

EFFECTS OF WAXY CORN-COTTON INTERCROPPING ON SOIL CO₂ EMISSION AND CROP PRODUCTIVITY

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Abstract

To explore the effects of waxy corn-cotton intercropping on soil CO₂ emissions and crop productivity, three planting methods, namely, waxy corn monoculture (M), cotton monoculture (C), and waxy corn-cotton intercropping (MC) were established. The results revealed that the cumulative emissions of soil CO₂ were C (22250 kg·hm⁻²) > MC (21035 kg·hm⁻²) > M (20390 kg·hm⁻²). In the intercropping mode, the land equivalent ratio was greater than one, which indicated that the intercropping model had improved land productivity. The relative competitiveness between waxy corn and cotton was less than zero, and the nutritional competition ratio is less than one, which indicated that waxy corn is a disadvantaged crop, while cotton is a dominant crop in this intercropping mode. Compared with waxy corn or cotton monocultures, intercropping can effectively increase the marketability of waxy corn and the boll number per cotton plant, boll weight, and seed yield. Moreover, it reduced the boll shedding rate of the cotton plants. Therefore, compared with waxy corn or cotton monocultures, waxy corn-cotton intercropping was a better planting method.

Introduction

Cotton is an important economic crop which is very important to the textile and clothing industry (Zhang *et al.* 2022). Cotton intercropped with other crops can utilize light, heat, and water resources at multiple levels (Chang *et al.* 2025, Zhang *et al.* 2024, 2025). Compared with monocultures, cotton intercropping can result in ecological niche differentiation through differences in crop growth stages and growth characteristics, leading to spatial complementarity. This can improve the interception of light energy and nutrient utilization efficiency, as well as the material output and environmental conditions of agricultural ecosystems, thereby increasing crop yields and land productivity (Zhan *et al.* 2023). There are various intercropping modes in cotton fields, such as cotton-wheat intercropping (Li *et al.* 2025a), cotton-peanut intercropping (Li *et al.* 2025b), cotton-watermelon intercropping (Li and Xu 2025), cotton-jujube tree intercropping (Li *et al.* 2022), cotton-chili intercropping (Zhao *et al.* 2022), cotton-mung bean intercropping (Gabhane *et al.* 2023, Zhang 2024), and cotton-sweet waxy corn intercropping (Wang *et al.* 2025). Under the intercropping mode, with changes in crop spatial structure, field permeability also changes, which affects crop growth and soil physicochemical properties, thereby affecting soil CO₂ emissions and crop yield.

Therefore, in this study, a waxy corn-cotton intercropping treatment was established; waxy corn and cotton monocultures were used as controls, and the changes in the soil respiration rate, total soil CO₂ emissions, and interspecies competitiveness under the intercropping mode were analyzed.

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Materials and Methods

The experimental site is located at the Tangshan Agricultural Science Research Institute farm (latitude, 39.1627° N; longitude, 118.5731° W; altitude, 12 m; Tangshan, Hebei, China), characterized by a warm temperate marine monsoon climate with annual rainfall of 500–800 mm. The experimental site consisted of sandy loam soil, and the basic physicochemical properties are shown in Table 1.

Table 1. Basic physical and chemical properties of the tested soil.

pH	Organic matter (g/kg)	Alkali hydrolyzed nitrogen (mg/kg)	Available phosphorus (mg/kg)	Available potassium (mg/kg)
7.01	15.6	36.4	15.9	177.4

This experiment involved three treatments i.e., waxy corn monoculture (M), waxy corn-cotton intercropping (MC), and cotton monoculture (C). The experiment adopted a single-factor randomized block design, with 3 replicates and a total of 9 treatment plots, each covering. On the basis of the practical experience of Cui *et al.* (2023), the treatment was administered as follows: In case of waxy corn-cotton intercropping (MC) the strip width measured 4.20 meters. Waxy corn was planted in 2 rows, the row spacing was 0.35 m, and the plant spacing was 0.15 m. The planting density was approximately 3.0×10^4 plants/hectare. Cotton was planted in 4 rows, the row spacing was 0.76 m, and the plant spacing was 0.135 m. The planting density was approximately 6.9×10^4 plants/hectare. The space between adjacent cotton rows and corn rows was 0.90 m. Cotton and waxy corn were both planted with plastic film.

