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Response of sorghum commercial hybrids to sugarcane aphid, *Melanaphis sacchari* (Hemiptera: Aphididae) and threshold-based chemical management in Guanajuato, Mexico

Respuesta de híbridos comerciales de sorgo al áfido de la caña de azúcar, *Melanaphis sacchari* (Hemiptera: Aphididae) y manejo químico basado en un umbral en Guanajuato, México

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Abstract: The sugarcane aphid, *Melanaphis sacchari* (Hemiptera: Aphididae) (SCA) affects grain sorghum, *Sorghum bicolor* (Poaceae) production. The response of sorghum hybrids to SCA was evaluated during 2017 in Guanajuato, Mexico. Experiments were established under strip-plot designs with two factors (hybrids, threshold-based chemical management -TBCM-treatments) and under irrigated or dryland conditions. Experiments were established on two sowing dates at Celaya and Valle de Santiago (irrigated) using the SCA-tolerant hybrids APACHE, BRS-70, MEZQUITE, SCAP-618, and SCA-susceptible UPM-219. Dryland experiments were established at Celaya, Valle de Santiago, and Pénjamo using MEZQUITE, and SCAP-618 (tolerant), and lines UPM-219, SHORTER, and MAJESTIC-355 (susceptible). The TBCM strategies were a) with TBCM (seed treatment with thiamethoxam; flupyradifurone or sulfoxaflor applied to foliage), and b) without TBCM (control). Significant differences ($p < 0.05$) between treatments under irrigated and dryland conditions for the number of aphids per leaf and grain yield were found. APACHE, BRS-70, and MEZQUITE had the highest grain yields under both TBCM and no-TBCM. UPM-219 was competitive under TBCM conditions, but without TBCM showed total yield losses. The yield–aphid cumulative density linear regressions were negatively significant ($p \leq 0.05$) to sorghum cultivated without TBCM. Irrigation increased 64 % grain yields compared with dryland experiments. TBCM increased grain yield (50 % in irrigated and 100 % in dryland conditions). TBCM increased grain yields and reduced cumulative SCA populations under irrigated or rainfed conditions, mainly for susceptible sorghum. Resistant germplasm and TBCM could control SCA in sorghum cultivated in Guanajuato, mainly at late sowings frequently carried out under dryland conditions.

Keywords: Control, hybrids, insect pests, *Sorghum bicolor*, tolerance.

Resumen: El pulgón de la caña de azúcar, *Melanaphis sacchari* (Hemiptera: Aphididae) (PCA) afecta la producción de sorgo granífero, *Sorghum bicolor* (Poaceae). Se evaluó la respuesta de híbridos de sorgo a PCA durante 2017 en Guanajuato, México. Los experimentos se establecieron bajo diseños de parcelas en franjas con dos factores (híbridos, tratamientos de manejo químico basado en umbral -MQBU) y bajo condiciones de riego o secano. Los experimentos se establecieron en dos fechas de siembra en Celaya y Valle de Santiago (con riego) utilizando los híbridos tolerantes a PCA APACHE, BRS-70, MEZQUITE, SCAP-618 y UPM-219, susceptible a PCA. Los experimentos de secano se establecieron en Celaya, Valle de Santiago y Pénjamo utilizando MEZQUITE y SCAP-618 (tolerantes) y las líneas UPM-219, SHORTER y MAJESTIC-355 (susceptibles). Las estrategias de MQBU fueron a) con MQBU (tratamiento de semillas con tiametoxam; flupiradifurona o sulfoxaflor aplicado al follaje), y b) sin MQBU (control). Se encontraron diferencias significativas ($p < 0,05$) entre los tratamientos bajo riego y secano para el número de pulgones por hoja y rendimiento de grano. APACHE, BRS-70 y MEZQUITE tuvieron los mayores rendimientos de grano con MQBU y sin MQBU. UPM-219 fue competitivo en condiciones de MQBU, pero sin MQBU mostró pérdidas totales de rendimiento. Las regresiones lineales rendimiento-densidad acumulada de áfidos fueron negativamente

