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Research Article

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Combined use of improved maize hybrids and nitrogen application increases grain yield of maize, under natural *Striga hermonthica* infestation

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Abstract: *Striga hermonthica* (Del.) Benth infestation is one of the major constraints to maize production in the Nigeria savannas. The application of nitrogen fertilizer to *Striga*-resistant hybrids may reduce *Striga* infection and increase grain yields. The objective of this study was to assess the performance of six maize hybrids at low (30 kg ha^{-1}) and high (120 kg ha^{-1}) nitrogen application under natural infestation with *Striga* in northern Nigeria in 2014 and 2015. The two nitrogen rates and the six hybrids were arranged in a split-plot design with three replications. The nitrogen treatment was assigned to the main plot while the maize hybrids were assigned to the subplot. Data were collected on number of emerged *Striga* plants, *Striga* damage score, total dry matter and grain yield. Results showed that the application of nitrogen at 120 kg ha^{-1} reduced the number of *Striga* plants by 58% compared to application at 30 kg N ha^{-1} in Kafin Madaki and by 48% in Tudun Wada. Nitrogen application at 120 kg N ha^{-1} also reduced *Striga* damage rating by 22% in Kafin Madaki and by 33% in Tudun Wada. Both the commercial hybrid (OBASUPER 1) and the susceptible hybrid (8338-1) exhibited higher *Striga* damage ratings compared to the new hybrids at both locations. Grain yield was 86 and 98% higher in Kafin Madaki and Tudun Wada, respectively, when N was applied at 120 kg N ha^{-1} than at 30 kg N ha^{-1}. The hybrids M1124-3 and M1227-14 produced grain yields that were significantly higher than those of the other hybrids in all locations. Our results showed that the application of 120 kg N ha^{-1} to *Striga*-resistant maize hybrids will reduce *Striga* infection and increase grain yield.

Keywords: *Striga* infestation, *Striga* damage score, yield loss, nitrogen application, maize hybrids

1 Introduction

Maize is a dominant crop in the savanna cropping systems of most sub-Saharan African (SSA) countries [1]. It is considered a strategic food security crop consumed by a number of consumers along the crop's value chain. Owing to its high yielding potency, stress-tolerance, and wide adaptation to the major agro-ecological zones across the SAA sub-region [2], maize production has been increasing throughout the last three decades [3]. In Nigeria, maize is the second most important cereal crop after rice [3], and it directly provides a source of food to over 70% of the country's population. Majority of the maize produced in Nigeria (>75%) is being cultivated by smallholder farmers who faced a range of biophysical production challenges [4,5]. As a result of this, yields are unrealistically as low as less than 2 t/ha, compared with that (>5 t/ha) reported from experimental fields, and under similar biophysical conditions [6].

Among the several biophysical constraints to maize production, drought and poor soil fertility [6,7], and the parasitic weed, *Striga hermonthica* (Del.) Benth) [8,9], pose some serious threat to the productivity of maize and other staple cereals in Nigeria. In the absence of timely control measures, the parasitic weed *Striga* can cause yield losses between 20 and 80% or total crop failure when infestation is

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acute [10,11]. More threatening, *Striga* infestation has been attributed to low soil fertility (especially nitrogen and organic carbon) and poor structure and land use intensification [12,13], and these are all present in the major maize production areas of Nigeria. Yield losses due to *Striga* in the production systems in Nigeria depend on the level of infestation, soil fertility status, agro-climatic conditions, the plant species, and the crop variety grown [14]. Surveys in the northern Guinea savanna (NGS) of Nigeria reported serious *Striga* infestation on millet (*Pennisetum glaucum* (L.) R. Br.), sorghum (*Sorghum bicolor* L. Moench), maize (*Zea mays* L.), and upland rice (*Oryza sativa* L.) [15]. Over 85% of the surveyed fields planted with maize and sorghum in northeast Nigeria were found to be infested with *Striga* [16]. A similar field study conducted in the area showed that *Striga* incidence ranges from 0 to 100% in farmers' maize fields [14]. The most important *Striga* species in Nigeria and West Africa at large is *S. hermonthica.* The parasite impairs host normal growth by developing and attaching their haustoria to the host xylem, hence drawing water and nutrients, resulting in a stunted growth, reduction of biomass, and poor grain filling [17].

Several methods have been recommended for the control of *Striga* in maize fields. These include the use of *Striga*-tolerant or resistant maize cultivars [18,19], application of nitrogen particularly for poor soils [20,21], legume–maize rotation [22,23], and herbicide seed coating [24]. Maize breeders at the International Institute of Tropical Agriculture (IITA) have considered breeding for polygenic resistance to *Striga* as a viable approach to provide durable protection to the crop against diverse parasite populations [25]. As a result, significant increases in grain yield, coupled with reductions in parasite-induced damage symptoms, and number of emerged parasites have been reported [25–27]. Significant progress has been made in the deployment of some extra-early, early, and late maize cultivars that combine resistance/tolerance to *Striga* with drought tolerance [25,28].

