NRC Research Press

ARTICLE

Witchweed [*Striga hermonthica* (Del.) Benth] control using imazapyr seed coating in maize hybrids in the Nigerian savannah

David Chikoye, Ayeoffe Fontem Lum, and Abebe Menkir

Abstract: Witchweed [*Striga hermonthica* (Del.) Benth] is a major parasitic weed of most cereal crops in Africa, including maize. Seed treatment with low doses of acetolactate synthase–inhibiting herbicides, such as imazapyr, was introduced in the 1990s to control witchweed. Field trials were conducted in four locations in Nigeria in 2007 and 2008, to assess the effect of coating seeds of several maize hybrids with imazapyr on witchweed control. The hybrids had genes for imidazolinone herbicide resistance (IR), as well as genetic tolerance to witchweed (ST). Treatments were 12 IR maize hybrids with ST and three checks without the IR gene (commercial, witchweed tolerant, and witchweed susceptible hybrids). Averaged across all locations, the coated IR hybrids with ST yielded more and supported fewer witchweed plants than the uncoated IR hybrids with ST. The IR hybrids with ST yielded 57%–60% more than the commercial and witchweed tolerant hybrid checks that were not coated. The witchweed susceptible hybrid check suffered a yield loss of 88% under infestation without seed coating. The IR hybrids with ST yielded 3564 kg ha^{-1} of grain when coated with imazapyr and 3266 kg ha^{-1} otherwise. The findings indicate that coating of IR/ST maize seeds with imazapyr improved tolerance to witchweed.

Key words: imazapyr, imidazolinone-herbicide resistant hybrids, seed coating, *Striga hermonthica*, witchweed.

Résumé : La striga [*Striga hermonthica* (Del.) Benth] est une importante adventice qui parasite la plupart des cultures céréalières en Afrique, dont le maïs. Pour la combattre, dans les années 1990, on a commencé à traiter les semences avec une faible dose d'herbicides inhibant l'acétolactate synthase comme l'imazapyr. Les auteurs ont procédé à des essais sur le terrain à quatre endroits du Nigeria en 2007 et 2008, l'idée étant d'évaluer comment l'enrobage des grains de plusieurs hybrides de maïs avec de l'imazapyr permettrait de lutter contre la striga. Les hybrides incorporaient un gène de résistance à l'imidazolinone (IR — « imidazolinone herbicide resistance »), un herbicide, et toléraient génétiquement la striga (ST — « tolerance to witchweed »). Les expériences ont porté sur 12 hybrides IR tolérant la striga et trois variétés témoins sans gêne IR (un cultivar commercial, un tolérant la striga et un qui y était sensible). En moyenne, pour tous les endroits testés, les hybrides IR avec ST dont la graine avait été traitée donnent un meilleur rendement et supportent moins de plants de striga que ceux dont la graine n'avait subi aucun traitement. Les hybrides IR avec ST ont enregistré un rendement de 57 % à 60 % plus élevé que celui de la variété commerciale et des hybrides témoins tolérant l'adventice qui n'avaient pas été traités. L'hybride sensible à la striga dont les graines n'avaient pas été enrobées a vu son rendement reculer de 88 % en raison de l'infestation. Les hybrides RI avec ST ont donné 3 564 kg ha^{-1} lorsque les semences étaient traitées avec de l'imazapyr et 3 266 kg ha^{-1} sans traitement. Ces résultats indiquent qu'enrober les graines de maïs IR/ST avec de l'imazapyr améliore la résistance à la striga. [Traduit par la Rédaction]

Mots-clés : imazapyr, hybrides résistance à l'imidazolinone, enrobage des semences, *Striga hermonthica*, striga.

Received 30 May 2019. Accepted 18 October 2019.

