

Additive intercropping of sunflower and soybean to improve yield and land use efficiency: Effect of thinning interval and nitrogen fertilization

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ABSTRACT

An additive intercropping model was adopted to improve land use efficiency and productivity of two prominent oil crops grown in Egypt, that is, sunflower (*Helianthus annuus* L.) and soybean (*Glycine max* [L.] Merr.) A 2-yr field trial was conducted in Northern Egypt during the summers of 2017 and 2018. The effects on yield, crop components, and land use efficiency of the system were tested with three N fertilizer rates (70, 105, and 140 kg N ha⁻¹) and three thinning intervals of 15, 30, and 45 d after sowing (DAS) for sunflower and 30, 45, and 60 DAS for soybean. Late thinning increased plant height in both crops, but reduced sunflower stem and head diameters and seed weight per head. The maximum seed yield occurred in the pure stands and reached 4.00 and 1.61 t ha⁻¹ for sunflower and soybean, respectively. Early thinning positively affected seed yield and fresh and dry biological yields, while the effect of N rates was limited. Seed oil content of both crops was slightly affected by the treatments and generally averaged approximately 50% and 20% in sunflower and soybean, respectively. While the land equivalent ratio (LER) indicated the advantage of intercropping sunflower and soybean (LER > 1), the DM equivalent ratio (DMER) provided a more realistic estimate as to the effect of intercropping compared with sole cropping in an additive model. Early and intermediate thinning intervals across all N fertilizer rates resulted in yield gain (DMER > 1), while late thinning reduced yield (DMER < 1). Intercropping sunflower and soybean crops is recommended for low input farming systems, particularly in developing countries.

Key words: *Helianthus annuus*, *Glycine max*, intercropping, land use efficiency, thinning.

INTRODUCTION

The rate of population growth in Egypt, as well as in many developing countries, is very high in relation to the natural resources and cultivated land of the country. Hence, a food security gap is created as the escalating demand for different food products faces a limited supply. There is a pressing need to maximize land use to accelerate productivity gains and promote a rapid closing of the expected food security gap (Salama and Zeid, 2016). As a practice of agricultural intensification, intercropping has been widely promoted because of its potential to improve productivity, especially in low input farming systems by increasing resource use efficiency (Bedoussac et al., 2013). Intercropping is believed to improve the use of light, soil moisture, and nutrients and to enhance biomass conversion (Najafi and Keshtehgar, 2014). This is achieved by the differences in competitive ability of the growth factors between intercrop components. Therefore, the selection of crops for intercropping is crucial. It is necessary to pay attention to crops that can grow together with minimum competition and maximum profit (Salama et al., 2016).

Oil crops are among the important crops in the Egyptian agricultural system. The production of edible oil in Egypt is still far below population demand. Only 13% of the total oil requirements is covered by local production, and large amounts of edible oil are imported each year to satisfy the increasing demand (Abdel-Wahab and El Manzlawy, 2016). Therefore, increasing domestic oil yield per unit area of oil crops is in demand and could be achieved by adopting suitable cultural practices and applying intercropping. There is heightened interest for sunflower (*Helianthus annuus* L.) and soybean (*Glycine max* [L.] Merr.) intercropping. Sunflower, soybean, peanut, and canola are the four most important oil crops worldwide (FAO, 2013). Sunflower oil is gaining more importance because of its light color, low saturated fatty acid content, and ability to withstand high cooking temperatures; in addition, it is affordable for the Egyptian consumer. Soybean oil is also characterized by its excellent frying and flavor capabilities, which contribute to its premium quality (Olowe and Adebimpe, 2009). In an intercropping context, sunflower is expected to perform very well due to its erect growth habit, limited land coverage, easily harvestable heads, and considerable drought tolerance. Many studies have reported the advantage of intercropping sunflower with legume crops (Amujoyegbe et al., 2013; Obong et al., 2016; Anas et al., 2017); however, results always depend on the location, environmental conditions, and applied cultural practices.

Nitrogen is a component of nucleic acids, nucleotides, and proteins that are essential for the metabolic function of a plant (Ali et al., 2014). Besides, N is an essential input in the Egyptian agricultural system. Therefore, the N fertilizer rate is among the most important cultural practices that need to be carefully adjusted to achieve the maximum benefit from the intercropping model. Adjusting the optimal seeding rate through replanting or thinning is crucial in determining the final seed yield of the intercrops and the gain from the system (Davis et al., 2015). A widespread effect of thinning and thinning timing on sunflower and soybean productivity was reported (Conley et al., 2008). The growth and yield component of a stand is greatly affected by the crop's stage of maturity when removing neighboring plants (i.e., thinning), which depends on biotic and abiotic stresses related to a certain environment (Davis et al., 2015). In a multipurpose intercropping system, plants removed from a stand by thinning can be used as green forage, and this provides additional value to the system, especially on small farms. Early thinning reduces plant competition within a stand, which allows better use of light, soil moisture, and nutrients, while late thinning provides a high amount of DM for animal feeding. It is therefore useful to determine the latest thinning interval at which plants should be removed from the stand without negatively impacting final yield.

