ferraz Jardim [b], George do Nascimento Araújo Júnior [b], Luciana Sandra Bastos de Souza [a], Gherman Garcia Leal de Araújo [c], Carlos André Alves de Souza [b], Kaique Renan da Silva Salvador [a], Renan Matheus Cordeiro Leite [a], Antonio Gebson Pinheiro [b], Thieres George Freire da Silva [a,b]

[a] *Academic Unit of Serra Talhada, Federal Rural University of Pernambuco, Serra Talhada, Pernambuco, Brazil*
[b] *Department of Agricultural Engineering, Federal Rural University of Pernambuco, Recife, Pernambuco, Brazil*
[c] *Brazilian Agricultural Research Corporation, Petrolina, Pernambuco, Brazil*

ARTICLE INFO

Keywords:
Opuntia stricta
Nopalea cochenillifera
Sorghum bicolor
Agricultural resilience
Crop yield

ABSTRACT

Clarifying cultivation techniques and making production systems more efficient are practices that have been much sought after in agricultural systems in recent decades. In this context, the forage yield, biological efficiency, and competitive ability, of different cultivation strategies for intercropping forage cactus and sorghum were determined in biosaline production systems from 2018 to 2020 in Brazil. Four experiments were carried out, comprising: 1) cropping configurations for the forage cactus-sorghum intercropping system; 2 and 3) planting densities for the forage cactus intercropped with sorghum with an east-west and north-south row orientation, respectively; and 4) planting densities for the forage cactus and sorghum. Each experiment used a randomised block design with four replications. The intercropped forage cactus and sorghum showed higher productivity than the monocropped systems. The indices of biological efficiency (LER, ATER, LEC and SPI with mean values equal to 1.6, 1.8, 0.6 and 29.0, respectively) and competitive ability (ALGY in average 870.6) show better performance under the intercropped system compared to the single crops. The increased planting density resulted in an increase in productivity under the intercropped forage cactus-sorghum system (on average an increase of 69.4% dry matter). In turn, the orientation had no influence on the productivity of the intercropping system but offered better conditions for the forage cactus when cultivation was in an east-west direction (21.7 Mg ha^{-1} of dry matter) compared to north-south (17.5 Mg ha^{-1} of dry matter). Intercropping forage cactus and sorghum using biosaline agriculture is an excellent alternative for a production system in semi-arid environments, especially at higher planting densities (50,000 and 100,000 plants ha^{-1}).

1. Introduction

In semi-arid regions there is a predominance of animal farming, which plays an important role in the economy, however, the soil and climate conditions are unfavourable to the production of forage in quantity or quality. The arid and semi-arid regions occupy a territorial area of approximately 66.7 million km^2 of the globe, housing around 2 billion people, and are tending to increase in size due to the effects of climate change (Ayangbenro and Babalola, 2020; Jardim et al., 2022). These environments have biophysical restrictions, such as high temperatures, low rainfall, irregular rainfall distribution, and extremes of climate, such as droughts and floods, which result in high seasonal and interannual climate variability, jeopardising agricultural activities (Singh and Chudasama, 2020).

* Correspondence to: Unidade Acadêmica de Serra Talhada, Universidade Federal Rural de Pernambuco, Avenida Gregório Ferraz Nogueira, Bairro José Tomé de Souza Ramos, Caixa Postal 063, 56909-535 Serra Talhada, Pernambuco, Brazil.

E-mail addresses: cleberp.alves@hotmail.com (C.P. Alves), alexandremrfj@gmail.com (A.M.R.F. Jardim), georgejunior_91@hotmail.com (G.N. Araújo Júnior), sanddrabastos@yahoo.com.br (L.S.B. Souza), gherman.araujo@embrapa.br (G.G.L. Araújo), carlosandre08_@msn.com (C.A.A. Souza), kaiquersalvador@outlook.com (K.R.S. Salvador), renanmatheuscl@gmail.com (R.M.C. Leite), gebson10@hotmail.com (A.G. Pinheiro), thieres.silva@ufrpe.com.br (T.G.F. Silva).

https://doi.org/10.1016/j.indcrop.2022.115059

Available online 18 May 2022
0926-6690/

In Brazil, the semi-arid region covers an area of 982,566 km^2 (i.e., 18.2% of the country). It is the largest and wettest semi-arid region in the world, with annual precipitation ranging from 400 to 800 mm (Silva et al., 2020). Among the agricultural activities carried out in this environment is the cultivation of forage species that are adapted to the climate conditions (Araújo Júnior et al., 2021; Silva et al., 2020). However, the improper use of cultivation management makes crop production difficult. As such, to achieve good results in production systems, it is necessary to use practices for improving agricultural resilience (i.e., system capacity, maintaining full growth and satisfactory productivity even under climate perturbations) by means of techniques that help mitigate the adverse conditions, ensuring plant yield (Eeswaran et al., 2021). Among these practices, the use of crops adapted to the climate should be noted, i.e., the choice of species and clone/variety, diversification of species in the production system and the use of irrigation (Rai et al., 2018; Rao et al., 2019; Jardim et al., 2021b), as well as density and planting orientation.

Two adapted crops that deserve to be highlighted in a semi-arid environment are the forage cactus (*Opuntia* spp. and *Nopalea* spp.) and forage sorghum (*Sorghum bicolor* (L.) Moench) due to their high water-use efficiency, a result of their crassulacean acid metabolism (CAM), and C4 metabolism, respectively (Diniz et al., 2017). These species play an important role, both economically and in feeding the herds in the semi-arid region (Jardim et al., 2020). Several studies show the success of cactus-sorghum intercropping systems, which, in addition to enabling the efficient use of biophysical resources, afford greater profitability and productivity than the single crops (SNG), giving positive results when irrigated (Amorim et al., 2017; Lima et al., 2018a; Lima et al., 2018b).

Linked to the intercropping system, irrigation is an essential practice for the success of agricultural crops in hot and dry environments (Alves et al., 2019). However, these regions are affected by a gradual reduction in the quantity and quality of the water resources, making it necessary to use biosaline agriculture (i.e., agricultural practices that aim at the sustainable and efficient use of brackish water, reflecting in greater production in the system) (Díaz et al., 2018; Khorsandi et al., 2020). In addition to irrigation, plant density and the orientation of the plantation are practices to improve agricultural resilience, optimizing the efficiency of water and soil use, through the ideal number of plants per unit of area (Silva et al., 2019; Meng et al., 2020) and improve interception of solar radiation by the plants, with a direct influence on dry matter production and translocation of photoassimilates, respectively (Oliveira et al., 2012; Tonini et al., 2019; Buesa et al., 2020). Studies show that there is a productive increase in forage cactus when subjected to higher densities (Cavalcante et al., 2014; Lemos et al., 2021; Silva et al., 2014a) and east-west orientation (Peixoto et al., 2018).

To understand the productive characteristics and the competitiveness between crops of an intercropping system that are a result of changes in the cropping configuration, is essential to assist in decision making, favouring the choice of the best system to be used by the producer (Diniz et al., 2017; Hendges et al., 2019). In addition, there is little information regarding the use of cactus-sorghum intercropping systems using biosaline agriculture under different configurations, densities, and orientations. Therefore, the hypothesis of this study is that the correct choice of production system when intercropping the forage cactus and sorghum under biosaline agricultural, using the ideal configuration (OEM-467 and OEM-P.288), higher planting densities (50,000 and 100, 000 plants ha^{-1}), and changes in the orientation of the plants (east--west), affords greater efficiency in the use of natural resources, with satisfactory crop productivity and significant economic return for the producer.

The present study aimed to determine practices to improve agricultural resilience in cactus and sorghum intercropped production systems, aiming to maximize productivity and increase profitability for the producer in a semi-arid environment. For this, it was determined the (i) forage yield, (ii) biological efficiency, and (iii) competitive ability of different cultivation strategies for intercropping forage cactus and sorghum in biosaline production systems.

2. Materials and methods

2.1. Location of the experiment

The study was carried out at the International Reference Centre for Agrometeorological Studies of the Cactus and other Forage Plants, located at the Serra Talhada Academic Unit of the Federal Rural University of Pernambuco (UFRPE-UAST), in the municipality of Serra Talhada, Pernambuco State, Brazil (7º56' 20" S, 38º17'31" W and an altitude of 431 m).

According to the Köppen classification, the climate in the region is type BSh (i.e., warm semi-arid), with a rainy summer and dry winter (Alvares et al., 2013). The average air temperature is 24.8 °C, with an average rainfall of 642 mm $year^{-1}$, relative humidity of around 63% and evapotranspiration demand greater than 1800 mm $year^{-1}$ (Pereira et al., 2015; Silva et al., 2015). The characteristic soil of the experimental area is classified as a typical Eutrophic Ta Haplic Cambisol (Jardim et al., 2021a) (Table 1).

Meteorological data during the experimental period were monitored by an automatic weather station of the National Institute of Meteorology, located approximately 20 m from the experimental area. During the experimental period, rainfall was concentrated from December 2018 to May 2019 and December 2019 to July 2020, with drought from August to November 2018 and 2019. Accumulated rainfall during the entire period was 1888.80 mm, less than the total atmospheric demand, which had a total value of 3556.81 mm. The mean ET_0 was 4.95 mm day^{-1}, with a maximum value of 7.42 mm day^{-1} and a minimum of 0.54 mm day^{-1} (Fig. 1).

2.2. Experimental design and crop management

The study was divided into four experiments, which differed in relation to treatment, species of forage cactus, and sorghum variety (Table 2). For each experiment, the experimental design was of randomised blocks (RBD), with four replications. Before setting up the experiments, the soil was prepared by ploughing, harrowing, and furrowing. Cladodes of the forage cactus were then planted in double rows, burying up to 50% of the total length of the cladode in the soil. The sorghum varieties were sown in furrows parallel to the rows of forage cactus. Whenever necessary, weeds were removed from the experimental areas, affording ideal conditions for crop development. Fertilisation was carried out in the crop rows in a single dose when cactus and sorghum were established, considering the density of the forage cactus. To ensure optimal plant growth, doses equal to 200–80–130 kg ha^{-1} of N-P-K, respectively, were applied, based on a density of 40,000 plants ha^{-1}.

Irrigation was carried out three times a week (Mondays, Wednesdays, and Fridays), using a drip irrigation system with emitters spaced 0.20 m apart, a flow rate of 1.57 L h^{-1}, and a coefficient of uniformity equal to 92% at a pressure of 100 kPa. The mean electrical conductivity of the water used in the experiment was 1.62 dS m^{-1}, classified as C3 (high salinity) according to the Richards classification (Richards, 1954), with a pH of 6.84 and a mean concentration of sodium and potassium of 168.66 mg L^{-1} and 28.17 mg L^{-1}, respectively. The water came from an artesian well with a depth of 48 m and a flow rate of 12 m^3 h^{-1}.

The forage cactus was considered the main crop in the system in each experiment. Therefore, the irrigation depth was based on 80% of its water requirement (crop evapotranspiration - ETc), considering a crop coefficient (Kc) of 0.52 (Queiroz et al., 2016). The ETc was obtained from the product of the crop coefficient (Kc) and the reference evapotranspiration (ET_0), which was determined daily using the Penman-Monteith equation and parameterised by the FAO (Allen et al., 1998).

Table 1
Physical and chemical properties of a typical Eutrophic Ta Haplic Cambisol in the 0.00–0.20 m layer in the municipality of Serra Talhada, Pernambuco, Brazil.

Soil physical properties											
ρ_s	φt		Sand			Silt			Clay		
g cm^{-3}	— % —		g kg^{-1}								
1.5	42.3		828.6			148.3			23.2		
Soil chemical properties											
pH	ECe	P	OC	OM	Ca	K	Na	Mg	SB	CEC	V
	dS m^{-1}	mg dm^{-3}	– g kg^{-1} –		cmol$_c$ dm^{-3}						%
6.0	0.3	169.0	4.6	7.9	3.5	13.8	1.1	1.9	20.3	20.9	97.2

ρs = Soil bulk density; φt = Total soil porosity; ECe = Electrical conductivity of the saturated soil extract; P = Phosphorus; OC = organic carbon; OM = organic matter; Ca = Calcium; Na = Sodium; K = Potassium; Mg = Magnesium; SB = sum of bases; CEC = cation exchange capacity; and V = Base saturation.