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Introduction

For many smallholder farmers in Africa, one main constraint to achieving high cereal productivity is the menace of parasitic weeds such as the *Striga* species. Among the numerous species, the purple witchweed *Striga hermonthica* (Del.) Benth. is the most widespread, affecting many cereals, especially maize (Lagoke et al. 1991; Berner et al. 1995). The weed is estimated to have infested between 2.4 and 4 million ha of land under maize production causing yield losses of 30%–80%, valued at between US$ 383 million and 1 billion, and negatively affecting the livelihoods of about 100 million people in Africa who are unable to grow enough food (Gressel et al. 2004; Ejeta 2007; Woomer et al. 2008). In West and Central Africa, the mean estimated yield loss in maize is 68% (Kim et al. 2002). In Nigeria, it has invaded about 835 000 ha of maize, directly affecting approximately 20 million people (Lagoke et al. 1991; Woomer et al. 2008). Infestation in some places has reached epidemic levels. Over 85% of fields planted to maize are infested and crop damage ranges from 10% to 100% (Dugje et al. 2006). In situations where infestation is most severe, farmers abandon the fields and search for those less affected (Doggett 1984; Ransom et al. 1990; Haussmann et al. 2000).

Witchweed is very difficult to control because it produces large numbers of seeds, and their adaptation and (or) dormancy mechanisms permit them to stay alive in the soil for several years (Kust 1963; Westerman et al. 2007). Seeds are triggered to germinate when they are close to the roots of host plants. After germination, the weed attaches itself to the roots of the host and becomes a major sink for crop photosynthate, thereby debilitating crop growth and yield (Stewart and Press 1990; Gurney et al. 1995, 2006; Joel 2000; Ayongwa et al. 2010). The problem is increasing in Africa because of the deteriorating soil fertility, shortening of the fallow period, and expansion of production into marginal lands with little use of external inputs. Other factors include the increasing trend towards continuous cultivation of monocultures in place of the traditional rotation with fallow and intercropping systems. Fallowing land for at least 10 yr has traditionally been used to improve soil fertility, reduce the weed seed bank from the previous cropping seasons, and reduce weed pressure (Akobundu et al. 1999). Small-scale farmers are most affected by the weed because they lack adequate resources to buy inputs and have little flexibility in their cropping systems. With the growing population pressure in Africa and the increase in cropping intensities, the witchweed problem is becoming more acute, particularly in areas with poor fertility and low rainfall. In these areas host plants are too weak to compete for assimilates, water, and light, and yet the parasite is able to grow vigorously and produce large quantities of seeds (Singh and Emechebe 1997).

The variety of control options to reduce witchweed damage in susceptible crops includes hand and mechanical weeding, host plant resistance, use of trap crops, heavy application of nitrogen (N) fertilizers, herbicide application, land fallowing, crop rotations, mixed cropping or intercropping with non-hosts, soil disinfectants, fumigation, solarization, and biological control or soil antagonists (Kim 1991, 1994; Berner et al. 1995; Carsky et al. 2000; Kling et al. 2000; Gacheru and Rao 2001; Oswald and Ransom 2001; Oswald et al. 2001; Gbèhounou and Adango 2003; Schulz et al. 2003; Fasil and Verkleij 2007; Joel et al. 2007; Menkir and Kling 2007; Udom et al. 2007; Westerman et al. 2007; Badu-Apraku et al. 2008; Jamil et al. 2011; Menkir et al. 2012). However, most of these options are not very effective, economical, or environmentally friendly, especially when applied individually under the subsistence production systems prevailing in African agriculture.

The use of witchweed tolerant maize varieties is the most economically feasible and sustainable approach available to smallholder farmers for managing the parasitic weed (DeVries 2000; Badu-Apraku et al. 2004). Past research efforts have resulted in the development of open pollinated maize varieties (OPVs), hybrids, and inbred lines that are resistant or tolerant to witchweed (Menkir et al. 2007; Badu-Apraku and Yallou 2009). Some of the available *Striga* resistant OPVs give 55% higher yields than susceptible check varieties and are also tolerant to drought and low soil N (Badu-Apraku et al. 2010). Maize varieties differ in their tolerance or resistance to witchweed from different geographic zones because the parasite is likely to have a high degree of genetic diversity, as it is an obligate out-crossing species. Therefore, to increase its efficacy, this control option needs to be combined with other management practices.