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significativas ($p \leq 0,05$) para el sorgo cultivado sin MQBU. El riego aumentó el rendimiento de grano en 64 % en comparación con los experimentos en secano; el MQBU aumentó el rendimiento de grano (50 % en condiciones de riego y 100 % en secano). El MQBU aumentó los rendimientos de grano y redujo las poblaciones acumuladas de PCA en condiciones de riego o secano, principalmente para el sorgo susceptible. El germoplasma resistente y el MQBU podrían controlar al PCA en sorgo cultivado en Guanajuato, principalmente en siembras tardías frecuentemente realizadas en condiciones de secano.

Palabras clave: control, híbridos, plagas insectiles, *Sorghum bicolor*, tolerancia.

Introduction

The sugarcane aphid, *Melanaphis sacchari* (Zehntner, 1897) (Hemiptera: Aphididae), is currently one of the main pests of sorghum, *Sorghum bicolor* (L.) Moench (Poaceae) since it causes direct damage (sap feeding) and indirect damage (presence of fungi on leaves) to plants (Singh et al., 2004). Varietal resistance against *M. sacchari* is one of the main control tactics suggested, both for sugarcane and sorghum. Sugarcane aphids (SCAs) were reported to affect sorghum in Mexico for the first time in 2013 in the states of Tamaulipas, San Luis Potosi, Veracruz, and Nuevo Leon, where they caused total losses in most of the area planted with sorghum (Rodríguez-Del Bosque & Terán, 2015).

The management of SCA in sorghum depends largely on the appropriate applications of insecticides when populations reach an economic threshold (Knutson et al., 2015), which is considered when a population of ≥ 50 aphids per leaf is reached (Rodríguez-Del Bosque & Terán-Vargas, 2018; Silva-Martinez et al., 2019). Although applications of insecticides to the SCA are necessary to prevent economic losses of yield, the increase in production costs to protect grain yields reduces the profitability for sorghum producers. Therefore, sorghum hybrids with resistance or at least, tolerance to the SCA are desirable because they reduce or eliminate farmers' dependence on insecticides for their management (Bowling et al., 2016; Pecina-Quintero et al., 2021).

Stout (2013) proposed a dichotomous scheme for 'resistance', with a major division between resistance (those plant traits that limit injury to the plant) and tolerance (plant traits that reduce amount of yield loss per unit injury); resistance is subdivided into constitutive/inducible and direct/indirect subcategories. Resistance and, tolerance, can play variable roles against SCA (Dogramaci et al., 2007; Perales-Rosas et al., 2019). Tolerance does not affect the insect and only helps the plant to recover from the damage they cause; strictly speaking, a tolerant genotype shows higher yield than a susceptible one, when both are subjected to the same level of infestation. Tolerance is useful and important in annual crops or when there is a risk that biotypes of the insect will develop that can break resistance, which can occur with antibiosis mechanisms (Cardona & Sotelo, 2005; Smith, 2005). The genetic improvement of resistance to SCA in sorghum should consider the development of genotypes that combine both resistance mechanisms: tolerance to damage by adults and resistance (Cardona & Sotelo, 2005).

In the spring-summer cycle of 2015, the SCA affected a large part of the area established with sorghum in the Bajío region, which is located at Guanajuato state in Mexico, and it was estimated that the yield losses reached 40% of the sorghum grain production, which, on average was 1.2 million tons per year before the presence of the SCA (Pecina et al., 2016). Although different control measures were established, including the use of insecticides and biological control, the damage was severe. Studies to identify SCA-tolerant hybrids have been carried out in other countries and indicate that it is essential to monitor sorghum cultivation even in tolerant genotypes to determine if it is necessary to apply chemical products that complement SCA control (Knutson et al., 2016). The identification of SCA resistant genotypes has been carried out through field trials under natural or artificial infestation conditions (Sharma et al., 2014; Van den Berg, 2002). In Mexico, Pecina et al. (2016) evaluated 80 commercial sorghum genotypes over six planting dates under natural infestation conditions, and 30 sorghum genotypes were identified with a good SCA tolerance response and good yield potential performance. *M. sacchari* shows antixenosis for some sorghum hybrids (Perales-Rosas et al., 2019). Pecina-Quintero et al. (2021) identified tolerant sorghum genotypes to SCA, which can be used by producers and allows a higher management threshold by reducing the number of insecticide applications required to control SCA (Pecina-Quintero et al., 2021). This study evaluated the response of some sorghum hybrids to SCA under two field conditions (irrigation and dryland conditions) and under two management schemes of SCA management: the evaluation under a threshold-based chemical management (TBCM) scheme TBCM and evaluation of genotypes without TBCM.