In case of waxy corn monoculture (M) waxy corn was planted with plastic film. The row spacing was 0.6 m, and the plant spacing was 0.2 m. The density was 8.3×10^4 plants/hectare. On the other hand cotton monoculture (C) cotton was planted with plastic film. The row spacing was 0.76 m, and the plant spacing was 0.135 m. The density was 9.8×10^4 plants/hectare.

The waxy corn variety was Nongkenuo 336, whereas the cotton variety was Jimian 30. The two varieties are widely used in waxy corn–cotton intercropping in Hebei Province, China. Waxy corn was sown on March 10, 2024, and March 15, 2025, and the harvesting times were July 1, 2024, and July 7, 2025, respectively. Cotton was sown on May 10, and the harvesting occurred on November 5 during 2024–2025.

The soil CO₂ emission rate was measured by using a soil respiration measurement system (Li-COR 8100 A, USA) following the method described by Gao *et al.* (2008). During the measurement, the breathing chamber was placed on the PVC base, and CO₂ released from the soil was collected. In the monoculture community, three PVC bases were uniformly buried between rows. In the intercropping community, three PVC bases were buried evenly at the center of the crop belts, and three PVC bases were buried evenly between the belts. The measurement time was after the glutinous corn was sown. Measurements were taken every 15 days until the cotton was harvested in November. Sunny weather was chosen from 9–11 am for soil respiration measurements. In the intercropping treatment, the weighted average of the CO₂ emission rate derived from the waxy corn belt, cotton belt, and blank area of the inter belt was used as the CO₂ emission rate value.

During the cotton budding stage, 11.4 m² (2.28 m × 5 m) of sampling points were marked in each processing area with tags. At the end of the cotton boll opening period, the total number of plants, total number of bolls, and number of stiff and rotten bolls were investigated, and the effective number of per plant and the rates of bud and boll shedding were calculated. Thirty cotton

bolls from the lower, middle, and upper parts of the cotton plant were used to measure their weight, and the yield of the seed cotton was calculated on the basis of the number of bolls per unit area and their weight. During the suitable harvesting period, thirty waxy corn plants whose growth was uniform and consistent were selected from each treatment area. The plant height was measured 3 days before the plants were harvested. On the day of harvest, the fresh weight, ear length, ear thickness, and bald tips of the ears of the corn were measured. On the day of harvest, the fresh weight, ear length, ear thickness, and bald tips of the waxy corn ears were measured.

Data processing and analysis were performed using Excel 2016 and DPS V19.05. One-way ANOVA was used to evaluate the significance of differences in various indicators between different treatments. SigmaPlot 10.0 software was used for plotting. The formula of Li *et al.* (2019) was used to calculate cumulative CO₂ emission (CE):

$$CE = \sum_{i=1}^n \left[\frac{(F_{i+1} + F_i)}{2} \times (t_{i+1} - t_i) \times 60 \times 60 \times 24 \times 10^{-6} \times 44 \right] \times 10$$

In the formula, *CE* represents the total CO₂ emissions from the soil (kg·hm⁻²), and (*F_{i+1}*+*F_i*) is the sum of the soil CO₂ emission rates between two consecutive measurements (μmol·m⁻²·s⁻¹). (*t_{i+1}*-*t_i*) is the interval between the two consecutive measurements (Li *et al.* 2019).

The land equivalent ratio (LER) is an important indicator for measuring the productivity of crop intercropping (Lei *et al.* 2025).

$$LER = LER_M + LER_C = \frac{Y_{M,I}}{Y_M} + \frac{Y_{C,I}}{Y_C}$$

In the formula, LER_M is the relative land equivalent ratio of waxy corn in the intercropping mode, and LER_C is the relative land equivalent ratio of cotton in the intercropping mode. *Y_M* and *Y_C* represent the yield (kg/hm²) of waxy corn and cotton in monoculture, respectively, whereas *Y_{M,j}* and *Y_{C,j}* represent the yield (kg/hm²) of waxy corn and cotton in intercropping, respectively. When the LER is >1, the advantages of intercropping are indicated; when the LER is <1, the disadvantages of intercropping are indicated (Mao *et al.* 2012).