Several studies have shown that low doses of acetolactate synthase (ALS) inhibiting herbicides applied as seed coating to maize with ALS resistance provided effective control (Abayo et al. 1996, 1998; Berner et al. 1997; Kanampiu et al. 2001, 2006, 2007; De Groote et al. 2007; Kabambe et al. 2008; Chikoye et al. 2011). This control option is relatively economical and very attractive to the African subsistence farmers because the herbicides are applied at very low rates without the need for capital equipment expenditure on sprayers (Berner et al. 1997; Kanampiu et al. 2001). These herbicides translocate to parasitic weeds attached to the roots of maize and control them underground before they cause any significant reduction in crop yields (Gressel et al. 1996; Abayo et al. 1998; Kanampiu et al. 2001). Incorporating the ALS resistance genes into maize genotypes adapted to the tropics could lead to higher levels of efficacy in its control. There is a paucity of information on the use of imazapyr seed treatment for witchweed control on tropically adapted maize germplasm with resistance to the parasite and tolerance to imazapyr in West Africa.

In previous studies, conducted in three ecological zones in Nigeria, the results showed that imidazolinone resistant (IR) hybrids with genetic tolerance to the parasite had similar grain yields and other agronomic traits in both infested and witchweed-free conditions (Menkir et al. 2010; Chikoye et al. 2011). Therefore, the objective of this study was to evaluate the response of 12 IR tropically adapted maize hybrids with genetic tolerance to the parasite and coated with imazapyr, to witchweed infestation in three environments [southern Guinea savannah (SGS), northern Guinea savannah (NGS), and Sudan savannah (SS)] in Nigeria.

Materials and Methods

Description of trial sites

Multilocational field trials were conducted in 2007 and 2008 in Nigeria, at the International Institute of Tropical Agriculture (IITA) research farms in Abuja and Mokwa (both in the SGS), the Institute for Agricultural Research farm, Zaria (in the NGS), and on a farmer's field at Sabongari in Damboa (in the SS). These locations represented three savannah agroecological zones where witchweed is a significant problem. The characteristics of the trial sites are presented in an earlier publication (Chikoye et al. 2011).

Plant material

The trials consisted of 12 IR maize hybrids with genetic tolerance to witchweed (ST) and three checks [a commercial hybrid Oba Super 1, a witchweed tolerant hybrid (9022-13) and a susceptible hybrid (8338-1)] without the IR gene. An IR gene was incorporated into tropical maize inbred lines with known field tolerance to witchweed, to develop IR maize lines with ST using the standard backcross breeding method at IITA (Menkir et al. 2010). These hybrids were developed from diverse germplasm sources and were late maturing varieties (120 d from planting to physiological maturity). They were homozygous for the IR gene. The checks had the same maturity period as the IR maize hybrids.

Experimental design and treatments

The experimental design was a split plot with three replications. Treatments were 12 IR maize hybrids with ST and three checks without the IR gene, which were with or without imazapyr coating and sown in fields infested with witchweed. The main plots consisted of seed coating (two levels: coated and uncoated), and the subplots were the 12 IR maize hybrids and the three checks. Each plot consisted of one row, 5 m long, with 0.25 m spacing between plants within the row. The plots were spaced 0.75 m apart.

Procedure for seed coating

Imazapyr acid was dissolved in distilled water, and potassium hydroxide was gradually added to the solution to raise the pH to between 6 and 8 to increase solubility. To bind the herbicide to the seeds, 1.8% of polyvinylpyrollidone (PVP-40) was added to the 21 mmol L^{-1} of the K-salt of imazapyr, which was sourced from BASF (Ludwigshafen, Germany). Seeds of the IR hybrids and checks were added to this solution, mixed thoroughly, and kept for 24 h to attain a dose of 0.4 mg a.e. imazapyr per seed after drying. The treated seeds were planted in the field within 2 d of being coated.