Materials and methods

Experimental locations. The present study was conducted during the spring-summer cycle of 2017 in three locations in the state of Guanajuato (Celaya, Valle de Santiago, and Pénjamo). The Valle de Santiago and Pénjamo have subtropical subhumid climatic conditions with spring rains, while Celaya has subtropical conditions with dry winters. Geographic location and maximum and minimum temperatures and rain precipitation are shown in Table 1. Monthly maximum and minimum temperatures during the development of each experiment were similar at the three experimental locations, although the rain precipitation was 50% greater in Celaya and Valle de Santiago as compared to Pénjamo.

Experimental conditions. Experiments were established under irrigated or dryland conditions. Experiments under irrigated conditions were established in two locations (Celaya and Valle de Santiago) at two sowing dates (Celaya = May 10 and June 01; Valle de Santiago = June 01 and 06) using the tolerant hybrids APACHE, BRS-70, MEZQUITE, SCAP-618, and susceptible UPM-219. Experiments under dryland conditions were established in three locations: Celaya (July 17), Valle de Santiago (June 27), and Penjamo (June 27) including the tolerant hybrids MEZQUITE, SCAP-618, and susceptible UPM-219, SHORTER, and MAJESTIC-355. All experiments were established using a strip-plot experimental design with four replications and two factors (sorghum hybrids, TBCM treatments). Treatments resulted after combination of levels of each factor. Plots were 8 rows of 50 m per genotype. The space between rows was 0.76 m, and the sowing density was 350 thousand plants per hectare. Agronomic management was applied according to the technological package recommended by INIFAP in the Bajío area for irrigation conditions (Hernandez-Martinez & Pecina-Quintero, 2013). Irrigated experiments were subjected to three irrigations in addition to rainfall, while dryland experiments were only exposed to rainfall during development of each experiment.

Table 1. Geographical locality and climatic conditions of three municipalities of Guanajuato, México where TBCM and no TBCM strategies against sugarcane aphid were tested during 2017.

Station	Municipality	Geographical locality			Temperature (°C)		Rain (mm)	Date of sowing	
		Longitude	Latitude	Altitude (m)	Maximum	Minimum		Irrigated experiments	Dryland Experiments
Celaya	Celaya	100.826	20.588	1706	31	7	452	May 10 June 01	July 17
Las Estacas	Valle De Santiago	101.354	20.437	1711	30	9	459	June 01 June 06	June 27
La Gavilana	Pénjamo	101.784	20.319	1654	31	7	308		June 27

The TBCM treatments were: a) with TBCM, the seeds of all genotypes were treated with thiamethoxan (Cruiser® 5FS; Syngenta), followed by, one or two applications of foliar insecticides: the first insecticide was flupyradifurone, Sivanto® Prime 200SL; Bayer (200 mL.ha^{-1} in 300 L of water). In some cases, a second application was required, and the insecticide sulfoxaflor (Isoclast® Active, Toretto®; Dow Agrosciences) was applied (100 mL.ha^{-1} in 300 L of water) (Quijano et al., 2017). Insecticides were applied to foliage when a population of ≥ 50 aphids per leaf was reached (Rodríguez-Del Bosque & Terán-Vargas, 2018; Silva-Martinez et al., 2019); b) without TBCM, where no applications were made to seeds or foliage for control of SCA (without TBCM).