The application of nitrogen has been reported to be effective in reducing *Striga* infection and damage in maize [21,29]. Adequate nitrogen, especially urea and cereal–legume rotation, had been reported to be effective in reducing *Striga* emergence, damage, and increasing dry weight in maize and sorghum [21,30]. Most studies, however, reported that the effect of nitrogen on *Striga* infection is only effective at very high doses [21]. Rates between 120 [21] and 280 kg N ha^{-1} [31] reduced *Striga* damage on cereal crops, such as maize and sorghum. Kamara et al. [20] also reported significant reductions in the number of emerged *Striga* at N application of 120 kg N ha^{-1} for early-maturing varieties and 60 kg N ha^{-1} for late maturing varieties in northeast Nigeria. Showemimo et al. [15] reported that a combination of fertilizer between 50 and 100 kg N ha^{-1}, and some level of *Striga* tolerance reduced *Striga* emergence and increased sorghum grain yield. Farmers in Nigeria, however, do not generally apply high doses of N to maize crops because of high cost. This makes it difficult to rely on N application alone to control *Striga* infection in maize.

The combination of the use of *Striga*-resistant or tolerant maize varieties or hybrids with the application of N fertilizers has been reported to significantly reduce *Striga* infection and damage in maize. For example, Kim et al. [21] reported that the application of between 120 and 150 kg ha^{-1} of N to *Striga*-tolerant maize hybrids reduced the number of emerged *Striga* and *Striga* damage in maize under artificial infestation. Under natural field infestations, Kamara et al. [20] reported significant reduction of number of emerged *Striga* and *Striga* damage on open-pollinated varieties (OPVs) of maize that were bred for resistant to *Striga* when N was applied between 60 and 120 kg ha^{-1}. The *Striga* infection in maize can be managed by integrating appropriate resistant and tolerant maize varieties with adequate N fertilization.

Previous studies on the combined effects of improved maize varieties and N application on *Striga* emergence and damage had considered either *Striga*-tolerant hybrids [21,32] or *Striga*-resistant/tolerant open-pollinated maize varieties [29]. Most of the reports on the effects of N application to *Striga*-resistant and tolerant maize genotypes on *Striga* infection and damage in Nigeria have focused on OPVs except for the studies of Kim et al. [21,32]. Recently, breeders at IITA have developed several high-yielding modern maize hybrids that are resistant and/or tolerant to *Striga* infection (Abebe Menkir, personal communication). These hybrids were, however, evaluated under artificial *Striga* infestation. Information on their performance under natural infestation of *Striga* is not known. Moreover, the combined effects of these hybrids and N application are not known. Therefore, there is a need to evaluate these hybrids at low and high doses of N application under natural *Striga* infestation. The objective of this study was to assess the effect of two N fertilizer rates on *Striga*-resistant maize hybrids in fields naturally infested with *Striga.*

2 Materials and methods

2.1 Experimental sites

This study was conducted at Kafin Madaki (N 10°42.296′ E009°46.536′ altitude 623 m above sea level [asl]) in the Sudan savanna in Bauchi State and at Tudun Wada (N 11°13.123′ E 008°29.969′, altitude 621 m asl) in the NGS of

Kano State; both sites are located in the northwest Nigeria. The site selection was guided by prior knowledge of high endemic and recurrent *Striga* infestation when cereals are planted. Both the experimental sites are characterized by mono-modal rainfall distribution. The weather conditions of the two sites during the 2-year (2014–2015) experimental period are shown in Figure 1. The weather variables which include total monthly rainfall and monthly average of minimum and maximum temperatures and solar radiation were recorded using WatchDog 2000 series weather station, installed at each site. At Kafin Madaki, total annual rainfall was 559 and 880 mm, respectively, for 2014 and 2015. Although the rainfall was higher in 2015 the distribution was more uniform in 2014. Average minimum temperature during the seasons was 22.1°C in 2014 and 22.4°C in 2015. Average maximum temperature was 34.7°C in 2014 and 35.3°C in 2015. At Tudun Wada, rainfall was higher in 2014 (1,064 mm) than in 2015 (893 mm). Across 2 years, amount of rainfall for the Tudun Wada site was highest in August with rainfall distribution being more normal in 2014. Average maximum temperature was 33.4°C in 2014 and 33.8°C in 2015. The temperature was higher around March to May, and then lowered from July in both experimental years.

Soil analysis results for the two locations in Table 1 show little variation in the soil particle composition of both locations between the experimental years. The soil pH in Kafin Madaki was moderately acidic (6.0) in 2014 and slightly alkaline (7.1) in 2015. At Tudun Wada, pH was neutral (6.6) in 2014 and then slightly alkaline (7.3) in 2015. Across the two locations pH was generally lower in 2014 than in 2015. Also, organic carbon was very low at both locations in 2014; 3.2 and 2.4 g/kg in 2014 at Kafin Madaki and Tudun Wada, respectively, and 7.9 and 5.6 g/

