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Optimum strip width increases dry matter, nutrient accumulation, and seed yield of intercrops under the relay intercropping system

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Abstract

Strip width management is a critical factor for producing higher crop yields in relay intercropping systems. A 2-year field experiment was carried out during 2012 and 2013 to evaluate the effects of different strip width treatments on dry-matter production, major-nutrient (nitrogen, phosphorus, and potassium) uptake, and competition parameters of soybean and maize in relay intercropping system. The strip width (SW) treatments were 0.40, 0.40, and 0.40 m (SW1); 0.40, 0.40, and 0.50 m (SW2); 0.40, 0.40, and 0.60 m (SW3); and 0.40, 0.40, and 0.70 m (SW4) for soybean row spacing, maize row spacing, and spacing between soybean and maize rows, respectively. As compared to sole maize (SM) and sole soybean (SS), relay-intercropped maize and soybean accumulated lower quantities of nitrogen, phosphorus, and potassium in all treatments. However, maize in SW1 accumulated higher nitrogen, phosphorus, and potassium than SW4 (9%, 9%, and 8% for nitrogen, phosphorus, and potassium, respectively). Soybean in SW3 accumulated 25% higher nitrogen, 33% higher phosphorus, and 24% higher potassium than in SW1. The improved nutrient accumulation in SW3 significantly increased the soybean dry matter by 19%, but slightly decreased the maize dry matter by 6% compared to SW1. Similarly, SW3 increased the competition ratio value of soybean (by 151%), but it reduced the competition ratio value of maize (by 171%) compared to SW1. On average, in SW3, relay-cropped soybean produced 84% of SS seed yield and maize produced 98% of SM seed yield and achieved the land equivalent ratio of 1.8, demonstrating the highest level in the world. Overall, these results suggested that by selecting the appropriate strip width (SW3; 0.40 m for soybean row spacing, 0.40 m maize row spacing, and 0.60 m spacing between soybean and maize rows), we can increase the nutrient

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Raza, Feng and van der Werf contributed equally to this work.

uptake (especially nitrogen, phosphorus, and potassium), dry-matter accumulation, and seed yields of relay-intercrop species under relay intercropping systems.

KEYWORDS
competition ratio, growing space, maize, relay intercropping, soybean

1 | INTRODUCTION

Intercropping and relay intercropping systems are practiced globally due to the potential of these practices for enhanced resource use efficiency (Chen et al., 2017; Raza, Feng, Werf, Cai, et al., 2019). Intercropping uses multiple crops sown and harvested at the same time, while relay intercropping uses intercrops with different growth stages (Raza, Feng, Iqbal, Ahmed, et al., 2019). When assessed with the land equivalent ratio (LER), the productivity benefits of relay intercropping systems are often higher than those of intercrops, because under intercropping systems, both intercrops have the same growth stages and the competition to use land, light, water, and nutrients is high. In contrast, in relay intercropping systems, both intercrops have different growth stages, and the competition for available resources is less (Raza, Khalid, Zhang, Feng, et al., 2019). The maize–soybean relay intercropping system (MSR) is the dominant cropping system of China (Iqbal et al., 2018). At present, MSR is practiced in many regions of China (Du et al., 2017; Liu et al., 2018) because of the potential for high productivity, shown by a mean LER of 1.6 (Du et al., 2017). Globally, the LER of the MSR system in China is highly ranked and higher than the global mean LER of 1.34 (Yu, Stomph, Makowski, & Werf, 2015).

Crop growth and development in relay intercropping systems are limited by nitrogen (N), phosphorus (P), and potassium (K). Crop N requirement is mainly determined by dry-matter production, which differs among different crop species because of the crop growth stage and photosynthetic variations (Chen et al., 2017). The demand for P is associated with metabolic variations or the rates of internal phosphate recycling among crops (Chen, Dunbabin, Diggle, Siddique, & Rengel, 2013). The N, P, and K accumulation in intercrop species are collectively affected by intrinsic crop characteristics, photosynthetic properties, and environmental factors (Raza, Khalid, Zhang, Feng, et al., 2019). In MSR, higher accumulation of significant nutrients is a crucial factor for vegetation composition and plant community function. However, the variations in the ratio of N and P in intercrop species may affect the competitive balance between intercrop species (Fujita, Ruiter, Wassen, & Heil, 2010; Güsewell, Koerselman, & Verhoeven, 2002). Furthermore, the growth performance of intercrops is affected by the accumulation of major nutrients, because intercrop plants in MSR require a fixed stoichiometric balance of major nutrients to function efficiently under the prevailing conditions (Raza, Khalid, Zhang, Feng, et al., 2019). Thus, it is vital to measure the nutrient accumulation patterns in soybean and maize under MSR in order to reduce the interspecific competition for nutrients in relay intercropping systems.

In MSR, maize produces higher seed yield due to optimum growth and an edge row-effect, and in some studies, relay-cropped maize produced higher seed yield as compared to maize yield in sole cropping systems (Chen et al., 2017; Raza, Feng, Khalid, Iqbal, Meraj, et al., 2019; Raza, Feng, van der Werf, Iqbal, Khalid et al., 2019; Raza, Feng, van der Werf, Iqbal, Khan et al. 2019; Yang et al., 2017). However, soybean in MSR produced lower crop yield than sole soybean because it is planted two months after maize sowing, and the severe competition for available resources with maize plants reduces the initial growth of soybean plants (Fan et al., 2018). Moreover, past studies have confirmed the adverse impacts of shading conditions on soybean morphology (Khalid et al., 2019; Raza, Feng, Iqbal, Ahmed, et al., 2019), physiology (Feng et al., 2018), and dry-matter accumulation (Ahmed et al., 2018; Yang et al., 2014). However, after maize harvesting in MSR, soybean exhibit strong recovery growth (Wu et al., 2016), and the competition for available resources with maize is compensated from the vegetative stage to the flowering stage (Fan et al., 2018). At the reproductive stage, soybean in MSR has better access to available resources compared to sole soybean plants, especially for light and nutrients (Chen et al., 2017). The recovery growth ability of soybean plants was found to be strong in MSR (Fan et al., 2018), and it improved with increased nutrient accumulation (Gou, Ittersum, Wang, Putten, & Werf, 2016). Thus, optimized planting arrangements can increase nutrient accumulation in soybean plants under MSR. Although MSR is the main cropping system of China (Wu, Gong, & Yang, 2017; Yang et al., 2017), no experiment has been conducted to evaluate the effects of different strip width (SW) treatments on nutrient accumulation and intercrop yields under this system. Therefore, in this experiment, we aimed to determine the differences in nutrient accumulation and dry-matter production between relay-cropped and sole-cropped soybean and maize, providing a possible explanation for observations of higher relay-cropped yields and LER in MSR. The objectives of this experiment were as follows: (a) to examine