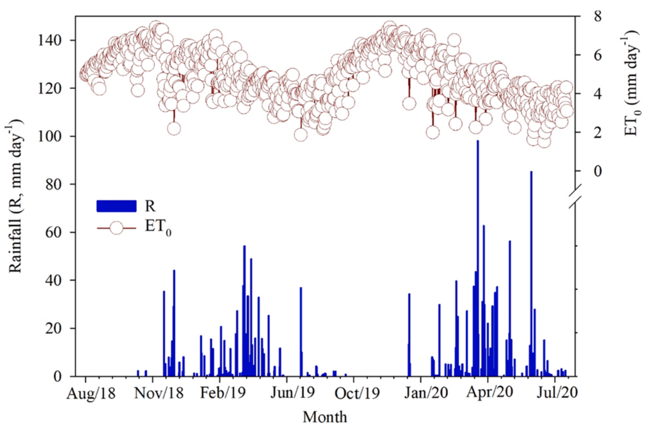

Fig. 1. Rainfall (R) and reference evapotranspiration (ET$_0$) during the experimental period from August 2018 to July 2020 in Serra Talhada, Pernambuco, Brazil.

2.2.1. *Experiment 1: different cropping configurations*

Experiment 1 consisted of different cropping configurations. Three forage cactus clones were used, of the genera *Nopalea* and *Opuntia*: IPA-Sertânia – IPA (*Nopalea cochenillifera* (L.) Salm-Dyck), Miúda – MIU (*Nopalea cochenillifera* (L.) Salm-Dyck) and Orelha de Elefante Mexicana – OEM (*Opuntia stricta* (Haw.) Haw.) and three sorghum varieties (*Sorghum bicolor* (L.) Moench) (IPA-467, SF11 and Progenitor 288 – P.288), all of which show good adaptability to the conditions of the semi-arid climate (Fig. 2).

In the present study, the intercropping pattern was an additive series system, being the cactus as a base crop. The forage cactus clones were planted at a spacing of 1.0 × 0.2 m (50,000 plants ha^{-1}), with the sorghum varieties sown in furrows at a depth of 0.05 m, spaced 0.25 m from the rows of forage cactus. The experiment comprised 15 treatments, arranged in a 3 + 3 + 3 × 3 scheme (three forage cactus clones + three of single sorghum + nine intercropped combinations of the forage cactus and sorghum, i.e., OEM-SF11; OEM-P.288; OEM-467; IPA-SF11; IPA-P.288; IPA-467; MIU-SF11; MIU-P.288 and MIU-467), characterising the different cropping configurations (Supplementary Fig. S1A).

Each experimental plot consisted of 4 rows, 5 m in length, with an area equal to 20 m^2, containing 25 plants in each row. The two central rows of each plot were considered the working plot, disregarding the two plants at either end, to give a total of 46 working plants in a working area of 9.20 m^2 plot^{-1}.

Two cuts of the forage cactus were evaluated in this study, the first at 12 months and the second at six months, so that the forage cactus was in its second production cycle from 02/2019–02/2020 and 02/2020–07/2020, respectively (giving a total duration of ~18 months). The forage cactus clones were planted in January 2016, with a uniform cut in March 2017, leaving only the basal and primary cladodes in the field, and followed by the start of the treatments and irrigation, which were based on the ETc of the forage cactus. The forage cactus was first harvested in June 2018 and grown with no irrigation or intercropping until February 2019. During this period, there was one uniform cut, and the treatments and irrigation were resumed, with the harvest carried out in February 2020. Shortly afterwards, the intercropping system and irrigation were resumed, with harvesting carried out in July 2020.

Table 2
Description of experimental areas of forage cactus-sorghum production systems, comprising: cropping configurations; planting densities for the forage cactus intercropped with sorghum with an east-west and north-south orientation; and planting densities for the forage cactus and sorghum.

Experiment	Production system	Forage cactus clones	Sorghum varieties	Treatments	
1	Different cropping configurations	OEM IPA MIU	SF11 IPA-467 P.288	OEM-SNG IPA-SNG MIU-SNG SF11-SNG 467-SNG P.288-SNG OEM + SF11 OEM + 467 OEM + P.288 IPA + SF11 IPA + 467 IPA + P.288 MIU + SF11 MIU + 467 MIU + P.288	
2	Planting densities (plants ha^{-1}) with a east-west row orientation	OEM	IPA-467	100,000 50,000 33,333 25,000 20,000	
3	Planting densities (plants ha^{-1}) with a north-south row orientation	OEM	IPA-467	100,000 50,000 33,333 25,000 20,000	
4	Cactus and sorghum planting density (plants ha^{-1})	OEM	IPA-467	Cactus: 50,000 40,000 33,333 28,571	Sorghum: 200,000 160,000 133,333 114,285

Forage cactus clones: OEM – Orelha de Elefante Mexicana; IPA – IPA-Sertânia; MIU – Miúda. Sorghum varieties: SF11; IPA-467 – 467 and P.288 – Progenitor 288. SNG – Single cropping system.

Four sorghum cycles were grown, including two sowings and two periods of regrowth. The first sowing was carried out on 8 February 2019 and thinned 15 days after seedling emergence, leaving 20 plants per linear metre (200,000 plants ha^{-1}). For each variety, the first cycle (first growth) lasted 110 days after emergence (DAE) and was harvested in June 2019. The second cycle (first regrowth) lasted 72 days after cutting (DAC) and was cut in August 2019. The third cycle (second regrowth) lasted 82 DAC and was harvested in November 2019, while

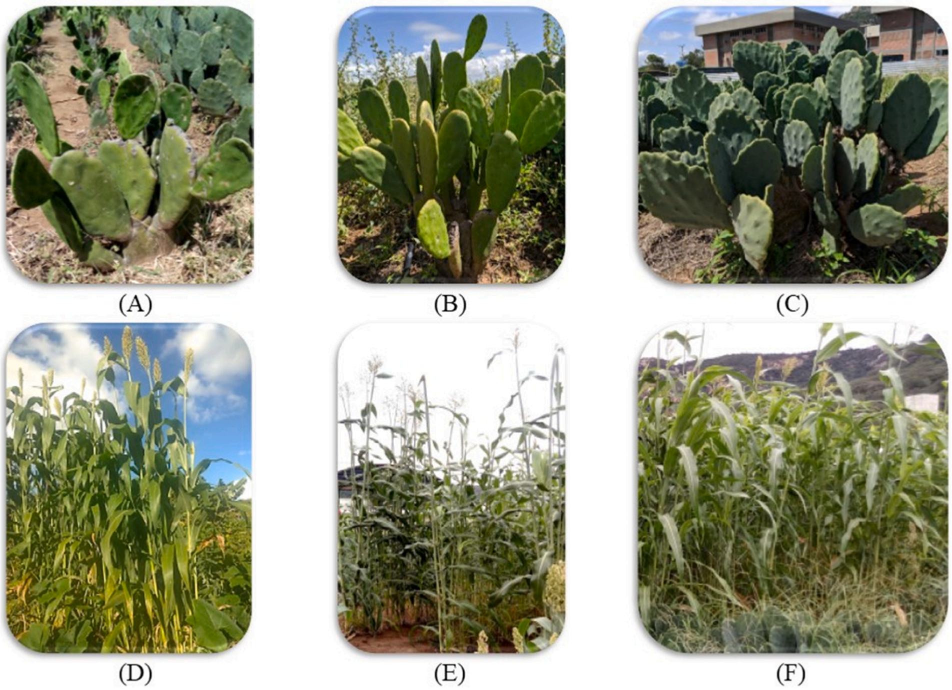

Fig. 2. Forage cactus clones: IPA-Sertânia – IPA (A); Miúda – MIU (B) and Orelha de Elefante Mexicana – OEM (C) and sorghum varieties: Progenitor 288 – P.288 (D); SF11 (E) and IPA-467 – 467 (F) cultivated in Serra Talhada, Pernambuco, Brazil.

the last cycle (second growth) was sown on 3 March 2020 and harvested 106 DAE in June 2020.

For the entire experimental period, the water depth applied via irrigation was 682.3 mm, which added to 1699.20 mm of rain, giving a total of 2381.5 mm received by the system.

2.2.2. *Experiment 2: planting densities with a east-west orientation*

This experiment evaluated different planting densities, sown in an east-west row orientation. The Orelha de Elefante Mexicana clone was used together with the sorghum IPA-467 variety in an intercropping system.

The forage cactus was planted in August 2018 in an east-west row orientation, at a fixed spacing of 1 m between rows and five different spacings between plants, of 0.10, 0.20, 0.30, 0.40, and 0.50 m, which comprised the treatments, representing planting densities of 100,000; 50,000; 33,333; 25,000 and 20,000 plants ha^{-1}, respectively (Supplementary Fig. S1D). Each experimental plot had an area of 12 m^2, formed by four plant rows, 3 m in length. The working plot consisted of the two central rows, excluding the two plants at each end.

The forage cactus remained under rainfed conditions and with no intercropping system until January 2019. Then, on 28 January 2019, the sorghum was sown in furrows parallel to the rows of forage cactus. During the same period, irrigation began. After the sorghum was established in the field, the seedlings were thinned, leaving 20 plants per linear metre to give a stand of 200,000 plants ha^{-1}.

The forage cactus was harvested in April 2020, characterising the first production cycle (~20 months). For the sorghum, four consecutive cycles were evaluated, equal to one plant cycle and three periods of regrowth. The duration of the first cycle (plant) was 115 DAE, with a cut made in May 2019; for the second cycle (first regrowth), the duration was 84 DAC, with a cut in August 2019; the third cycle (second regrowth) had a duration of 99 DAC and was harvested in November 2019; the fourth and last cycle (third regrowth) lasted 112 DAC, with a cut in March 2020.

The water replaced by the irrigation system was equal to 286.90 mm, which together with the rainfall (1692.00 mm), totalled 1978.90 mm of water added to the system.

2.2.3. *Experiment 3: planting densities with a north-south orientation*

This experiment consisted of different planting densities sown in a north-south row orientation. The Orelha de Elefante Mexicana clone was used intercropped with the sorghum IPA-467 variety. In this case, the planting time, the number of cycles, forage cactus and sorghum harvest times, as well as the size of the plots and imposed treatments, were similar to those in experiment 2, except for the orientation, which for this experiment was north-south (Supplementary Fig. S1G).

The water applied via the irrigation system during the experimental period was 294.6 mm, which added to 1692 mm of rainfall, giving a total of 1986.6 mm received by the experiment.

2.2.4. *Experiment 4: cactus and sorghum planting density*

Experiment 4 consisted of different planting densities for the forage cactus and sorghum by modifying the spacing between the plant rows to validate this observation. The Orelha de Elefante Mexicana clone of the forage cactus was used in the experiment, intercropped with the sorghum IPA-467 variety.

The forage cactus was planted at a fixed spacing between plants of 0.20 m, and four different spacings between rows (four treatments), 1.00, 1.25, 1.50 and 1.75 m, resulting in a final planting density for the forage cactus of 50,000; 40,000; 33,333 and 28,571 plants ha^{-1}, respectively, and 200,000; 160,000; 133,333 and 114,285 plants ha^{-1}, respectively for the sorghum (Supplementary Fig. S1I). The sorghum was sown in furrows parallel to the rows of forage cactus, leaving 20 plants per linear metre after thinning. The experimental plots consisted of four plant rows of 15 cactus plants each; the two central rows were considered the working plot, except for the two plants at each end.

During the period from planting to harvesting and throughout the experiment, both in the cactus and the sorghum, the conditions were the same as those described for experiments 2 and 3. During the experimental period, 283.1 mm were applied via the irrigation system, which added to the rainfall (1692 mm), totalling 1975.1 mm.

2.3. *Forage yield*

The productivity of the forage cactus was determined at harvest when the plants in the working plot were counted to obtain the final plant density. These plants were then cut, leaving only the basal and first-order cladodes in the field. The cut material was then weighed on an electronic balance to obtain the total fresh weight of the plants (kg). Two representative cladodes from each plot were selected, weighed, cut up, placed in properly identified paper bags, and left in a forced air circulation oven at 55 °C to constant weight.