Researchers have developed different indices to evaluate the productivity and efficiency of intercropping systems. These indices include effective land equivalent ratio, area time equivalent ratio, land equivalent coefficient, and staple land equivalent ratio. However, among these, the land equivalent ratio (LER) developed by De Wit (1960) and De Wit and Van den Bergh (1965) is the most used index to determine the effectiveness of intercropping compared with sole cropping. While LER is the best index to use in the case of replacement intercropping series (Willey, 1979), using it as an indicator of intercropping effectiveness in an additive intercropping series, such as in the present study, would overestimate the final gain (Salama et al., 2016). Therefore, the DM equivalent ratio (DMER) was proposed by Shaalan et al. (2015) and Salama et al. (2016) as an index that would provide a more realistic estimate of the yield gain from additive intercropping compared with sole crops.

The objective of this research study was to determine the yield and yield component response of sunflower and soybean plants after thinning at different stages of maturity and different N fertilizer rates in an additive intercropping model. It was hypothesized that the combined effect of the thinning interval and N fertilizer level on the intercrops would be different than the expected effects of each of the studied factors alone. The effectiveness of intercropping using DMER compared with the traditional LER was also examined.

MATERIALS AND METHODS

Field characteristics and preparation

The study was conducted at the Agricultural Research Station (31°20' N, 30° E), Faculty of Agriculture, Alexandria University, Alexandria, Egypt, during the 2017 and 2018 summer seasons. With its hot and dry weather during the summer season, the location is classified as having a Mediterranean climate. The mean monthly temperature from May to September was 26.33 and 26.89 °C for 2017 and 2018, respectively. Soil texture at the experimental location is sandy loam (55.50% sand, 29.00% silt, and 15.50% clay), pH 8.30, 1.35 dS m⁻¹ electrical conductivity, and 8.20% CaCO₃. The top 20 cm of soil contained 1.67% organic matter and 200, 4.80, and 890 mg kg⁻¹ available N, P, and K, respectively.

The experimental plot included two wide adjacent beds with 60 cm spacing between them for a total plot area of 1.5 × 2.4 m. In each plot, four rows of sunflower (*Helianthus annuus* L.) ‘Sirena’ were sown 30 cm apart; two of these rows were sown on the opposite borders of the wide beds. Six rows of soybean (*Glycine max* [L.] Merr.) ‘Giza 111’ were set between the sunflower rows with 15 cm spacing between them (Figure 1). Seeds of the four sunflower rows and four soybean rows were sown in hills 10 cm apart and with 2 and 4 seeds per hill for sunflower and soybean, respectively. The remaining two soybean rows were heavily drilled, mainly for forage production. The sowing pattern allowed an additive intercropping model in which sunflower was the main crop sown at 100% plant density (12 kg ha⁻¹) and soybean was the companion crop sown at 50% plant density (36 kg ha⁻¹).

Soybean was sown on 15 May and sunflower 15 d later (1 June) in 2017 and 2018. All plots received the same irrigation, weed management, and P fertilization, regardless of the treatment. Irrigation was scheduled for 8- to 10-d intervals. On the basis of soil analysis and current recommendations for sunflower and soybean production in the area, P was added once during seed bed preparation at 200 kg ha⁻¹ as calcium monophosphate (15.5% P₂O₅). Nitrogen, as ammonium nitrate (33.5% N), was split into two equal doses applied to the experimental plots at sowing (side-banded between the planted sunflower and soybean rows) and after thinning (top-dressed).

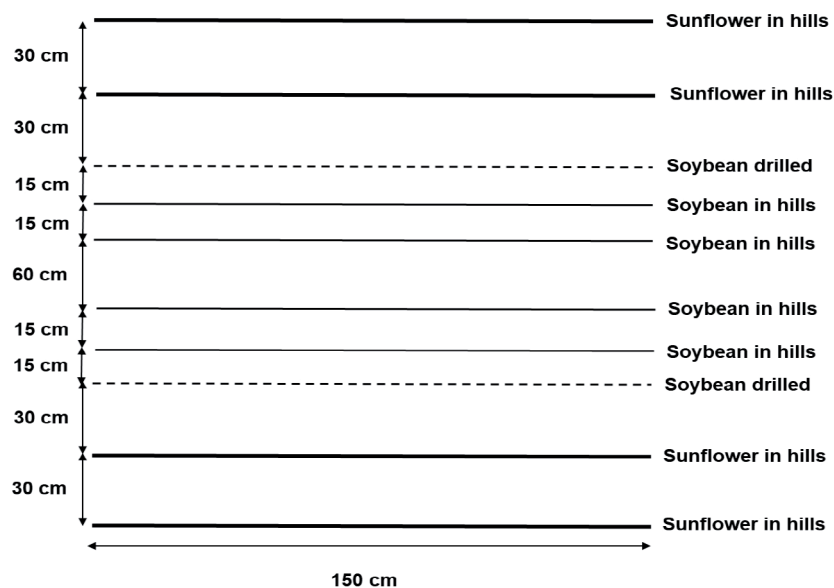
Experimental design and field procedures