TABLE 1 Monthly rainy days, rainfall, minimum temperature, maximum temperature, and average temperature from April to November during the cropping seasons of 2012 and 2013

Month	Years									
	2012					2013				
	Rainy days	Rainfall (mm)	Minimum T (°C)	Maximum T (°C)	Mean T (°C)	Rainy days	Rainfall (mm)	Minimum T (°C)	Maximum T (°C)	Mean T (°C)
March	16	28.20	16.3	7.50	11.9	07	23.50	22.4	11.4	16.9
April	14	36.90	24.4	14.3	19.4	22	80.84	23.5	14.1	18.8
May	18	55.35	27.5	18.2	22.9	18	57.77	27.7	18.6	23.2
June	20	52.60	29.1	19.5	24.3	14	58.60	32.1	21.8	27.0
July	20	134.6	30.6	21.2	25.9	27	221.3	32.9	22.2	27.6
August	19	46.70	31.8	21.1	26.5	15	55.70	34.3	23.9	29.1
September	23	94.40	25.2	17.1	21.2	20	63.15	28.6	19.1	23.9
October	20	62.10	20.8	14.5	17.7	14	18.55	24.2	16.7	20.5
November	15	16.80	14.1	8.50	11.3	17	28.90	16.5	10.2	13.4

the effects of different strip width treatments on dry matter and yield of soybean and maize in MSR; (b) to assess the impact of different strip width treatments on the nutrient accumulation in soybean and maize under MSR, and (c) to recommend an appropriate strip width for growing soybean and maize in MSR.

2 | MATERIALS AND METHODS

2.1 | Research area

This experiment was conducted at the Yaan (30°08′N, 103°13′E, altitude 620 m) Research Farm of Sichuan Agricultural University, China. The climatic conditions of the research site were subtropical and humid. The research area had an annual mean rainfall of 1,008.9 mm and a temperature (T) of 17.5°C. Weather data of both cropping seasons from 2012 to 2013, including the number of rainy days, monthly precipitation, maximum T, minimum T, and mean T, are shown in Table 1. In both years of the experiment, we used the same field, and treatments were located in the same plots, and after the harvesting, soybean and maize crop residues were not mixed in the field. The potato was sown before the start of this experiment in both years. To measure the soil properties, we collected the soil samples before the start of the experiment in 2012. The soil had the pH of 6.81, organic matter of 50.25 g/kg, total N of 1.56 g/kg, total P of 0.88 g/kg, total K of 16.42 g/kg, available N of 159.97 mg/kg, available P of 36.43 mg/kg, and available K of 98.27 mg/kg in the 0–30 cm soil layer.

2.2 | Planting material and experimental details

This field study consisted of 6 treatments with three replications, which were organized randomly (Figure 1). The different planting treatments included sole soybean (SS with a row to row distance of 0.7 m), sole maize (SM with a row to row distance of 0.7 m), and MSR (2 soybean rows relay-intercropped with 2 maize rows). In MSR, four different strip width (SW) treatments are given as: SW1, row spacing for soybean and maize rows was 0.40 m, distance between the rows of soybean and maize was 0.40 m with a total strip width of 1.60 m; SW2, row spacing for soybean and maize rows was 0.40 m, distance between the rows of soybean and maize was 0.50 m with a total strip width of 1.80 m; SW3, row spacing for soybean and maize rows was 0.40 m, distance between the rows of soybean and maize was 0.60 m with a total strip width of 2.0 m; SW4, row spacing for soybean and maize rows was 0.40 m, distance between the rows of soybean and maize was 0.70 m with a total strip width of 2.20 m, and the soybean to maize row ratio in each strip was 2:2. Every plot contained three strips of maize and soybean. The size of every experimental plot in SW1, SW2, SW3, and SW4 was 28.8 m^2, 32.4, 36, and 39.6 m^2, respectively. The plant to plant distance of 14.3, 12.5, 11.1, 10, and 9.09 cm for soybean was kept within each row of soybean in SS, SW1, SW2, SW3, and SW4, respectively. For maize, the plant to plant distance of 23.80, 20.82, 18.52, 16.68, and 15.15 cm was maintained within each row of maize in SM, SW1, SW2, SW3, and SW4, respectively. The row direction was east to west. The varieties of soybean and maize used in this study were Gongxiang-1 (late maturing) and Chuandan-418 (semicompact), respectively. The planting density of 60,000 plants/ha for maize was kept uniform in MSR and SM, and 100,000 plants/ha for soybean were maintained in MSR and SS. The maize crop was planted on 9 and 11 April and harvested on 4 and 7 August in 2012 and 2013, respectively. The soybean crop was planted on 10 and 11 June and harvested on 27 and 30 October in 2012 and 2013, respectively. At the time of maize sowing, basal N, P, and K were applied at 135, 40, and 10 kg/ha, respectively, in maize rows under MSR and SM. At the V6 stage of maize, the 2nd N application for maize crop was applied at 75 kg/ha in all maize rows under MSR and SM. Furthermore, at soybean sowing, basal N, P, and K were applied at 75, 40, and 4 kg/ha, respectively, in soybean rows under MSR and SS (Yang et al., 2017). All the other agronomic practices were kept uniform in all treatments according to the crop demand and farmer's practices of the area. For seedbed preparations, conventional tillage, that is, three cultivations with tractor-mounted cultivator followed by planking, was practiced for both crops in both years of study. Furthermore, in this experiment, no irrigation was applied during the both years of study, and the crop was grown under rainfed conditions. The weeds were controlled manually (hand hoeing), which was done 8 weeks after maize sowing. Crop pests were also controlled during the experiment and to control the sucking insects and soil pests we used chemicals chlorantraniliprole and thiamethoxam.

