Effects of Different Intercropping Sowing Dates and Densities on Nitrogen Use Efficiency in Melon/Sunflower Intercropping System Postprint

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Abstract

Under field conditions, using melon and sunflower as test materials, this study investigated the effects of monoculture of both crops and intercropping sowing dates of sunflower (melon vine extension stage, flowering and fruit-setting stage, fruit expansion stage) and intercropping densities [high (24 975 plants · hm ^{2}), medium (22 200 plants · hm ^{2}), and low (19 980 plants · hm ^{2})] on nitrogen accumulation, nitrogen use efficiency, and light use efficiency in the intercropping system and monocultures of both crops. The results showed that intercropping significantly improved nitrogen accumulation and utilization efficiency of melon in the intercropping system, but reduced those of sunflower. The nitrogen accumulation in aboveground parts of intercropped melon plants averaged 195.08 kg · hm ^{2}, which was 13.0% higher than that of monoculture melon (172.61 kg · hm ^{2}), and both nitrogen use efficiency and partial factor productivity of nitrogen fertilizer were significantly higher than those of monoculture (increased by 40.5% and 55.4%, respectively). In the intercropping system, nitrogen use efficiency and partial factor productivity of nitrogen fertilizer of sunflower decreased by 8.2% and 58.4% compared with monoculture, while nitrogen harvest index increased by 4.9% compared with monoculture. When sunflower was intercropped during the melon vine extension stage, flowering and fruit-setting stage, and fruit expansion stage, the nitrogen use efficiency of the intercropping system increased by 43.5%, 12.5%, and 59.8% compared with monoculture sunflower at the same sowing dates, respectively; when sunflower was intercropped during the fruit expansion stage, the nitrogen use efficiency of the intercropping system increased by 6.7% compared with monoculture melon. When sunflower was intercropped during the melon vine extension stage, flowering and fruit-setting stage, and fruit expansion stage, the partial factor productivity of nitrogen fertilizer of the intercropping system increased by 6.5%, 32.1%, and 40.4%

compared with monoculture sunflower at the same sowing dates, and decreased by 22.5%, 10.1%, and 34.3% compared with monoculture melon, respectively; when sunflower was intercropped during the melon vine extension stage, flowering and fruit-setting stage, and fruit expansion stage, the nitrogen harvest index of the intercropping system decreased by 7.2%, 7.7%, and 12.5% compared with monoculture sunflower at the same sowing dates, respectively. Under the three intercropping densities of high, medium, and low, the nitrogen use efficiency of the intercropping system decreased by 14.2%, 20.4%, and 13.9% compared with monoculture melon at the same densities, and increased by 25.2%, 20.0%, and 9.5% compared with monoculture sunflower, respectively, the partial factor productivity of nitrogen fertilizer decreased by 29.6%, 15.6%, and 21.1% compared with monoculture melon at the same densities; the nitrogen harvest index of the intercropping system under high- and low-density intercropping treatments increased by 2.7% and 1.4% compared with monoculture sunflower, while that under medium-density intercropping decreased by 7.6%. In the intercropping system, the light use efficiency of melon showed a significant positive correlation with nitrogen use efficiency, while that of sunflower showed no significant correlation with nitrogen use efficiency. Under irrigated conditions in the Hexi Oasis, the suitable sowing date for sunflower intercropping with higher nitrogen use efficiency was the melon fruit expansion stage, and the suitable intercropping plant spacing was 40 cm (density of 24 975 plants · hm ^{2}).

Full Text

Effects of Intercropping Time and Planting Density on Nitrogen Use Efficiency in Melon/Sunflower Intercropping Systems*