Productivity in the sorghum was determined at the end of each crop cycle. At harvest, the two central rows of each plot were considered when counting the number of plants in two linear metres to obtain the final plant density. Eight plants from each working plot were then harvested and weighed to obtain the total fresh weight of the plants (kg). To determine the dry matter content, two representative plants were collected from each plot, cut up, weighed on a semi-analytical balance, placed in paper bags, and left in a forced air circulation oven at 55 °C to constant weight.

For both crops, the dry matter content of the plant was determined from the ratio between the values of dry and fresh matter. The fresh matter yield (FM, Mg ha^{-1}) was estimated considering the total fresh weight and final plant density. Whereas the dry matter yield (DM, Mg ha^{-1}) was estimated considering the estimated values for plant FM and the dry matter content.

2.4. Biological efficiency

The biological efficiency of the cactus-sorghum intercropping system was determined using the land equivalent ratio (LER) (Amanullah et al., 2020; Jardim et al., 2021a), area time equivalency ratio (ATER), land equivalent coefficient (LEC), and system productivity index (SPI), which were obtained as per Eqs. 1, 2, 3 and 4, respectively (Sadeghpour et al., 2013; Yilmaz et al., 2015; Diniz et al., 2017; Jardim et al., 2021a).

$$LER = \frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}} \tag{1}$$

where Y_{ab} and Y_{ba} = yield of the forage cactus and sorghum for the intercropped systems, respectively; Y_{aa} and Y_{bb} = yield of the forage cactus and sorghum for the monocropped systems, respectively. When LER > 1, there is a productive advantage to the intercrop over the single system; if LER = 1, there is no productive advantage, and if LER < 1, there is a disadvantage to the intercropping system (Yilmaz et al., 2015; Jardim et al., 2021a).

$$ATER = \frac{(LER_a . t_a) + (LER_b . t_b)}{T_{ab}} \tag{2}$$

where LER_a and LER_b = partial land use efficiency of the forage cactus and sorghum, respectively; t_a and t_b = respective duration of the forage cactus and sorghum cycle in days; T_{ab} = total time of the intercropping system. An ATER > 1 indicates a productive advantage; if ATER = 1, there is no productive advantage, and if ATER < 1, there is a disadvantage (Diniz et al., 2017).

$$LEC = LER_a \; . \; LER_b \tag{3}$$

If LEC > 0.25, there is a productive advantage to the intercropping system since the minimum production coefficient is 25% (Diniz et al., 2017).

$$SPI = \left(\frac{Y_{aa}}{Y_{bb}}\right) . Y_{ba} + Y_{ab} \tag{4}$$

where the main advantage of this index is to standardise the yield of the secondary crop (sorghum) in relation to the primary crop (forage cactus) (Sadeghpour et al., 2013).

2.5. Competitive ability

The competitive ability of the cactus-sorghum intercropping system was determined by means of the relative density coefficient (K) (Eq. 5), aggressivity index (A) (Eq. 6), actual loss or gain in yield (ALGY) (Eq. 7) and competitiveness ratio (CR) (Eq. 8) (Sadeghpour et al., 2013; Diniz et al., 2017).

$$K = \left[\frac{(Y_{ab} \; . \; Z_{ba})}{(Y_{aa} - Y_{ab}).Z_{ab}}\right] . \left[\frac{(Y_{ba} \; . \; Z_{ab})}{(Y_{bb} - Y_{ba}).Z_{ba}}\right] \tag{5}$$

where Z_{ab} = the proportion of forage cactus intercropped with sorghum; Z_{ba} = the proportion of sorghum intercropped with cactus. So that, if K > 1, there is an advantage in the yield of the intercropping system compared to the single system, if K = 1, there is no productive advantage to the intercropping system, and if K < 1, there is a disadvantage to the system. When $K_{ab} > K_{ba}$, it indicates that the forage cactus is highly competitive with the sorghum (Sadeghpour et al., 2013).

$$A_{ab} = \frac{Y_{ab}}{Y_{aa} \; . \; Z_{ab}} - \frac{Y_{ba}}{Y_{bb} \; . \; Z_{ba}} \tag{6}$$

If $A_{ab} = 0$, both crops are equally competitive, while if $A_{ab} > 0$ (positive), the forage cactus is dominant over the sorghum in the system, and if $A_{ab} < 0$ (negative), the sorghum is dominant over the forage cactus in the system (Sadeghpour et al., 2013). The same logic applies to A_{ba}.

$$ALGY = \left[LER_a\left(\frac{100}{Z_{ab}}\right) - 1\right] + \left[LER_b\left(\frac{100}{Z_{ba}}\right) - 1\right] \tag{7}$$

If ALGY > 0 (positive), it indicates an advantage to the intercropping system in relation to the single system. On the other hand, if ALGY < 0 (negative), it indicates a disadvantage to the intercropping system.

$$CR_a = \frac{LER_a}{LER_b} . \frac{Z_{ba}}{Z_{ab}} \tag{8}$$

where $CR_a < 1$, there is a positive effect on the intercropping system, and the crops can be grown together. On the other hand, if $CR_a > 1$, there is a negative effect due to greater crop competitiveness, and intercropping is not indicated (Sadeghpour et al., 2013). The same reasoning applies to sorghum (CR_b).

2.6. Statistical analysis

All the data were submitted to an analysis of normality and homoscedasticity. Given the premises, an analysis of variance (ANOVA) was carried out using the F-test ($p < 0.05$). When the hypothesis test was significant, the mean values were compared by Tukey's test at 5% significance in the case of the qualitative treatments, and regression analysis in the case of the quantitative treatments. Due to the similarity between treatments, a joint analysis was carried out for experiments 2 and 3 only to verify any significance in the interaction of the factors under study. All the statistical analysis was carried out using the R software (R Core Team, 2018).

3. Results

3.1. Forage yield

Dry matter (DM) yield showed significant differences ($p < 0.05$) when subjected to different cropping configurations for the four sorghum cycles and the two cuts of forage cactus under irrigation with saline water (Table 3).

For the first cut of the forage cactus, all the sorghum varieties, regardless of configuration, showed a reduction in productivity over time. When the sum of sorghum dry matter yields was evaluated, the best results were for the 467-SNG and SF11-SNG configurations (42.5

Table 3
Dry matter yield (DM) and dry matter content (DMC) in four cycles of sorghum varieties and two cuts of forage cactus clones, grown under single and intercropping systems, in a semi-arid environment (Section 1-02/2019 –02/2020 and Cut 2–02/2020–07/2020).

First Cut - 02/2019–02/2020						
Dry matter yield (Mg ha^{-1})						
Treatment	Variable					
	Y_{SC1}	Y_{SC2}	Y_{SC3}	Σs	Y_{FC}	Y_{FC+S}
IPA-467	17.4ab	11.9abc	3.2abcd	32.4abc	3.1b	35.5ab
IPA-P.288	21.6ab	9.1bc	3.3abcd	34.0abc	3.3b	37.4ab
IPA-SF11	16.5ab	8.3bc	2.7abcd	27.5abc	4.1b	31.6abc
MIU-467	12.6ab	7.9bc	1.8bcd	22.4bc	5.0b	27.4bc
MIU-P.288	18.7ab	8.7bc	3.1abcd	30.5abc	4.8b	35.3ab
MIU-SF11	14.9ab	7.6bc	2.5abcd	25.0bc	6.0b	31.0abc
OEM-467	13.3ab	6.6c	1.1d	20.9bc	16.6a	37.6ab
OEM-P.288	20.7ab	7.6bc	2.3abcd	30.5abc	13.8a	44.2a
OEM-SF11	10.9b	6.3c	1.6 cd	18.9c	15.9a	34.7ab
IPA-SNG	–	–	–	–	3.3b	3.3d
MIU-SNG	–	–	–	–	5.2b	5.2d
OEM-SNG	–	–	–	–	18.0a	18.0cd
467-SNG	21.9ab	15.4a	5.3a	42.5a	–	42.5a
P.288-SNG	21.9ab	9.8abc	4.4abc	36.1ab	–	36.1ab
SF11-SNG	24.1a	12.9ab	5.1ab	42.0a	–	42.0ab
Mean	17.9	9.3	3.0	30.2	8.2	30.8
P-value	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV%	26.5	26.3	43.8	20.6	34.0	19.2
Dry matter content (g g^{-1})						
Treatment	**Variable**					
	Y_{SC1}	Y_{SC2}	Y_{SC3}	Σs	Y_{FC}	Y_{FC+S}
IPA-467	0.32	0.29	0.34	0.31	0.07	0.24
IPA-P.288	0.28	0.26	0.33	0.28	0.06	0.22
IPA-SF11	0.33	0.27	0.28	0.30	0.06	0.20
MIU-467	0.31	0.30	0.31	0.30	0.08	0.20
MIU-P.288	0.30	0.28	0.29	0.29	0.08	0.22
MIU-SF11	0.29	0.28	0.29	0.28	0.09	0.20
OEM-467	0.36	0.31	0.31	0.34	0.07	0.13
OEM-P.288	0.26	0.28	0.29	0.27	0.07	0.15
OEM-SF11	0.27	0.28	0.27	0.28	0.08	0.13
IPA-SNG	–	–	–	–	0.07	0.07
MIU-SNG	–	–	–	–	0.07	0.07
OEM-SNG	–	–	–	–	0.07	0.07
467-SNG	0.39	0.30	0.37	0.35	–	0.35
P.288-SNG	0.34	0.27	0.32	0.32	–	0.32
SF11-SNG	0.34	0.26	0.35	0.31	–	0.31
Mean	0.32	0.28	0.31	0.30	0.07	0.19
Second Cut - 02/2020 a 07/2020						
Dry matter yield (Mg ha^{-1})						
Treatment	**Variable**					
	Y_{SC1}		Y_{FC}		Y_{FC+S}	
IPA-467	16.3abc		3.4b		19.7bc	
IPA-P.288	15.1abc		1.2b		16.3bcd	
IPA-SF11	9.3bcd		1.9b		11.1cde	
MIU-467	16.7abc		3.0b		19.7bc	
MIU-P.288	12.2abcd		2.5b		14.7bcd	
MIU-SF11	3.3d		3.6b		6.9de	
OEM-467	21.6a		10.3a		31.9a	
OEM-P.288	14.4abcd		10.4a		24.8ab	
OEM-SF11	8.5 cd		9.9a		18.4bc	
IPA-SNG	–		1.6b		1.6e	
MIU-SNG	–		2.5b		2.5e	
OEM-SNG	–		11.6a		11.6cde	
467-SNG	20.7a		–		20.7bc	
P.288-SNG	20.3ab		–		20.3bc	
SF11-SNG	13.6abcd		–		13.6cd	
Mean	14.3		5.2		15.6	
P-value	< 0.001		< 0.001		< 0.001	
CV%	31.5		36.1		27.3	
Dry matter content (g g^{-1})						
Treatment	**Variable**					
	Y_{SC1}		Y_{FC}		Y_{FC+S}	
IPA-467	0.54		0.07		0.25	
IPA-P.288	0.50		0.07		0.33	
IPA-SF11	0.50		0.07		0.23	
MIU-467	0.49		0.06		0.24	

Table 3 (*continued*)

First Cut - 02/2019–02/2020						
Dry matter yield (Mg ha^{-1})						
Treatment	Variable					
	Y_{SC1}	Y_{SC2}	Y_{SC3}	Σs	Y_{FC}	Y_{FC+S}
MIU-P.288	0.50		0.07		0.25	
MIU-SF11	0.39		0.08		0.13	
OEM-467	0.51		0.08		0.18	
OEM-P.288	0.50		0.08		0.15	
OEM-SF11	0.57		0.08		0.13	
IPA-SNG	–		0.06		0.06	
MIU-SNG	–		0.07		0.07	
OEM-SNG	–		0.09		0.09	
467-SNG	0.49		–		0.49	
P.288-SNG	0.47		–		0.47	
SF11-SNG	0.49		–		0.49	
Mean	0.50		0.07		0.24	

Mean values followed by the same lowercase letter in a column do not differ statistically by Tukey's test at a 5% probability level. IPA – IPA Sertânia; MIU – Miúda; OEM – Orelha de Elefante Mexicana; Sorghum varieties – 467, SF11, and P.288 – Progenitor 288. SNG – Single cropping system; Y – Yield; SC1, SC2 and SC3 – Sorghum Cycle 1, Cycle 2 and Cycle 3, respectively; ΣS – Sum of the yield of the sorghum cycles; FC – Forage Cactus; FC+S – Sum of the Cactus-sorghum; and CV% – Coefficients of variation.

and 42.0 Mg ha^{-1}, respectively), while the OEM-SF11 configuration had the lowest performance (18.9 Mg ha^{-1}). In addition, and in the case of the forage cactus, the highest yields were obtained for the configurations that included the OEM clone, with a mean of 16.1 Mg ha^{-1}. Based on the values shown in Table 3, the single crops of forage cactus and sorghum showed good productivity but less than the intercropping systems, where the OEM-P.288 configuration was better ($p < 0.05$), with a mean of 44.24 Mg ha^{-1}.