Factorial combinations of three N fertilizer rates (70, 105, and 140 kg N ha⁻¹) and three thinning intervals were tested in a randomized complete block design with four replicates in each of the two experimental years. Sunflower was thinned at 15, 30, and 45 d after sowing (DAS), equivalent to the vegetative (V4), early reproductive (R1), and mid-reproductive (R4) stages of maturity, respectively, according to the description by Schneiter and Miller (1981) for sunflower growth stages. Soybean was thinned at 30, 45, and 60 DAS, equivalent to the vegetative (V3), beginning bloom (R1), and beginning pod development (R3) stages of maturity, respectively, as described by Fehr and Caviness (1977). When thinning each crop, every second plant was removed to maintain the optimum 20 cm spacing between hills; in addition, only one plant per hill for sunflower and two plants per hill for soybean were left and the rest were removed. At the same thinning time, the two heavy drilled soybean forage rows were removed.

Data collection and statistical analyses

At crop maturity, data were collected from each experimental plot. Plant height (cm) was determined in the field for five random plants per plot by measuring stems from the soil surface to the base of the head in case of sunflower or uppermost node with at least one pod for soybean. Plants were then manually harvested by clipping at the soil surface.

Figure 1. Design of an experimental plot illustrating the sowing pattern of sunflower and soybean intercrops.



The means of sunflower stem and head diameters (cm) and seed weight per head (g) were determined for five random plants in the middle of each plot. Fresh biological yield (t ha⁻¹) was weighed directly after harvesting. Harvested plants were air-dried until constant weight was reached to determine the dry biological yield (t ha⁻¹). Sunflower and soybean plants were manually threshed, seeds were weighed to determine seed yield (t ha⁻¹), and then sieved to remove seed splits. The harvest index was calculated as seed yield/fresh biological yield expressed as a percentage. The 100-seed weight (g) was determined as the mean of three random seed samples taken from each plot for both crops. Oil contents (g kg⁻¹) of sunflower and soybean seed samples were determined by the Soxhlet extraction technique (AOAC, 2012).

The factorial combinations of N rates and thinning intervals were tested for significance using the SAS 9.4 MIXED Procedure (SAS Institute, Cary, North Carolina, USA). The crop was not considered as an experimental factor, and the statistical analysis was conducted separately for each crop. The ranking of treatments was fairly stable over the 2 yr and the interaction between years and experimental treatments was ignored; reported results were therefore pooled over the 2 yr. In the statistical model, only replicates were considered random. Means were compared by Fisher's least significant difference (LSD) test at $P < 0.05$.

Land use efficiency and yield advantage

Land equivalent ratio (LER): Determined as the sum of the fractions of the yield (t ha⁻¹) of sunflower and soybean intercrops compared with their sole crop yields (De Wit, 1960; De Wit and Van den Bergh, 1965):

$$LER = \frac{Yab}{Yaa} = \frac{Yba}{Ybb}$$

where *Yab* is the yield of sunflower "a" intercropped with soybean "b", *Yaa* is the pure stand yield of sunflower "a", *Yba* is the yield of soybean "b" intercropped with sunflower "a", and *Ybb* is the pure stand yield of soybean "b".

Dry matter equivalent ratio (DMER): Determined as the sum of the dry yield of the main sunflower crop and the soybean companion crop compared with the DM yield of the main sunflower crop alone (Shaalán et al., 2015; Salama et al., 2016):

$$DMER = \frac{DMYSFc + DMYSB}{DMYSFs}$$

where *DMYSFc* is DM yield of sunflower intercropped with the soybean companion crop, *DMYSFs* is DM yield of pure sunflower, and *DMYSB* is DM yield of the soybean companion crop.

RESULTS

Sunflower yield, yield components, and agronomic characteristics

The ANOVA revealed that all the studied sunflower parameters, except the harvest index, were significantly variable among the tested N fertilizer treatments combined with plant age at thinning (Table 1).

It is clear from the means shown in Table 2 that the highest plant height (226.83 cm) was reached at late thinning (45 DAS) with the highest N rate (140 kg N ha⁻¹). On the contrary, the application of the lowest N rate (70 kg N ha⁻¹) and thinning at an early stage of plant maturity (15 DAS) resulted in the lowest plant height (185.83 cm). Plant height usually

Table 1. F-values and levels of significance for plant height, stem diameter, head diameter, seed weight head⁻¹, 100-seed weight, fresh and dry biological yields, seed yield, seed oil content, and harvest index of sunflower as influenced by treatment combinations of nitrogen fertilizer rate and thinning interval in a combined analysis of two experimental seasons.