Procedure for determining witchweed seed viability

At Sabongari and Zaria, the trial was planted on naturally infested fields; at Abuja and Mokwa, it was established on fields artificially infested with witchweed seeds that had been collected from fields of sorghum [*Sorghum bicolor* (L.) Moench] at different locations around Abuja, Mokwa, and Zaria at the end of the previous growing season. Fifty seeds were randomly selected from the collected seed lot, disinfected with 1% sodium hypochlorite for 5 min, and placed on moist filter paper in each of 10 sterile Petri dishes that were incubated in complete darkness at 25 °C for 14 d. The filter paper in each Petri dish was moistened daily with sterile deionized water. Each Petri dish received two drops (10 μL) of 10 mg of a synthetic germination stimulant (GR24) and was placed in a dark incubator at 30 °C for 24–48 h. Germinated witchweed seeds were observed under a dissecting microscope (Menkir and Kling 2007). The germination percentage was calculated from the ratio of seeds with emerging radicles to the total number of seeds placed on each Petri dish. This percentage was used to determine the quantity required to deliver approximately 5000 viable seeds per hill in the field trials. Witchweed seeds were mixed with sand (1:99 ratio) to facilitate application.

Field procedure

Two maize seeds of each herbicide-coated hybrid were planted per hole, and artificially infested with approximately 5000 viable seeds from 8.5 g of sand per witchweed seed inoculum to ensure uniform infestation (Kling et al. 2000). Also, two seeds of each uncoated hybrid were planted in rows that were adjacent to the coated hybrids. The seeds of each hybrid were sown in May 2007 and June 2008 at Abuja; in June 2007 and July 2008 at Mokwa; and in June 2007 and 2008 at Zaria and Sabongari. Two weeks after planting (WAP), the maize plants were thinned to one plant per hill to give a final population density of approximately 53 333 plants ha^{-1}. Fertilizer was applied at the rate of 30 kg ha^{-1} each of N, phosphorus (P), and potassium (K) at 2 WAP and an additional 30 kg ha^{-1} of N was applied at 6 WAP. Weeds other than witchweed were regularly removed manually. The same management practices were used for both coated and uncoated treatments at all locations.