Interestingly, the results for productivity at the second cut (Table 3) were similar to the first cut. The intercropping system significantly increased biomass due to the positive synergistic effect, with higher values observed in the OEM-467 configuration (31.9 Mg DM ha^{-1}).

When the orientations and planting densities were evaluated for DM yield in the cactus-sorghum intercropping system, sorghum, and forage cactus, it was found that the interaction between factors was not significant ($p > 0.05$). However, a change in the north-south and east-west row orientations significantly influenced ($p < 0.05$) the productivity of the forage cactus, showing better performance when subjected to east-west orientation (21.7 Mg ha^{-1}) compared to the north-south (17.5 Mg ha^{-1}). On the other hand, no significant results were found for sorghum yield during the four cycles under study (40.7 Mg ha^{-1}), nor in the sum of the cactus-sorghum intercropping system (60.3 Mg ha^{-1}) using the different cultivation orientations ($p > 0.05$) (Table 4).

In relation to planting density, the result of modifying the spacing between plants, the variables with a significant effect (i.e., dry matter yield of forage cactus and fresh matter yield of cactus-sorghum intercropping) showed a positive quadratic response to the increase in the density of forage cactus planting (Fig. 3). Hence, the maximum value for the east-west orientation was equal to 91,463 and 91,836 plants ha^{-1}, and north-south equal to 93,625 and 98,726 plants ha^{-1}, for DM yield in the forage cactus, and FM yield for the sum of the cactus-sorghum intercropping, respectively.

When comparing the two extremes of density (100,000 and 20,000 plants ha^{-1}), it was found that the increase in DM yield in the forage cactus was 99.72% greater for the east-west orientation (29.3 and 14.7 Mg ha^{-1}, respectively) (Fig. 3A); whereas with the north-south orientation (Fig. 3D), the increase was 105.78% (25.3 and 12.3 Mg ha^{-1}, respectively). Summing the productivity of the forage cactus and sorghum, for the east-west orientation, the increase in FM yield was 77.24% (622.2 and 351.1 Mg ha^{-1}, for higher and lower density, respectively) (Fig. 3C). On the other hand, in the north-south row orientation, the

Table 4
Dry matter yield (DM) and dry matter content in the OEM clone of the forage cactus (*Opuntia stricta* (Haw.) Haw.) and sorghum (*Sorghum bicolor* (L.) Moench) variety 467, with an east-west and north-south orientation.

Dry matter yield (Mg ha^{-1})							
Row orientation	Variable						
	Y_{SC1}	Y_{SC2}	Y_{SC3}	Y_{SC4}	Σ_S	Y_{FC}	Y_{FC+S}
East-west	12.9	13.9	8.3	5.0	40.0	21.7a	61.7
North-south	12.7	16.4	8.1	4.5	41.4	17.5b	58.9
Mean	12.8	15.1	8.2	4.8	40.7	19.6	60.3
P-value	0.91	0.18	0.87	0.57	0.63	0.01	0.33
CV%	32.5	38.0	43.1	66.1	22.1	25.2	15.1
Dry matter content (g g^{-1})							
Row orientation	Variable						
	Y_{SC1}	Y_{SC2}	Y_{SC3}	Y_{SC4}	Σ_C	Y_{FC}	Y_{FC+S}
East-west	0.34	0.33	0.39	0.31	0.34	0.06	0.13
North-south	0.29	0.35	0.33	0.31	0.32	0.06	0.13
Mean	0.31	0.34	0.36	0.31	0.33	0.06	0.13

Mean values followed by the same lowercase letter in a column do not differ statistically by Tukey's test at a 5% probability level. Y – Yield; SC1, SC2, SC3 and SC4 – Sorghum Cycle 1, Cycle 2, Cycle 3 and Cycle 4, respectively; ΣS – Sum of the yield of the sorghum cycles; FC – Forage Cactus; FC+S – Sum of the Cactus-sorghum; and CV% – Coefficients of variation.

increase was 52.34% (552.3 Mg FM ha^{-1} at the highest density and 362.5 Mg FM ha^{-1} at the lowest) (Fig. 3F). The DM of the cactus-sorghum intercropping system showed no significant difference, with a mean value of 60.8 Mg ha^{-1} for the east-west orientation and 58.9 Mg ha^{-1} for the north-south orientation.

The different planting densities of the forage cactus did not affect the yield of the sorghum (Fig. 4). Therefore, the average value DM yield of sorghum, considering all cycles, was equal to 40.0 Mg ha^{-1} in east-west rows (Figs. 4A) and 41.4 Mg ha^{-1} with plants growing in a north-south orientation (Fig. 4C). The DM yield of the forage cactus, as also the sum of the four sorghum cycles and the cactus-sorghum intercropping system, showed a significant difference ($p < 0.05$), with a positive linear response to the increase in planting density and when modifying the spacing between the rows (Fig. 5). Furthermore, considering the highest and lowest planting density (50,000 and 28,571 plants ha^{-1}, respectively), it was found that the increase in DM yield of forage cactus (Fig. 5A) was 128.91% (28.7 and 12.5 Mg ha^{-1}, respectively). The sum of the four sorghum cycles showed an increase a 44.85% DM yield (44.1 and 30.4 Mg ha^{-1} with highest and lowest planting density, respectively) (Fig. 5B). Regarding the sum of the productivity (i.e., forage cactus and the four sorghum cycles), when the DM yield was evaluated (Fig. 5C), it was found that the highest density provided an increase of 69.36% compared to the lowest (72.7 and 43.0 Mg ha^{-1}, respectively).

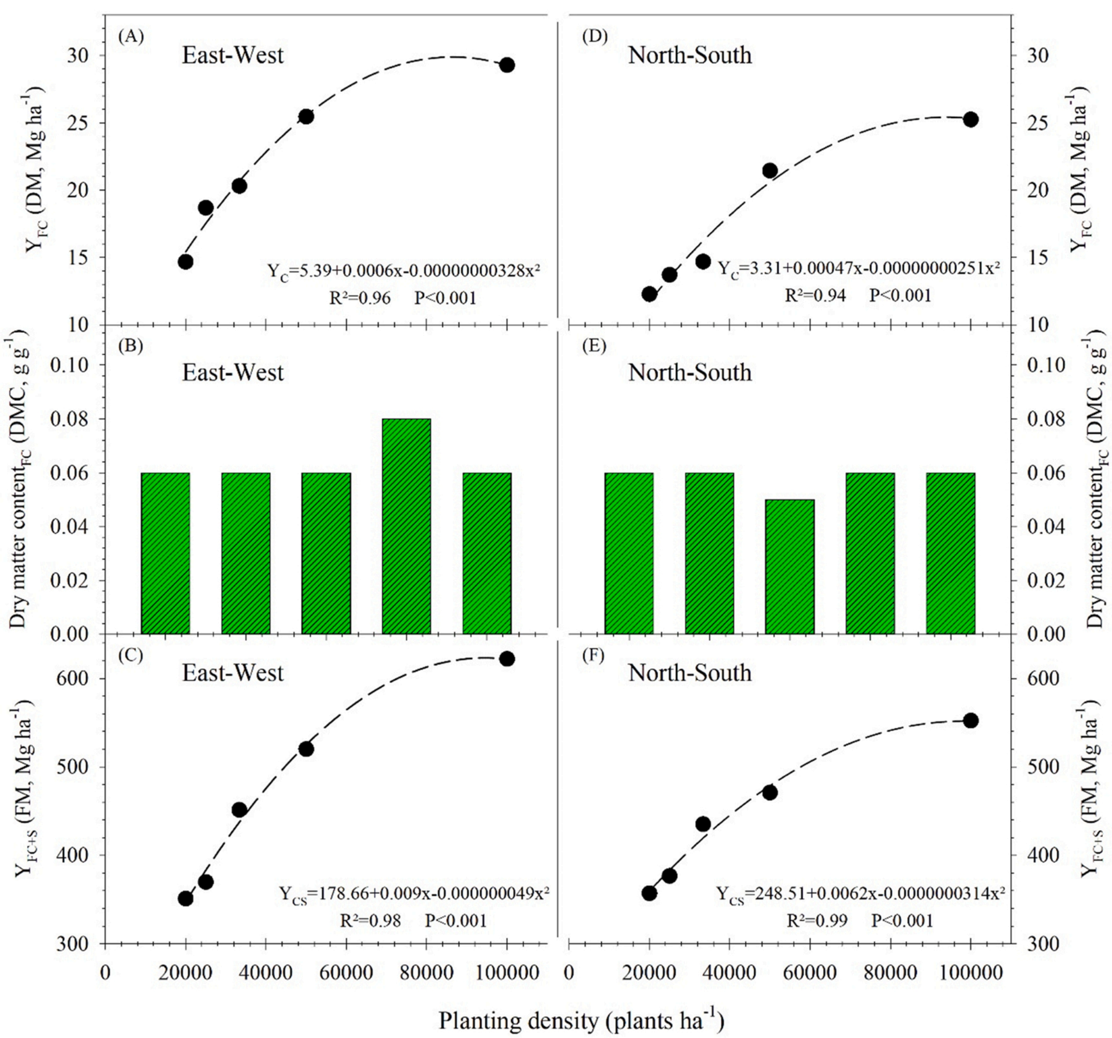

Fig. 3. Yield of the cactus-sorghum intercropping system with an east-west (A, B and C) and north-south (D, E and F) row orientations, cultivated under different planting densities (different plant spacing), in a semi-arid environment. FM – Fresh Matter; DM – Dry Matter; DMC – Dry matter content; Y – Yield. Note: Subscript indicates FC – Forage Cactus; and FC+S – Sum of the Cactus-sorghum.