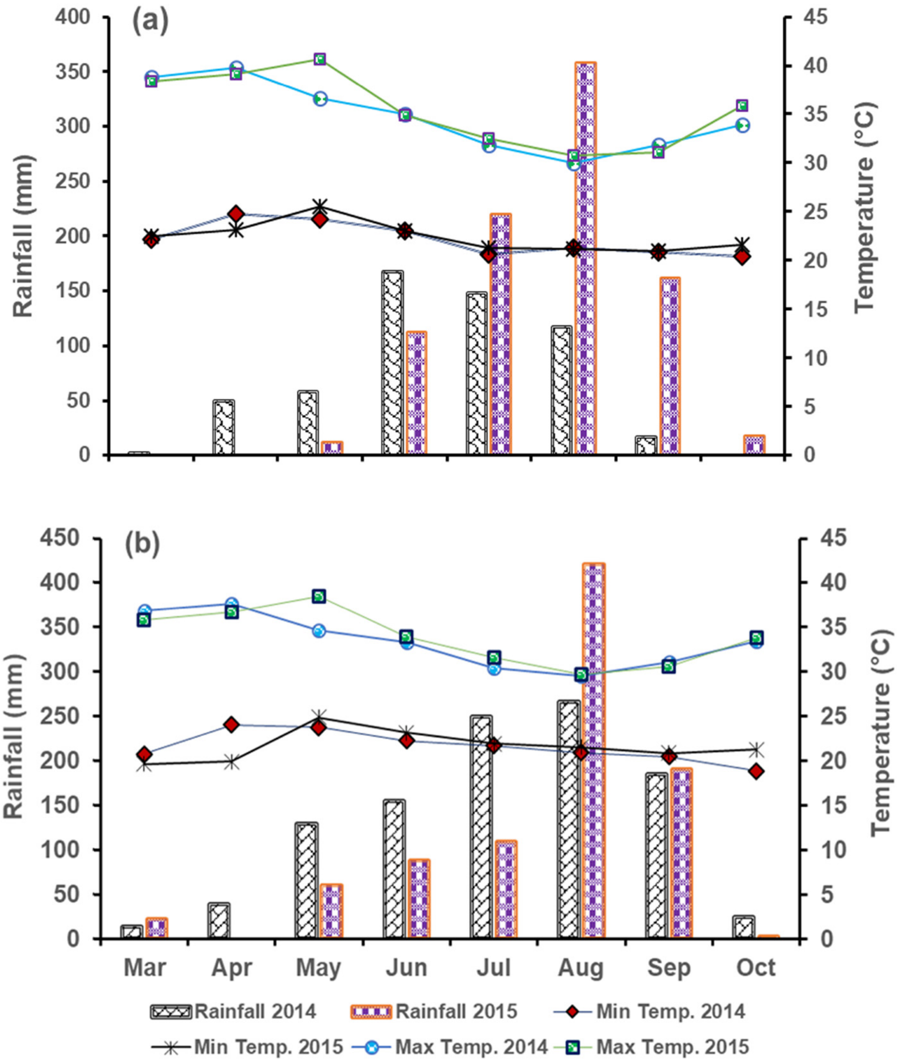

Figure 1: Rainfall and temperature values for Kafin Madaki (a) and Tudun Wada (b) experimental sites for 2014 and 2015 seasons.

Table 1: Physico-chemical properties of soils for the experimental sites

Soil properties	Kafin Madaki		Tudun Wada	
	2014	2015	2014	2015
Mechanical analysis (0–15 cm)				
Sand (g/kg)	793	790	776	770
Silt (g/kg)	122	120	78	80
Clay (g/kg)	85	90	146	150
Textural class	Sandy-loam	Sandy-loam	Sandy-loam	Sandy-loam
Chemical analysis				
pH in H_2O	6.00	7.10	6.60	7.30
Organic carbon (g/kg)	3.20	7.90	2.40	5.60
Total N (g/kg)	0.30	1.05	0.19	0.40
Available P (mg/kg)	3.39	13.70	3.70	7.88
Echangeable bases (cmol (+) kg^{-1})				
Ca	1.06	1.00	1.98	1.92
Mg	0.53	0.25	0.60	1.17
K	0.21	0.30	0.20	0.26
Na	0.09	0.06	0.11	0.07
CEC	1.98	4.80	2.77	4.00

kg in 2015 for Kafin Madaki and Tudun Wada, respectively. Total nitrogen is rated low using Esu [33] classification, at both locations with Kafin Madaki having 0.3 g/kg while Tudun Wada had 0.19 g/kg in 2014. In 2015, the total nitrogen content is rated moderate, 1.05 and 0.40 g/kg, respectively, for Kafin Madaki and Tudun Wada. Available phosphorus is rated very low, with values of 3.39 and 3.70 mg/kg, respectively, for Kafin Madaki and Tudun Wada in 2014. The available phosphorus values were moderate (13.7 mg/kg for Kafin Madaki and 7.88 mg/kg for Tudun Wada) in 2015. Exchangeable cations (Ca, K, and Na) were also higher in 2015 than in 2014 across the sites. Following Esu [33] fertility rating criteria, exchangeable cations across the sites fall under low fertility class a fertility rating apart from 4.8 Mg which is moderate.