SOV	DF	F-Value									
		Plant height	Stem diameter	Head diameter	Seed weight head ⁻¹	100-seed weight	Fresh yield	Dry yield	Seed yield	Seed oil content	Harvest index
Replicate	3	0.66	9.97	10.04	3.95	9.62	2.74	3.75	6.78	1.28	0.68
Treatment	9	3.33**	3.66**	3.04**	2.73*	2.83*	4.96**	3.98**	2.70*	2.64*	0.77ns
CV		6.31	11.24	10.35	11.85	11.09	25.53	23.76	21.52	8.63	21.52

*, **: Significant at $P = 0.05$ and $P = 0.01$, respectively; ns: nonsignificant.
SOV: Source of variation; DF: degrees of freedom; CV: coefficient of variability.

Table 2. Means of plant height, stem diameter, head diameter, seed weight head⁻¹, 100-seed weight, fresh and dry biological yields, seed yield, seed oil content, and harvest index of sunflower as influenced by the treatment combinations of nitrogen fertilizer rate and thinning interval.

N rate	Thinning interval	Plant height	Stem diameter	Head diameter	Seed weight head ⁻¹	100-seed weight	Fresh yield	Dry yield	Seed yield	Seed oil content	Harvest index
kg ha ⁻¹	DAS		cm		g		t ha ⁻¹		g kg ⁻¹	%	
70	15	185.83d	1.92abc	19.00abc	110.53ab	6.81abc	17.76cd	3.75b	3.07ab	483.63ab	24.66a
	30	193.75cd	1.79abc	17.96bc	92.30c	6.35bc	16.38cd	3.26b	2.84b	492.88ab	24.79a
	45	201.67bcd	1.73bc	17.21c	93.67bc	6.27bc	15.81d	3.27b	2.79b	519.00a	25.24a
105	15	195.00cd	2.00abc	19.96abc	110.27abc	7.85a	20.71ab	4.36ab	3.98a	462.45ab	27.57a
	30	198.22bcd	1.87abc	18.62abc	95.54bc	7.28ab	18.72bc	3.82b	3.33ab	481.70ab	25.43a
	45	209.99abc	1.71c	17.71bc	94.53bc	6.15c	18.15cd	3.66b	3.28ab	510.85ab	25.79a
140	15	205.00bc	2.04ab	20.09ab	117.59a	7.65a	22.09a	4.05b	3.70ab	450.40b	23.90a
	30	213.75ab	2.02ab	20.96a	120.30a	7.71a	21.79a	3.68b	3.42ab	478.63ab	22.40a
	45	226.83a	1.75bc	18.21abc	104.76abc	6.40bc	20.81a	3.40b	3.34ab	486.35ab	22.92a
Pure stand		198.40bcd	2.06a	20.04abc	108.05abc	7.16abc	23.01a	6.00a	4.00a	494.74ab	24.73a

Different letters in the same column indicate statistically significant differences according to the LSD test ($P = 0.05$). DAS: Days after sowing.

decreased with the application of the low N rate and early plot thinning. The application of the highest N rate accompanied with early thinning produced sunflower plants with the highest stem diameter (2.04 cm), while the lowest stem diameter occurred when thinning was delayed to 45 DAS with the three N rates and with values of 1.73, 1.71, and 1.75 cm for 70, 105, and 140 kg N ha⁻¹, respectively. As for the head diameter, increasing the N rate usually increased head diameter, and the highest value reached 20.96 cm; a slight reduction in head diameter was observed with delayed plot thinning. The smallest heads were produced in the plots fertilized with 70 kg N ha⁻¹ and thinned at 45 DAS, which reached 17.21 cm. The reduction in head diameter with delayed thinning from 15 to 45 DAS reached 1.79, 2.25, and 1.88 cm when applying 70, 105, and 140 kg N ha⁻¹, respectively. At the highest N rate (140 kg N ha⁻¹), the variation was nonsignificant for seed weight per head among the three plant ages at thinning, which averaged 114.22 g. On the other hand, when applying the low (70 kg N ha⁻¹) and intermediate (105 kg N ha⁻¹) N levels, early thinning (15 DAS) produced the highest seed weight per head, which gradually decreased with delayed thinning. The highest 100-seed weight was achieved for early thinning at the three N rates, and the intermediate thinning for intermediate and high N rates. However, late thinning always had the lowest 100-seed weight at the three N rates. The highest 100-seed weight was 7.85 g, while the lowest value was 6.15 g.