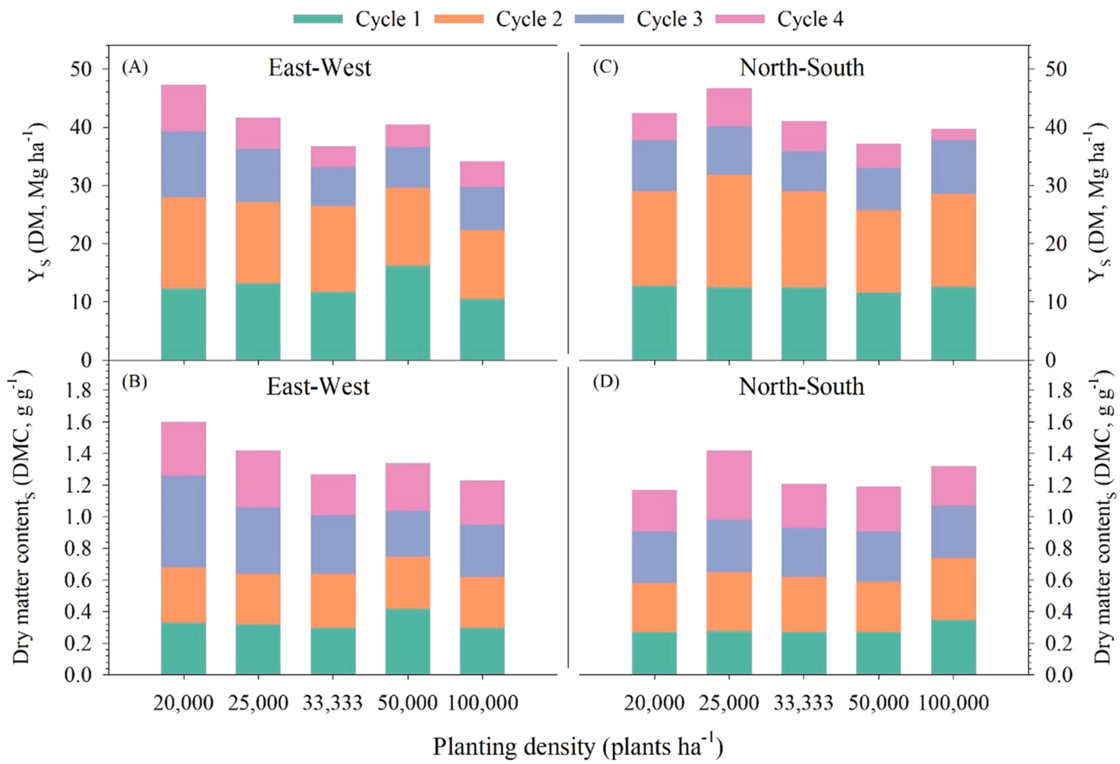

Fig. 4. Dry matter yield (A and C) and dry matter content (B and D) in the four sorghum cycles (*Sorghum bicolor* (L.) Moench), intercropped with forage cactus at different planting densities with an east-west (A and B) and north-south (C and D) orientation. Y – Yield. Note: The subscript letter (S) indicates the contribution of sorghum.

3.2. Biological efficiency

Table 5 shows the values of the indices of biological efficiency for the forage cactus-sorghum cropping configurations, in the four sorghum cycles and the two cuts of the forage cactus. The behaviour of the biological efficiency indices for the different cycles is observed (Supplementary Table S1), where the different configurations of the cactus-sorghum intercropping system resulted in a difference in the values of the indices under evaluation, except for the sum at the end of the first cut of the forage cactus (Table 5), where not being evidenced, in the first cut of forage cactus, significant difference for LER, ATER, LEC and SPI ($p > 0.05$), with mean values of 1.6, 1.8, 0.6 and 29.0, respectively.

In the second cut of forage cactus, it was observed that there was a significant difference for all biological efficiency indices ($p < 0.05$). However, when the LER is evaluated, it is seen that for all configurations, there is a positive effect when using the intercropped system (LER > 1), with the exception of IPA-P.288 (LER = 0.84). For the ATER and LEC index, the behaviour is similar to that observed in the LER, with a productive advantage for the intercropped system, except for the IPA-P.288 configuration, which has a lower value than the other treatments (ATER = 0.9 and LEC = 0.16). SPI showed higher values when the configuration included the OEM clone of the forage cactus, irrespective of the sorghum varieties used, and differed statistically from the other configurations, which had mean values of 13.50, 11.70, and 11.65 (OEM-SF11, OEM-467, and OEM-P.288, respectively). As such, the other configurations showed no significant difference between them. In general, the values of LER (> 1), ATER (> 1), LEC (> 0.25), and high SPI show good results for the intercropping system. These results indicate an advantage in biological efficiency and productive performance, thus opting for the intercropping system instead of the single cropping system.

3.3. Competitive ability

The values of the indices of competitive ability for the different cropping configurations in the four sorghum cycles and two cycles of the cactus-sorghum intercropping system are shown in Table S2 (see Supplementary Material). In general, the indices under study showed similar behaviour for the different sorghum and forage-cactus cycles, demonstrating the dominance of the forage cactus over the sorghum.

Regardless of the configuration under study, there was an accumulated advantage to the intercropping compared to the single system (Table 6). That said, the values of the partial coefficients of relative density in the forage cactus (K_{ab}) and sorghum (K_{ba}), as well as the product of K_{ab} and K_{ba} (K), showed no significant difference for the different configurations. In the forage cactus, the aggressivity index (A_a) was positive. In contrast, the values for aggressivity (A_b) were negative for the sorghum, indicating the dominance of the forage cactus relative to the sorghum. These results are confirmed by the higher values found for the competitiveness ratio in the forage cactus (CR_a), which are greater than 1 and lower values for the competitiveness ratio of the sorghum (CR_b). When studying the actual loss or gain in yield of the forage cactus ($ALGY_a$) and sorghum ($ALGY_b$), and their sum (ALGY > 0), an advantage can be seen in opting for the intercropping system over the single system.

4. Discussion

4.1. Forage yield

The gradual reduction in sorghum productivity with each cycle is associated with its productive vigour. Over time and with the cuts made when harvesting, stress is caused in the crop, with a decrease in reserve carbohydrates demonstrated by a reduction in the productive potential from one cycle to another (Silva et al., 2012). In addition, the decrease in

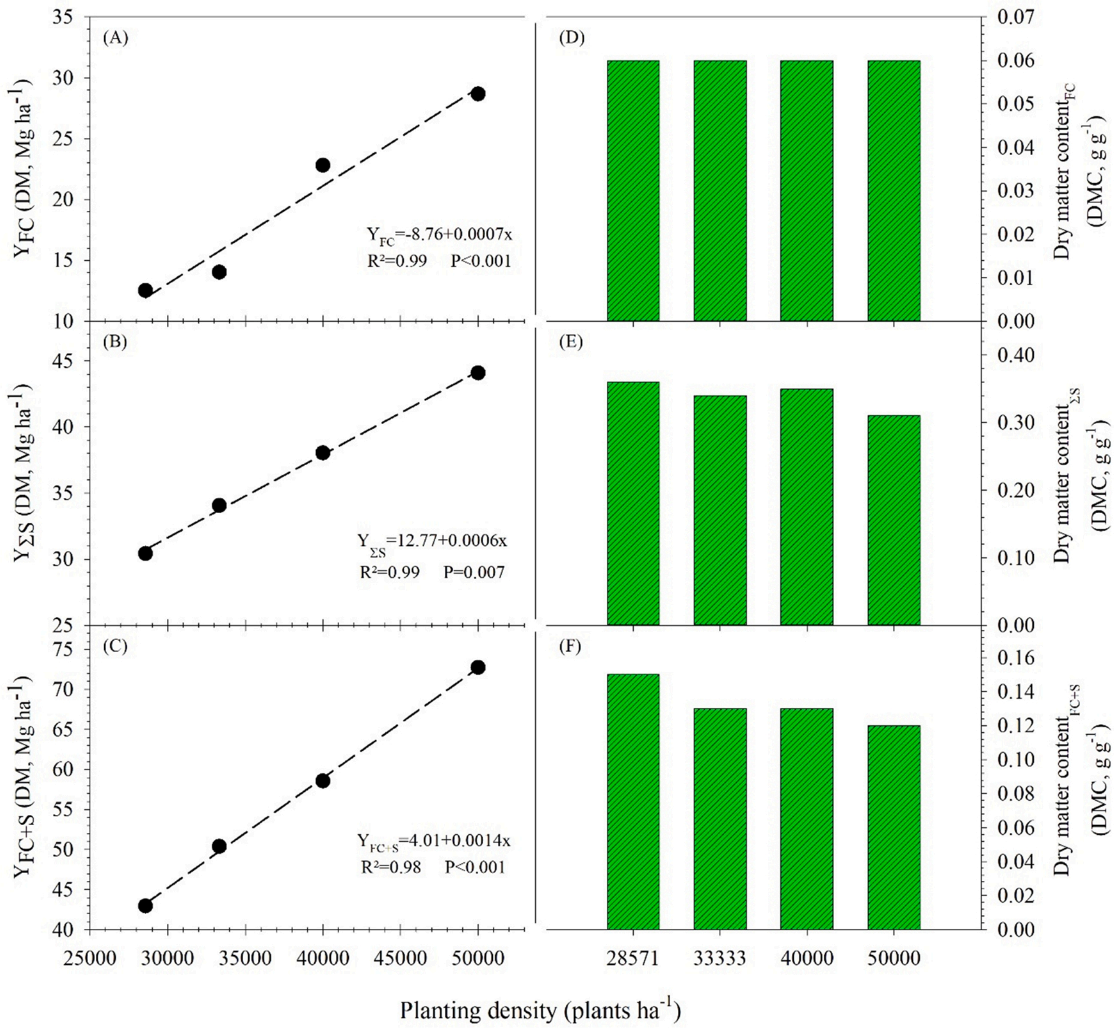

Fig. 5. Dry matter yield (A, B and C) and dry matter content (D, E and F) in the forage cactus (*Opuntia stricta* (Haw.) Haw.) and sorghum (*Sorghum bicolor* (L.) Moench), in an intercropping system under different planting densities (row spacing). DM – Dry matter; DMC – Dry matter content; Y – Yield. Note: Subscript indicates FC – Forage Cactus; ΣS – Sum of the yield of the sorghum cycles; and FC+S – Sum of the Cactus-sorghum.

production over the cycles may be associated with fertilisation carried out in the system, since it was performed only at the beginning during the entire cycle of forage cactus. The highest values for dry matter yield in the sorghum for the single crop in relation to the intercrop is associated with interspecific competition between the crops under the intercropping system (Makino et al., 2019). Thus, there is greater inter-and intraspecific competition between the plants for available resources, i.e., water, light, and nutrients (Jardim et al., 2021a).

From the results, it was seen that the forage cactus and sorghum have a tolerance to saline stress since the water applied was characterised as of high salinity (1.62 dS m^{-1}) and classified as C3; however, the values for productivity were satisfactory. This response may have been due to the efficiency of the water application (i.e., 80% of the ETc of forage cactus), as well as the rainfall that occurred during the experimental period, promoting the leaching of salts preventing accumulation in the root zone of the species studied. In a study with the forage cactus, Gajender et al. (2013) found that the crop has a moderate tolerance to salinity, where it exhibits high sensitivity under conditions above 4 dS m^{-1}. In turn, sorghum productivity under saline stress depends on the variety and cropping arrangement. Costa et al. (2019) found that sorghum is sensitive to salinity and consequently shows a reduction in productivity when the salt concentration is greater than 4.8 dS m^{-1}.

The reason for the productivity of the forage cactus being higher in systems that included the OEM clone is associated with factors intrinsic to this clone. This is because OEM clone has lower mortality than the MIU and IPA clones (Silva et al., 2015; Jardim et al., 2021a), superior biometric variables (Pereira et al., 2015), high FM and DM production per plant, high water use efficiency (Silva et al., 2014b); and greater capacity for dry matter accumulation per unit area (Nunes, al. et al., 2020). Furthermore, in terms of competitive ability has high aggressivity and marked adaptability, being a great option when used in intercropping systems. Moreover, Silva et al. (2015) found greater productivity in the OEM clone than the IPA and MIU clones.

The planting systems in the OEM-P.288 and OEM-467 configurations had higher yields (see Table 3) due to the above characteristics of the clone, as well as the morphological characteristics of the P.288 and 467 varieties, i.e., number, width and length of the leaves, the height and stem diameter (data not shown). By studying cropping configurations of cactus-sorghum intercropping systems (IPA, MIU, OEM, 467, SF11, 2502, IPA-467, IPA-SF11, IPA-2502, MIU-467, MIU-SF11, MIU-2502, OEM-467, OEM-SF11, and OEM-2502), Jardim et al. (2021a) found that the OEM-467 configuration obtained better production stability due to the low mortality of the forage cactus, high aggressiveness, and competitiveness, as well as the good performance of the 467 variety in intercropping systems. The loss in yield of less competitive crops in intercropping systems, in this case, the sorghum, is reduced by changes in their morphology, functional characteristics, extended cycle duration and dry matter accumulation (Zhang et al., 2020).

Table 5
Biological efficiency indices in forage cactus clones and sorghum varieties under an intercropping system grown in a semi-arid environment (first cut of the forage cactus – 02/2019–02/2020 and second cut of the forage cactus – 02/2020–07/2020).