2.3 | Measurements

2.3.1 | Dry matter

Ten soybean and five maize plants were harvested successively from all the treatments at different days after sowing (DAS): 60, 90, and 120 DAS of maize, and 30, 60, 90, 120 DAS of soybean. Sampled plants were harvested manually with shears and oven-dried for 1 hr at 105°C to destroy the fresh tissues of each species and then at 70°C to obtain constant weight for analysis of dry-matter accumulation (kg/ha) in soybean and maize. A final sampling, 4 m square area of soybean, and maize plants were sampled from every treatment.

2.3.2 | Seed yield and harvest index

All collected samples were air-dried for 10 days. After drying, soybean and maize samples were threshed and weighed to measure the seed yield of soybean and maize in MSR, SM, and SS. Furthermore, the harvest index (HI) was determined as a ratio of seed yield (kg/ha) to total aboveground dry matter (kg/ha) at maturity of soybean and maize and expressed as a percentage (%).

2.3.3 | Nutrient accumulation

The N content in plant samples of soybean and maize was analyzed using the Kjeldahl procedure, the P content in plant samples of soybean and maize was estimated following the vanadomolybdate procedure (Xia et al., 2013), and the K content in plant samples of soybean and maize was analyzed using a previously described procedure (Yildiz et al., 2010). At each sampling time, the N, P, and K concentration in plant samples of soybean and maize were determined by multiplying the content of N, P, and K with the total dry matter of each plant and expressed in kg/ha. After the measurement of nutrient accumulation, we measured the partial N, P, and K accumulation equivalent ratio by following the previously described method (Gou et al., 2018):

$$\mathrm{pNERm} = \frac{\mathrm{Nurm}}{\mathrm{Nusm}} \tag{1}$$

$$\mathrm{pPERm} = \frac{\mathrm{Purm}}{\mathrm{Puss}} \tag{2}$$

$$\mathrm{pKERm} = \frac{\mathrm{Kurm}}{\mathrm{Kuss}} \tag{3}$$

$$\mathrm{pNERs} = \frac{\mathrm{Nurs}}{\mathrm{Nuss}} \tag{4}$$

$$\mathrm{pPERs} = \frac{\mathrm{Purs}}{\mathrm{Puss}} \tag{5}$$

$$\mathrm{pKERs} = \frac{\mathrm{Kurs}}{\mathrm{Kuss}} \tag{6}$$

where Nuss, Puss, and Kuss are the N, P, and K accumulation in soybean under SS, and Nusm, Pusm, Kusm, are the N, P, and K accumulation in maize under SM, respectively, and Nurs, Purs, and Kurs are the N, P, and K accumulation in soybean under