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Abstract

A field experiment comprising monoculture and intercropping of two crops (melon and sunflower) was conducted at three sunflower sowing times (at vine running, flowering and fruit expansion stages of melon) and three intercropping densities [high (24,975 plant · hm ^{2}), medium (22,200 plant · hm ^{2}) and low (19,980 plant · hm ^{2})] to study plant nitrogen accumulation and nitrogen use efficiency and to determine the relationship between solar energy utilization efficiency and nitrogen use efficiency. The results showed that intercropping significantly increased nitrogen accumulation and nitrogen use efficiency of melon, but reduced those of sunflower. Under intercropping conditions, nitrogen accumulation of above-ground parts of melon was 195.08 kg · hm ^{2}, increasing by 13.0% compared with monocultured melon (172.61 kg · hm ^{2}). Nitrogen use efficiency and partial nitrogen productivity of intercropped melon significantly increased by 40.5% and 55.4%, respectively, over those of monocultured melon. Nitrogen use efficiency and nitrogen partial productivity of sunflower under intercropping decreased by 8.2% and 58.4%, respectively, compared with monocultured sunflower, but nitrogen harvest index increased by 4.9%. Nitrogen use efficiency of the intercropping system at three sunflower intercropping times (vine running, flowering and fruit expansion stages of melon) increased by 43.5%, 12.5% and 59.8%, respectively, over that of monoculture sunflower at the same sowing times. Additionally, nitrogen use efficiency of the intercropping system intercropped at fruit expansion period of melon increased by 6.7% compared with the average nitrogen use efficiency of monocultured melon. Partial nitrogen productivity of the intercropped system with three intercropping times increased by 6.5%, 32.1% and 40.4%, respectively, compared with monocultured sunflower at the same sowing time, but decreased by 22.5%, 10.1% and 34.3%, respectively, compared with the average value for monocultured melon. Nitrogen harvest index of the intercropping system at three sunflower intercropping times decreased by 7.2%, 7.7% and 12.5%, respectively, compared with that of monocultured sunflower. Nitrogen utilization efficiencies of the intercropping system at three intercropping densities reduced by 14.2% (high density), 20.4% (medium density) and 13.9% (low density), respectively, compared with monocultured melon at the same density, but increased by 25.2%, 20.0% and 9.5%, respectively, compared with the average value of monocultured sunflower. Partial nitrogen productivity of the intercropping system with three intercropping densities decreased by 29.6%, 15.6% and 21.1%, respectively, compared with the corresponding treatments of monocultured melon. Nitrogen harvest index of the intercropping system at high and low intercropping densities increased by 2.7% and 1.4%, respectively, compared with the average nitrogen harvest index of monocultured sunflower, but decreased by 7.6% at medium density. There was a significantly positive correlation between nitrogen use efficiency and light use efficiency of melon under intercropping system, but not with sunflower. The results suggested that fruit expansion period of melon was the most suitable intercropping time for sunflower and 40 cm plant spacing was the optimum planting density in melon-sunflower intercropping system, which resulted in high nitrogen use efficiency.

Keywords: Melon-sunflower intercropping; Intercropping time; Planting density; Nitrogen use efficiency; Partial nitrogen productivity; Nitrogen harvest index; Light use efficiency

Introduction

Intercropping is an intensive cultivation method that enhances the utilization of land and climate resources in both temporal and spatial dimensions, promoting efficient and sustained crop production while increasing farmland biodiversity [1]. Crop nitrogen uptake and utilization represent crucial processes in the nitrogen cycle of agroecosystems, with nitrogen absorption and accumulation forming the foundation for crop yield formation [2]. Research has demonstrated that dry matter accumulation during crop growth periods, plant nitrogen content, and nitrogen uptake and utilization are key factors influencing crop yield and quality [3].

Rational intercropping systems improve system productivity by enhancing nutrient interception and utilization by crops [4]. Under intercropping conditions, crop nitrogen uptake and utilization efficiency are often higher than in monoculture, demonstrating clear intercropping advantages. The primary reason is that intercropping expands the nitrogen ecological niche for crops within the system, particularly in terms of nitrogen nutrition supply, thereby better meeting crop nitrogen requirements [2,5]. In rye (*Avena sativa*)/red clover (*Trifolium pratens*) and rye/pea (*Pisum sativum*) intercropping systems, both nitrogen accumulation and biomass of crops were higher than in monoculture [6]. Wheat/faba bean (*Triticum aestivum*/*Vicia faba*) intercropping significantly increased aboveground nitrogen content throughout the growth period, substantially enhancing nitrogen content in wheat leaves and spikes, which laid the foundation for dry matter formation and yield improvement in the intercropping system [7-8]. Plant nitrogen nutritional status directly affects photosynthetic rate and growth development, ultimately influencing yield and light use efficiency. In monoculture systems, farmland light use efficiency is only approximately 1% [9]. Intercropping enables rational crop population configuration, creating layered canopies with alternating rows of tall and short crops. Through measures such as selecting high light-efficiency plants, matching tall and short species, nested canopy layers, and temporal staggering, intercropping expands photosynthetic area per unit land area, extends photosynthetic duration, captures more effective light energy, and increases light use efficiency. Light and nitrogen interact synergistically to affect plant material production, distribution and carbon-nitrogen metabolism. Only when light and nitrogen maintain balanced and coordinated supply levels can their optimal interactive effects on crop growth be realized, ensuring normal crop development [8,10].

Intercropping time and density are critical for intercropped crops, affecting nitrogen nutritional status, nitrogen use efficiency and light use efficiency. Research has shown that in spring wheat/maize (*Zea mays*) strip intercropping, wheat nitrogen content was higher than in monoculture throughout the co-growth period (from wheat three-leaf stage to maturity, and maize sowing to tasseling stage), while maize nitrogen content was lower than in monoculture [11]. In intercropping systems with short co-growth periods, the later crop avoids competition for light and nutrients during the peak growth period of the earlier crop, enabling rapid recovery and vigorous growth after the earlier crop is harvested. Studies on sunflower (*Helianthus annuus*)/potato (*Solanum tuberosum*) intercropping systems have indicated that appropriate early sowing of potatoes or using early-maturing shade-tolerant potato varieties can improve nitrogen use efficiency in intercropped crops by staggering the maximum canopy coverage periods of the two crops, reducing the shading effect of sunflowers on potatoes and enhancing productivity of the intercropping system [12]. Research on two intercropping densities in sunflower/potato systems demonstrated that under a 4-row potato:4-row sunflower density, potato nitrogen use efficiency was lower than in monoculture, while sunflower nitrogen use efficiency was higher than in monoculture; under a 2-row potato:2-row sunflower density, sunflower nitrogen use efficiency showed no significant difference from monoculture [12].