2.2 Experimental design and treatments

The experiment was conducted under rainfed conditions in 2014 and 2015 on adjacent pieces of land. Prior to this study, the fields have been dominantly cropped with sorghum and have a history of high level of *Striga* infestation. The fields were prepared for the experiment, first, by plowing using a tractor, and ridged using draught animals. Six maize hybrids (four hybrids combining tolerance to drought with resistance to *Striga* (DTSTR) developed in the maize breeding program at IITA plus a commercial and a susceptible hybrid checks) were assessed at two nitrogen rates under natural infestation with *Striga*. The characteristics of the hybrids are shown in Table 2. The experiment was arranged in split plot design with three replications. Nitrogen treatment with application rates of 30 and 120 kg N ha^{-1} was assigned as main plot treatment. The maize hybrids were assigned to the subplot. Each plot consisted of four rows of 4 m length spaced 0.75 m apart. The maize hybrids were sown on the ridges at a spacing of 0.5 m between planting stations. Three maize seeds were initially sown in each planting hole at a depth of 5 cm. Two weeks after planting all plants were thinned to two per station to give a final recommended plant population of 53,333 plants ha^{-1}. All the plots received 40 kg ha^{-1} each of P_2O_5 (in the form of single super phosphate) and K_2O (in the form of muriate of potash) as basal application on the date of planting. The fertilizers were band-applied on ridges approximately at a distance of 0.05 m from the planting holes. Nitrogen was applied in the form of urea in two equal splits (depending on the application rate) a week after sowing (WAS) and then at five WAS. Immediately after sowing, gramozone (1:1-dimethly-4, 4′-bipyridinium dichloride) was applied at a rate of 280 g a.i ha^{-1} to control weeds. Hoe weeding was done at four WAS. Subsequently, hand pulling of weeds was done regularly to keep the field clean.

2.3 Measurements

Striga damage symptoms and number of emerged plants were recorded from both locations. Damage symptoms were visually rated on the maize plants from the two middle rows at 10 and 12 WAS using a scale of 1 to 9, where 1 = no visible symptoms and 9 = all leaves completely scorched resulting in premature death [34,35]. Similarly, *Striga* count was done by individually counting all emerged *Striga* plants within the two inner rows (amounting to 7.5 m^2) of each plot at 12 WAS and the number was converted to per meter square. Maize grain yield was determined by harvesting all the ears of plants in the two middle rows, excluding the last two plants of each row. The ears from each plot were dried, shelled, and the percentage grain moisture was determined using a FARMEX MT-16 grain moisture tester (Model HH21 GH350142 from Farmex manufacturers Finland). Grain yield adjusted to 12% moisture was computed from the shelled grains.

2.4 Statistical analysis

Statistical analysis of the data was done with SAS version 9.3 [36]. The data were analyzed separately for each

Table 2: Characteristics of maize hybrids used in the study

Entry	Hybrid name	Color	Seed size	Reaction to *Striga*
1	M1124-3	White	Large	*Striga* resistant and drought tolerant
2	M1124-4	White	Medium	*Striga* resistant and drought tolerant
3	M1227-14	White	Large	*Striga* resistant and drought tolerant
4	M1227-17	White	Large	*Striga* resistant and drought tolerant
5	OBASUPER 1	White	Medium	Commercial hybrid
6	8338-1	White	Small	Susceptible hybrid

location using mixed-model procedure using the PROC Mixed command of SAS [36]. Replication and year were treated as random effect, whereas nitrogen rates and hybrids were treated as fixed effects in determining the expected mean squares and appropriate *F*-test. Mean differences of treatments were separated at 5% probability level using LSD.

3 Results

Summary of the analysis of variance (Table 3) shows that the variation between the experimental years (Y) was significant for all measured traits, except *Striga* count in Kafin Madaki and *Striga* damage rating at Tudun Wada. Nitrogen had a significant effect on all measured traits in both locations, whereas nitrogen (N) × year (Y) interaction had significant effect only on grain yield in the two locations. Differences among hybrids (H) and the H × Y interaction were significant for all traits, except the H × Y interaction for *Striga* damage rating in both locations. The H × N interaction was only significant for grain yield in both locations. The H × Y × N was significant for total dry matter and grain yield at Kafin Madaki and for only grain yield at Tudun Wada.

The application of nitrogen at the rate of 120 kg ha^{-1} reduced the number of emerged *Striga* plants by 58% at Kafin Madaki and by 48% at Tudun Wada compared to the application of 30 kg N ha^{-1} (Table 4). Among the hybrids, OBASUPER 1 and 8338-1 recorded larger number of emerged *Striga* plants than the new DTSTR hybrids at the two locations. The difference among the new hybrids was not significant in Kafin Madaki. In Tudun Wada, the number of emerged *Striga* counted on hybrid M1227-17 was significantly higher than those counted on other DTSTR hybrids (Table 4).