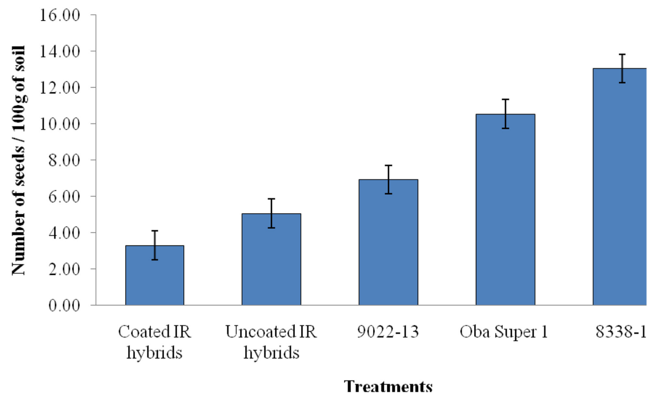
Witchweed seed extraction and counts

At the onset of the experiment when maize was planted, and at harvest in Zaria and Sabongari, soil samples were collected using a soil auger to a depth of 15 cm in plots that were naturally infested with witchweed and bulked to form representative samples. The bulked soil from each plot was mixed thoroughly and air-dried for 1 wk. The soil samples were sieved, and the witchweed seeds were separated from the soil following procedures described by other researchers (Eplee and Norris 1990). A series of sieves was stacked down from 250 through 212 to 90 μm. Each soil sample (100 g) was poured on a small piece of coarse screen placed over the 250 μm sieve to remove the largest particles. The stacked sieves with soil were placed under flowing tap water and the particles sequentially washed through the sieves until they were collected on the 90 μm sieve. Each sieve was washed for 5 min. The witchweed size particles were separated by weight to further reduce the amount of trash in the sample and facilitate subsequent counting by using specific gravity in a separator funnel. A K_2CO_3 solution with a specific gravity of 1.4 was prepared; it was heavier than both water and witchweed seeds. A total of 500 g of K_2CO_3 was mixed with 700 mL of tap water, and 400–500 mL of the solution was poured into a 1 L separator funnel in a ring stand. The contents of the 90 μm sieve were washed with the remaining solution into the separator funnel. Water was slowly added over the K_2CO_3 solution to prevent them from mixing and to wash any adhering particles into the solution and form two layers. The water layer was 200–300 mL thick. After addition of water, the soil and witchweed were allowed to settle for 20 min, after which the heavier particles had precipitated at the bottom of the funnel while the lighter particles were floating on the surface of the water. The intact witchweed seeds were at the water–K_2CO_3 interface. A nylon screen of 60 μm was used to drain off the K_2CO_3 into a beaker, and particles were collected on the screen. After collection, the witchweed seeds on each screen were counted under a dissecting microscope at a magnification of 20–30×. The concentration was determined gravimetrically and expressed as number of seeds per 100 g of dried soil.

Data collection and analyses

Data were collected on maize plant height, numbers of emerged witchweed plants, maize leaf area index (LAI), and grain yield. The data for all traits were recorded for all treatments with both the herbicide-coated and uncoated seeds. Plant height was measured at 12 WAP as the distance from the base of the plant to the height of the first tassel branch. The number of emerged witchweed plants was recorded on a plot basis at 8 and 10 WAP. The LAI of maize was determined using a LI-COR LAI-2000 canopy analyzer at canopy closure, approximately 8 WAP. Measurements (one above canopy and four below canopy) were taken from each treatment. Those below the canopy were made directly underneath the maize row at 20–30 cm above the ground and below the last maize leaf. Grain yield was adjusted to 15% moisture using a moisture tester (model 14998, Dickey-John Corporation, Auburn, IL, USA) and computed from the shelled kernel dry weight.

Fig. 1. Effect of imazapyr coating and maize variety on witchweed seed production in soils at Sabongari and Zaria. Coated, coated with imazapyr; uncoated, no seed coating; IR, imidazolinone resistant; Oba Super 1, a commercial hybrid; 9022-13, a witchweed tolerant hybrid; 8338-1, a susceptible hybrid. [Colour online.]



Levene's test for homogeneity was carried out, and it revealed that the variances were homogeneous. Analysis of variance (ANOVA) was performed for all data combined across years and locations using PROC MIXED in SAS version 8 (SAS Inc., Cary, NC, USA) (Little et al. 1996). Locations, replications, and years were considered as random effects; the coated and uncoated hybrids were fixed effects. Data for number of emerged witchweed plants at 8 and 10 WAP were transformed prior to ANOVA using the formula $Y = \log(X + 1)$, where X refers to the original data obtained for this parameter. This method was used for these data because the variances tend to be heterogeneous. Treatment means were compared using standard error at 5% level of probability.

Results and Discussion

Witchweed seeds in the soil

At the onset of this experiment, when the maize seeds were planted at Zaria and Sabongari under natural infestation, the number of witchweed seeds in the soil did not differ with location. The mean number of seeds in the soil at both locations was 7.4 ± 3.03 seeds per 100 g of soil. There were more witchweed seeds in the soil at the onset of the experiment than at maize harvest (mean = 6.1 ± 2.29).