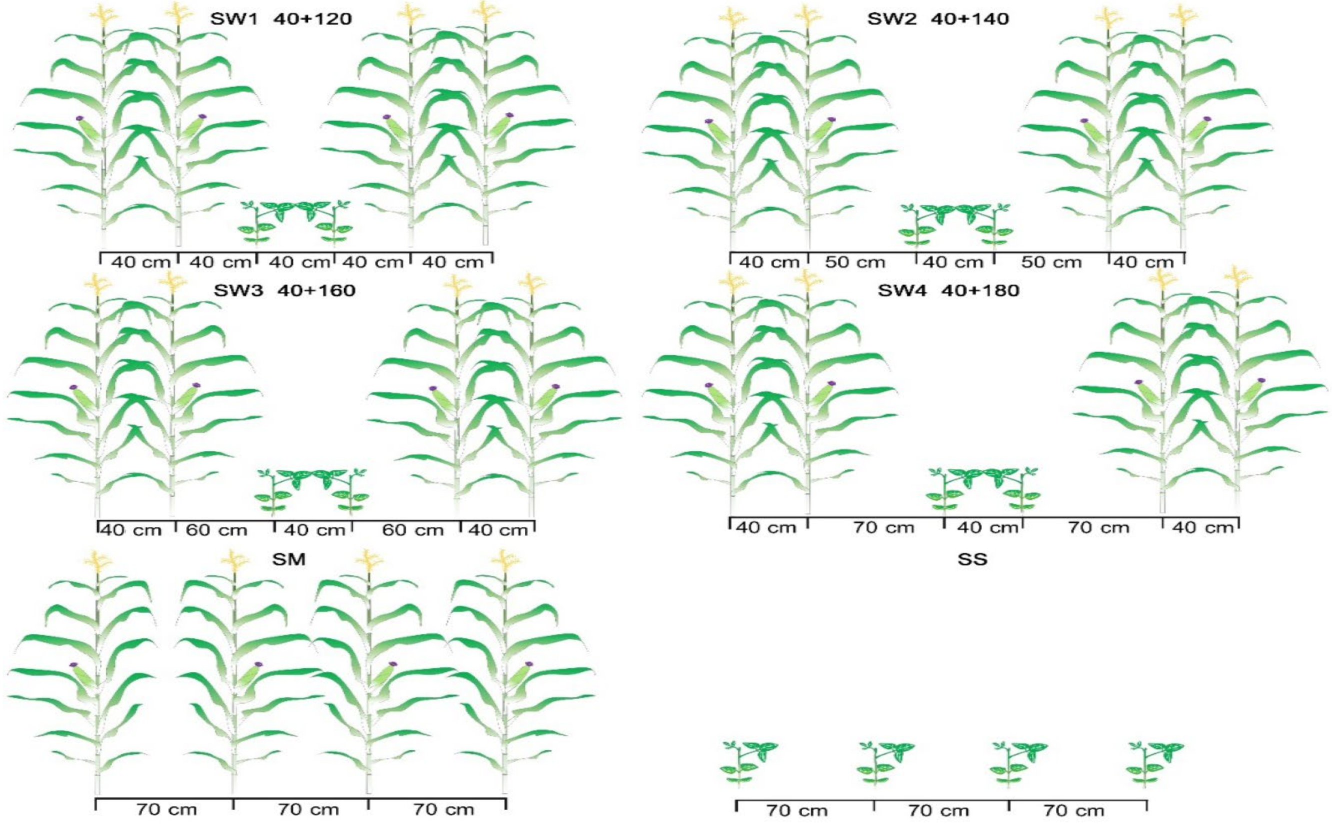

FIGURE 1 Field layout of different strip width arrangements of relay-intercropped maize–soybean. SW1, SW2, SW3, SW4, SM, and SS represent the layout of 40 + 120 cm (40 cm row distance for maize and soybean rows, 40 cm spacing between the rows of maize and soybean with a total strip width of 160 cm), 40 + 140 cm (40 cm row distance for maize and soybean rows, 50 cm spacing between the rows of maize and soybean with a total strip width of 180 cm), 40 + 160 cm (40 cm row distance for maize and soybean rows, 60 cm spacing between the rows of maize and soybean with a total strip width of 200 cm), 40 + 180 cm (40 cm row distance for maize and soybean rows, 70 cm spacing between the rows of maize and soybean with a total strip width of 220 cm), 70 cm (row to row distance was 70 cm), and 70 cm (row to row distance was 70 cm), respectively. SW1, SW2, SW3, SW4 are relay intercropping strip width arrangements, SM and SS are sole cropping systems of maize and soybean, respectively

MSR, and Nurm, Purm, Kurm, are the N, P, and K accumulation in maize under MSR.

2.3.4 | Competition parameters

The land equivalent ratio (LER) was calculated to determine the yield advantage of MSR in response to different strip width treatments (Mead & Willey, 1980):

$$\mathrm{LER} = \frac{\mathrm{Ymr}}{\mathrm{Yms}} + \frac{\mathrm{Ysr}}{\mathrm{Yss}} \tag{7}$$

where Ymr and Yms are the seed yield of maize under SM and MSR, respectively. Yss and Ysr are the seed yield of soybean under SS and MSR, respectively. The competition ratio (CR) was determined to evaluate the competition between soybean and maize in MSR. CR was calculated as:

$$\mathrm{CRm} = \frac{\mathrm{LERm}}{\mathrm{LERs}} \times \frac{\mathrm{Zsr}}{\mathrm{Zmr}} \tag{8}$$

$$\mathrm{CRs} = \frac{\mathrm{LERs}}{\mathrm{LERm}} \times \frac{\mathrm{Zmr}}{\mathrm{Zsr}} \tag{9}$$

where Zmr and Zsr are the sown proportion area of maize and soybean in MSR, respectively, and LERs and LERm are the LER of soybean and maize (Dhima, Lithourgidis, Vasilakoglou, & Dordas, 2007).

2.4 | Statistical analysis

The statistical analyses were done using Statistix 8.1. Significant differences between sole cropping systems (SM and SS) and different strip width treatments in MSR were measured using ANOVA (one way) in combination with the LSD (least significance difference) test. All differences were recognized as significant at the 5 percent probability level ($p < .05$).

3 | RESULTS

3.1 | Effect of strip width treatments on dry-matter accumulation

Different strip width treatments significantly affected the accumulation of dry matter in maize and soybean at different sampling times in both years (Table 2). In this experiment, sole soybean (SS) and sole maize (SM) always produced a higher dry matter as compared to different strip width treatments under MSR. However, average over two years, within MSR treatments at 120 DAS, the highest average dry matter of maize (16,771.3 kg/ha) was recorded in SW1 and the lowest in SW4, while the maximum average dry matter of soybean (3,334.7 kg/ha) was obtained under treatment SW3, and the lowest average dry matter of soybean was recorded in SW1. On average, at 120 DAS, the treatment SW1 increased the final dry matter of maize plants by 8% as compared to the final dry-matter value of maize plants in SW4 (Table 2), whereas the treatment SW3 enhanced the final dry matter of soybean plants by 19% as compared to the final dry-matter value of soybean in SW1 (Table 2).

3.2 | Effect of strip width treatments on seed yield and harvest index

Different strip width treatments significantly changed the intercrop yields of soybean and maize in both years (Table 3). The highest maize seed yield (9,130.8 kg/ha in 2012 and 6,330.7 kg/ha in 2013) was obtained under treatment SW1, while the lowest maize seed yield (7,420.6 kg/ha in 2012 and 5,220.8 kg/ha in 2013) was obtained in treatment SW4. In addition, the maximum soybean seed yield (1960.2 kg/ha in 2012 was obtained in SS and 1,520.5 kg/ha in 2013) was recorded under SW3 treatment, whereas the lowest soybean seed yield (480.2 kg/ha in 2012 and 710.6 kg/ha in 2013) was found in SW1 in both years. On average, under treatment SW3, maize achieved 98% of SM seed yield, and soybean achieved 84% of SS seed yield. Overall, treatment SW1 significantly improved the average seed yield of maize by 22% as compared to seed yield of maize in SW4, and SW3 increased the average seed yield of soybean by 136% than those of under SW1 in MSR. Furthermore, all the strip width treatments significantly affected the harvest index (HI) of both intercrop species (Table 3). The average highest HI of maize (46%) was calculated in SW1, and the lowest HI of maize (41%) was measured in treatment SM. The maximum average HI of soybean (43%) was determined in SS, and the minimum HI of soybean (21%) was calculated under SW1.