The formula for calculating interspecies relative competitive ability (*A_{MC}*) is as follows (Yang *et al.* 2013, Yong *et al.* 2015):

$$A_{MC} = \frac{Y_{M,I}}{Y_M} - \frac{Y_{C,I}}{Y_C}$$

When the *A_{MC}* is >0, waxy corn is more competitive than cotton. In contrast, when the *A_{MC}* is <0, waxy corn is less competitive than cotton is. The formula for calculating the yield nutrient competition ratio (CR_{MC}) is as follow (Lei *et al.* 2025):

$$CR_{MC} = \frac{Y_{M,J}}{Y_M} \times \frac{Y_C}{Y_{C,J}}$$

In the equation, the nutrient competition ratio for maize (CR_{MC}) represents the nutrient competition ratio of waxy corn relative to that of cotton in the waxy corn-cotton intercropping system. When the CR_{MC} is > 1, it indicates that compared with cotton, waxy corn has a stronger nutrient competition ability. In contrast, when the CR_{MC} is < 1, the nutrient competition ability of waxy corn is weaker than that of cotton.

Results and Discussion

Under the different planting modes, the soil respiration rate tended to first increase but then decrease. Owing to factors such as rainfall, individual jumps in the soil respiration rate occurred (Fig. 1). In the M treatment, the soil respiration rate during the seedling stage was relatively low. After the jointing stage, as the temperature increased, the soil respiration rate increased gradually.

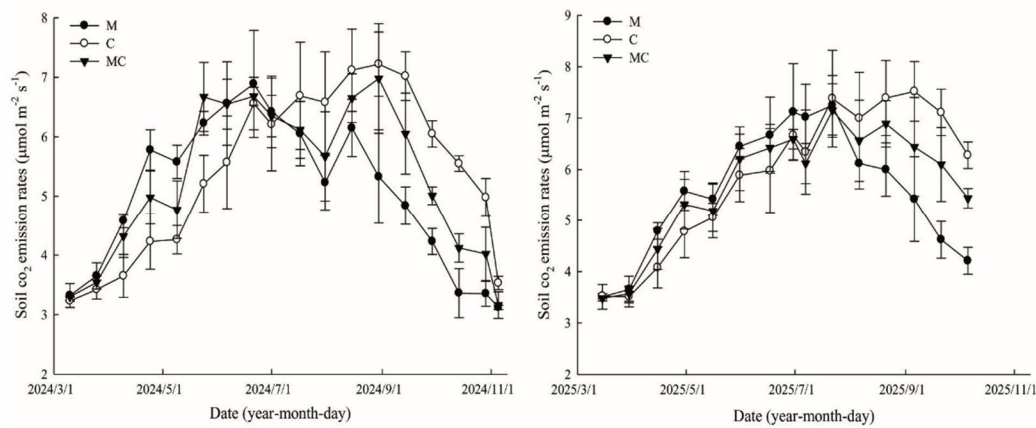


Fig. 1. Dynamic changes in the soil CO₂ emission rate.

The soil respiration rate reached its peak in the later stage of grouting, with values of $6.89 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (2024) and $7.12 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (2025), respectively. Afterward, soil respiration weakened gradually and reached its lowest point during the cotton maturity period. In the C treatment, the soil respiration rate was relatively low during the seedling stage. The soil respiration rate peaked during the cotton boll opening period, when the values were $7.22 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (2024) and $7.52 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (2025), respectively. In the MC treatment, the soil respiration rate was between that in the M and C treatments. The maximum values occurred at the cotton boll stage and were $6.98 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (2024) and $7.15 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (2025), respectively.

