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Putting Plant Genetic Diversity and Variability at Work for Breeding: Hybrid Rice Suitability in West Africa

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Abstract: Rice is a staple food in West Africa, where its demand keeps increasing due to population growth. Hence, there is an urgent need to identify high yielding rice cultivars that fulfill this demand locally. Rice hybrids are already known to significantly increase productivity. This study evaluated the potential of Asian hybrids with good adaptability to irrigated and rainfed lowland rice areas in Mali, Nigeria, and Senegal. There were 169 hybrids from China included in trials at target sites during 2009 and 2010. The genotype × environment interaction was highly significant ($p < 0.0001$) for grain yield indicating that the hybrids' and their respective cultivar checks' performance differed across locations. Two hybrids had the highest grain yield during 2010 in Mali, while in Nigeria, four hybrids in 2009 and one hybrid in 2010 had higher grain yield and matured earlier than the best local cultivar. The milling recovery, grain shape and cooking features of most hybrids had the quality preferred by West African consumers. Most of the hybrids were, however, susceptible to African rice gall midge (AfRGM) and *Rice Yellow Mottle Virus* (RMYV) isolate Ng40. About 60% of these hybrids were resistant to blast. Hybrids need to incorporate host plant resistant for AfRGM and RYMV to be grown in West Africa.

Keywords: *Oryza sativa*; adaptability; food security; genotype × environment interaction; grain yield; heterosis; hybrid vigor; quality; resilience; sustainability

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1. Introduction

Rice (*Oryza sativa* L.) is the most important staple food crop in the world. About 3.5 billion people depend on rice globally, since this staple provides in excess of 20% of their daily calorie intake [1]. In Africa alone, where currently rice consumption is the most rapidly growing food source, about 30 million t more rice will be required by 2035, thus representing an increase of 130% in rice consumption from 2010. Nigeria would require almost one third of this additional rice [2]. More than 90% of West African rice farmers are smallholders (mostly women) who cultivate less than 1 ha and whose crop yields depend on rainfall. Crop production from these small plots is often insufficient to provide a reasonable household income for maintaining a minimum standard of living. These farmers manage complex farming systems, cultivating rice and other food crops based on its degree of importance as food and as a cash crop, unlike farmers in Asia, where rice is a crop mainly grown in lowland and irrigated agro-ecosystems. The major constrains of global rice production are drought, flood, heat, pathogens, pests, declining productivity in intensive rice production systems, low grain yield in some areas of the developing world, increasing production costs in the industrialized world, and rising public concern regarding sustainability of rice farming. In addition, mechanization, the high cost of irrigated rice production, as well as the poor management of uplands and rainfed lowlands are among the main challenges for producing rice in Africa [3,4].

Advances in rice production in Africa are at various developmental stages due to its relative importance to respective local economy. Hybrid rice seed technology is key for increasing its production and maintaining self-sufficiency and food security. Hybrid rice has been used in rice production for more than 40 years in Asia and North America, and more recently in Egypt because of its high grain yield potential. This yield advantage plus water and nitrogen use efficiency, and host plant resistance to pathogens and pests are the main determining factors for adapting hybrid seed technology in rice production. Heterosis improves grain yield and quality for many crops especially when facing a limited area for farming. Hybrid cultivars have been developed to take advantage of heterosis in the production of many field crops such as cotton, maize, oilseed rape, rice, sorghum, sunflower, and vegetables [5,6]. African farmers may boost rice production by using hybrids particularly in the largely unutilized lowland rice areas. Mali, Nigeria, and Senegal are willing to adopt this seed technology to increase their rice production.

Rice breeders in China led the developing and commercializing of rice hybrids that had 15 to 20% yield advantage [7] or at least 1 t ha^{-1} [8] over inbred cultivars. The new set of Green Super Rice (GSR) hybrids need less chemical inputs to increase grain yields than the old rice hybrids. Likewise, many of these GSR hybrids show adaptation to drought, thereby requiring less water and could be grown in rainfed agro-ecosystems. Nonetheless, their adaptability to African farming systems needs to be assessed across target areas, as well as the relative inputs they require vis-à-vis local cultivars. Farmers need to invest in both seeds and inputs for getting high grain yields when using rice hybrids. The increased grain yield of rice hybrids should pay for this investment and bring profitability to those using this seed technology.