Variables measured. Evaluations of SCA populations were carried out every ten days after emergence in all plots according to the protocol established by Bowling et al. (2019), sampling five randomly selected plants per plot. The accumulated populations of all the samplings were analyzed assuming a better integration of the individual counting that varied in intensity by sampling date according to the effects of the sorghum hybrid, planting date or treatment (Pecina et al., 2016; Pecina-Quintero et al., 2021; Rodríguez-Del Bosque & Terán-Vargas, 2018). In addition, the variables of days to flowering, panicle size, exertion, plant height, grain yield, and beneficial fauna were evaluated.

Statistical analysis. With the data collected, the statistical analysis of the variables consisted of ANOVA and the Tukey means test. To evaluate the yield-SCA global density relationships, linear regressions were calculated for each combination of location x date of sowing x TBCM treatment (eight individual simple linear regressions) or location x TBCM treatment (six regressions). Data analyses were performed using SAS (SAS Institute, 2010) and STATISTICA ver. 7 (StatSoft, 2007) software.

Results

Irrigated experiments. On the first planting date (Table 2) in Celaya and Valle de Santiago, the presence of the SCA was not observed until the first sorghum genotypes reached the flag leaf stage. At 50 days after emergence (DAE), the susceptible control (UPM-219) in Celaya reached a population of ≥ 50 aphids per leaf (APL) in 20 % of the plants, both in the protected control (TBCM) and in the control without TBCM, so flupyradifurone was applied to the control under the TBCM scheme. Meanwhile, in the SCAP-618 and BRS-70 genotypes, the application of insecticide was required at 60 DAE, and in APACHE and MEZQUITE, the application was needed at 70 DAE. In addition, the susceptible hybrid required a second application of insecticide (sulfoxaflor) at 90 DAE.

Table 2. Cumulative population of sugarcane aphids per leaf, *Melanaphis sacchari* (Zehntner), observed in sorghum hybrids at two locations of Guanajuato, México under irrigated conditions during 2017.

Hybrid	Company	Celaya		Valle de Santiago	
		1st Planting date	2nd Planting date	1st Planting date	2nd Planting date
		With TBCM			
APACHE*	WARNER	105.0 c	227.1 c	93.3 b	60.0 b
BRS-70*	DEKALB	121.8 c	151.3 c	71.7 b	138.8 b
MEZQUITE*	AVANTE	81.5 c	178.3 c	121.3 b	78.7 b
SCAP-618*	SUN REY SEEDS	79.2 c	121.3 c	132.2 b	133.0 b
UPM-219**	ADVANTA	159.2 c	229.7 c	273.6 b	227.8 b
Mean		181.5	181,5	138.4	127.7
		Without TBCM			
APACHE	WARNER	724.9 bc	327.9 bc	190.9 b	185.6 b
BRS-70	DEKALB	742.5 bc	539.6 bc	348.9 b	430.6 b
MEZQUITE	AVANTE	292.8 c	189.9 c	253.6 b	207.2 b
SCAP-618	SUN REY SEEDS	1,496.2 b	784.0 b	1,037.1 a	1,042.3 a
UPM-219	ADVANTA	2,987.9 a	2,806.6 a	1,408.4 a	1,143.7 a
Mean		1248.9	929.6	647.8	601.9

[1] Means grouped with the same letter within each planting date in each location are statistically similar according to the Tukey test (P < 0.05). *Seed treatment with Crusier® 5FS and one foliar application of Sivanto® Prime. **Foliar application of Toretto®.

In Valle de Santiago on the first date, the susceptible control (UPM-219) and BRS-70 and SCAP-618 genotypes required insecticide application (flupyradifurone) at 60 DAE, MEZQUITE at 70 DAE, and APACHE at 90 DAE. On the second planting date, only one application was made to genotypes UPM-219 (susceptible) and BRS-70, and SCAP-618 (tolerant), while for MEZQUITE and APACHE, no application was required. The analysis of variance (ANOVA) for the cumulative number of aphids per leaf (APL) per genotype under irrigated conditions indicated significant differences ($p < 0.05$) between the treatments, both in Celaya and in Valle de Santiago on the two planting dates (data not included). The susceptible control UPM-219 without TBCM presented the highest populations of SCA on both planting dates, with 2,987 and 2,806 APL in Celaya and 1,408 and 1,143 APL in Valle de Santiago, while MEZQUITE and APACHE (tolerant) presented the lowest number of APL (Table 2); the SCAP-618 genotype exhibited high infestation but less than that of the UPM-219 susceptible control. On the other hand, when comparing treatments with TBCM and without TBCM, the differences were significant ($p < 0.05$) between the two types of management.