Sunflower and melon (*Cucumis melo*) are important economic crops in the Hexi Oasis region of Gansu Province. In recent years, intercropping sunflowers with other crops has been adopted by farmers in many sunflower-producing areas, bringing significant economic benefits to agricultural production [13]. In regions where watermelon (*Citrullus lanatus*) and melon have surplus capacity for one crop but insufficient capacity for two crops, intercropping and relay cropping of melons with sunflowers—specifically intercropping oil sunflowers (*Helianthus annuus*) or edible sunflowers with melons and watermelons—can maximize economic benefits per unit land area. Planting density and sowing time affect dry matter accumulation, light use efficiency and nitrogen use efficiency in intercropping systems.

However, for a long time, research on the effects of sowing time and density in intercropping systems has primarily focused on crop population canopy structure [14], light use efficiency [15], water use characteristics and efficiency [16], growth and development, yield and economic benefits [17-18]. Few reports have addressed the effects of intercropping time and planting density on crop nitrogen accumulation and nitrogen use efficiency under intercropping conditions. Therefore, this experiment was conducted under field conditions with different intercropping times and densities to compare and analyze nitrogen accumulation and utilization, as well as the relationship between nitrogen use efficiency and light use efficiency, in monoculture and intercropping systems of melon and sunflower at different intercropping times and densities, providing a theoretical basis for optimizing key techniques in melon/sunflower intercropping patterns.

1.1 Experimental Site Description

The experiment was conducted from April to October 2013 at the Minqin County Agricultural Technology Extension Center Experimental Station in Gansu Province. The experimental area is located at the eastern end of the inland river basin in Hexi, Gansu, with geographical coordinates between E103°02 -104°02 and N38°05 -39°06 . It is a semi-enclosed inland desert region with a temperate continental extremely arid climate. The multi-year average precipitation is 110 mm, mostly ineffective precipitation below 5 mm, with annual evaporation of 2,644 mm, mean annual temperature of 7.4 °C, and annual sunshine duration of 2,832 hours.

1.2 Experimental Materials

The melon cultivar used was ‘Jinhongbao’ (mid-maturing), widely planted locally with advantages of good yield potential, superior quality, storage and transport tolerance, and strong disease resistance. The sunflower (edible type) cultivar was ‘LD5009’ (mid-late maturing), a hybrid with good commercial seed characteristics, large kernels and full shells, rapid emergence and easy seedling establishment, drought resistance, tolerance to poor soil, and high yield. Both cultivars were provided by the Minqin County Agricultural Technology Extension Center in Gansu Province.

1.3 Experimental Design and Treatments

This experiment employed a two-factor split-plot design for melon/sunflower intercropping treatments. The main plot factor was intercropping (sunflower sowing) time, with three levels: melon vine running stage, flowering and fruit setting stage, and fruit expansion stage. The subplot factor was intercropping planting density, adjusted through the spacing of the main crop (melon), with three levels: high (40 cm), medium (45 cm), and low (50 cm). Intercropped sunflowers were directly sown between two melon plants within the row, with plant spacing adjusted according to melon spacing at 40 cm, 45 cm, and 50 cm. The high, medium, and low density intercropping treatments corresponded to 24,975 plants · hm ^{2}, 22,200 plants · hm ^{2}, and 19,980 plants · hm ^{2}, respectively, with a row spacing of 100 cm. Monoculture sunflowers were sown at melon sowing time, seedling stage, vine running stage, flowering and fruit setting stage, and fruit expansion stage, without density treatments, at 40 cm plant spacing and 50 cm row spacing, with a density of 49,995 plants · hm ^{2}. Monoculture melon had the same three plant spacing levels as intercropping, with 100 cm row spacing. The experiment comprised 17 treatment combinations with three replications, totaling 51 plots. Both monoculture and intercropped melon plots measured 2 m × 10 m = 20 m^{2}, while monoculture sunflower plots measured 4 m × 5 m = 20 m^{2}. Both monoculture and intercropped melon were sown on April 30, 2013, and harvested on August 5. Monoculture sunflower was sown on April 30, 2013, while intercropped sunflower was sown on June 9 (melon vine running stage), June 29 (flowering and fruit setting stage), and July 13 (fruit expansion stage), and harvested on September 20, October 10, and October 20, respectively.