There are various pathogens and pests affecting rice production in Africa. The African rice gall midge (AfRGM; *Orseolia oryzivora*; Diptera: *Cecidomyiidae*) is an important insect pest in irrigated lowland rice areas, causing 25 to 80% grain yield loss in West Africa [9]. AfRGM is an endemic pest to Africa, where was first reported in Sudan, and currently spreading throughout the continent. It can be found in 12 West African, two Central African, and five East and Southern African countries [10]. The insect pest causes 20 to 100% grain yield loss in the worst-affected areas. There are 16 quantitative trait loci (QTL) associated with host plant resistance to AfRGM, of which three are in [ITA306 × BW348-1], five in [ITA306 × TOS14519], and eight in [ITA306 × TOG7106] breeding populations. The major effect genomic region for AfRGM resistance was in the [ITA306 × TOS14519] population, which was at 111cM on chromosome 4 (qAfrGM4), had a LOD score of 60 and accounted for 34.1% of the total phenotypic variance [11]. Likewise, *Rice Yellow Mottle Virus* (RYMV, a Sobemo virus) is another major constraint to rice production in the continent [12] because it causes 17 to 100% grain yield loss according to both the infection date and time, and the cultivar host [13,14]). RYMV is highly infectious to rice, especially to Asian *indica* cultivars in lowland and irrigated agro-ecosystem. RYMV is prevalent in all major rice growing ecosystems of Africa [15]. Rice blast, caused by *Magnaporthe oryzae* (anamorph: *Pyricularia oryzae*) [16], is another serious disease affecting rice in temperate and tropical regions, including Africa [17,18].

The main purpose of this research was to determine the suitability of GSR hybrid cultivars bred in China at the irrigated lowland rice areas of Mali, Nigeria, and Senegal. We assessed their grain yield across suitable West African rice growing areas.

2. Materials and Methods

2.1. Plant Materials

The Chinese Academy of Agricultural Sciences provided two sets of GSR hybrids consisting of 122 and 47 F_1s. Africa Rice included eight inbred rice cultivars that were used as checks because farmers in Mali, Nigeria, and Senegal grow them widely.

2.2. Methods

The multi-location trials were conducted during 2009 and 2010. For each country, two trials were conducted in an augmented design layout [19] in a randomized complete block (RCB), with each cultivar plot comprising of five rows of 3 m length with a plant to row spacing of 20 × 20 cm. In Senegal, 122 hybrids and 13 checks were evaluated during the 2009 wet season (June–November) at Ndiaye (the Africa Rice Research Station near Saint-Louis), and 47 hybrids were evaluated with checks during the 2010 dry season (February–June) 2010 at the Research Station of L' Institut Sénégalais de Recherche Agricole (ISRA) in Fanaye. There are two seasons in Senegal, the rainy season from June to October, characterized by heat, humidity and storms, and the dry season from December to May, characterized by cool ocean breeze and dust from the Harmattan winds. A total of 122 hybrids and 8 checks were evaluated in Mali during the 2010 dry season (January–May) at N'Debougou in the Office du Niger, and 47 hybrids and checks were evaluated during 2010 wet season (June–November) at the Agriculture Research Station in Niono. The Office du Niger irrigation scheme is the largest in West Africa and located in the Segou region of Central Mali. Rainfall in the Office du Niger area ranges from 450 to 600 mm per year. The rainy season lasts three to five months, and the dry season is divided into a cool and a hot period. In Nigeria, 122 hybrids and checks were evaluated during the 2009 dry season (October–April) at the research field of the National Cereals Research Institute (NCRI) in Badeggi, and 47 hybrids evaluated with eight checks during the 2010 wet season (May–October) at Wushishi. Both Nigerian locations are in the Southern Guinea Savanna, a typical rainfed lowland agro-ecology with iron toxicity and high AfRGM severity. The trials used known cultural practices of each country. The fertilizer applications varied as follows: 115–36 kg N–K ha^{-1} in Mali, 80–40–40 kg N–P–K ha^{-1} in Nigeria, and 150–17.5–33 kg N–P–K ha^{-1} in Senegal. The data recorded in the field included plant height, panicles m^{-2}, spikelets $plant^{-1}$, 1000-grain weight and grain yield. Grain quality traits and milling properties of 18 promising hybrids were evaluated at Africa Rice Sahel Station, near Saint Louis, Senegal. The most popular cultivar Sahel 108, widely preferred by farmers and consumers, was used as grain quality check. The traits assessed were brown rice length, grain length and shape, percentage of total milling, alkali-spreading value (ASV), and gelatinization temperature (GT). A high and low GT indicates more or less energy necessary for cooking rice, respectively. All traits were measured according to the standard's evaluation system used by the International Rice Research Institute (IRRI, Manila, Philippines) [20].