At maize harvest, no differences were observed in the number of witchweed seeds in the soil for the herbicide seed-coated treatments. For the uncoated treatments, the hybrids significantly influenced the number of seeds in the soil (Fig. 1). The mean number of seeds in the soil with the herbicide-coated hybrids was 3.2 ± 1.58 seeds per 100 g of soil. Across both locations, there were 50% more witchweed seeds in soils with uncoated hybrids than in soils with coated hybrids. The mean number of seeds recorded in all treatments with IR hybrids when coated or uncoated was lower than that recorded at the onset of the experiment and for the three checks when uncoated. The highest number of witchweed seeds was recorded in soils with the uncoated susceptible hybrid check (mean = 13.1 seeds ± 2.29 per 100 g of soil). These had 78.8% more seeds than the IR hybrids when coated and 61.2% more when uncoated. The lower seed population in the soil at harvest may be attributed to reduced production in coated treatments with ST background.

Witchweed shoots

Across the years and locations, there were significant differences in the number of witchweed shoots among the hybrids at 8 WAP. The coated IR hybrids had a comparable number of witchweed shoots which ranged from 0.21 to 0.42 shoots m^{-2} (Table 1). When uncoated, the witchweed susceptible and tolerant hybrids, as well as the commercial hybrid, had more witchweed shoots than those with IR. In general, witchweed emergence was much lower on the coated IR hybrids (mean = 0.29 ± 0.05 shoots) than the uncoated (mean = 0.64 ± 0.07 shoots). The witchweed susceptible hybrid had the highest number of shoots, which was 82.4% higher than that in the coated IR hybrids and 61.2% higher than that in the uncoated IR hybrids.

At 10 WAP, all the seed-coated IR hybrids had a similar number of witchweed shoots (mean = 0.52 ± 0.06 shoots). All the uncoated IR hybrids had more shoots than the coated ones. The three uncoated checks had higher shoot numbers than the uncoated IR hybrids. The witchweed susceptible hybrid check had 55.4% more counts than the IR hybrids without herbicide coating and 68.7% more counts than the coated ones. Witchweed was absent in plots with seed-coated non-IR hybrids that did not germinate. Overall, numbers of witchweed shoots were higher at 10 WAP than at 8 WAP.

The lower counts of witchweed shoots, including the number of seeds in the soil with the coated IR hybrids when compared with the uncoated IR hybrids or the uncoated witchweed susceptible hybrid check, showed that imazapyr was effective in reducing the number of attached parasites on these hybrids, as well as the concentration of seeds in the soil. Several studies have demonstrated the effectiveness of IR maize hybrids treated with imazapyr in controlling witchweed (Abayo et al. 1996, 1998; Berner et al. 1997; Kanampiu et al. 2001, 2006, 2007, 2018; De Groote et al. 2007; Kabambe et al. 2008; Menkir et al. 2010; Chikoye et al. 2011). The absence of witchweed plants in plots with coated non-IR hybrids was because the herbicide killed these hybrids, and therefore, there were no maize plants for the weed to parasitize. These results are consistent with previous findings (Menkir et al. 2010; Chikoye et al. 2011). The higher counts of witchweed shoots obtained at 10 WAP than earlier in the season

Table 1. Effect of imazapyr seed coating on witchweed shoots at Abuja, Mokwa, Sabongari, and Zaria in 2007 and 2008.

	Witchweed shoots (No. m^{-2})			
IR hybrid	8 WAP		10 WAP	
Code/controls	Coa	Unc	Coa	Unc
1	0.23	0.50	0.45	0.57
2	0.31	0.68	0.55	0.77
3	0.27	0.65	0.48	0.75
4	0.24	0.43	0.37	0.53
5	0.27	0.64	0.48	0.77
6	0.31	0.69	0.46	0.70
7	0.21	0.50	0.40	0.63
8	0.22	0.52	0.51	0.63
9	0.33	0.72	0.63	0.79
10	0.42	0.83	0.77	0.95
11	0.36	0.60	0.61	0.76
12	0.29	0.79	0.53	0.83
8338-1	—[a]	1.65	—	1.66
9022-13	—	1.27	—	1.29
Oba Super 1	—	1.52	—	1.60
SE (±)	0.05	0.07	0.06	0.07
Year (Y)	***	***	**	***
Location (L)	***	***	***	***
Y × L	***	***	***	NS
Entry (E)	***	***	***	***
Y × E	*	NS	NS	NS
L × E	***	NS	NS	NS
Y × L × E	***	NS	NS	NS