The ANOVA for grain yield indicated significant differences ($p < 0.05$) between the treatments in both Celaya and Valle de Santiago on the two planting dates evaluated. On the first date in Celaya, BRS-70 exhibited 12 $t.ha^{-1}$ under the TBCM scheme (Table 3), while the other three tolerant genotypes (APACHE, MEZQUITE, SCAP-618) were statistically similar ($p > 0.05$) considering the two types of management with TBCM and without TBCM. The susceptible hybrid UPM-219 with TBCM yielded more than 10 $t.ha^{-1}$ compared to the uncontrolled treatment, which exhibited a total yield loss (0 $t.ha^{-1}$). On the second planting date in Celaya, MEZQUITE without TBCM and UPM-219 with TBCM had the highest grain yields of 9.9 and 10 $t.ha^{-1}$, respectively. In Valle de Santiago on the first planting date, the susceptible UPM-219 showed higher yields under the TBCM scheme (7 to 9 $t.ha^{-1}$), while under the scheme without TBCM, the yields of the tolerant genotypes were lower (6.4 to 5.6 $t.ha^{-1}$), and the susceptible control had a total loss (0 $t.ha^{-1}$). Something similar occurred on the second date, where the tolerant genotypes with TBCM management had good grain yields (6 to 8.8 $t.ha^{-1}$) and the susceptible genotype reached 5.9 $t.ha^{-1}$. On the other hand, without TBCM, the tolerant genotypes ranged from 4 to 6.9 $t.ha^{-1}$ and the susceptible control was a total loss.

Dryland trials. In Celaya, the ANOVA for the number of aphids per leaf indicated significant differences ($p < 0.05$) between treatments. Without TBCM, the susceptible control UPM-219 had an average of 407 aphids per leaf (APL) (Table 4) followed by the other susceptible hybrids SHORTER with 119 APL and MAJESTIC-355 with 77 APL, while the tolerant genotypes SCAP-618 and MEZQUITE had 57 APL and 34 APL, respectively. It should be noted that after the third count carried out on August 28, the SCA populations declined drastically until they reached barely detectable levels of one or two aphids per leaf. The ANOVA for grain yield indicated significant differences ($p < 0.05$) between the treatments, both between management schemes (with TBCM and without TBCM) and between genotypes. The susceptible control with TBCM yielded more than seven tons per hectare (Table 5), followed by MAJESTIC-355, SCAP-618, SHORTER and MEZQUITE. There was no significant difference gr grain yield for MEZQUITE, SCAP-2018 and SHORTER for IMP vs. without IMP.

In Penjamo, treatments under the TBCM scheme showed an increase in the SCA populations until the fourth monitoring, so an application was made with flupyradifurone to SHORTER, MAJESTIC-355, SCAP-618 and UPM-219, while MEZQUITE did not require an application. ANOVA for cumulative APL indicated significant differences ($p < 0.05$) between treatments, especially when comparing genotypes with TBCM treatment and without TBCM. Without TBCM, the susceptible control (UPM-219) had 1588 APL, followed by MAJESTIC-355 with 1555 APL and SHORTER with 1552, while the tolerant genotypes SCAP-618 had 1243

Table 3. Grain yield of sorghum hybrids submitted to the sugarcane aphid, *Melanaphis sacchari* (Zehntner) under irrigated conditions at two locations of Guanajuato, México during 2017.