2.3. Host Plant Resistance (HPR) to AfRGM, RYMV and Blast

The first set of 122 hybrids along with eight inbred lowland cultivars were evaluated for HPR to AfRGM at a paddy screenhouse in Ibadan, Nigeria during 2009. Two rice cultivars were used as checks: ITA 306 as susceptible and TOS14519 as resistant to AfRGM. Conventional "spreader rows" of the highly susceptible cultivar ITA 306 were around the GSR plants. Newly hatched larvae were deposited on "spreader" plants to increase infestation in the screenhouse [18]. Data were taken 45 and 70 days after transplanting (DAT) to estimate the percentage of tillers infested or damage by AfRGM. In the 2010 wet season, 47 hybrid lines and eight check cultivars were screened for resistance to AfRGM under natural infestation at Edozhigi in Niger State, Nigeria. The GSR hybrids and checks were laid out in an RCB with three replications. Data were taken at 42 and 63 DAT. Rice blast was evaluated in a trapping nursery as described by Sere, et al. [21] on blast hot spot at Ouedeme, Benin in 2009. Trapping nurseries consists of exposing cultivars with known resistance genes to natural inoculum. The reaction of each of the cultivars is an indication of the presence/activation (non-compatible reaction) or absence/inactivation (compatible reaction) of the corresponding avirulence genes without prejudging their association into distinct races. This trapping nursery was laid out in an RCB design. We scored disease severity weekly using IRRI's standard evaluation system [20]. Standard cultivars and near isogenic lines (NIL) were used as checks to define host plant resistance clusters to blast. A highly resistant rating was given to those hybrids similar to the cultivar check and a NIL possessing the gene *Pi9*, while for the resistant cluster the check was the NIL bearing the *Pi2* gene. The susceptible cluster included as checks five NIL with *Pi33*, *Pif*, *Pii*, *Pish*, and *Pi1b* genes. Hybrids were rated as highly susceptible when showing scores similar to a susceptible check and 22 NIL. There were 122 hybrids tested against RYMV through artificial inoculation of two strains (NG-01 and NG-40) in a screenhouse. We included two resistant (Gigante and TOG 5681) and one susceptible check in this screening. RYMV was evaluated 21 and 42 days after inoculation using the standard evaluation system with a 1–9 scale, in which 1 means lack of any symptom and 9 a completely damaged leave. The disease severity score (S) was calculated as $S = \{(n_1 \times 1 + n_3 \times 3 + n_5 \times 5 + n_7 \times 7 + n_9 \times 9) \times 100\}/\{(n_1 + n_3 + n_5 + n_7 + n_9) \times 9\}$, where n_1, n_3, n_5, n_7, and n_9 represent the number of plant scoring 1, 3, 5, 7, and 9, respectively [22]. The following hybrid clusters were defined for both strains according to their host plant resistance scores: (1) rated as the resistant checks, (2) moderately susceptible, and (3) rated as the susceptible checks.

2.4. Statistical Analysis

Data were subjected to an analysis of variance using SAS/STAT 9.2 (SAS Institute, Cary, NC, USA). We investigated the genotype × country interaction (G × E) using a SAS mixed model [23]. If a significant G × E was detected, we analyzed the performance of hybrids and their respective cultivar checks within each country because they performed differently across environments. A multiple comparison adjustment for the probability (p) values was then performed to test whether the adjusted means of the hybrids were significantly higher than the best check for each country at a significance level of $p \leq 0.05$.

3. Results

The G × E was highly significant ($p < 0.0001$) for grain yield in both sets of experiments, thereby indicating that hybrids and check cultivars performed differently across Mali, Nigeria, and Senegal. Hence, we analyzed separately each set of experiments within each country (Table 1).

Table 1. Combined analysis of variance for grain yield of two sets of hybrids and their cultivar checks across sites in Mali, Nigeria, and Senegal.

Source of Variation	DF ^{z}	MSE ^{y}	F Value	*p* Value
First set: 122 hybrids + 13 inbred				
Genotypes (G)	134	4,833,250	2.58	<0.001
Country (E)	2	723,984,958	386.79	<0.001
G × E	240	4,316,391	2.306	<0.001
Error	117	1,871,732		
Second set: 47 hybrids + 13 inbred				
Genotypes (G)	59	6,770,649.3	1.34	0.0990
Country (E)	2	120,454,097.3	23.91	<0.001
G × E	111	6,880,333.9	1.37	0.0496
Error	95	5,038,496.0		

^{z} Degrees of freedom, ^{y} Mean square error.