Monoculture and intercropped melon were cultivated using the water-drought ridge method, with water furrows 70 cm wide and drought ridges 130 cm wide, using double-vine pruning with one fruit per plant. During furrow opening, 150 kg · hm ^{2} of diammonium phosphate, 300 kg · hm ^{2} of urea, and 750 kg · hm ^{2} of calcium superphosphate were applied. After fruit setting, 150 kg · hm ^{2} of urea and 75 kg · hm ^{2} of potassium sulfate were top-dressed; during fruit expansion, 75 kg · hm ^{2} of urea was applied. Monoculture sunflower was cultivated with plastic film mulching on flat land, with film width of 140 cm and three rows per film. Base fertilizer included 750 kg · hm ^{2} of calcium superphosphate, 150 kg · hm ^{2} of diammonium phosphate, 300 kg · hm ^{2} of urea, and 150 kg · hm ^{2} of potassium sulfate. Before budding, 225 kg · hm ^{2} of urea was top-dressed, and at initial flowering, 150 kg · hm ^{2} of urea was applied.

1.4 Measurement Indicators and Methods

Total radiation during crop growth periods was automatically obtained using a HOBO weather observation system (Model H21). The cumulative total solar radiation during the monoculture melon growth period (April 30–August 5) was 1.66×10^{13} J · hm ^{2}, and during the monoculture sunflower growth period (April 30–September 2) was 2.02×10^{13} J · hm ^{2}. The intercropping treatments had growth periods of April 30–September 20, April 30–October 10, and April 30–October 20, with cumulative total solar radiation values of 2.30×10^{13} J · hm ^{2}, 2.66×10^{13} J · hm ^{2}, and 2.84×10^{13} J · hm ^{2}, respectively.

Melon and sunflower plant nitrogen content analysis was conducted before harvest. Five plants per plot were selected and separated into whole plant, leaf, stem, and product organ (fruit, seed) samples. Samples were killed at 105 °C for 30 minutes, dried at 80 °C to constant weight, and dry matter weight was determined. Plant total nitrogen content was determined using the semi-micro Kjeldahl method [19].

Light use efficiency (PUE) = (H × M) / E × 100% (1)
where H is the heat released per unit dry matter (g), generally using an average value of 1.779×10 J · g ^{1}; M is the average material harvest per unit area (g · hm ^{2}); and E is the cumulative total solar radiation during the crop growth period (J · hm ^{2}) [20].

Nitrogen use efficiency (NUE) = Economic yield / Mature plant nitrogen accumulation [21] (2)
Nitrogen harvest index = Product organ nitrogen accumulation / Aboveground nitrogen accumulation [22] (3)
Nitrogen partial productivity (NPFP) = Economic yield / Nitrogen application rate [23] (4)

1.5 Data Processing and Analysis

Statistical analysis of data was performed using SPSS 19.0 software, with Duncan' s new multiple range test used to compare significant differences among treatments. Correlations were tested using Pearson coefficients with two-tailed tests, and Microsoft Excel 2007 software was used for figure preparation.

2.1.1 Nitrogen Accumulation in Monoculture and Intercropped Melon

The aboveground nitrogen accumulation of melon plants under intercropping treatment (195.08 kg · hm ^{2}) was 13.0% higher than under monoculture treatment (172.61 kg · hm ^{2}), with significant difference . Under different sowing times, aboveground nitrogen accumulation showed a decreasing trend with delayed intercropping sowing. The vine running stage intercropping treatment had the highest value, averaging 212.30 kg · hm ^{2}; the flowering and fruit setting stage intercropping treatment was second, averaging 199.13 kg · hm ^{2}; and the fruit expansion stage intercropping treatment was the lowest, averaging 173.82 kg · hm ^{2}. Both vine running and flowering-fruit setting stage intercropping treatments were significantly higher than monoculture, while the fruit expansion stage intercropping treatment showed no significant difference from monoculture. Under different densities, aboveground nitrogen accumulation showed an increasing trend with decreasing intercropping density. Low-density intercropping had the highest value at 203.58 kg · hm ^{2}, with the three density treatments increasing aboveground nitrogen accumulation by 3.4%–23.1% compared with monoculture.

These results indicate that intercropping increased aboveground nitrogen accumulation in melon plants compared with monoculture, with intercropping enhancing nitrogen absorption by melon plants.

Under different intercropping sowing times, among various melon organs under intercropping treatments, the average nitrogen accumulation in vines was highest at flowering-fruit setting stage > fruit expansion stage > vine running stage, with the flowering-fruit setting stage intercropping having the highest nitrogen accumulation of 9.27 kg · hm ^{2}, significantly higher than the vine running stage (6.56 kg · hm ^{2}). With delayed intercropping sowing, leaf nitrogen accumulation showed an increasing trend, with the fruit expansion stage intercropping having the highest value of 24.75 kg · hm ^{2} and the vine running stage the lowest at 20.77 kg · hm ^{2}. Fruit nitrogen accumulation showed a decreasing trend with delayed intercropping sowing, with the vine running stage intercropping having the highest value of 184.97 kg · hm ^{2}, which was 11.7% and 31.1% higher than the flowering-fruit setting and fruit expansion stages, respectively, with significant differences. These results indicate that intercropping during the middle and late growth stages of melon is beneficial for increasing nitrogen accumulation in melon vines and leaves, while intercropping during the early stage is favorable for enhancing fruit nitrogen accumulation.