3.3 | Effect of strip width treatments on competition parameters

The average LER value in all treatments (SW1, SW2, SW3, and SW4) under MSR were all >1, showing the yield

TABLE 2 Effect of different strip width treatments on dry-matter accumulation (kg/ha) of maize and soybean grown under relay intercropping system from 2012 to 2013

		Maize			Soybean			
Years	Treatments	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
2012	SW1	5,312ab	14,178b	19,384ab	43c	267d	1,173c	2,423c
	SW2	5,186ab	13,434bc	18,602b	46bc	293c	1,263c	2,467c
	SW3	5,008b	13,036c	18,458b	47b	347b	1,567b	3,060b
	SW4	4,746b	12,570c	18,042b	45bc	333b	1,543b	2,940b
	SM	5,798a	15,578a	20,718a	–	–	–	–
	SS	–	–	–	57a	547a	2,443a	4,230a
	LSD	742.82	869.93	1,690.80	4.18	20.19	134.93	279.09
2013	SW1	4,479a	10,662b	14,158b	34d	340c	1,410d	3,180c
	SW2	4,210ab	9,870c	13,477bc	41c	350c	1,640c	3,350b
	SW3	4,069ab	9,555cd	13,139c	44bc	373b	1,880b	3,623a
	SW4	3,688b	9,242d	12,917c	45ab	387b	1,557cd	2,833d
	SM	4,655a	11,187a	15,250a	–	–	–	–
	SS	–	–	–	48a	447a	2,137a	3,447b
	LSD	735.32	346.35	804.53	3.18	22.54	205.14	130.29

Note: SW1, SW2, SW3, and SW4 are the different strip width treatments under the relay intercropping system, SM and SS are the sole cropping system of maize and soybean, respectively. 30, 60, 90, and 120 days after sowing (DAS), refer to different sampling times. Means are averaged over three replicates. Means do not share the same letters in the column differ significantly at $p \leq .05$.

TABLE 3 Effect of different strip width treatments on competition ratio (CR), land equivalent ratio (LER), seed yield (kg/ha), and harvest index (HI) of maize and soybean grown under relay intercropping system from 2012 to 2013

		Maize				Soybean				
Years	**Treatments**	**CRm**	**LERs**	**SYm**	**HIm**	**CRs**	**LERs**	**Sys**	**HIs**	**LER**
2012	SW1	4.42a	1.08a	9,130.8a	47.1a	0.22c	0.24d	480.2e	19.9e	1.32d
	SW2	2.63b	0.99b	8,410.5b	45.4ab	0.37b	0.38c	740.7d	30.2d	1.37c
	SW3	1.50c	0.97b	8,330.4b	45.2ab	0.67a	0.66a	1,290.1b	42.3b	1.64a
	SW4	1.63c	0.88c	7,420.6c	41.2b	0.61a	0.54b	1,060.1c	36.0c	1.42b
	SM	–	–	8,450.8b	40.8b	–	–	–	–	–
	SS	–	–	–	–	–	–	1,960.2a	46.4a	–
	LSD	0.35	0.05	424.69	5.67	0.09	0.05	118.73	3.66	0.03
2013	SW1	2.03a	1.04a	6,330.7a	44.9a	0.49c	0.51c	710.6c	22.5c	1.56c
	SW2	1.25b	0.95b	5,800.1b	43.1a	0.80b	0.77b	1,060.2b	31.6b	1.72b
	SW3	0.87c	0.96ab	5,870.0ab	44.8ab	1.14a	1.10a	1,520.5a	42.1a	2.07a
	SW4	1.30b	0.86c	5,220.8c	40.6ab	0.78b	0.66b	920.2b	32.6b	1.53c
	SM	–	–	6,070.5ab	40.1b	–	–	–	–	–
	SS	–	–	–	–	–	–	1,380a	40.3a	–
	LSD	0.22	0.09	476.41	4.44	0.14	0.11	153.71	4.62	0.15

Note: SW1, SW2, SW3, and SW4 are the different strip width treatments under the relay intercropping system, SM and SS are the sole cropping system of maize and soybean, respectively. The CRm, LERm, SYm, and HIm, and CRs, LERs, SYs, and HIs represent the competition ratio, land equivalent ratio, seed yield, and harvest index of maize and soybean, respectively. Means are averaged over three replicates. Means do not share the same letters in the column differ significantly at $p \leq .05$.

advantage over SS and SM (Table 3). Among all the treatments, SW3 (40:160) had the average highest LER (1.85) in both years, while the average lowest LER (1.44) was calculated under treatment SW1 (40:120). Besides, the value of LER increased as the spacing between soybean and maize rows increased. Relative to 40:120 (SW1), treatment SW3 (40:160) increased LER by 24% in 2012 and 33% in 2013. Likewise, the average values of CR followed a similar trend with the values of LER (Table 3). On average over the 2 years, the average maize CR values (3.23, 1.94, 1.19, and 1.47 in SW1, SW2, SW3, and SW4, respectively) were found significantly higher than the average soybean CR values (0.36, 0.59, 0.90, and 0.70 in SW1, SW2, SW3, and SW4, respectively). However, by increasing the gap distance between the rows of soybean and maize, the partial CR values of maize were decreased, and the partial CR values of soybean were increased significantly in both study years. For instance, in SW3, the CR values of soybean were increased by 196% in 2012 and 131% in 2013 (Table 3) as compared to the CR values of soybean in treatment SW1.

3.4 | Effect of strip width treatments on the nutrient accumulation

The N, P, and K accumulation in soybean and maize plants were significantly greater in SM and SS than relay-intercropped soybean and maize plants at all sampling times in both years. However, for maize, these differences were very small. In MSR, different strip width treatments significantly affected the N, P, and K accumulation in soybean and maize plants. At 120 DAS, the maximum average accumulation of N (191.4 kg/ha), P (39.7 kg/ha), and K (180.0 kg/ha) in maize were observed under treatment SW1, and the minimum average N (174.0 kg/ha), P (36.1 kg/ha), and K (165.6 kg/ha) accumulation in maize were measured under SW4 in both years (Tables 4–6). In addition, at 120 DAS, the highest average accumulation of N (125.8 kg/ha), P (18.5 kg/ha), and K (41.1 kg/ha) in soybean were recorded under treatment SW3, and the lowest average N (100.8 kg/ha), P (13.9 kg/ha), and K (33.2 kg/ha) accumulation in soybean were determined under treatment SW1 in both years (Table 4–6). Overall, at 120 DAS, treatment SW3 improved the accumulation of N by 25%, P by 33%, and K by 24% in soybean plants as compared to SW1, and treatment SW1 increased the accumulation of N by 9%, P by 9%, and K by 8% in maize plants as compared to the maize plants in SW4.