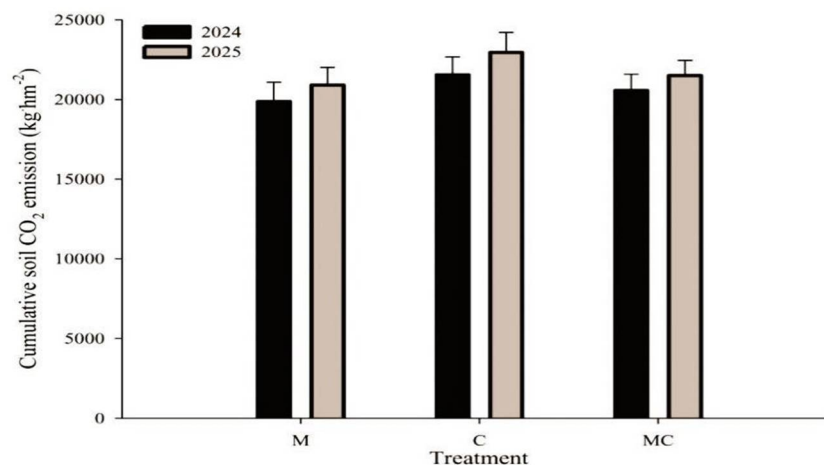


Fig. 2. Cumulative CO₂ emissions under different treatments in 2024 and 2025.

Under different treatments, the variation pattern of total soil CO₂ emissions among the different years was essentially the same, with the result being M<MC<C (Fig. 2). Under the C treatment, the total soil CO₂ emissions were 21548 kg/hm² (2024) and 22951 kg/hm² (2025), respectively, and the average total CO₂ emissions were 22250 kg/hm². Compared with those in the MC and M treatments, CO₂ emissions increased by 5.46% and 8.36%, respectively. The effects of the different intercropping models on soil CO₂ emissions differed. Some studies suggest that compared with monocultures, intercropping can reduce soil CO₂ emissions. Cui *et al.* (2025) reported that under the intercropping of soybean and maize, the cumulative emissions of soil CO₂ were as follows: maize monoculture (21231 kg/hm²) > soybean monoculture (19715 kg/hm²) > maize-soybean intercropping (17321 kg/hm²). Li and Gao (2022) reported that compared with maize monocultures, maize-alfalfa and maize-sweet intercropping can reduce soil CO₂ emissions. Compared with those under the maize monoculture, the cumulative soil CO₂ emissions under the maize-alfalfa intercropping system decreased by 16% (Tang *et al.* 2016). Corn-pea and corn-cowpea experiments demonstrated that CO₂ emissions from intercropping systems were lower than those from monocultures (Liang *et al.* 2023, Shen *et al.* 2025).

Compared with the M treatment, the MC treatment increased plant height, ear height, ear length, and 100-grain weight, which reached 2.08, 3.07, 5.58, and 3.60%, respectively. In contrast, the bald tip length decreased by 166.67% (Table 2). It follows that compared with the M treatment, the MC treatment can effectively improve the marketability of waxy corn ears.

Table 2. Yield trait indicators of waxy corn.

Treatment	Plant height (cm)	Ear length (cm)	Ear diameter (cm)	Bare tip (cm)	100-grain weight (g)	Fresh spike yield (kg/hm ²)
M	249.3 ± 6.6 a	94.6 ± 3.3 b	20.3 ± 1.0 b	0.8 ± 0.2 a	40.1 ± 2.4 b	22262 ± 1456 a
MC	254.6 ± 6.3 a	97.6 ± 5.1 a	21.5 ± 0.7 a	0.3 ± 0.1 b	41.6 ± 2.6 a	10170 ± 909 b

M: waxy corn monoculture and MC: waxy corn-cotton intercropping. Different lowercase letters indicate significant differences between treatments at $P < 0.05$.

Compared with the C treatment, the MC treatment reduced the plant height and boll shedding rate, which reached 3.71 and 7.46%, respectively. In contrast, the boll number per plant and boll weight increased by 10.54 and 1.56%, respectively (Table 3).

Table 3. Cotton yield trait indicators.