		Celaya ($t.ha^{-1}$)		Valle de Santiago ($t.ha^{-1}$)	
Hybrid	**Company**	**1st Planting date**	**2nd Planting date**	**1st Planting date**	**2nd Planting date**
			With TBCM		
APACHE*	WARNER	11.04 ab	7.85 bc	7.10.abc	8.87 a
BRS-70*	DEKALB	12.09a	9.65 ab	8.54 ab	8.15 ab
MEZQUITE*	AVANTE	9.56ab	9.37 ab	7.18 abc	6.40 cd
SCAP-618*	SUN REY SEEDS	8.86 b	9.10 ab	7.55 abc	6.12 cd
UPM-219**	ADVANTA	10.59 ab	10.27 a	9.32 a	5.91 cd
Mean		10.43	9.25	7.94	7.09
			Without TBCM		
APACHE	WARNER	11.15ab	8.48 abc	6.42 bc	6.48 cd
BRS-70	DEKALB	9.45 ab	9.44 ab	5.63 c	6.93 bc
MEZQUITE	AVANTE	9.91 ab	9.92a	5.67 c	5.24 de
SCAP-618	SUN REY SEEDS	8.91 ab	7.11 c	6.40 bc	4.12 e
UPM-219	ADVANTA	0.00 c	0.00 d	0.0 d	0.0 f
Mean		7.88	6.99	4.83	4.56

[1] Means grouped with the same letter within each planting date in each location are statistically similar according to the Tukey test ($P < 0.05$). * Seed treatment with Crusier® 5FS and one foliar application of Sivanto® Prime. **Foliar application of Toretto®.

APL and MEZQUITE had 134 (Table 4). Concerning grain yield, the ANOVA indicated significant differences ($p<0.05$) between the treatments, both between management schemes (with TBCM and without TBCM) and between genotypes, where it could be observed that MEZQUITE had a similar behavior under both management schemes, while SCAP-618 was tolerant to the SCA. The TBCM scheme allowed an increase in yield by reducing the damage caused by the SCA. The susceptible hybrids MAJESTIC-355, SHORTER and UPM-219 should require TBCM to obtain an adequate performance, otherwise the losses were total (98-100%) in Valle de Santiago and Pénjamo (Table 5). Finally, the yield – aphid cumulative density linear regressions for experiments, dates of sowing or TBCM treatments are shown (Table 6). Significant ($p<0.05$) negative regressions between grain yield vs. aphid per leaf cumulative densities were found when sorghum hybrids were cultivated without TBCM.

Table 4. Cumulative population of the sugarcane aphids per leaf, *Melanaphis sacchari* (Zehntner), observed in sorghum hybrids evaluated under dryland conditions in three locations of Guanajuato, México during 2017.

Hybrid	Company	Celaya	Valle de Santiago	Pénjamo
			With TBCM	
MEZQUITE*	ADVANTE	18.7 b	46.6 d	57.7 b
SCAP-618*	SUN REY SEEDS	26.6 b	47.2 d	166.7 b
UPM-219**	ADVANTA	37.9 b	59.8 d	375.2 b
SHORTER*	SUN REY SEEDS	28.9 b	70.5 d	119.2 b
MAJESTIC-355 *	MAJESTIC	30.3 b	47.2 d	171.4 b
Mean		28.5	54.3	890.2
			Without TBCM	
MEZQUITE	ADVANTE	34.9b	324.9 cd	134.5 b
SCAP-618	SUN REY SEEDS	57.1 ab	619.7 c	1,243.9 a
UPM-219	ADVANTA	407.9 a	940.4 b	1,588.8 a
SHORTER	SUN REY SEEDS	119.0 ab	1,407.6 a	1,552.6 a
MAJESTIC-355	MAJESTIC	77.1 ab	974.0 b	1,555.7 a
Mean		139,2	853.3	1215.1

[1] Means grouped with the same letter within each planting date in each location are statistically similar according to the Tukey test ($P < 0.05$). * Seed treatment with Crusier® 5FS and one foliar application of Sivanto® Prime. **Foliar application of Toretto®.

Table 5. Grain yield of sorghum hybrids submitted to the sugarcane aphid, *Melanaphis sacchari* (Zehntner) under dryland conditions at two locations of Guanajuato, México during 2017.