Furthermore, the partial values of nitrogen equivalent ratio (pNER), phosphorus equivalent ratio (pPER), and potassium equivalent ratio (pKER) of maize and soybean are presented in Table 7, and different strip width treatments significantly changed the pNER of maize and soybean, while no significant differences were detected for partial values of PER and KER of maize and soybean. At 120 DAS, the maximum average (0.91) partial value of NERm was found in SW1, whereas the minimum average (0.82) partial value of NERm was recorded under SW4. In addition, the highest average (0.76) partial value of NERs was noted under treatment SW3, while the lowest average (0.61) partial value of NERs was calculated in treatment SW1. On average, the partial values of NER, PER, and KER of maize were increased by decreasing the strip width distance between soybean and maize rows, whereas the opposite trends were observed for soybean under MSR (Table 7). Importantly, in both years, we observed the same trends in all measured parameters in all treatments under the relay intercropping system and sole cropping systems.

4 | DISCUSSION

4.1 | Effect of strip width treatments on crops yields

One of the main achievements in adopting MSR is the production of higher dry-matter accumulation in relay-intercropped maize plants due to the facilitation and complementary effects of soybean during the cogrowth period (Feng et al., 2019; Yang et al., 2017). This is ascribed to the fact that maize plants exhibit extensive and robust growth during the cogrowth phase (Ahmed et al., 2018), whereas the soybean plants show decreasing growth and dry-matter accumulation with inferior morphological characteristics (Feng et al., 2018; Khalid et al., 2019; Liu et al., 2016; Wu et al., 2017). In this experiment, maize dry matter decreased, and soybean dry matter increased with increasing the gap width between soybean and maize rows from 0.40 to 0.70 m. This reduction in dry matter of intercropped maize is mainly attributed to the large competition between intercrop species in MSR. The increased distance between the rows (0.60 m) of soybean and maize significantly enhanced the dry-matter yield of soybean plants in MSR, particularly in SW3 (40:160). This increase might be due to higher light interception at the top of soybean plants (Yang et al., 2017). The narrow-wide row strip width treatment SW3 (40:160) at 120 DAS significantly increased the soybean dry matter by 19%, but it reduced the maize dry matter by 8%, indicating that maize exhibited the small decline in dry-matter accumulation relative to the increase in dry-matter accumulation by soybean in SW3. Similarly, treatment SW3 significantly ($p < .05$) increased the seed yields of both intercrops in MSR as compared to other treatments. This improvement in seed yield of soybean and maize might be related to optimum growing space (Feng et al., 2019) and adequate availability of major nutrients, which improved the seed yield of oilseed crops in other studies (Raza, Feng, Iqbal, et al., 2018; Raza, Feng, Manaf, et al., 2018).

TABLE 4 Effect of different strip width treatments on nitrogen accumulation (kg/ha) of maize and soybean grown under relay intercropping system from 2012 to 2013

		Maize			Soybean			
Years	**Treatments**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
2012	SW1	129.2b	184.5b	220.1b	1.83c	6.81c	36.22e	85.87e
	SW2	125.5c	169.3c	214.4c	1.84c	7.44bc	37.87d	93.71d
	SW3	120.1d	168.7d	209.2d	1.90b	7.61b	43.62b	116.69b
	SW4	111.7e	158.5e	204.2e	1.93ab	7.63b	39.12c	115.41c
	SM	141.2a	206.4a	244.8a	–	–	–	–
	SS	–	–	–	1.96a	11.62a	77.86a	181.99a
	LSD	2.02	0.29	2.01	0.04	0.66	0.93	1.26
2013	SW1	96.4a	137.5b	162.2b	1.22b	9.05bc	49.18c	115.76d
	SW2	90.1b	121.8c	152.5c	1.44a	9.03c	51.99b	123.18c
	SW3	86.5c	119.3c	147.1d	1.43a	9.54bc	52.75b	134.89b
	SW4	82.7d	112.1d	143.8e	1.45a	9.67b	37.94d	107.90e
	SM	99.1a	148.5a	178.3a	–	–	–	–
	SS	–	–	–	1.43a	10.65a	72.07a	153.65a
	LSD	2.83	2.91	2.25	0.05	0.63	0.91	1.49

Note: SW1, SW2, SW3, and SW4 are the different strip width treatments under the relay intercropping system, SM and SS are the sole cropping system of maize and soybean, respectively. 30, 60, 90, and 120 days after sowing (DAS), refer to different sampling times. Means are averaged over three replicates. Means do not share the same letters in the column differ significantly at $p \le .05$.

TABLE 5 Effect of different strip width treatments on phosphorus accumulation (kg/ha) of maize and soybean grown under relay intercropping system from 2012 to 2013

		Maize			Soybean			
Years	**Treatments**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
2012	SW1	26.4b	37.1a	45.1b	0.22$^{\text{NS}}$	1.15d	4.28c	11.52c
	SW2	25.2c	33.6b	43.8c	0.22	1.20c	4.55bc	12.30c
	SW3	24.2d	31.8b	42.1d	0.23	1.26b	5.04b	16.60b
	SW4	22.8e	31.8b	41.4e	0.23	1.27b	4.43bc	16.02b
	SM	28.8a	39.6a	47.8a	–	–	–	–
	SS	–	–	–	0.23	1.68a	9.18a	23.60a
	LSD	0.29	2.79	0.29	0.00	0.04	0.63	0.94
2013	SW1	21.6$^{\text{NS}}$	28.6$^{\text{NS}}$	34.4a	0.17$^{\text{NS}}$	1.24b	6.47b	16.32c
	SW2	19.6	26.6	33.2ab	0.18	1.26b	6.57b	17.53b
	SW3	17.2	26.0	31.4ab	0.18	1.27b	6.74b	20.49a
	SW4	17.4	25.2	30.8b	0.18	1.27b	5.28c	16.51bc
	SM	21.6	30.2	36.1b	–	–	–	–
	SS	–	–	–	0.18	1.45a	9.72a	20.33a
	LSD	4.76	4.15	1.79	0.01	0.08	0.29	1.09

Note: SW1, SW2, SW3, and SW4 are the different strip width treatments under the relay intercropping system, SM and SS are the sole cropping system of maize and soybean, respectively. 30, 60, 90, and 120 days after sowing (DAS), refer to different sampling times. Means are averaged over three replicates. Means do not share the same letters in the column differ significantly at $p \le .05$.