Within the same sowing time, during vine running stage intercropping, nitrogen accumulation in fruit, leaves, and stems all showed the trend of medium density > low density > high density. During flowering-fruit setting stage intercropping, both vine and fruit nitrogen accumulation under high density were higher than other densities, at 11.52 kg · hm ^{2} and 184.80 kg · hm ^{2}, respectively, without significant differences. During fruit expansion stage intercropping, both vine and leaf nitrogen accumulation under medium density were higher than other densities, at 9.58 kg · hm ^{2} and 27.82 kg · hm ^{2}, respectively, without significant differences; fruit nitrogen accumulation under low density was significantly higher than under high and medium densities. These results indicate that low-density intercropping within the same sowing time is beneficial for increasing fruit nitrogen accumulation in melon, while different densities had no significant effect on vine and leaf nitrogen accumulation.

2.1.2 Nitrogen Use Efficiency in Monoculture and Intercropped Melon

The nitrogen use efficiency (45.48 kg · kg ^{1}) and nitrogen partial productivity (35.70 kg · kg ^{1}) of intercropped melon were both significantly higher than those of monoculture (32.36 kg · kg ^{1} and 22.98 kg · kg ^{1}), increasing by 40.5% and 55.4%, respectively. The nitrogen harvest index (83.76%) was higher than that of monoculture (80.34%), though the difference was not significant . These results indicate that intercropping can improve nitrogen use efficiency and nitrogen partial productivity in melon.

Under different sowing times, nitrogen use efficiency of melon first increased then decreased with delayed intercropping sowing, with the flowering-fruit setting stage intercropping having the highest value of 51.12 kg · kg ^{1}, which was 24.9% higher than vine running stage intercropping (40.93 kg · kg ^{1}) with significant difference, and 15.2% higher than fruit expansion stage intercropping (44.38 kg · kg ^{1}) without significant difference. Nitrogen partial productivity first increased then decreased with delayed sowing, with the flowering-fruit setting stage intercropping having the highest value of 41.31 kg · kg ^{1}, followed by vine running stage intercropping at 35.61 kg · kg ^{1}, both significantly higher than the fruit expansion stage intercropping at 30.17 kg · kg ^{1}. Nitrogen harvest index showed a decreasing trend with delayed intercropping sowing, with vine running stage intercropping having the highest value of 87.32%, significantly higher than fruit expansion stage intercropping (80.68%), but not significantly different from flowering-fruit setting stage intercropping (83.27%). These results indicate that intercropping during the flowering-fruit setting stage can improve nitrogen use efficiency and nitrogen partial productivity in melon.

Within the same intercropping sowing time, during vine running stage intercropping, nitrogen use efficiency showed no significant difference with density changes; nitrogen partial productivity first increased then decreased with density, with medium density having the highest value of 40.20 kg · kg ^{1}, which was 20.3% and 21.0% higher than high and low density intercropping, respectively, with significant differences; there was no significant difference in nitrogen harvest index among the three densities. During flowering-fruit setting stage intercropping, nitrogen use efficiency first increased then decreased with density, with medium density having the highest value of 53.36 kg · kg ^{1}, without significant difference from other densities; nitrogen partial productivity showed no significant difference with density changes; both high and medium density intercropping had higher nitrogen harvest index than low density, without significant differences. During fruit expansion stage intercropping, nitrogen use efficiency increased with density, with high density intercropping having the highest value of 52.96 kg · kg ^{1}, medium density at 47.08 kg · kg ^{1}, both significantly higher than low density intercropping at 33.10 kg · kg ^{1}; nitrogen partial productivity first increased then decreased with density, with medium density intercropping having the highest value of 32.03 kg · kg ^{1}, significantly higher than low density but not significantly different from high density; nitrogen harvest index first decreased then increased with decreasing density, with low density intercropping having the highest value of 84.98%, which was 6.4% and 10.1% higher than high and medium density, respectively, significantly higher than medium density but not significantly different from high density. These results indicate that within the same sowing time, medium and high density intercropping are beneficial for improving nitrogen use efficiency and nitrogen partial productivity in melon.

2.2.1 Nitrogen Accumulation in Monoculture and Intercropped Sunflower

The aboveground nitrogen accumulation of sunflower plants under intercropping treatment (125.29 kg · hm ^{2}) was significantly lower than under monoculture treatment (263.29 kg · hm ^{2}). Under different intercropping sowing times, both vine running stage and flowering-fruit setting stage intercropping had significantly lower aboveground nitrogen accumulation than their respective monoculture treatments at the same stages. The fruit expansion stage intercropping treatment was higher than the fruit expansion stage monoculture treatment, without significant difference . These results indicate that intercropping generally reduced aboveground nitrogen accumulation in sunflower plants compared with monoculture, suggesting that intercropping is not conducive to nitrogen absorption and accumulation in sunflower.