3.1. Country Performance

Most of the hybrids showed on average 10 days earlier 50% flowering than check cultivars during the 2009 wet season at Saint Louis, Senegal (Table 2a). The best yielding check cultivar, Sahel 108, had the highest number of tillers (23), while hybrids, whose grain yield was above Sahel 108, had 13 to 15 tillers. The promising hybrids QYI, HanF1-39, and HS706 exhibited panicles whose lengths were 25, 24, and 29 cm, respectively, while the panicle of Sahel 108 measured on average 20 cm. There were not significant differences for average of plant height between hybrids and checks cultivars.

The average grain yield of hybrids (7 t ha^{-1}) and checks (6.5 t ha^{-1}) was not significantly different. Only hybrids QYI, HanF1-39, and HS706 had a significant grain yield advantage (38 to 43.5%) vis-à-vis Sahel 108. Most of the hybrids and checks had early flowering (89 and 92 days, respectively) during the 2010 wet season at Fanaye, Senegal (Table 2b). The hybrid CNY498 was the earliest flowering (82 days) and shortest (80 cm). There was no significant difference for average plant height between hybrids (101 cm) and checks (102 cm). The check cultivars showed a higher average number of tillers plant^{-1} and panicle length than the hybrids. The hybrid HS706 had the longest panicle (29 cm), and the hybrid XYR24 was the only one out-yielding significantly the check cultivar Sahel 108.

Table 2. Grain yield and other agronomic traits of promising rice hybrids and best cultivar check (C) at (**a**) Ndiaye (2009 wet season) and (**b**) Fanaye (2010 wet season), Senegal. The *p*-value indicates that hybrids' yield was significantly higher than Sahel 108. Standard errors (S.E.) given for each trait.

Cultivar	Days to 50% Flowering	Plant Height (cm)	Tiller Plant^{-1}	Panicle Length (cm)	Grain Yield (t ha^{-1})	Yield Advantage (%)	*p*-Value
			(a) Ndiaye 2009 Wet Season				
Qy1	80	108	14	25	10.5	43.54	0.0285
HanF1-39	87	97	13	24	10.5	42.86	0.0307
HS706	87	108	15	29	10.1	37.96	0.0480
Sahel 108 (C)	88	86	23	20	7.4		
Hybrid mean	84	102	15	24	7.1	8.91	
Check mean	94	101	18	27	6.5		
Hybrid S.E.	4	5	3	2	1.5		
Check S.E.	2	2	1	1	0.6		
			(b) Fanaye 2010 Wet Season				
XYR24	91	106	20	25	12.2	82.46	0.027
CXY727	93	121	20	25	10.7	59.97	0.077
NEY2123	92	79	20	23	10.6	59.37	0.078
CNY498	82	99	20	27	10.5	57.42	0.085
3LYR24	89	108	20	23	10.3	54.87	0.095
Sahel 108 (C)	87	82	25	23	6.7		
Hybrids mean	89	101	21	21	6.1	59.74	
Check mean	92	102	20	20	3.8		
Hybrid S.E.	4	7	2	3	2.0		
Check S.E.	3	14	2	2	0.9		

There were no significant differences for days to 50% flowering and panicle m^{-2} between hybrids and check cultivars grown during the 2010 dry season at N'Debougou in Mali (Table 3a). The average plant height for the hybrids was 108 cm and 111 cm for the check cultivars. The tallest hybrid, among those out-yielding the best check, was 49youR24 (122.5 cm). The hybrid 49youR24 had the highest number of spikelets per panicle (242), which was about 49% above the best check WITA 9. The average 1000-grain weight of this hybrid (27.5 g) was 23% higher than the average of the checks (23.5 g). Grain yield of the high-yielding promising hybrids ranged from 11.5 to 12.5 t ha^{-1}, but there were not significantly different that the best check cultivar WITA 9 (10.2 t ha^{-1}).

There was an early 50% flowering for both hybrids (88 days) and checks (95 days) during the 2010 wet season at Niono, Mali (Table 2b). XYR24 was the earliest (82 days) among the most promising hybrids due to their high grain yield, though most of these hybrids (and high yielding checks) were among the tallest in this trial. The best hybrids and check cultivar had a high number of spikelets per panicle (152–254). On average the hybrids had less panicles per m^2 (292) than the check cultivars (325), but the hybrid GXY803067 had the most panicles (347). The hybrids' grains weighed higher than the check cultivars; and the hybrid CYX2 had the largest grains. Only one hybrid showed a significantly higher grain yield (14.7 t ha^{-1}) than the best cultivar check NericaL-19 (10.6 t ha^{-1}).