Hybrid	Company	Celaya (t.ha)	Valle de Santiago (t.ha)	Pénjamo (t.ha)
			With TBCM	
MEZQUITE*	ADVANTE	2.78 bc	7.09 ab	8.10 ab
SCAP-618*	SUN REY SEEDS	4.12 abc	8.13 a	7.63 abc
UPM-219**	ADVANTA	7.18 a	6.51 b	7.59 abc
SHORTER*	SUN REY SEEDS	3.70 bc	4.09 c	7.03 abc
MAJESTIC-355*	MAJESTIC	4.36 ab	5.90 b	6.26 bc
Mean		4.43	6.34	7.32
			Without TBCM	
MEZQUITE	ADVANTE	1.46 bc	6.29 b	7.96 abc
SCAP-618	SUN REY SEEDS	2.82 bc	5.60 b	5.74 c
UPM-219	ADVANTA	2.23 bc	0.0 e	0.0 d
SHORTER	SUN REY SEEDS	9.21 bc	0.0 e	0.0 d
MAJESTIC-355	MAJESTIC	0.66 c	2.00 b	0.0 d
Mean		3.38	2.78	2.74

[1] Means grouped with the same letter within each planting date in each location are statistically similar according to the Tukey test ($P < 0.05$). * Seed treatment with Crusier® 5FS and one foliar application of Sivanto® Prime. **Foliar application of Toretto®.

Table 6. Regression analysis between grain yield and cumulative incidences of the sugarcane aphid per leaf *Melanaphis sacchari* (Zehntner) in experiments conducted in Guanajuato, Mexico, during 2017.

Location	Date of sowing	Intercept	β	P	R^2
			Irrigated experiments		
With TBCM					
Celaya	First	9.61	0.711	0.289	0.72
	Second	11.22	-0.744	0.254	0.75
Valle de Santiago	First	9.16	-0.621	0.381	0.72
	Second	8.56	-0.572	0.318	0.76
Control					
Celaya	First	12.82	-0.941	0.022 *	0.94
	Second	10.45	-0.986	0.001 *	0.99
Valle de Santiago	First	7.21	-0.836	0.049 *	0.74
	Second	8.00	-0.877	0.046 *	0.82
			Dryland experiments		
With TBCM					
Celaya		1.87	0.281	0.625	0.86
Valle de Santiago		12.45	-0.795	0.108	0.80
Pénjamo		7.38	-0.063	0.911	0.63
Control					
Celaya		1.39	-0.843	0.049 *	0.68
Valle de Santiago		8.43	-0.894	0.041 *	0.90
Pénjamo		9.41	-0.887	0.045 *	0.89

* Significant ($p \leq 0.05$).

Discussion

The three locations included in this study are located at similar growing regions of the state of Guanajuato, México with slight differences in landscape features and environmental conditions. Average maximum and minimum temperatures did not differ among locations by more than two degrees during the months when vegetative and reproductive development was completed, but precipitation and irrigation were different. When sorghum was grown under dryland conditions, total rainfall was 50 % higher in Celaya and Valle de Santiago compared with Pénjamo. Averaged grain yields were 64 % higher in irrigated experiments than dryland experiments while TBCM increased grain yields 50 % and 100 % under irrigated and dryland conditions, respectively. Any plant stress stemming from variety–environment interactions during panicle initiation and development reduces seed set and resulting yield (Haar et al., 2019).

Variety–environment interactions are recognized to impact overall plant health and grain yields (Szczepaniec, 2018), and abiotic factors influence aphid population dynamics (Zapata et al., 2018). Tolerant hybrids exhibited variation in aphid populations, injury, and yield among experiments, or TBCM conditions. Our data suggested, as described by Pekarcik and Jacobson (2021) that abiotic factors as rainfall or irrigation or strategies as TBCM such as those evaluated in this work can influence aphid suppression, injury, and grain yields of sorghum tolerant genotypes. Based on grain yield averages and cumulative incidences of SCA, regression analysis demonstrated the effectiveness of TBCM in irrigated or rainfed sorghum in Guanajuato, Mexico.