Note: Means were separated using standard error (SE). ***, $P \leq 0.0001$; **, $P \leq 0.01$; *, $P \leq 0.05$. WAP, weeks after planting; NS, not significantly different; Coa, imazapyr-coated hybrids; Unc, uncoated hybrids; IR, imidazolinone resistant; Oba Super 1, a commercial hybrid; 9022-13, a witchweed tolerant hybrid; 8338-1, a susceptible hybrid.

[a]This does not mean witchweed damage but indicates that the non-IR hybrids (8338-1, 9022-13, and Oba super 1) did not germinate.

could possibly be attributed to a reduction in the concentration of imazapyr in the soil over time. The herbicide gradually dissipated and probably leached down the soil profile, and its concentration in the maize root zone was therefore reduced with time (Kanampiu et al. 2018). This did not adversely affect the maize because this technology ensures that witchweed is controlled early in the season and thus favors early crop establishment.

Maize height

Averaged over years and locations, all the seed-coated IR hybrids had similar height (mean = 215 ± 2.81 cm) (Table 2). The three hybrid checks without the IR gene did not germinate at all locations when coated with imazapyr. This confirms that the herbicide was phytotoxic to these hybrids. Similar findings have also been

Table 2. Effect of imazapyr seed coating on maize height, leaf area index (LAI), and grain yield at Abuja, Mokwa, Sabongari, and Zaria in 2007 and 2008.

IR hybrid	Maize height (cm)		LAI (cm^{-2})		Grain yield (kg ha^{-1})	
Code/controls	Coa	Unc	Coa	Unc	Coa	Unc
1	211.6	221.7	2.9	2.6	3671	3246
2	218.4	224.2	2.8	2.7	3615	3450
3	216.1	219.8	2.7	2.7	3646	3360
4	207.9	217.9	2.8	2.7	3362	3051
5	221.8	228.2	2.9	2.9	3175	3159
6	215.6	219.0	2.8	2.6	4009	3448
7	210.9	217.9	2.6	2.6	3127	2923
8	219.7	225.8	2.8	2.7	3847	3497
9	212.9	219.2	2.7	2.6	4232	3650
10	221.4	228.7	2.8	2.7	3743	3435
11	213.7	221.2	2.9	2.7	3334	3180
12	209.8	212.6	2.8	2.7	3006	2789
8338-1	—[a]	119.2	—	1.8	—	395
9022-13	—	174.7	—	2.5	—	1438
Oba Super 1	—	182.4	—	2.6	—	1529
SE(±)	2.81	3.83	0.08	0.09	208.61	218.83
Year (Y)	NS	***	***	***	**	**
Location (L)	***	***	***	***	***	***
Y × L	***	***	***	***	***	***
Entry (E)	***	***	***	***	***	***
Y × E	NS	*	NS	***	NS	NS
L × E	***	***	**	**	**	NS
Y × L × E	*	NS	***	NS	NS	NS

Note: Means were separated using standard error (SE). ***, $P \leq 0.001$; **, $P \leq 0.01$; *, $P \leq 0.05$. NS, not significantly different; Coa, imazapyr-coated hybrids; Unc, uncoated hybrids; IR, imidazolinone resistant; Oba Super 1, a commercial hybrid; 9022-13, a witchweed tolerant hybrid; 8338-1, a susceptible hybrid.

[a]The non-IR hybrids (8338-1, 9022-13, and Oba super 1) did not germinate.

reported by other scientists (Berner et al. 1997; Menkir et al. 2010; Chikoye et al. 2011).