Under different intercropping sowing times, aboveground nitrogen accumulation in sunflower first decreased then increased with delayed intercropping sowing, with the fruit expansion stage intercropping treatment having the highest value of 149.28 kg · hm ^{2}, which was 10.1% and 64.0% higher than vine running stage (135.54 kg · hm ^{2}) and flowering-fruit setting stage intercropping (91.04 kg · hm ^{2}), respectively, significantly higher than the flowering-fruit setting stage intercropping but not significantly different from the vine running stage intercropping. These results indicate that intercropping during the fruit expansion stage is beneficial for nitrogen absorption and accumulation in sunflower plants.

Among different organs of sunflower under various intercropping sowing times, the average nitrogen accumulation in stems was highest under vine running stage intercropping at 21.85 kg · hm ^{2}, significantly higher than flowering-fruit setting stage intercropping (14.26 kg · hm ^{2}), but not significantly different from fruit expansion stage intercropping (18.58 kg · hm ^{2}). Leaf nitrogen accumulation was highest under vine running stage intercropping, averaging 24.58 kg · hm ^{2}, significantly higher than flowering-fruit setting stage intercropping (6.60 kg · hm ^{2}), but not significantly different from fruit expansion stage intercropping (16.47 kg · hm ^{2}). Floral disc and grain nitrogen accumulation were highest under fruit expansion stage intercropping, at 28.34 kg · hm ^{2} and 85.89 kg · hm ^{2}, respectively, both significantly higher than flowering-fruit setting stage intercropping, but not significantly different from vine running stage intercropping. These results indicate that intercropping during the vine running and fruit expansion stages is beneficial for nitrogen accumulation in sunflower stems and leaves, while intercropping during the fruit expansion stage is favorable for nitrogen accumulation in floral discs and grains.

Within the same intercropping sowing time, during vine running stage intercropping, grain nitrogen accumulation under medium density was significantly higher than under high and low densities, while leaf and floral disc nitrogen accumulation showed no significant differences among densities; aboveground nitrogen accumulation was highest under medium density at 169.07 kg · hm ^{2}, significantly higher than low and high densities. During flowering stage intercropping, low density had higher nitrogen accumulation in stems, leaves, and grains than high and medium densities, without significant differences; floral disc nitrogen accumulation was highest under medium density at 19.44 kg · hm ^{2}, without significant differences from other densities. During fruit expansion stage intercropping, floral disc nitrogen accumulation was highest under low density at 39.30 kg · hm ^{2}, without significant differences from other densities; stem and leaf nitrogen accumulation under medium density were higher than other densities, without significant differences; grain and aboveground nitrogen accumulation under medium density were significantly higher than under high density, but not significantly different from low density. These results indicate that low and medium density intercropping are beneficial for nitrogen accumulation in sunflower plants and organs.

2.2.2 Nitrogen Use Efficiency in Monoculture and Intercropped Sunflower

The average nitrogen use efficiency of intercropped sunflower (18.90 kg · kg ^{1}) was 8.2% lower than that of monoculture (20.69 kg · kg ^{1}), without significant difference; nitrogen partial productivity (7.18 kg · kg ^{1}) was significantly lower than that of monoculture (17.24 kg · kg ^{1}), decreasing by 58.4%; nitrogen harvest index (54.41%) was 4.9% higher than that of monoculture (51.87%), without significant difference . These results indicate that intercropping can increase nitrogen harvest index in sunflower, but reduces nitrogen use efficiency and nitrogen partial productivity.

Under different intercropping sowing times, nitrogen use efficiency showed an increasing trend with delayed intercropping sowing, with fruit expansion stage intercropping having the highest value of 21.20 kg · kg ^{1}, higher than vine running stage intercropping at 17.40 kg · kg ^{1}, without significant difference. Nitrogen partial productivity first decreased then increased with delayed sowing, with fruit expansion stage intercropping having the highest value of 9.29 kg · kg ^{1}, significantly higher than flowering-fruit setting stage intercropping (4.99 kg · kg ^{1}), but not significantly different from vine running stage intercropping. Nitrogen harvest index showed an increasing trend with delayed intercropping sowing, with fruit expansion stage intercropping having the highest value of 57.76%, followed by flowering-fruit setting stage intercropping at 57.52%, both significantly higher than vine running stage intercropping (47.95%). These results indicate that among intercropping treatments, fruit expansion stage intercropping was superior to other sowing times for improving nitrogen use efficiency, nitrogen partial productivity and nitrogen harvest index in sunflower.