It was observed that the fresh biological yield significantly increased with the application of the highest N rate, with 21.56 t ha⁻¹ as the mean for the three plant ages at thinning compared with 23.01 t ha⁻¹ for the pure stands. Delayed thinning combined with the application of low or intermediate N rates significantly reduced fresh biological yield. The lowest significant fresh biological yield was 15.81 t ha⁻¹ and occurred when plots were thinned at 45 DAS and fertilized with 70 kg N ha⁻¹. The highest dry biological yield was produced by the pure sunflower plots (6.00 t ha⁻¹). Among the treatments, the application of 105 kg N ha⁻¹ and with early thinning produced the highest dry biological yield of 4.36 t ha⁻¹, which was significantly similar to the pure plots. All the other treatments had a significantly lower dry biological yield. As for seed yield, the lowest values were produced with the application of 70 kg N ha⁻¹ when plots were thinned at 30 and 45 DAS. All the other treatments produced seed yield significantly similar to the highest value (4.00 t ha⁻¹) found in the pure plots. Analysis of the seed oil content revealed a clear decreasing trend with an increasing applied N rate. On the contrary, delaying thinning was always accompanied with increasing seed oil content. In general, the highest seed oil content was 519.00 g kg⁻¹, which was achieved with delayed thinning combined with the application of the lowest N rate. At the same time, the lowest seed oil content (450.40 g kg⁻¹) was recorded for early thinning and the application of the highest N rate. The harvest index was nonsignificantly affected by the tested treatments and generally ranged from 22.40% to 27.57%, with a 24.73% harvest index for the pure plots.

Soybean yield, yield components, and agronomic characteristics

The ANOVA (Table 3) demonstrated a significant variation among the tested N fertilizer treatments and different plant ages at thinning for all the studied soybean parameters, except seed oil content and harvest index.

Table 3. *F*-values and levels of significance for plant height, 100-seed weight, fresh and dry biological yields, seed yield, seed oil content, and harvest index of soybean as influenced by the treatment combinations of nitrogen fertilizer rate and thinning interval in a combined analysis of two experimental seasons.

SOV	DF	<i>F</i> -Value						
		Plant height	100-seed weight	Fresh yield	Dry yield	Seed yield	Seed oil content	Harvest index
Replicate	3	0.78	1.16	0.45	0.36	0.43	1.23	0.22
Treatment	9	2.92*	3.96**	5.90**	4.69**	2.42*	0.80ns	0.09ns
CV		9.10	6.00	19.39	19.31	23.59	12.72	23.44

*, **: Significant at $P = 0.05$ and $P = 0.01$, respectively; ns: nonsignificant.
SOV: Source of variation; DF: degrees of freedom; CV: coefficient of variability.

Despite the clear and consistent decreasing trend in soybean plant height with increasing N fertilizer rate and early thinning, variations among most of the treatments were nonsignificant (Table 4). The shortest plants were produced with the highest N rate (140 kg N ha⁻¹) when thinning was done at 30 DAS (114.17 cm). On the other hand, the tallest plants were obtained with the lowest N rate (70 kg N ha⁻¹) and late thinning at 60 DAS (138.33 cm). The lowest N fertilizer rate with early thinning resulted in the highest 100-seed weight (16.52 g), while the lowest 100-seed weight was 15.07 g obtained for the same low N rate when plants were thinned late at 60 DAS. Analysis of the yield potential of soybean revealed that the pure plots produced the highest fresh and dry biological yields, with values of 4.77 and 1.19 t ha⁻¹, respectively. In addition, late thinning of the crop with the three N rates significantly reduced fresh and dry biological yields. In general, the lowest values for fresh and dry biological yields were achieved when 105 kg N ha⁻¹ was applied and plants were thinned at 60 DAS (2.12 and 0.43 t ha⁻¹, respectively). A maximum reduction of 55.55%, and 63.87% in the fresh and dry biological yields, respectively, was recorded when the crop was left without thinning until 60 DAS. Furthermore, the pure soybean stands produced the highest amount of seeds (1.61 t ha⁻¹), significantly similar seed yields were produced with early thinning under the three tested N rates. On the contrary, delaying thinning resulted in a pronounced reduction in seed yield, regardless of the N rate. Soybean seed oil content was nonsignificantly affected by the tested treatments and generally ranged from 174.55 to 210.33 g kg⁻¹. Similarly, the influence detected for the treatments on the harvest index was nonsignificant, which ranged from 30.23% to 38.23% and a 33.75% harvest index for the pure plots.

Land use efficiency and yield advantage

The data for LER (Table 5) indicated that all the treatments had a positive impact on land use. A general trend was observed in which LER values tended to increase with higher N rates, although values tended to decrease with late thinning; this highlights the positive effects of high N rates and early thinning on land use and yield gain. Despite this trend, all LER values for all treatments were > 1, suggesting that intercropping sunflower with soybean under the three N rates combined with thinning at any plant age tended to increase land use. The highest LER value was 1.65 with the highest N rate and

Table 4. Means of plant height, 100-seed weight, fresh and dry biological yields, seed yield, seed oil content, and harvest index of soybean as influenced by the treatment combinations of nitrogen fertilizer rate and thinning interval.