	02/2019–02/2020						
‡Total Cut 1st	Treatment	Variable					
		LER_a	LER_b	LER	ATER	LEC	SPI
	IPA-467	1.2a	0.6abc	1.9	2.1	0.7	32.8
	IPA-P.288	0.6b	0.9ab	1.5	1.6	0.5	34.3
	IPA-SF11	0.9ab	0.7abc	1.6	1.8	0.6	27.9
	MIU-467	0.8ab	0.5c	1.3	1.5	0.4	23.1
	MIU-P.288	0.6b	0.8ab	1.4	1.6	0.5	26.2
	MIU-SF11	1.2a	0.6bc	1.8	2.0	0.7	25.8
	OEM-467	1.2a	0.5c	1.7	1.9	0.6	27.7
	OEM-P.288	0.9ab	0.9a	1.8	2.0	0.8	37.4
	OEM-SF11	1.1ab	0.6bc	1.6	1.8	0.6	25.8
	Mean	0.9	0.7	1.6	1.8	0.6	29.0
	P-value	0.001	< 0.001	0.060	0.080	0.11	0.09
	02/2019–07/2020						
⁋Total Cut 2nd	Treatment	Variable					
		LER_a	LER_b	LER	ATER	LEC	SPI
	IPA-467	1.8a	0.6abc	2.4a	2.9a	1.1abc	1.6b
	IPA-P.288	0.3b	0.6abc	0.8b	0.9b	0.2c	0.8b
	IPA-SF11	1.3a	0.5bc	1.9ab	2.3ab	0.7bc	1.3b
	MIU-467	1.4a	0.8ab	2.3a	2.7a	0.9bc	2.3b
	MIU-P.288	2.0a	0.5bc	2.5a	3.1a	0.8bc	1.5b
	MIU-SF11	2.3a	0.3c	2.5a	3.2a	0.4bc	1.3b
	OEM-467	1.6a	1.1a	2.7a	3.2a	1.9a	11.7a
	OEM-P.288	1.8a	0.8abc	2.6a	3.2a	1.2ab	11.7a
	OEM-SF11	1.4a	0.8ab	2.3a	2.7a	1.2ab	13.5a
	Mean	1.6	0.7	2.2	2.7	0.9	5.1
	P-value	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001

Mean values followed by the same lowercase letter in a column do not differ statistically by Tukey's test at a 5% probability level. IPA – IPA-Sertania; MIU – Miúda; and OEM – Orelha de Elefante Mexicana. Sorghum varieties – 467; SF11; and P.288 – Progenitor 288. LERa – Partial land equivalent ratio for the forage cactus; LERb – Partial land equivalent ratio for the sorghum; LER – Total land equivalent ratio; ATER – Area time equivalency ratio; LEC – Land equivalent coefficient; and SPI – System productivity index (Mg DM ha^{-1}).
Note: ‡Considering the first cut of the forage cactus and the three sorghum cycles; and ⁋Considering the second cut of the forage cactus and the fourth sorghum cycle.

Table 6
Competitive ability indices in forage cactus clones and sorghum varieties under an intercropping system grown in a semi-arid environment (first cut of the forage cactus – 02/2019–02/2020 and second cut of the forage cactus – 02/2020–07/2020).

	02/2019–02/2020										
‡Total Cut 1st		K_{ab}	K_{ba}	K	A_{ab}	A_{ba}	CR_a	CR_b	$ALGY_a$	$ALGY_b$	ALGY
	IPA-467	13.8ab	0.2	3.4	14.2	-14.2	27.1a	0.04b	1097.3a	69.0b	116.3a
	IPA-P.288	-22.1b	0.7	-10.9	14.5	-14.5	8.4b	0.18ab	775.1ab	94.0ab	869.0ab
	IPA-SF11	7.8ab	0.5	-1.5	13.4	-13.4	18.0ab	0.07ab	951.4ab	71.9b	1023.3ab
	MIU-467	12.6ab	0.1	1.6	9.1	-9.1	13.2ab	0.08ab	786.5ab	57.1b	843.6ab
	MIU-P.288	11.7ab	0.3	1.7	11.0	-11.0	8.4b	0.15ab	706.7ab	92.1ab	798.8ab
	MIU-SF11	-9.1ab	0.2	-1.5	8.0	-8.0	18.1ab	0.06ab	916.1ab	65.9b	982.0ab
	OEM-467	7.4ab	0.4	3.4	3.0	-3.0	6.3b	0.18ab	430.0b	69.2b	499.2b
	OEM-P.288	26.6a	0.0	17.8	3.1	-3.1	3.1b	0.32a	369.9b	119.1a	489.0b
	OEM-SF11	-2.5ab	0.5	-0.8	2.2	-2.2	6.0b	0.30ab	412.7b	82.2ab	495.0b
	Mean	5.1	0.3	1.5	8.7	-8.7	12.1	0.15	716.2	80.1	679.6
	P-value	0.04	0.99	0.15	0.07	0.07	0.002	0.01	0.006	< 0.001	0.009
	02/2019–07/2020										
⁋Total Cut 2nd	Treatment	Variable									
		K_{ab}	K_{ba}	K	A_{ab}	A_{ba}	CR_a	CR_b	$ALGY_a$	$ALGY_b$	ALGY
	IPA-467	-23.1	0.4	-6.4	28.5a	-28.5b	35.6ab	0.03bc	2033.7a	91.3	2125.0a
	IPA-P.288	4.5	0.1	-1.1	6.3b	-6.3a	9.8b	0.13bc	722.5bc	94.5	816.9bc
	IPA-SF11	-7.8	0.1	-1.5	14.9ab	-14.9ab	20.5b	0.05bc	1132.4ab	81.9	1214.4abc
	MIU-467	-19.3	0.4	3.5	14.1ab	-14.1ab	18.7b	0.09bc	1507.8ab	95.7	1603.5ab
	MIU-P.288	-2.2	-0.1	-5.9	16.1ab	-16.1ab	20.9b	0.05bc	722.5bc	72.1	794.6bc
	MIU-SF11	10.2	0.0	0.4	16.4ab	-16.4ab	65.3a	0.02c	1409.7ab	29.0	1438.7abc
	OEM-467	-3.0	-0.1	-8.0	2.2b	-2.2a	2.8b	0.43a	367.6c	148.1	515.7c
	OEM-P.288	-14.2	1.1	1.5	3.0b	-3.0a	4.4b	0.27ab	405.3c	104.5	509.8c
	OEM-SF11	1.9	0.9	10.0	3.6b	-3.6a	5.0b	0.24abc	448.4c	87.5	535.9c
	Mean	-5.9	0.3	-0.8	11.7	-11.7	20.3	0.15	972.2	89.4	1061.6
	P-value	0.62	0.37	0.76	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.06	< 0.001

Mean values followed by the same lowercase letter in a column do not differ statistically by Tukey's test at a 5% probability level. IPA – IPA Sertânia; MIU – Miúda; OEM – Orelha de Elefante Mexicana. Sorghum varieties – 467; SF11; P.288 – Progenitor 288. Kab – Relative density coefficient of the cactus over the sorghum; Kba – Relative density coefficient of the sorghum over the cactus; K – Relative density coefficient; Aab – Aggressivity of the cactus over the sorghum; Aab – Aggressivity of the sorghum over the cactus; ALGYa – Actual loss or gain in cactus yield; ALGYb – Actual loss or gain in sorghum yield; ALGY – Actual loss or gain in yield; CRa – Competitiveness ratio in the cactus; and CRb – Competitiveness ratio in the sorghum.
Note: ‡Considering the first cut of the forage cactus and the three sorghum cycles; and ⁋Considering the second cut of the forage cactus and the fourth sorghum cycle.

In general, the cactus-sorghum intercropping system promotes increased crop productivity compared to single crops and is an excellent practice in the semi-arid region. This increase is due to the biological capacity of the companion crops to adapt to a new cropping system and compete for the available resources (Diniz et al., 2017; Jardim et al., 2021a). Furthermore, compared to the single crops, the intercropping systems showed an increase in productivity due to the efficient use of the land and the limited resources by means of spatio-temporal complementarity (Moghbeli et al., 2019; Zhang et al., 2020).

It should be noted that in the cactus-sorghum intercropping system, there is a difference between the metabolism of the intercropped plants, where the forage cactus has CAM pathway, with high water use efficiency and a large amount of water in its cladodes, and where the stomata open at night and close during the day (Scalisi et al., 2016; Jardim et al., 2021b; Souza et al., 2022). In contrast, sorghum has C4 pathway, where the opposite is seen. Therefore, competition may be less under this system, with mutual advantages between the crops. In addition, sorghum has the physiological characteristic of interrupting or limiting metabolic activity under water deficit (Santos et al., 2020).

Another factor that promotes a productive increase in the crops is planting density (Khan et al., 2017; Makino et al., 2019). However, an increase in the productivity of intercropped plants is seen only when there is a change in the density of both crops. This was demonstrated by the productivity of the sorghum intercropped with forage cactus under different row orientations (i.e., east-west and north-south), where no significant difference in yield was found for the different densities (Fig. 4). This is because only the forage cactus had different spacing between the plants, while the stand of the sorghum was fixed (200,000 plants ha^{-1}). On the other hand, when both crops are submitted to different densities, they each show an increase in productivity, as well as in the sum of their productivity (Fig. 5), an alternative way of improving the cropping arrangements.

Therefore, it is evident that the increase in planting density under the cactus-sorghum intercropping system favoured greater productivity per unit of occupied area. This increase in forage yield with the increase in densification is mainly associated with the greater number of plants per area, optimising the available space (Silva et al., 2014a; Petter et al., 2016), and better water use due to the smaller area of exposed soil favouring less soil water evaporation (Ahmadi et al., 2019; Alves et al., 2019), as well as the adaptive capacity of the species to the environment in which it is inserted, with direct reflections on growth, development and productivity characteristics.

In the cactus-sorghum intercropping system, the higher yield of the forage cactus under the east-west orientation compared to the north-south (see Table 4) may be related to the greater light capture of plants in east-west orientation, which directly contributes to their development (Peixoto et al., 2018), on the other hand, plants in north-south row orientation suffer shading caused by the sorghum crop on the cactus. Crop shading in intercropping systems can reduce the incidence of light on the smaller crop, causing a reduction in photoassimilates and, consequently, a reduction in the productivity of the shaded crop (Franck et al., 2013; Almeida et al., 2014). This directly influences plant physiology and results in lower levels of chlorophyll compared to plants in full sun (Texeira et al., 2020; Jardim et al., 2021b). In the case of sorghum, the orientation did not affect the yield, which can be explained by the high capacity of C4 crops to absorb solar radiation (Corrêa et al., 2019). In addition, among its morphological characteristics, sorghum has an alternate leaf arrangement, with changes in the leaf angle that help reduce self-shading.

4.2. Biological efficiency

The LER index is used to assess the land use of the intercropping system compared to the single crops and indicates the relative land area needed for the single system to obtain a similar yield to the intercropping system (Amanullah et al., 2020; Li et al., 2020; Jardim et al., 2021a). The fluctuation in partial and total LER values for the different sorghum cycles is due to variations in the yield of each cycle and to increases in the forage cactus. LER values greater than 1 in the first cut of the forage cactus (mean = 1.61) indicate that for the single system to produce the same as the intercropping system, an additional 61% of land is necessary (i.e., 0.61 ha) (Sadeghpour et al., 2013; Yilmaz et al., 2015; Morais et al., 2018; Jardim et al., 2021a). In the second cut of the forage cactus, the LER was less than 1 only in the IPA-P.288 configuration, possibly due to the high mortality of the cactus, reflecting in a smaller stand and, consequently, lower productivity per unit area. For the other configurations, the values are greater than 1, showing the high efficiency of the cactus-sorghum intercropping system in relation to the single system. LER values greater than 1 indicate that the intercropping system is more efficient than the single system in land use, including biological sustainability and a productive advantage under this system (Diniz et al., 2017; Jardim et al., 2021a). Silva et al. (2013) studied different cropping configurations for the forage cactus intercropped with cotton, sesame, and peanut; Souza et al. (2022) evaluated the intercropping systems cactus-millet; and Diniz et al. (2017) and Jardim et al. (2021a), in a study of a cactus-sorghum intercropping system, obtained values greater than one, reinforcing the efficiency of the crop when subjected to different intercropping configurations.