Abbreviation: NS, nonsignificant.

Similar to our results, scientists have concluded that optimum growing space significantly increased the accumulation of nitrogen and phosphorus, which in turn increased the intercrop yields in MSR (Feng et al., 2019; Raza, Feng, Werf, Cai, et al., 2019; Raza, Khalid, Zhang, Feng, et al., 2019; Yang et al., 2015).

TABLE 6 Effect of different strip width treatments on potassium accumulation (kg/ha) of maize and soybean grown under relay intercropping system from 2012 to 2013

		Maize			Soybean			
Years	**Treatments**	**60 DAS**	**90 DAS**	**120 DAS**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**
2012	SW1	144.6b	220.8b	218.4b	1.08c	7.35d	24.25d	24.19d
	SW2	137.0c	217.8b	212.4c	1.21b	7.95c	27.78c	27.98c
	SW3	136.8c	211.2c	206.8d	1.23b	8.15b	33.58b	33.81b
	SW4	124.4d	200.4c	202.8d	1.31a	8.14b	33.35b	33.12b
	SM	153.2a	245.2a	226.6a	–	–	–	–
	SS	–	–	–	1.22b	11.75a	53.75a	53.91a
	LSD	2.97	4.80	5.13	0.03	0.14	0.64	1.12
2013	SW1	90.2b	142.2b	141.6a	0.96c	7.53c	20.90d	42.24e
	SW2	83.4c	138.0c	136.2b	1.14b	7.55bc	24.42c	44.19b
	SW3	79.8d	133.2d	130.2c	1.17ab	7.71bc	27.11b	48.24a
	SW4	78.4e	124.2e	128.4c	1.23a	7.78b	21.56d	36.81d
	SM	91.2a	153.2a	146.4a	–	–	–	–
	SS	–	–	–	1.15ab	8.85a	32.14a	44.71b
	LSD	0.58	3.67	5.05	0.03	0.22	1.98	1.47

Note: SW1, SW2, SW3, and SW4 are the different strip width treatments under the relay intercropping system, SM and SS are the sole cropping system of maize and soybean, respectively. 30, 60, 90, and 120 days after sowing (DAS), refer to different sampling times. Means are averaged over three replicates. Means do not share the same letters in the column differ significantly at $p \leq .05$.

4.2 | Effect of strip width treatments on crop nutrient accumulation

Legume and cereal planting together are a common practice in agricultural production. However, scientists have rarely investigated the accumulation of N, P, and K in soybean and maize in response to different strip width treatments in MSR. In this paper, differences in N, P, and K accumulation of maize and soybean among different strip width treatments in the relay intercropping system were significant at different sampling stages. The N, P, and K concentrations in maize were usually greater than soybean, especially at the reproductive stage. During the cogrowth period, smaller amounts of N, P, and K accumulation were measured in relay-intercropped soybean and maize than those of in SS and SM, which suggests interspecific competition for nutrients occurred between intercrop species (Gou et al., 2018). In contrast, several scientists have observed that in a maize–wheat intercropping system, wheat plants accumulated higher amounts of N and P compared to wheat plants in the sole system (Zhang, Li, & Sun, 2001; Zhu et al., 2016). The yield advantage of maize in MSR shows that maize plants accumulate an almost equal amount of nutrients plant^{-1} than maize plants in a sole cropping system, possibly as a result of earlier planting than soybean and associated increases in nutrient accumulation ability at early growth stages. However, the second crop in relay intercropping systems experiences a decreased level of nutrients in the soil profile (Gou et al., 2018). During the cogrowth phase in MSR, interspecific competition for resources leads to decreasing dry matter and nutrient accumulation of the second crop (Ahmed et al., 2018; Li, Sun, Zhang, Li, Rengel, et al., 2001). After the harvest of the first crop, the recovery growth of the second crop is important for nutrient accumulation and seed yield (Li, Sun, Zhang, Li, Yang, et al., 2001). However, an adequate supply of nutrients is needed for this recovery growth. Previously, researchers had demonstrated recovery growth of the second crop was reduced when no fertilizer of N and P was applied (Li, Sun, Zhang, Li, Rengel, et al., 2001).

In this experiment, during the cogrowth period, relay-intercropped soybean accumulated less N, P, and K due to the intensive competition between intercrop species, which decreased the dry-matter accumulation of soybean in both years. However, different strip width treatments directly affected the nutrient accumulation of soybean plants in MSR, and treatment SW3 (40:160) improved the accumulation of nutrients in soybean, which may be because of an optimum growing arrangement for intercrop species in MSR that increased the nutrient uptake ability of soybean plants. Additionally, the partial values of NER, PER, and KER of soybean plants were higher under SW3 as compared to the partial values of NER, PER, and KER of soybean plants in SW1 (40:120), which indicated the increased growth rate and nutrient acquisition of soybean plants with optimum spacing in MSR., The present findings are in line with previously reported results in which it was they concluded that

TABLE 7 Effect of different strip width treatments on partial values of nitrogen equivalent ratio, phosphorus equivalent ratio, and potassium equivalent ratio of maize and soybean grown under relay intercropping system from 2012 to 2013