N rate	Thinning interval	Plant height	100-seed weight	Fresh yield	Dry yield	Seed yield	Seed oil content	Harvest index
kg ha ⁻¹	DAS	cm	g	t ha ⁻¹			g kg ⁻¹	%
70	30	131.50ab	16.52a	3.30bcd	0.63b	1.10ab	189.88a	33.33a
	45	137.50a	15.30ab	3.01bcde	0.65b	0.91b	190.35a	30.23a
	60	138.33a	15.07b	2.80bcde	0.52bc	0.90b	210.33a	32.14a
105	30	122.92abc	15.36ab	3.31bcd	0.50bc	1.26ab	174.55a	38.07a
	45	124.42abc	15.25ab	2.45de	0.53bc	0.79b	208.99a	32.24a
	60	128.33abc	15.51ab	2.12e	0.43c	0.77b	202.68a	36.32a
140	30	114.17c	15.88ab	3.27bcd	0.59bc	1.25ab	204.23a	38.23a
	45	118.81bc	15.28ab	3.09bcde	0.54bc	0.94b	194.28a	30.42a
	60	126.67abc	16.06ab	2.71cde	0.46c	0.95b	194.26a	35.06a
Pure stand		137.64a	15.92ab	4.77a	1.19a	1.61a	208.47a	33.75a

Different letters in the same column indicate statistically significant differences according to the LSD test ($P = 0.05$).
DAS: Days after sowing.

Table 5. Land equivalent ratio (LER) vs. dry matter equivalent ratio (DMER) treatment combinations of nitrogen fertilizer rate and thinning interval.

N rate	Thinning interval	LER	DMER
N1	T1	1.46	1.15
	T2	1.34	1.09
	T3	1.23	0.98
N2	T1	1.59	1.15
	T2	1.33	1.08
	T3	1.27	0.97
N3	T1	1.65	1.17
	T2	1.59	1.07
	T3	1.47	0.95

N1: 70 kg N ha⁻¹, N2: 105 kg N ha⁻¹, N3: 140 kg N ha⁻¹, T1: 1st thinning interval, T2: 2nd thinning interval, T3: 3rd thinning interval.

early thinning, while the lowest value was 1.23 for late thinning combined with the lowest N rate. However, determining yield gain in terms of DMER (Table 5) showed a slight yield gain (DMER > 1); this was achieved when the intercropped sunflower and soybean were thinned at early and intermediate plant ages for the three N rates, while late thinning resulted in a loss in overall yield (DMER < 1) as a result of severe competition in the stand.

DISCUSSION

Delayed thinning of intercrops maintained high plant density in the field for a certain period of the plant life cycle, which led to increasing plant competition for light, soil moisture, and nutrients. Thus, the effect of delayed thinning was similar to the effect of increasing plant density by any means, such as narrowing inter- or intra-row spacing or increasing the number of plants per unit area.

A consistent increasing trend in sunflower plant height was detected with delayed thinning, revealing that the long period of plant competition due to high plant density produced the tallest plants. This could be partially attributed to the fact that plants strive for more solar radiation under high plant densities (Chang, 1974). Stem elongation is one of the mechanisms used by plants to increase the possibility of capturing more solar radiation. However, an inversely proportional relationship was detected between plant height and stem diameter of sunflower, which is known to have a genetic origin (Miller and Hammond, 1991). Treatments that increased plant height decreased stem diameter, and stem diameter decreased with delayed thinning. Similar to sunflower, delayed thinning was accompanied by a consistent increase in plant height of soybean, mainly due to the shading effect exerted by the sunflower plants, especially at high plant densities, as a result of delayed thinning of sunflower. This shading effect is believed to create an unfavorable environment around the soybean plants that would enhance some hormonal activities in the soybean plants and would result in the formation of more nodes and stem elongation (Abdel-Wahab and El Manzlawy, 2016). Our results concur with Davis et al. (2015), who reported that thinning of soybean at the V3 stage of maturity reduced plant height as compared with thinning at later maturity stages. Another attempt was made to explain these differences in soybean plant height by the variations in light quantity and quality reaching the stands. Ballaré et al. (1990) suggested that red/far red light ratios are early signs of plant competition. Plants grown in dense vs. sparse populations were reported to have lower red/far red light ratios that were responsible for greater internode elongation and greater plant height (Board, 2001). The differences in red/far red light ratios were therefore suggested as a probable cause for plant height differences between soybean stands thinned at different maturity stages.