To better understand the efficiency of the intercropping system, applying the ATER is of paramount importance since it considers the time spent by the crop in the field until harvested (Diniz et al., 2017). In general, the values for ATER were greater than 1, except for the IPA-P.288 configuration in the second cut of the forage cactus due to the high mortality of the clone. This result reflected an LEC value of 0.16, indicating a disadvantage to the system. ATER values greater than 1 show that the cactus-sorghum intercropping system has a biological advantage in land use and time, just as a value for LEC greater than 0.25 demonstrates the superiority of the intercropping system in relation to the single system (Diniz et al., 2017; Jardim et al., 2021a).

The SPI index shows the equivalence of the yield of the secondary crop (sorghum) to the yield of the primary crop (forage cactus). In this study, the SPI values were higher than the yields of the forage cactus as a single crop, underlining the stability of forage production in the cactus-sorghum intercropping system (Diniz et al., 2017).

4.3. Competitive ability

The negative values for partial K and total K obtained in this study are associated with a higher crop yield under the intercropping system than the single crops in some replications, showing that the interspecific competition was greater than the intraspecific. The indices of aggressivity (A) and competitiveness (CR) show that the forage cactus is the dominant crop while the sorghum is the secondary crop. Similar results were obtained by Diniz et al. (2017) and Jardim et al. (2021a) when studying the cactus-sorghum intercropping system in a semi-arid environment, and Souza et al. (2022) when studying intercropping systems cactus-millet. Morais et al. (2018) stated that the dominance of one crop over another in an intercropping system is due to the better productive response of the dominant crop. As such, competition between the intercropped species can be defined by the interaction between them, playing an important role in determining the system's productivity (Zhang et al., 2011).

The ALGY index plays an important role in understanding intra-and interspecific competition in an intercropping system, providing more accurate evidence than other indices (Amanullah et al., 2020). For example, the cactus-sorghum intercropping system resulted in a productive gain (i.e., ALGY > 1). The forage cactus obtained higher values than those found for the sorghum (i.e., $ALGY_a > ALGY_b$), showing that, under an intercropping system, cactus is less susceptible to a loss in yield than is sorghum (Yilmaz et al., 2015). This characteristic is probably associated with morpho-physiological adaptability and high yield under adverse environmental conditions.

5. Conclusions

The forage cactus-sorghum intercropping system is an excellent alternative for biosaline agriculture cultivation in semi-arid environments. This alternative is made even more viable using the OEM-467 and OEM-P.288 configurations. The indices of biological efficiency (LER, ATER, LEC and SPI with mean values equal to 1.6, 1.8, 0.6 and 29.0, respectively) and competitive ability (ALGY in average 870.6) showed that there is an advantage in opting for the cactus-sorghum intercropping system, helping to maximise yields and making it a profitable practice for hot and dry environments.

Changing the row orientation of the crop did not alter the productive yield of the forage cactus-sorghum intercropping system; it did, however, offer better conditions for the productive development of the forage cactus when grown in an east-west orientation (21.7 Mg ha^{-1} of dry matter) compared to north-south (17.5 Mg ha^{-1} of dry matter). In addition, the highest planting densities under study (50,000 and 100,000 plants ha^{-1}) resulted in a productive increase under the cactus-sorghum intercropping system by changing the spacing between plants and between rows.

It is suggested that further research be developed aimed at intercropping the forage cactus with other sorghum varieties and different forage species, as well as the use of water with a higher saline content and different irrigation depths, in order to obtain results and alternatives that favour forage production in different environments and under adverse conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Fundação de Amparo à Ciência e Tecnologia de Pernambuco, Brazil [FACEPE - APQ-0215-5.01/10 and FACEPE - APQ-1159-1.07/14] and the Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq, Brazil [309421/2018-7, and 152251/2018-9] for their financial support. The authors would also like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil [CAPES - Finance Code 001] for the research and study grants. We are grateful to four anonymous reviewers for their excellent comments and suggestions that helped to improve the paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2022.115059.

References

Ahmadi, S.H., Solgi, S., Sepaskhah, A.R., 2019. Quinoa: a super or pseudo-super crop? Evidences from evapotranspiration, root growth, crop coe ffi cients, and water productivity in a hot and semi-arid area under three planting densities. Agric. Water Manag. 225. https://doi.org/10.1016/j.agwat.2019.105784.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop requirements. Irrigation and Drainage. FAO, p. 56.

Almeida, F.L., Calonego, J.C., Catuchi, T.A., Tiritan, C.S., Araújo, F.F., Silva, P.C.G., 2014. Produtividade de soja em diferentes posições entre renques de eucalipto em cultivo consorciado. Colloq. Agrar. 10 (1), 33–44. https://doi.org/10.5747/ca.2014.v10.n1.098.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Z. 22 (6), 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Alves, C.P., Silva, T.G.F., Alves, H.K.M.N., Jardim, A.M., da, R.F., Souza, L.S.B., de, Cruz Neto, J.F. da, Santos, J.P.A., de, S., 2019. Consórcio palma-sorgo sob lâminas de irrigação: balanço de água no solo e coeficientes da cultura. Agrometeoros 27 (2), 347–356. https://doi.org/10.31062/agrom.v27i2.26448.

Amanullah, K., Khalil, S., Imranuddin, F., 2020. Influence of irrigation regimes on competition indexes of winter and summer intercropping system under semi-arid regions of Pakistan. Sci. Rep. 10 (1), 1–21. https://doi.org/10.1038/s41598-020-65195-7.

Amorim, D.M., Silva, T.G.F., Pereira, P., de, C., Souza, L.S.B. de, Minuzzi, R.B., 2017. Phenophases and cutting time of forage cactus under irrigation and cropping systems. Pesqui. Agropecu. Trop. 47 (1), 62–71. https://doi.org/10.1590/1983-40632016v4742746.

Araújo Júnior, G., do, N., Silva, T.G.F., Souza, L.S.B., Souza, M., de, S., Araújo, G.G.L., Moura, M.S.B., Santos, J.P.A., de, S., Jardim, A.M., da, R.F., Alves, C.P., Alves, H.K. M., 2021. Productivity, bromatological composition and economic benefits of using irrigation in the forage cactus under regulated deficit irrigation in a semiarid environment. Bragantia *80*. https://doi.org/10.1590/1678-4499.20200390.

Ayangbenro, A.S., Babalola, O.O., 2020. Current Plant Biology Reclamation of arid and semi-arid soils: The role of plant growth-promoting archaea and bacteria. Curr. Plant Biol. 1. https://doi.org/10.1016/j.cpb.2020.100173.

Buesa, I., Mirás-avalos, J.M., Intrigliolo, D.S., 2020. Agricultural and Forest Meteorology Row orientation e ff ects on potted-vines performance and water-use e ffi ciency. Agric. For. Meteorol. 294. https://doi.org/10.1016/j.agrformet.2020.108148.

Cavalcante, L.A.D., Santos, G.R., de, A., Silva, L.M., da, Fagundes, J.L., Silva, M.A. da, 2014. Respostas de genótipos de palma forrageira a diferentes densidades de cultivo. Pesqui. Agropecu. Trop. 44 (4), 424–433. https://doi.org/10.1590/s1983-40632014000400010.

Corrêa, R.D.G., Furlani, C.E.A., Zerbato, C., Oliveira, D.T., De, Noronha, R.H.D.F., Warikoda, N.K., 2019. Sowing operation direction and population densities in corn. Rev. Bras. De. Eng. Agríc. e Ambient. 23 (3), 183–187. https://doi.org/10.1590/1807-1929/agriambi.v23n3p183-187.

Costa, A.R.F.C.D.A., Costa, J.P.N., Medeiros, J.F.D.E., Silva, M.V.T.D.A., Lino, V.A.D.S., 2019. Desempenho de variedades de sorgo dupla aptidão submetidas a diferentes lâminas de irrigação com água salina. Rev. Bras. De. Milho e Sorgo 18 (3), 417–428. https://doi.org/10.18512/1980-6477/rbms.v18n3p417-428.

Díaz, F.J., Grattan, S.R., Reyes, J.A., de la Roza-Delgado, B., Benes, S.E., Jiménez, C., Dorta, M., Tejedor, M., 2018. Using saline soil and marginal quality water to produce alfalfa in arid climates. Agric. Water Manag. 199, 11–21. https://doi.org/10.1016/j.agwat.2017.12.003.

Diniz, W.J., da, S., Silva, T.G.F., Ferreira, J.M., da, S., Santos, D.C., Moura, M.S.B., Araújo, G.G.L., Zolnier, S., 2017. Forage cactus-sorghum intercropping at different irrigation water depths in the Brazilian Semiarid Region. Pesqui. Agropecu. Bras. 52 (9), 724–733. https://doi.org/10.1590/S0100-204×2017000900004.

Eeswaran, R., Nejadhashemi, A.P., Alves, F.C., Saravi, B., 2021. Evaluating the applicability of soil moisture-based metrics for gauging the resiliency of rainfed agricultural systems in the midwestern United States. Soil Tillage Res. 205. https://doi.org/10.1016/j.still.2020.104818.

Franck, N., Muñoz, F.A., Arancibia, D., Pérez-Quezada, J., 2013. Estimating the carbon assimilation of growing cactus pear cladodes through different methods estimating the carbon assimilation of growing cactus pear cladodes through different methods. Acta Hortic. 995, 157–164. https://doi.org/10.17660/ActaHortic.2013.995.19.

Gajender, R.K.Y., Dagar, J.C., Lal, K., Singh, G., 2013. Growth and fruit characteristics of edible cactus (*Opuntia ficus-indica*) under salt stress environment. J. Soil Salin. Water Qual. 5 (2), 136–142.

Hendges, A.R.A.D.A., Guimarães, M.D.A., Dovale, J.C., Lima Neto, B.P., 2019. Agronomic performance and biological efficiency of kale intercropped with spice species. Rev. Caatinga 32 (1), 7–15.

Jardim, A.M., da, R.F., Silva, T.G.F., Souza, L.S.B., de, Araújo Júnior, G.D.N., Alves, H.K. M.N., Souza, M.D.S., de Araújo, G.G.L., de Moura, M.S.B., 2021a. Intercropping forage cactus and sorghum in a semi-arid environment improves biological efficiency and competitive ability through interspecific complementarity. J. Arid Environ. 188. https://doi.org/10.1016/j.jaridenv.2021.104464.

Jardim, A.M., da, R.F., Santos, H.R.B., Alves, H.K.M.N., Silva, S.L.F., Souza, L.S.B., de, Araújo Júnior, G., do, N., Souza, M., de, S., Araujo, G.G.L., De, de Souza, C.A.A., da Silva, T.G.F., 2021b. Plant Physiology and Biochemistry Genotypic differences relative photochemical activity, inorganic and organic solutes and yield performance in clones of the forage cactus under semi-arid environment. Plant Physiol. Biochem. 162, 421–430. https://doi.org/10.1016/j.plaphy.2021.03.011.

Jardim, A.M.R.F., Silva, T.G.F., Souza, L.S.B., De, Souza, M.D.S., Morais, J.E.F., De, Júnior, N.A., 2020. Multivariate analysis in the morpho-yield evaluation of forage cactus intercropped with sorghum. Rev. Bras. De. Eng. Agríc. e Ambient. 24, 756–761. https://doi.org/10.1590/1807-1929/agriambi.v24n11p756-761.

Jardim, A.M.R.F., Araújo Júnior, G.N., Silva, M.V., Santos, A., Silva, J.L.B., Pandorfi, H., Oliveira-Júnior, J.F., Teixeira, A.H.C., Teodoro, P.E., de Lima, J.L.M.P., Silva Junior, C.A., Souza, L.S.B., Silva, E.A., Silva, T.G.F., 2022. Using remote sensing to quantify the joint effects of climate and land use/land cover changes on the caatinga biome of northeast brazilian. Remote Sens. 14, 1911. https://doi.org/10.3390/rs14081911.

Khan, A., Najeeb, U., Wang, L., Kean, D., Tan, Y., Yang, G., Munsif, F., Ali, S., Hafeez, A., 2017. Field Crops Research Planting density and sowing date strongly in fl uence growth and lint yield of cotton crops. Field Crops Res. 209, 129–135. https://doi.org/10.1016/j.fcr.2017.04.019.