Striga damage rating was significantly affected by nitrogen level and hybrids at both locations. On an average, increasing nitrogen application from 30 to 120 kg ha^{-1} significantly reduced the *Striga* damage rating by 22% at Kafin Madaki and by 33% at Tudun Wada. The *Striga* damage rating was highest on the susceptible hybrid 8338-1 at both locations. The new DTSTR hybrids had damage ratings that were significantly lower than the commercial hybrid (OBASUPER 1) and the susceptible hybrid 8338-1 checks at the two locations. Differences among the new DTSTR hybrids in *Striga* damage rating

Table 3: *p*-Values of year, nitrogen level, hybrids, and their interactions on *Striga* count, *Striga* damage rating, total dry matter, and grain yield in Kafin Madaki and Tudun Wada

Sources of variation	Kafin Madaki				Tudun Wada			
	Striga count (m^{-2})	*Striga* damage rating	Total dry matter (m^{-2})	Grain yield (kg ha^{-1})	*Striga* count (m^{-2})	*Striga* damage rating	Total dry matter (m^{-2})	Grain yield (kg ha^{-1})
Year (Y)	0.2375	0.0009	<0.0001	0.0417	<0.0001	0.5286	0.0034	<0.0001
Nitrogen level (N)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Y × N	0.1167	0.6411	0.5208	<0.0001	0.3597	0.211	0.4157	<0.0001
Hybrid (H)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H × Y	0.0489	0.6907	0.0013	0.0001	0.0022	0.5786	0.0019	<0.0001
H × N	0.4659	0.1638	0.3407	0.0421	0.899	0.3032	0.3315	0.0025
H × Y × N	0.2118	0.8867	0.0394	0.0005	0.7472	0.7557	0.5949	0.01

Table 4: Combined effect of maize hybrids and nitrogen application rates on *Striga* count, *Striga* damage rating, and total dry matter in Kafin Madaki and Tudun Wada

Hybrids	***Striga* count (m^{-2})**			***Striga* damage rating**			**Total dry matter ($g\ m^{-2}$)**		
	30 kg N ha^{-1}	**120 kg N ha^{-1}**	**Mean**	**30 kg N ha^{-1}**	**120 kg N ha^{-1}**	**Mean**	**30 kg N ha^{-1}**	**120 kg N ha^{-1}**	**Mean**
Kafin Madaki									
M1124-3	6.8	1.7	4.3	4.8	3.0	3.9	938.9	1216.1	1077.5
M1124-4	2.5	1.7	2.1	4.3	3.2	3.8	910.8	1103.6	1007.2
M1227-14	3.3	1.0	2.2	4.2	3.3	3.8	865.2	1333.5	1099.3
M1227-17	4.7	1.5	3.1	4.3	3.0	3.7	791.8	1136.0	963.9
8338-1 ©	14.3	6.8	10.6	5.7	4.8	5.3	342.3	637.8	490
OBASUPER1 ©	17.0	7.7	12.3	4.3	4.2	4.3	757.2	870.4	813.8
Mean	8.1	3.4		4.6	3.6		767.7	1049.6	
LSD H	2.6			0.6			162.1		
LSD N	1.5			0.4			93.6		
LSD H × N	3.6ns			0.9ns			224.5ns		
Tudun Wada									
M1124-3	2.5	1.3	1.9	5.0	3.2	4.1	772.5	980.8	876.6
M1124-4	2.0	0.3	1.2	4.7	3.7	4.2	653.7	917.2	785.5
M1227-14	2.0	0.3	1.2	4.7	2.8	3.8	752.5	996.6	874.5
M1227-17	4.8	2.7	3.8	5.3	3.7	4.5	654	1040.2	847.1
8338-1©	13.0	8.3	10.7	7.0	4.5	5.8	298.8	505.9	402.4
OBASUPER1 ©	12.7	6.0	9.3	5.7	3.8	4.8	673.7	1115.2	894.5
Mean	6.2	3.2		5.4	3.6		634.2	926	
LSD H	1.7			0.6			129.1		
LSD N	1.0			0.4			74.6		
LSD H × N	2.4ns			0.8ns			178.9ns		

ns = not significant among the hybrids at 5% probability level.

were not significant. The susceptible hybrids 8338-1 and OBASUPER 1 sustained *Striga* damage symptoms exceeding 4.5 across the two levels of nitrogen (Table 4) in both sites.

Nitrogen application increased the total dry matter yield of the hybrids at both locations. Increasing nitrogen application from 30 to 120 kg ha^{-1} increased the total dry matter by 37% at Kafin Madaki and by 46% at Tudun Wada (Table 4). Total dry matter also differed significantly among the hybrids at both locations. Hybrid 8338-1 produced the lowest total dry matter and grain yield at both levels of nitrogen application in the two locations. The total dry matter produced by the new DTSTR hybrids was twice as high as that produced by the hybrid 8338-1 at both locations. The commercial hybrid (OBASUPER 1) produced total dry matter that was comparable to the new DTSTR hybrids at Tudun Wada. However, at Kafin Madaki, the commercial hybrid produced total dry matter that was significantly less than the DTSTR hybrids, except for M1227-17, that produced dry matter that was statistically similar to that of the commercial hybrid. The total dry matter response to nitrogen application did not differ among the hybrids. This was due to the non-significant H × N interaction observed at both the sites. M1124-3 produced the highest total dry matter when nitrogen was applied at 30 kg ha^{-1} at Kafin Madaki, while M1227-14 produced the highest total dry matter at 120 kg N ha^{-1}. Hybrid M1124-3 produced the highest total dry matter at nitrogen application of 30 kg ha^{-1} at Tudun Wada, while OBASUPER 1 produced the highest total dry matter at 120 kg N ha^{-1}.