It was clear in the present study that sunflower plant height tended to consistently increase when the applied N fertilizer rate increased. This was probably due to the positive effect of N in stimulating vegetative growth, root growth, and better absorption of other nutrients (Ali et al., 2014; Awais et al., 2015). Coupled with the previously explained action of the thinning interval, the tallest sunflower plants were obtained with the highest N fertilizer rate and delayed thinning. Similarly, applying the highest N rate produced the tallest soybean plants when thinning was delayed, while the effect at early thinning of the high N rate to increase plant height was offset and plant height was significantly low. In the case of the companion soybean crop, this suggests that the effect of N application was neutralized by the effect of the thinning interval.

Furthermore, early thinning was accompanied by increasing plant spacing within the experimental plots, thus decreasing plant competition. It resulted in increased sunflower head diameter, seed weight per head, and 100-seed weight. In their investigation on the effect of increasing plant spacing of sunflower-soybean intercrops, Abdel-Wahab and El Manzlawy (2016) reported a similar increase in seed yield per plant and 100-seed weight as a result of wide plant spacing. They attributed this to better light interception in the plant canopy that led to higher DM accumulation. Similar results were reported by Anas et al. (2017) for intercropping sunflower with soybean and mung bean, respectively. Similar to the present investigation, an increase in sunflower head diameter and seed weight per head with increasing N fertilizer rate was reported by Ali et al. (2014) and Awais et al. (2015). The positive effect of N application on the yield attributes of sunflower is probably due to the role of N in enhancing vegetative growth and increasing DM production (Ali et al., 2014). The effect of N application was slight; however, it was observed in the 100-seed weight of both sunflower and soybean. This result contrasted with the findings of Awais et al. (2015), but in line with results reported by Ali et al. (2014). In an attempt to clarify the small impact of N application on 100-seed weight, Ali et al. (2014) stated that the increase in sunflower head diameter and seed weight per head associated with the application of a high N rate probably produced smaller seeds.

It was clear in the present study that the highest fresh and dry biological yields and seed yields of soybean were produced from pure crop stands compared with intercropped stands. However, some intercropping treatments produced sunflower yields similar to the pure stands, especially at early crop thinning and high N fertilizer rates. An in-depth study into the differences in canopy structures of sunflower and soybean pure stands and intercrops could explain the contrasting yield responses of both crops to the intercropping treatments. Thinning intercropped sunflower at early stages of maturity increased spacing between plants and allowed more sunlight to reach lower canopy layers, reduced self-shading, and increased light interception efficiency (López, 2004); in addition, it reduced interplant competition among sunflower stands and the absence of considerable competition with soybean (Olowe and Adebimpe, 2009). Therefore, better sunflower yields were obtained when thinning occurred early in the season. In the current intercropping model, soybean was sown 15 d earlier than sunflower to prevent sunflower shading and inhibit inter-specific resource competition between the two crops during the critical period of soybean emergence. Another critical period in the soybean life cycle is the beginning of pod development and seed setting (R3-R4) in which resource demand (including N) reaches its peak (Mourtzinis et al., 2018). During this stage, sunflower plants were already taller than the soybean plants and shading and competition could not be prevented. Our results are similar to findings by Davis et al. (2015), who reported that thinning soybean stands at an early stage of maturity (V3) resulted in the lowest reduction in seed yield compared with intact stands. This response was probably due to the increase in light availability for the remaining plants after thinning and more photosynthetic capacity along with smaller increases in the number of seeds per plant. Among the different soybean yield components, it is expected that the number of pods plant⁻¹ has the strongest influence on soybean seed yield (Egli, 1994). Previous research has suggested that the increased number of pods in a soybean plant community is the primary component of yield compensation and yield stability in soybean (Board, 2001). Davis et al. (2015) concluded that the increase in the numbers of pods tended to be larger after early rather than late thinning of the soybean crop.

An almost insignificant increase in sunflower and soybean seed yields was observed when increasing the N fertilizer rate. This was in line with the findings of many researchers (Nasim et al., 2012). It is possible that the yield variations with different N rates are not as large as expected, and this might be due to environmental conditions, plant competition, and different plant densities (Cigelske, 2016) caused by the thinning strategies applied in our experiment. The small positive effect of N application on yield was mainly attributed to the enhancement of leaf development and increased leaf area per plant, which improved photosynthetic activity (Connor et al., 2002), led to the accumulation of more DM, and therefore improved yield. Nitrogen added in R3 to R6 have been shown to benefit soybean growth (Oplinger, 1991). In the present study, despite the stress caused by late thinning (R3) of the intercrops on the soybean plants, thinning was combined with the application of 105 kg N ha⁻¹; this means supplying the soybean crop with the N rate in the critical period of pod development and seed filling (R3-R4), which counterbalanced the harmful effect of late thinning on the crop, especially at higher N fertilizer rates. Oplinger (1991) also observed yield increases with N fertilization during soybean early pod fill.