Khorsandi, F., Siadati, S.M.H., Rastegary, J., 2020. Haloengineering as a vital component of sustainable development in salt-affected ecosystems. Environ. Dev. 35. https://doi.org/10.1016/j.envdev.2020.100545.

Lemos, M., Ferreira-Neto, M., Fernandes, C., dos, S., Lima, Y.B., Dias, N., da, S., Medeiros, J.F., de, Brito, R.F., Sá, F.V., da, S., 2021. The effect of domestic sewage effluent and planting density on growth and yield of prickly pear cactus in the semiarid region of Brazil. J. Arid Environ. 185. https://doi.org/10.1016/j.jaridenv.2020.104372.

Li, C., Ho, E., Kuyper, T.W., Yu, Y., Li, H., Zhang, C., Zhang, F., Werf, W., Van Der, 2020. Yield gain, complementarity and competitive dominance in intercropping in China: a meta-analysis of drivers of yield gain using additive partitioning. Eur. J. Agron. 113. https://doi.org/10.1016/j.eja.2019.125987.

Lima, L.R., Silva, T.G.F., Jardim, A.M. d R.F., de Souza, C.A.A., de Queiroz, M.G., Tabosa, J.N., 2018a. Growth, water use and efficiency of forage cactus sorghum intercropping under different water depths. Rev. Bras. De. Eng. Agric. e Ambient. 22 (2), 113–118. https://doi.org/10.1590/1807-1929/agriambi.v22n2p113-118.

Lima, L.R., Silva, T.G.F., Pereira, P., de, C., Morais, J.E.F., Assis, M.C.S., 2018b. Productive-economic benefit of cactus-sorghum intercropping systems irrigated with saline water. Rev. Caatinga 31 (1), 191–201. https://doi.org/10.1590/1983-21252018v31n122rc.

Makino, P.A., Ceccon, G., Fachinelli, R., 2019. Produtividade e teor de nutrientes em populações de milho safrinha solteiro e consorciado com braquiária. Rev. Bras. De. Milho Sorgo 18 (2), 206–220. https://doi.org/10.18512/1980-6477/rbms.v18n2p206-220.

Meng, X., Lian, Y., Liu, Q., Zhang, P., Jia, Z., Han, Q., 2020. Optimizing the planting density under the ridge and furrow rainwater harvesting system to improve crop water productivity for foxtail millet in semiarid areas. Agric. Water Manag. 238. https://doi.org/10.1016/j.agwat.2020.106220.

Moghbeli, T., Bolandnazar, S., Panahande, J., Raei, Y., 2019. Evaluation of yield and its components on onion and fenugreek intercropping ratios in different planting densities. J. Clean. Prod. 213, 634–641. https://doi.org/10.1016/j.jclepro.2018.12.138.

Morais, E.C. De, Suerda, J., Lima, S., De, Neto, F.B., 2018. Habilidade competitiva e biológica do consórcio beterraba com caupi-hortaliça proveniente de adubação verde e de arranjos espaciais. Rev. Ceres 65 (5), 433–442. https://doi.org/10.1590/0034-737×201865050008.

Nunes, J., da, S.L., Salvador, K.R., da, S., Jardim, A.M., da, R.F., Araújo Júnior, G., do, N., Carvalho, A.A., de, Souza, L.S.B., de, Montenegro, A.A., de, A., Silva, T.G.F. da, 2020. Índices morfofisiológicos e biofísicos da palma forrageira cultivada sob tecnologias hídricas na bacia do Rio Pajeú. J. Environ. Anal. Prog. 5 (1), 128–139. https://doi.org/10.24221/jeap.5.1.2020.2825.128-139.

Oliveira, K.M.G., Carvalho, L.G., Lima, L.A., Gomes, R.C.C., 2012. Modelagem para a estimativa da orientação de linhas de plantio de cafeeiros. Eng. Agríc. 32 (2), 293–305. https://doi.org/10.1590/S0100-69162012000200009.

Peixoto, M.J.A., Carneiro, M.S. deS., Amorim, D.S., Edvan, R.L., Pereira, E.S., Costa, M.R. G., 2018. Características agronômicas e composição química da palma forrageira em função de diferentes sistemas de plantio. Arch. De. Zootec. 67 (257), 35–39. https://doi.org/10.21071/az.v67i257.3489.

Pereira, P.D.C., Silva, T.G.F., DA, Zolnier, S., Morais, J.E.F. de, Santos, D.C., 2015. Morfogênese Da Palma Forrageira Irrigada Por Gotejamento. Rev. Caatinga 28 (3), 184–195. https://doi.org/10.1590/1983-21252015v28n321rc.

Petter, F.A., Alves, J., Zuffo, A.M.,Andrade, F.R. (2016). Elevada densidade de semeadura aumenta a produtividade da soja ? Respostas da radiação fotossinteticamente ativa Does high seeding density increase soybean productivity ? Photosynthetically active radiation responses. Bragantia, 75(2), 173–183. https://doi.org/10.1590/1678–4499.447 Fitotecnia.

Queiroz, M.G., Silva, T.G.F., da, Zolnier, S., Silva, S.M.S. e, Souza, C.A.A., Carvalho, H.F., de, S., 2016. Relações hídrico-econômicas da palma forrageira cultivada em ambiente semiárido. Irriga 1 (01), 141. https://doi.org/10.15809/irriga.2016v1n01p141-154.

R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

Rai, R.K., Bhatta, L.D., Acharya, U., Bhatta, A.P., 2018. Assessing climate-resilient agriculture for smallholders. Environ. Dev. 27, 26–33. https://doi.org/10.1016/j.envdev.2018.06.002.

Rao, C.S., Kareemulla, K., Krishnan, P., Murthy, G.R.K., Ramesh, P., Ananthan, P.S., 2019. Agro-ecosystem based sustainability indicators for climate resilient agriculture in India: A conceptual framework. Ecol. Indic. 105, 621–633. https://doi.org/10.1016/j.ecolind.2018.06.038.

Richards, L. A. (1954). Diagnosis and improviment of saline and alkali soils. Washington DC, US Department of Agriculture. 160 p. (USDA Agricultural Handook, 60).

Sadeghpour, A., Jahanzad, E., Esmaeili, A., Hosseini, M.B., Hashemi, M., 2013. Forage yield, quality and economic benefit of intercropped barley and annual medic in semi-arid conditions: additive series. Field Crops Res. 148, 43–48. https://doi.org/10.1016/j.fcr.2013.03.021.

Santos, G.C.L., Garcia, P.H.M., Viana, T.B.L., Borges, P.F., Araújo, L.S., Gonzaga Neto, S., 2020. Crescimento e eficiência do uso da água do sorgo sob distintos regimes hídricos contínuos. Arch. De. Zootec. 69 (266), 164–171. https://doi.org/10.21071/az.v69i266.5111.

Scalisi, A., Morandi, B., Inglese, P., Lo, R., 2016. Cladode growth dynamics in Opuntia ficus-indica under drought. Environ. Exp. Bot. 122, 158–167. https://doi.org/10.1016/j.envexpbot.2015.10.003.

Silva, A.S., Santos, E.M., Ramos, J.P.D.F., Perazzo, A.F., Muniz, A.C.S., Santos, F.N., de, S., Pereira, D.M., Cruz, G.F., de, L., 2019. Características agronômicas de variedades de Opuntia cochenilliferae Nopalea cochenillifera sob diferentes densidades de plantio. Colloq. Agrar. 15 (6), 88–96. https://doi.org/10.5747/ca.2019.v15.n6.a340.

Silva, G.S., Oliveira, R.A., De, Queiroz, N.L., Silva, M.N.B., Sousa, M.F., De, Silva, S.A., 2013. Desempenho agronômico de algodão orgânico e oleaginosas consorciados com palma forrageira. Rev. Bras. De. Eng. Agríc. Ambient. 17 (9), 975–981. https://doi.org/10.1590/S1415-43662013000900010.

Silva, L.L.G.G., Alves, G.C., Urquiaga, S., Souto, S.M., Figueiredo, M.V.B., Burity, H.A., 2012. Produtividade e carboidratos de reserva de pastagens sob intensidades de cortes. Arch. Latinoam. De. Prod. Anim. 20 (1–2), 7–16.

Silva, L.M., Fagundes, J.L., Viegas, P.A.A., Muniz, E.N., Rangel, J.H., de, A., Moreira, A. L., Backes, A.A., 2014a. Produtividade da palma forrageira cultivada em diferentes densidades de plantio. Cienc. Rural 44 (11), 2064–2071. https://doi.org/10.1590/0103-8478cr20131305.

Silva, T.G.F., Araújo Primo, J.T., Silva, S.M.S. e, Moura, M.S.B., de, Santos, D.C., Silva, M., da, C., Araújo, J.E.M., 2014b. Indicadores de eficiência do uso da água e de nutrientes de clones de palma forrageira em condições de sequeiro no Semiárido brasileiro. Bragantia 73 (2), 184–191. https://doi.org/10.1590/brag.2014.017.

Silva, T.G.F., Araújo Primo, J.T., Morais, J.E.F., de, Diniz, W.J., da, S., de Souza, C.A.A., Silva, M., da, C., 2015. Crescimento e produtividade de clones de palma forrageira no semiárido e relações com variavies meteorológicas. Rev. Caatinga 28 (2), 10–18.

Silva, T.G.F., Queiroz, M.G., Zolnier, S., Souza, L.S.B., Souza, C.A.A., Moura, M.S.B., Araújo, G.G.L., Steidle Neto, A.J., Santos, T.S., Melo, A.L., Cruz Neto, J.F., Silva, M. J., Alves, H.K.M.N., 2020. Soil properties and microclimate of two predominant landscapes in the Brazilian semiarid region: Comparison between a seasonally dry tropical forest and a deforested area. Soil Tillage Res. 207. https://doi.org/10.1016/j.still.2020.104852.

Singh, P.K., Chudasama, H., 2020. Pathways for climate change adaptations in arid and semi-arid regions. J. Clean. Prod. 284. https://doi.org/10.1016/j.jclepro.2020.124744.

Souza, M., de, S., Araújo Júnior, G. do N., Souza, L.S.B., Jardim, A.M., da, R.F., Silva, G.I. N., Araújo, G.G., Campos, L., Leite, F.S., de M. V, M.L., Tabosa, J.N., Silva, T.G.F., 2022. Forage yield, competition and economic benefit of intercropping cactus and millet with mulch in a semi-arid environment. Afr. J. Range Forage Sci. https://doi.org/10.2989/10220119.2021.2016967.

Texeira, A., das, G., Oliveira, F.L., Parajara, M., do, C., Zucoloto, M., Dalvi, L.P., 2020. Yacon planting density in intercropping with corn under banana orchard. Hortic. Bras. 38 (1), 83–88. https://doi.org/10.1590/S0102-053620200113.

Tonini, H., Morales, M.M., da Silva, V.P., Lulu, J., Farias Neto, A.L., 2019. Efeito do sistema de plantio e da exposição solar sobre a alocação da biomassa no desenvolvimento inicial do eucalipto. Cienc. Florest. 29 (1), 86–95. https://doi.org/10.5902/1980509817808.

Yilmaz, Ş., Özel, A., Atak, M., Erayman, M., 2015. Effects of seeding rates on competition indices of barley and vetch intercropping systems in the Eastern Mediterranean. Turk. J. Agric. For. 39, 135–143. https://doi.org/10.3906/tar-1406-155.

Zhang, D., Sun, Z., Feng, L., Bai, W., Yang, N., Zhang, Z., Du, G., Feng, C., Cai, Q., Wang, Q., Zhang, Y., Wang, R., Arshad, A., Hao, X., Sun, M., Gao, Z., Zhang, L., 2020. Field Crops Research Maize plant density a ff ects yield, growth and source-sink relationship of crops in maize / peanut intercropping. Field Crops Res. 257. https://doi.org/10.1016/j.fcr.2020.107926.

Zhang, G., Yang, Z., Dong, S., 2011. Field Crops Research Interspecific competitiveness affects the total biomass yield in an alfalfa and corn intercropping system. Field Crops Res. 124 (1), 66–73. https://doi.org/10.1016/j.fcr.2011.06.006.