The identification, and/or development of SCA-tolerant sorghum genotypes is essential for the sustainability of sorghum cultivation and the development of a comprehensive pest management program (Armstrong et al., 2017; Smith, 2005). In this study, the tolerance of six sorghum hybrids to the sugarcane aphid (SCA) was ratified based on a previous screening of 80 commercial sorghum genotypes in Mexican Bajío and coincided with that reported in other studies on the effectiveness of selecting tolerant genotypes under conditions of natural infestation (Van der Berg, 2002). Some researchers have mentioned that initial tests under controlled conditions are valuable for evaluating a high number of genotypes and that genotype selection must be evaluated in greater detail in field tests to confirm the resistance categories (Armstrong et al., 2015).

In this evaluation, we confirmed that the evaluation under field conditions was effective since genotypes were evaluated on six planting dates, which prevented false positives (Pecina et al., 2016). In the evaluation without TBCM, the APACHE, BRS-70, and MEZQUITE had the lowest SCA population numbers with the highest grain yields as has been reported in other studies (Armstrong et al., 2019). The tolerance of the sorghum host plant should be an indispensable and economically valuable tool for the management of SCA when used in conjunction with other compatible control tactics since it allows a higher management threshold and decreases the number of foliar applications of insecticides for the control of the SCA (Armstrong et al., 2015; Pecina-Quintero et al., 2021; Pecina et al., 2016; Perales-Rosas et al., 2019; Rodríguez-Del Bosque & Terán-Vargas, 2015, 2018; Sharma et al., 2013, 2014)

In this study, tolerant hybrids grown under irrigation at an early planting date (Valle de Santiago) had a similar behavior between the TBCM scheme and without TBCM. However, as the crop cycle progressed, it became more evident that it is necessary to include the TBCM scheme in both irrigation and dryland conditions in the agronomic management of tolerant hybrids. It is also clear that in late sowings (July) that are usually carried out in drylands, the use of tolerant genotypes and the protection of the seed with insecticide may be sufficient for the control of the SCA, since during the last three years, the SCA populations declined significantly at the end of August and in September. Likewise, although the tolerance/resistance mechanisms of these genotypes to the SCA are not well known yet, it would be essential to carry out additional studies to recommend, with greater certainty, those genotypes that express more than one category of resistance, which would help confer a lower selection pressure to the SCA.

Recent studies reported the identification of genes related to cell wall modification, photosynthesis and phytohormone biosynthesis, and resistant genotypes showed antixenosis and antibiosis (Tetreault et al., 2019). That performance is less affected by infestations. It is desirable to have varieties that have a combination of antibiosis effects that limit population growth and tolerance traits that limit damage to plants (Paudyal et al., 2019). In addition, it is necessary to continue the selection of sorghum lines that may offer potential resistance to different biotypes of *M. sacchari* (Nibouche et al., 2018; Pecina-Quintero et al., 2021; Tetreault et al., 2019).

Conclusions

Averaged grain yields were 64 % higher in irrigated experiments than dryland experiments, while TBCM increased grain yields 50 % and 100 % under irrigated and dryland conditions, respectively. TBCM was effective to increase sorghum grain yields and to reduce cumulative populations of *M. sacchari* under irrigated or rainfed conditions of Guanajuato, Mexico, mainly for the susceptible germplasm. The use of tolerant germplasm and TBCM strategies such as seed protection and insecticides could control SCA in sorghum cultivated in Guanajuato, Mexico, mainly for frequent late sowings carried out under dryland conditions.

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Víctor Pecina-Quintero: Study design and development; data collection, manuscript review. Rafael Bujanos-Muñiz: Study design and development; data collection, manuscript review. Noé Montes-García: Study design and development; data collection, manuscript review. María Fernanda Jiménez-Becerril: Data collection, manuscript review. Andrea Pecina-Becerril: Data collection, manuscript review. Netzahualcoyotl Mayek-Pérez, Data analysis, manuscript review.

Conflict interests

The authors declare no conflict interests.