Within the same intercropping sowing time, during vine running stage intercropping, nitrogen use efficiency in sunflower showed the trend of high density > low density > medium density, with high density significantly higher than medium density but not significantly different from low density; nitrogen partial productivity showed no significant difference with density changes; nitrogen harvest index increased with density, with high density intercropping having the highest value of 52.73%, significantly higher than low density but not significantly different from medium density. During flowering-fruit setting stage intercropping, nitrogen use efficiency showed the trend of medium density > high density > low density, without significant differences among densities; nitrogen partial productivity showed no significant difference with density changes; nitrogen harvest index showed the trend of high density > low density > medium density, with high density significantly higher than medium density but not significantly different from low density. During fruit expansion stage intercropping, nitrogen use efficiency showed no significant difference with density changes; nitrogen partial productivity showed the trend of medium density > low density > high density, with medium density intercropping significantly higher than high density; nitrogen harvest index showed the trend of high density = medium density > low density, without significant differences among densities. These results indicate that within the same sowing time, intercropping density had no significant effect on nitrogen partial productivity in sunflower, while high and medium density intercropping were superior to low density for improving nitrogen use efficiency and nitrogen harvest index.

2.3 Nitrogen Use Efficiency of the Intercropping System

Sunflower intercropping time had a substantial effect on nitrogen use efficiency of the entire intercropping system. The nitrogen use efficiency of the whole intercropping system was highest under fruit expansion stage intercropping at 34.38 kg · kg ^{1}, which was higher than both sunflower monoculture at the same sowing time and the average of melon monoculture (32.23 kg · kg ^{1}), increasing by 59.8% and 6.7%, respectively. The vine running stage intercropping was second at 24.72 kg · kg ^{1}, which was 43.5% higher than sunflower monoculture at the same sowing time but 23.3% lower than the average of melon monoculture. The flowering-fruit setting stage intercropping had the lowest value for the whole intercropping system at 22.55 kg · kg ^{1}, which was 12.5% higher than sunflower monoculture at the same sowing time but 30.0% lower than the average of melon monoculture. The nitrogen partial productivity of the whole intercropping system was highest under flowering-fruit setting stage intercropping at 20.65 kg · kg ^{1}, which was 32.1% higher than sunflower monoculture at the same sowing time but 10.1% lower than the average of melon monoculture. The vine running stage was second at 17.80 kg · kg ^{1}, which was 6.5% higher than sunflower monoculture at the same sowing time but 22.5% lower than the average of melon monoculture. The fruit expansion stage had the lowest value at 15.09 kg • kg ^{1}, which was 40.4% higher than sunflower monoculture at the same sowing time. The nitrogen harvest index of the whole intercropping system was lower than both sunflower monoculture at the same sowing time and the average of melon monoculture, decreasing by 7.2%–12.5% compared with sunflower monoculture and by 28.9%–45.6% compared with the average of melon monoculture. In summary, the suitable sunflower intercropping time for high nitrogen use efficiency was the melon fruit expansion stage.

Planting density also substantially affected nitrogen use efficiency of the intercropping system. The nitrogen use efficiency of the whole intercropping system was lower than that of melon monoculture at the same density but higher than the average of sunflower monoculture. High-density intercropping had the highest value at 28.54 kg • kg ^{1}, which was 14.2% lower than melon monoculture at the same density but 25.2% higher than the average of sunflower monoculture. Medium-density intercropping (27.37 kg • kg ^{1}) was second, being 20.4% lower than melon monoculture at the same density but 20.0% higher than the average of sunflower monoculture. Low-density intercropping had the lowest value at 24.97 kg • kg ^{1}, being 13.9% lower than melon monoculture at the same density but 9.5% higher than the average of sunflower monoculture. The nitrogen partial productivity of the whole intercropping system was lower than both melon monoculture at the same density and the average of sunflower monoculture, with high, medium, and low density intercropping decreasing by 29.6%, 15.6%, and 21.1% compared with melon monoculture, and decreasing by 8.8%, 1.0%, and 12.1% compared with the average of sunflower monoculture. The nitrogen harvest index of the whole intercropping system was lower than that of melon monoculture at the same density, with high-density intercropping having the highest value at 53.26%, which was 35.0% lower than melon monoculture at the same density. Medium- and low-density intercropping were 47.93% and 52.58%, respectively, with high- and low-density intercropping being 2.7% and 7.6% higher than the average of sunflower monoculture. Therefore, the suitable intercropping density for the intercropping system was 40 cm plant spacing.

2.4 Relationship Between Nitrogen Use Efficiency and Light Use Efficiency in the Intercropping System

In the intercropping system, light use efficiency of melon was significantly correlated with nitrogen use efficiency ($r = 0.487$, $P < 0.05$), while light use efficiency of sunflower showed no significant correlation with nitrogen use efficiency ($r = 0.226$, $P > 0.05$) [Figure 1: see original paper]. Within the parameter range of this experiment, as light use efficiency increased, nitrogen use efficiency of melon in the intercropping system also increased, indicating a mutually promoting relationship between light use efficiency and nitrogen use efficiency for melon in the intercropping system. Therefore, when considering intercropping, the sunflower sowing time should be set during the middle and late growth stages of melon to reduce the shading effect of sunflower on melon, thereby improving light use efficiency and consequently nitrogen use efficiency of melon.