Across the hybrids, grain yield increased by 87% in Kafin Madaki and by 98% in Tudun Wada when the application of nitrogen was increased from 30 to 120 kg ha^{-1}. The new DTSTR hybrids produced grain yield that was significantly higher than that of the susceptible (8338-1) and commercial (OBASUPER1) hybrids when nitrogen was applied at either 30 or 120 kg ha^{-1} at both locations (Figure 2). The grain yield of the *Striga*-resistant hybrid M1227-14 under 30 kg N ha^{-1} application was statistically similar to that of the susceptible hybrid 8338-1 that was fertilized with 120 kg N ha^{-1} at Kafin Madaki (Figure 2a). At Tudun Wada (Figure 2b), there was a significant yield difference among the hybrids under both nitrogen treatments. At 120 kg N ha^{-1}, two DTSTR hybrids (M1124-3 and M1227-17) produced grain yields that were significantly higher than those of all other hybrids evaluated. The difference in yield among M1124-3, M1227-17, and OBASUPER1 was not significant, while the *Striga*-susceptible hybrid (8338-1) produced the lowest grain yield. At the lower nitrogen rate, however, M1227-14 had the

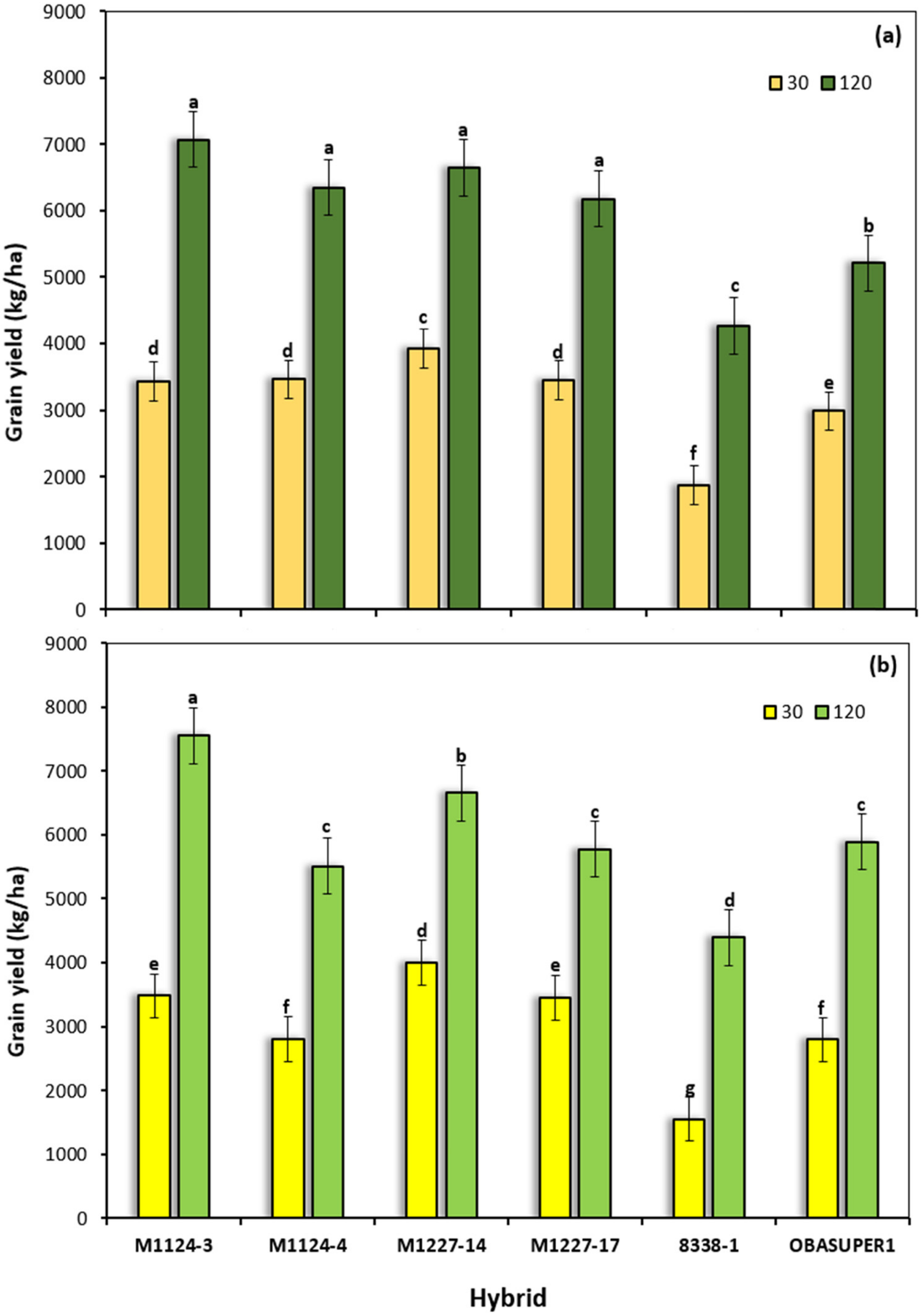

Figure 2: Bar charts showing the mean grain yield of the hybrids under 30 and 120 kg ha^{-1} nitrogen application rates for Kafin Madaki (a) and Tudun Wada (b). The error bars are standard error of means, while letter above each bar represents statistical (in)significance among the mean yield values of the hybrids across the nitrogen rates compared at 5% probability level.