Treatment	Plant height (cm)	Boll number / plant	Boll weight (g)	Boll shedding rate (%)	Seed cotton yield (kg/hm ²)
C	105.2 ± 4.4 a	10.91 ± 1.1 b	5.14 ± 0.6 a	40.2 ± 3.8 a	6798 ± 423.58 a
MC	101.3 ± 3.8 b	12.06 ± 0.8 a	5.22 ± 0.4 a	37.2 ± 3.3 b	5805 ± 398.11 b

C: cotton monoculture and MC: waxy corn-cotton intercropping.

Intercropping is important for enhancing crop productivity (Chen *et al.* 2025, Fu *et al.* 2025). A reasonable intercropping configuration is the foundation for increasing production (Liu *et al.* 2024, Yang *et al.* 2024, Hou *et al.* 2025, Long *et al.* 2025). In this study, compared with that of the waxy corn and cotton monoculture, the plant height of the waxy corn increased by 2.08%, whereas the height of the cotton decreased by 3.71% in the intercropping system. This is mainly due to the blocking effect of waxy corn on the edge rows of cotton in the intercropping system. From the

perspective of yield structure, compared with the monocultures, the waxy corn and cotton intercrops increased the number and weight of cotton bolls per plant, and the ear length, ear thickness, and 100-grain weight of the waxy corn increased significantly. Compared with those of the monocultures, the bald tip length of waxy corn and the shedding rate of cotton buds and bolls were reduced. The reason may be that adjusting the population structure reasonably in the intercropping system increased the photosynthetic area, reduced the loss of light and water, and improved the plant light energy utilization efficiency during the crop growth stage.

The results of the LER under the MC treatment during the two years are shown in Table 4. From the perspective of the entire intercropping system, the LER values were greater than one. These findings indicated that the MC treatment improved land productivity and further increased the potential for land production. The two-year average LER was 1.32, indicating that this intercropping pattern has higher land use efficiency.

Table 4. Changes in LER during the 2024-2025.

Treatment	Year	LER _M	LER _C	LER
MC	2024	0.44	0.86	1.30
	2025	0.45	0.88	1.33

As shown in Fig. 3, the A_{MC} under the MC treatment were -0.41 (2024) and -0.43 (2025), respectively, which were less than zero. The CR_{MC} were 0.51 (2024) and 0.53 (2025), respectively, which were less than one. These results indicate that the competitive ability of waxy corn was weaker than that of cotton in the intercropping treatment. In the intercropping system, waxy corn was a disadvantaged crop, while cotton was a dominant crop. From the perspective of crop height, waxy corn is advantageous as a tall pole crop, whereas cotton is disadvantageous as a short pole crop. In this study, although cotton is a dwarf crop, it has significant advantages, which is consistent with the findings of He *et al.* (2023).

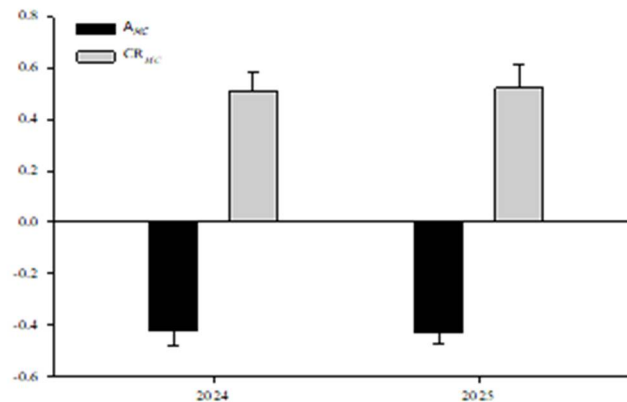


Fig. 3. Changes in A_{MC} and CR_{MC} during the 2024-2025.

In the intercropping system, improving the photosynthetic performance of the population during the later stage of growth increased the net photosynthetic rate of leaves and promoted the transportation and distribution of photosynthetic products and nutrients to reproductive organs. Compared with cotton monocultures, waxy corn and cotton intercropping can reduce soil CO₂

emissions and increase the yield of waxy corn and cotton. It is a planting mode that can be promoted.

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