3 Discussion and Conclusions

Under intercropping conditions, crop resource utilization differs from monoculture, and quantifying nitrogen utilization of each crop during the co-growth period is important for improving yield and benefits of intercropping systems. Different crops have different nutrient absorption and utilization capacities, and often the enhancement of one crop's nutrient absorption and utilization capacity comes at the cost of reducing the other crop' s capacity in the system [12]. Due to competition for resources between adjacent crops, relatively smaller canopy crops can obtain more resources, affecting crop biomass formation and causing differences in nitrogen distribution within plants, which leads to variations in nitrogen conversion efficiency among crops [24]. Research suggests that when sunflowers are intercropped with melons, the key is to shorten the co-growth period of the two crops, and to delay sunflower sowing as much as possible while ensuring melon maturity [13]. In this study, the intercropping system increased nitrogen accumulation and utilization efficiency in melon organs, but reduced nitrogen accumulation and nitrogen use efficiency in sunflower organs as a cost. When sunflower was intercropped during the melon flowering-fruit setting stage, melon nitrogen use efficiency was significantly higher than other intercropping times, indicating that too early intercropping may have adverse effects on both crops, while appropriate intercropping time can improve melon nitrogen utilization. Greenwood et al. [25] demonstrated that competition for light increases biomass allocation to plant support structures (e.g., stems), but simultaneously reduces plant nitrogen content. In this study, when sunflower was intercropped during the melon fruit expansion stage, nitrogen accumulation and nitrogen use efficiency in sunflower organs were significantly higher than at other sowing times, indicating that early intercropping prolonged the co-growth period of melon and sunflower. With stronger light competition ability, sunflower captured more light and produced more dry matter, consequently reducing nitrogen content in sunflower organs, consistent with previous research results [12–13]. Therefore, intercropping sunflower during the melon fruit expansion stage shortened the co-growth period, reduced the decline in melon organ nitrogen accumulation and nitrogen use efficiency caused by competition, and was beneficial for improving sunflower organ nitrogen accumulation and nitrogen use efficiency.

Research suggests that decreased plant nitrogen concentration is related to the strength of population light competition [26]. Compared with monoculture, intercropping systems form unique spatial structures where tall crops shade short crops, reducing light interception by short crops and consequently decreasing their nitrogen concentration. In this study, the combination of sunflower (tall crop) and melon (short crop) created a spatial three-dimensional structure, with melon at the lower canopy layer. During the vigorous growth period of sunflower, melon leaves were shaded by tall sunflower, reducing photosynthetic capacity, affecting dry matter synthesis, and leading to decreased nitrogen conversion efficiency in melon. In intercropping systems with short co-growth periods, the later crop avoids nutrient competition during the peak growth period of the earlier crop, enabling rapid recovery and vigorous growth after the earlier crop is harvested. Research on watermelon and oil sunflower intercropping showed that long co-growth periods caused competition for light, fertilizer, and water, restricting watermelon fruit setting and size and affecting yield. Therefore, sowing time needs to be adjusted to delay oil sunflower sowing, resulting in approximately 30 days of co-growth period, which not only improves watermelon yield and quality but also ensures good sunflower benefits [13]. In this study, intercropping sunflower during melon flowering-fruit setting and fruit expansion stages delayed sunflower sowing time, shortened the co-growth period, reduced sunflower shading on melon, and resulted in melon nitrogen use efficiency and nitrogen partial productivity higher than monoculture, effectively solving the problem of reduced nitrogen use efficiency in short crops caused by shading. Some studies have shown that appropriate density increase is beneficial for yield improvement and can significantly enhance nitrogen use efficiency [27]. In this study, intercropping sunflower during the melon fruit expansion stage, with increased melon intercropping density, may have significantly increased melon root system and canopy volume, particularly the proportion of deep root length density, significantly enhancing deep nitrogen absorption to meet nitrogen demand after aboveground population increase. Plant nitrogen nutritional status directly affects photosynthetic rate and growth development, ultimately influencing yield and light use efficiency. Therefore, in the optimization management of melon/sunflower intercropping, it is necessary to adjust sunflower intercropping time and melon intercropping density to improve productivity of this intercropping pattern.

The results of this experiment showed that melon intercropped with sunflower had higher nitrogen accumulation and utilization efficiency in all organs than monoculture, while sunflower intercropping had lower nitrogen accumulation than monoculture, though the difference in nitrogen use efficiency between sunflower intercropping and monoculture was not significant. When sunflower was intercropped during the melon fruit expansion stage, it was superior to other intercropping times in improving nitrogen partial productivity and nitrogen harvest index of the intercropping system. High-density intercropping was superior to other densities in improving nitrogen use efficiency and nitrogen harvest index of the intercropping system. Therefore, in melon/sunflower intercropping systems, the suitable sunflower intercropping time for obtaining higher plant nitrogen accumulation and nitrogen use efficiency is the melon fruit expansion stage, and the suitable intercropping density is 40 cm plant spacing. Light use efficiency of melon was significantly positively correlated with nitrogen use efficiency, while light use efficiency of sunflower showed no significant correlation with nitrogen use efficiency.

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