highest yield (4,000 kg ha^{-1}), and 8338-1 having the lowest. Hybrid M1227-14 produced the highest grain yield at both locations under nitrogen application rate of 30 kg ha^{-1}.

Average grain yield across the nitrogen application rates varied significantly among the hybrids at both locations (Figure 3). In both locations, the M1124-3 and M1227-17 hybrids produced similar and higher average grain yields than all other hybrids, followed by the M1124-4 and M1227-17 hybrids, which also produced statistically similar and higher grain yields than the commercial OBASUPER1 and the *Striga*-susceptible 8338-1 hybrids. However, at Tudun Wada, the M1124-4 and M1227-17 hybrids produced grain

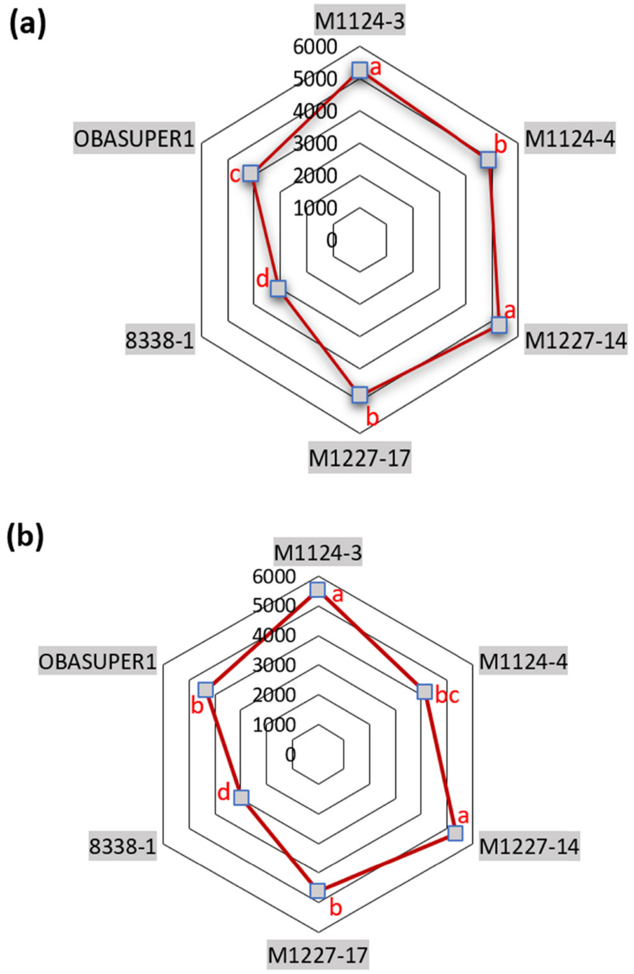

Figure 3: Radar charts representing the average yield levels for all the maize hybrids across the fertilizer application rates for the two locations: Kafin Madaki (a) and Tudun Wada (b). The letter(s) attached to each hybrid mean yield value indicates statistical (in)significance among the hybrids at 5% probability level.

yields that were statistically similar to OBASUPER1. The yield of 8338-1 was the lowest at this location (Figure 3a and b).