There were significant differences in the heights of the hybrids that were not coated with the herbicide. In general, all the IR hybrids were taller than the three checks without the IR gene by 16%–46%. All the uncoated IR hybrids were similar in height (mean = 221 ± 3.83 cm) (Table 2). The shortest plants were observed in the witchweed susceptible hybrid check which had a reduction of more than 45% in height. The IR hybrids had comparable heights when coated or uncoated and when under infestation. These results indicate that there was no crop injury resulting from the herbicide coating in the IR hybrids. Similar results have been reported by earlier researchers (Kanampiu et al. 2001; Chikoye et al. 2011).

Maize LAI

The LAI among herbicide-coated and uncoated hybrids was significantly affected by infestation. All the IR coated hybrids had similar LAI across all years and locations (mean = 2.8). The LAI of the IR hybrids without seed treatment was similar (mean = 2.7) and comparable with that of the witchweed tolerant and commercial hybrid checks (Table 2). The witchweed susceptible hybrid check had the lowest LAI, possibly due to competition. This is not surprising because that hybrid had the highest number of witchweed shoots and sustained the highest damage.

Grain yield

The year × location × hybrid interactions did not significantly influence the yield of the seed-coated and uncoated hybrids (Table 2). Across both years and all locations, nine of the IR seed-coated hybrids (Nos. 1, 2, 3, 4, 6, 8, 9, 10, and 11) had higher yields than the others. The nine high-yielding hybrids out-yielded the other three IR hybrids (Nos. 5, 7, and 12) by 17%. When seeds of the three hybrid checks without the IR gene were coated with imazapyr and planted at the four locations they did not germinate, and therefore did not produce any grain.

Across both years and all locations, the uncoated IR maize hybrids had similar and higher grain yields than those for all the checks (Table 2). The lowest grain yield among these treatments was recorded in the witchweed susceptible hybrid check. The uncoated IR hybrids out-yielded the susceptible hybrid by 88%, the witchweed tolerant hybrid by 56%, and the commercial hybrid by 53%. The mean grain yield among uncoated IR hybrids (3266 ± 208.61 kg ha^{-1}) was lower than that for the coated ones (3564 ± 219.02 kg ha^{-1}). In general, each IR hybrid had higher grain yield when the seeds were coated than when they were not. Seed coating of maize with imazapyr resulted in an adequate reduction in witchweed damage leading to an increase in grain yield. Several studies have also shown higher grain yield in plots that received herbicide seed treatment (Kanampiu et al. 2003, 2018; Chikoye et al. 2011; Makumbi et al. 2015).

The 12 herbicide-coated and uncoated hybrids that combined IR with ST, evaluated under artificial and natural witchweed infestation in our study, sustained less yield loss and supported fewer emerged witchweed shoots than the uncoated witchweed susceptible and tolerant hybrids, as well as the commercial hybrid check. However, nine of these IR hybrids with ST that were seed-coated were even more promising as they had the highest yields in both on-station and on-farm trials. Maize seed coating resulted in increased grain yield and a further reduction in witchweed shoot emergence or damage, possibly because the herbicide adequately managed the weed and prevented seed formation (data not shown). Consequently, a combination of these control options (herbicide seed treatment and genetic resistance) would serve as an effective integrated approach that would drastically reduce the parasite seed bank from the soil and prevent production of new seeds. The hybrids with the IR gene and ST provided enough crop tolerance to imazapyr and witchweed. These results are very encouraging because the modified ALS gene conferring herbicide resistance was incorporated into several tropical maize varieties with genes for resistance to the parasite. The performance of several OPVs tested in diverse environments revealed outstanding performance of selected varieties. Their use for witchweed control would reduce the seedbank and increase grain yield (Makumbi et al. 2015). In another study, Kanampiu et al. (2018) also reported that IR maize hybrids treated with imazapyr herbicide and IR OPV were effective in controlling witchweed. The IR hybrids used in our study are well adapted to the different savannah zones and should be extensively tested in on-farm trials to promote them for witchweed control in Africa.

Acknowledgements

This research was funded by IITA. We are grateful to all staff members who were involved in conducting the field trials and Rose Umelo for editorial assistance.

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