		Maize			Soybean		
Sampling time	**Treatments**	**pNERm**	**pPERm**	**pKERm**	**pNERs**	**pPERs**	**pKERs**
30 DAS	SW1	–	–	–	0.90 c	0.97^{NS}	1.06^{NS}
	SW2	–	–	–	0.97 b	0.97	1.03
	SW3	–	–	–	0.98 b	0.97	0.99
	SW4	–	–	–	1.00 a	0.65	0.67
	LSD	–	–	–	0.01	0.57	0.60
60 DAS	SW1	0.94 a	0.91^{NS}	0.93^{NS}	0.72 b	0.78^{NS}	0.78^{NS}
	SW2	0.90 b	0.85	0.90	0.75 ab	0.80	0.78
	SW3	0.86 c	0.82	0.86	0.77 ab	0.82	0.76
	SW4	0.81 d	0.57	0.60	0.78 a	0.53	0.52
	LSD	0.18	0.39	0.52	0.06	0.46	0.45
90 DAS	SW1	0.90 a	0.88^{NS}	0.90^{NS}	0.57 c	0.58^{NS}	0.70^{NS}
	SW2	0.82 b	0.85	0.88	0.61 b	0.61	0.68
	SW3	0.81 b	0.83	0.83	0.65 a	0.55	0.61
	SW4	0.76 c	0.56	0.57	0.51 d	0.36	0.40
	LSD	0.01	0.48	0.48	0.00	0.32	0.39
120 DAS	SW1	0.91 a	0.94^{NS}	0.95^{NS}	0.61 d	0.68^{NS}	0.82^{NS}
	SW2	0.87 b	0.90	0.91	0.66 c	0.80	0.76
	SW3	0.84 c	0.87	0.89	0.76 a	0.79	0.74
	SW4	0.82 d	0.61	0.62	0.67 b	0.48	0.48
	LSD	0.00	0.55	0.53	0.01	0.46	0.43

Note: SW1, SW2, SW3, and SW4 are the different strip width treatments under the relay intercropping system. The pNERs, pPERs, pKERs, and pNERm, pPERm, pKERm, represent the partial values of nitrogen, phosphorus, and potassium uptake equivalent ratio of soybean and maize, respectively. 30, 60, 90, and 120 days after sowing (DAS), refer to different sampling times. Means are averaged over two study years and three replicates. Means do not share the same letters in the column differ significantly at $p \leq .05$.

Abbreviation: NS, nonsignificant.

maize crop showed optimum growth and higher nutrient accumulation in a wheat–maize relay intercropping system (Gou et al., 2018).

4.3 | Effect of strip width treatments on competition parameters

Total values of LER were found higher than 1 in all the strip width treatments in MSR, which shows the yield advantage of intercropping over SM and SS (Yang et al., 2015). Specifically, the average LER values in SW1, SW2, SW3, and SW4 were 1.4, 1.5, 1.8, and 1.5, respectively, which means that 40%–80% more farmland will be required by SM and SS to equal the yields of soybean and maize in MSR. Similarly, in MSR, researchers have reported soybean and maize yield advantage with soybean and maize rows at a distance of 0.60 m (Yang et al., 2014). Less distance between the rows of soybean and maize significantly reduced light transmittance at the top of soybean canopy (Liu et al., 2015; Oseni, 2010; Yang et al., 2014), thus by maintaining the optimum space (40:160, SW3) between the rows of soybean and maize for planting soybean in MSR we can reduce the adverse impacts of maize shading on soybean, which can ultimately increase soybean nutrient accumulation and yield. Relative to a past report (Yu et al., 2015), the higher LER in narrow-wide row relay intercropping patterns were mainly due to the optimum growing space and nutrient accumulation. Planting of maize and soybean at relatively high densities (similar to SM and SS) under optimum strip width arrangement (SW3) brought increased N, P, K, dry matter, and seed yield by nearly 25%, 33%, 24%, 19%, and 141%, respectively, compared to SW1 by maintaining maize nutrient accumulation, dry-matter accumulation and seed yield.

The CR values exhibited that maize was the dominant crop in MSR, and similar findings were reported previously (Liu et al., 2017; Yang et al., 2015). The higher competitive ability of maize plants to use and exploit available resources in association with soybean in the intercropping system has also been reported by other researchers (Chen et al., 2017). Additionally, the optimum increase of distance between maize and soybean rows (SW3) led to increasing the competitive ability of relay-intercropped soybean (CRs), and adequate competitive ability of maize (CRm) resulted in adequate nutrient accumulation and seed yields of relay-intercropped maize and soybean. However, the values of CRm and CRs decreased under treatment SW4 as compared to the values of treatment SW3. This reduction in the CR values of maize and soybean in wide row planting arrangement (SW4) may be attributed to intense competition for resources because under the SW4 treatment plant to plant distance was decreased, which increased the interplant competition for available resources. Whereas, the narrow-wide row arrangement (SW3) for growing soybeans in MSR increased the photosynthetically active radiations transmittance at soybean canopy (Yang et al., 2014), and potentially increased the water use efficiency (Rahman et al., 2017) and radiation use efficiency (Liu et al., 2018; Raza, Feng, Werf, Cai, et al., 2019) of relay-intercropped soybean, which ultimately enhanced the soybean nutrient accumulation and seed yield under MSR. Thus, maintaining the optimum CRm and increasing the CRs by maintaining the optimum space between the rows of soybean and maize is an important agricultural practice to obtain the higher intercrop yields in MSR.

5 | CONCLUSION

In this experiment, an optimum width distance of 40:160 (SW3) between the rows of soybean and maize substantially increased the land equivalent ratio of maize–soybean relay intercropping system, which was potentially the result of an adequate accumulation of major nutrients in soybean and maize throughout the crop period of intercrop species. However, in maize–soybean relay intercropping system, as compared to sole maize and sole soybean, relay-intercropped maize and soybean accumulated lower amounts of nitrogen, phosphorus, and potassium in all treatments. Overall, by selecting the optimum planting arrangement in the maize–soybean relay intercropping system, we can produce higher seed yields of soybean and maize in maize–soybean relay intercropping system.

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CONFLICT OF INTEREST

The authors have declared that no conflict of interest.

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