4 Discussion

Evaluation of maize under natural infestation is considered important to confirm the performance and effects of *Striga* parasitism [20]. Screening for *Striga* resistance under natural infestation can prove useful when artificial infestation is not effective due to reduction in inoculum load and desirable growing conditions [34]. The poor soil fertility and low soil moisture in the savanna environment are usually associated with high levels of *Striga* seed bank [6] and infestation [14,35]. The low soil contents of organic carbon, total nitrogen, and available phosphorus at both experimental sites, as presented in Table 1, could contribute to high *Striga* infestation. Using boundary line analysis, Aliyu et al. [6] established that high *Striga* seed bank is strongly associated with areas with mild to extreme deficiencies of nitrogen, available phosphorus, and organic carbon. The highest nitrogen application rate of 120 kg ha^{-1} used in this study resulted in reduced *Striga* emergence at the two sites. Similar to our result, a negative relationship between *Striga* infestation level and increased application of nitrogen and both nitrogen and available phosphorus has been reported by Jamil et al. [37]. They reported that increasing rates of nitrogen and phosphorus reduced *Strigolactone* production by maize. The decrease in *Strigolactone* exudation resulted in lower Striga germination and infection. Roobroeck et al. [38] also reported that applying N fertilizer to maize led to a reduction in the number of Striga in Western Kenya. Woldemariam et al. [39] reported that the interaction of N at 92 kg ha^{-1} and cattle manure at 20 t ha^{-1} gave the highest grain and dry matter of sorghum with the least *Striga* counts in north Gondar region of Ethiopia. The lowest biomass, grain, and highest *Striga* count were in the control. Although the mechanism of how the applied nutrients reduces the efficacy of the *Striga* was not explained in those studies, Ayongwa et al. [40] suggested that the addition of nutrients (especially along with organic manure) elevates the soil microbial activity level, which potentially decomposes the *Striga* seeds. Our results are also consistent with the findings of several authors who reported reduced *Striga* infestation when N was applied at high doses [21,29,32]. Furthermore, Yoneyama et al. [41] reported that high *Striga* seed bank and infestation are associated with continuous cereals monoculture (sorghum, maize, and rice) that produce high amounts of Strigolactones that ultimately stimulate the germination of *Striga* seeds. They however, concluded that this scenario is more likely when soils are deficient in N and P. In addition to lowering *Striga* emergence, our study also indicates that high nitrogen application reduced *Striga* damage in the hybrids, corroborating the findings of Kim et al. [21] and Dugje et al. [29] who reported the reduction of *Striga* damage symptoms when nitrogen was applied at high doses. Our results show that although nitrogen application reduced *Striga* infection and damage in the maize hybrids, high doses may be needed for the nitrogen to be more effective in reducing the *Striga* damage. Kim et al. [21] also suggested that high doses of nitrogen are needed for effective suppression of *Striga* infection and damage in maize crops. The results clearly have shown that the use of resistant varieties in combination with high rates of nitrogen fertilizer provided much higher yields than use of susceptible hybrids in *Striga*-infested fields.

In this study, the hybrids 8338-1 and OBASUPER1 had *Striga* counts that were higher than those of the new hybrids combining tolerance to drought with resistance to *Striga*. The hybrid 8338-1 recorded higher damage scores than OBASUPER1 and the new DTSTR hybrids, consistent with the findings of Badu-Apraku et al. [26]. These authors concluded that 8338-1 is susceptible to *Striga*, while OBASUPER1 is tolerant to *Striga* infection. It is interesting to note that hybrids bred for tolerance to *Striga* allow more seed production and high emergence of the parasite with little damage and reduction in grain yield [25].

The lower number of emerged *Striga* on the resistant hybrids was mainly because they were bred for reduced *Striga* emergence consistent with the findings of Dhliwayo et al. [42] and possibly because resistant varieties produce little or no amount of the *Striga*-germination stimulant Strigol [10]. As expected, nitrogen application at 120 kg ha^{-1} significantly increased total dry matter and grain yield of all the hybrids at the two locations, confirming reports from other authors [43] that indicated nitrogen as a major limiting nutrient for maize in the Nigeria savannas. Oikeh et al. [7] reported significant response of maize cultivars to applied nitrogen in the Nigerian savannas with reported yield increase of 130%. Across the nitrogen rates, the new DTSTR hybrids produced grain yields that were 65% higher than the *Striga*-susceptible hybrid 8338-1 at the two locations, and 23 and 13% higher in Kafin Madaki and in Tudun Wada, respectively, than the commercial hybrid OBASUPER1. The new DTSTR hybrids were bred under controlled drought stress and artificial *Striga* infestation and were selected for low *Striga* emergence and damage (A. Menkir, personal communication). Our results show that varieties or hybrids that are bred for low *Striga* emergence and damage produced higher grain yields in fields naturally infested with *Striga*, consistent with findings of Dugje et al. [29]. In on-farm soybean maize rotation experiment in northern Nigeria, Kamara et al. [35] reported that continuously grown *Striga*-resistant maize varieties produced grain yields similar to that of *Striga*-resistant maize variety grown after soybean but had higher grain yields than the local susceptible maize hybrids. The higher dry matter and grain yields recorded in the new DTSTR hybrids may be due to the combined effects of N application and lower *Striga* infection and damage.

5 Conclusions

This study highlighted the usefulness of combined use of improved maize hybrids bred for *Striga* resistance and nitrogen application in reducing *Striga* infection and increasing maize grain yield in *Striga*-infested fields. Results from the field study showed a reduction in *Striga* infestation and damage when nitrogen application rate was increased from 30 to 120 kg ha^{-1} irrespective of maize hybrid. The new DTSTR hybrids used in this study were bred for resistance to *Striga* thus, they allowed only a few number of *Striga* plants to emerge, sustained lower damage scores, and produced higher dry matter and grain yields than the susceptible and commercial hybrids. The application of nitrogen at the recommended rate of 120 kg ha^{-1} in combination with DTSTR hybrids can reduce *Striga* damage and increase grain yield. We conclude that farmers can get better return on their investment when they plant DTSTR hybrids along with optimal level of nitrogen application. In situations of smallholder farmers who cannot afford the optimally recommended 120 kg N ha^{-1} application, the hybrid M1227-14 would most likely give better yield result as it yielded consistently better under the low nitrogen application rate at both locations of this experiment.

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