A suppressive effect was generally observed on different yield components of soybean under the intercropping treatments, compared with the pure stands, especially when thinning was delayed to a late stage of maturity. This might be attributed to the shading effect of sunflower on the lower canopy of the legume companion crop, in addition to the

interspecific competition for soil moisture and nutrients. This finding is strongly supported by reported results of several sunflower-legume intercropping systems (Amujoyegbe et al., 2013; Anas et al., 2017). Earlier studies have also reported decreased soybean DM production in sunflower-soybean intercropping systems (Shivaramu and Shivashankar, 1992).

The harvest index reflects the ability of the crop to convert DM into the economic component, represented by the seeds in the case of sunflower and soybean. The higher the value of the harvest index of a certain cultivar, the higher is its efficiency to convert DM into the economic component of the crop. Despite the significant variability of the harvest index components, that is, seed and fresh biological yields of the investigated crops as affected by the N levels and thinning intervals, the harvest index itself was negligibly variable across all treatments for both crops; this indicates that the effects of the treatments on intercrop efficiency in translocating assimilates in the economic yield were homogeneous.

Our results differed from those reported by Abdel-Wahab and El Manzlawy (2016), who indicated that decreasing sunflower plant density by increasing plant spacing exerted a positive effect on sunflower seed oil content. In the present study, seed oil content increased with delayed thinning. However, variations among thinning intervals were not biologically significant. Soybean seed oil content was nonsignificantly affected by the thinning interval combined with the different N rates. Similar results were reported by Abdel-Wahab and El Manzlawy (2016). It is well documented that seed oil content decreased with increasing N fertilizer levels (Nasim et al., 2012). This could have been attributed to the increase in seed protein content combined with the application of higher N rates, which led to decreasing the other seed components, including oil content (El-Kady et al., 2010).

In the present additive intercropping model, soybean was introduced to provide some 'bonus' seed yield, but only to the extent that it did not seriously jeopardize sunflower yield. Analysis of yield gain and land use efficiency revealed that all the LER values for the different treatments were > 1 , which indicated the advantages of intercropping sunflower and soybean over sole cropping both crops. The maximum LER value (1.65) was obtained when sunflower and soybean intercrops received the highest N rate and were subjected to early thinning, indicating a 65% yield gain over sole cropping. On the other hand, the lowest LER was 1.23 achieved in late thinning combined with the lowest N rate. Similar results for LER were observed in the case of intercropping sunflower and soybean (Obong et al., 2016), sunflower with maize and cowpea (Amujoyegbe et al., 2013), and sunflower with mung bean (Anas et al., 2017). Overyielding, in terms of high LER values could be partially attributed to the complementarity of resource use between intercrop components, which was derived from the intercropping pattern adopted in the present study by sowing soybean 15 d before sunflower. This intercropping model increased overall resource capture by prolonging the proportion of the growing season that is under intercropping. Therefore, as stated by Malézieux et al. (2009), the involvement of legume and non-legume crops together in an intercropping system would support agricultural intensification and could help to produce more food per resource unit and simultaneously eliminate the negative effects on the environment. When yield gain was estimated in terms of DMER, it was observed that early and intermediate thinning intervals across all N fertilizer rates resulted in yield gain (DMER > 1), while late thinning reduced yield (DMER < 1).

Comparing LER and DMER reveals that all the DMER values were lower than the LER values. This confirms the assumption that LER was not the most accurate index to determine the expected gain in an additive intercropping model. It overestimated the gain (all LER values were > 1). However, DMER provided a more realistic estimate of the effect of intercropping compared with growing sole crops (Salama et al., 2016), especially for crops in which DM is the main economic component (Nawar et al., 2018).

CONCLUSIONS

The results of the present study provide evidence that the application of high N rates does not compensate plant growth and yield components in the same way after plant stand reduction by any means, for example, thinning. The high N rate was able to improve seed yields of sunflower and soybean intercrops only in the case of early and intermediate thinning intervals. On the other hand, the effect of increasing the N rate on growth and yield components was almost neutralized at late thinning.

Data confirmed that stand reduction due to thinning or any biotic or abiotic stress early in the season is much less damaging to final yield and yield components *vs.* later reductions due to less time remaining for compensatory growth. A slight variation was detected among the treatments for seed oil content in sunflower and soybean. Seed oil percentages

of the tested cultivars usually averaged 50% and 20% for sunflower and soybean, respectively. All treatments produced harvest index ratios that were statistically equivalent to pure stands, suggesting that the effort to assimilate seed yield into total yield was as efficient as that of pure stands. The lack of change in the harvest index may support the idea that, even at late thinning, the remaining plants were able to produce yields in the same proportion as plants at early thinning.

Although intercropping reduced some yield attributes of sunflower and soybean, the combined yield of both crops should be considered. In terms of DM equivalent ratio (DMER), early and intermediate thinning intervals across all N fertilizer rates resulted in yield gain (DMER > 1), while late thinning reduced yield (DMER < 1). Intercropping sunflower and soybean crops is recommended for low input farming systems, particularly in developing countries.

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