Table 3. Grain yield and other agronomic traits of promising rice hybrids and best cultivar check (C) in 2010 at (**a**) N'Debougou, Mali dry season and (**b**) Niono, Mali wet season. The *p*-value indicates that hybrids' yield was significantly higher that WITA 9 and NERICA-L19. Standard errors (S.E.) given for each trait.

Cultivar	Days to 50% Flowering	Plant Height (cm)	Panicle (m^2)	Spikelets $Panicle^{-1}$	1000 Grain Weight (g)	Grain Yield (t ha^{-1})	Yield Advantage (%)	*p*-Value
(a) N'Debougou Dry Season								
HanF1-35	88	111	168	158	19.8	12.5	22.31	0.0938
HS33	94	108	228	126	27.2	12.0	17.42	0.1508
49youR24	96	122	288	242	27.5	11.5	12.52	0.2282
HanF1-22	95	117	175	187	24.5	11.5	12.52	0.2282
HanF1-30	98	105	214	212	28.5	11.5	12.52	0.2282
WITA 9 (C)	96	109	245	162	22.4	10.2	0.00	
Hybrid mean	96	108	238	164	25.5	6.3	8.58	
Check mean	97	111	237	142	23.5	5.8		
Hybrid S.E.	4	7	27	27	2.1	2.8		
Check S.E.	2	3	11	11	0.8	2.4		
(b) Niono Wet Season								
QS2	92	117	281	246	22.3	14.7	38.57	0.046
GSR-H-0007	89	133	291	152	26.4	12.0	12.89	0.291
CXY2	90	112	331	218	31.4	12.0	12.89	0.291
QS3	90	124	300	175	26.8	11.7	9.78	0.339
ZhongyouR24	85	125	271	254	27.9	11.3	6.59	0.389
GXY803067	89	125	347	183	29.9	11.3	6.59	0.389
NERICA-L19 (C)	92	143	255	209	25.2	10.6	0.00	
Hybrid mean	88	122	292	215	28.0	8.4	−4.99	
Check mean	95	119	325	182	25.3	8.8		
Hybrid S.E.	2	7	45	20	2.0	2.4		
Check S.E.	1	3	20	9	0.9	1.1		

The early sowing date affected days to 50% flowering, and most of the hybrids and check cultivars have their blooming after 100 days in the 2009 dry season at Badeggi (Table 4a). The average number of days to 50% flowering was 104 for the hybrids and 109 days for the check cultivars. Most of the promising hybrids were dwarf to semi-dwarf in plant height; i.e., not exceeding 100 cm. The most promising hybrids had more panicles per area than the best check WITA 4. Grain yield was on average very low for hybrids and checks (2.55 and 2.51 t ha^{-1}, respectively). The grain yield of the most promising hybrids ranged between 4.9 and 5.6 t ha^{-1}, which was at least 50% above the grain yield of the best check cultivar WITA 4. Most of the hybrids had early flowering (about two weeks of advantage than the average of the check cultivars) during the 2010 wet season at Wushishi. TY8022 was the earliest flowering (77 days) hybrid (Table 4b). Most hybrids and checks exhibited a tall plant height (112 and 119 cm on average, respectively). There were no significant differences for grain yield between most promising hybrids (ranging from 8.5 to 11.5 t ha^{-1}) and best check WITA 1 (8.5 t ha^{-1}).

3.2. Grain Quality

All hybrids and check cultivar had medium to long grain types (Table 5). Their grain shape was either medium or slender. The most promising hybrids exhibited milling recovery that was above the check Sahel 108. The hybrid ERHAO had high total milling recovery (70%), slender grain shape and low GT. The hybrids WZY2, CNY 549, and IL YOU Z2 showed the highest total milling recovery (above 70%). Only two promising hybrids had low GT while the others and Sahel 108 exhibited a medium GT.

Table 4. Grain yield and other agronomic traits of promising rice hybrids and best cultivar check (C) at (**a**) Badeggi 2009 dry season and (**b**) Wushishi 2010 wet season. The *p*-value indicates that the hybrids' yield was higher that WITA1 and WITA4. Standard errors (S.E.) given for each trait.

Cultivar	Days to 50% Flowering	Plant Height (cm)	Panicle (m^{-2})	Grain Yield (t ha^{-1})	Yield Advantage (%)	*p*-Value
			(a) Badeggi 2009 Dry Season			
HanF1-26	104	87	294	5.6	58.51	0.0267
XYR24	101	93	395	5.4	74.92	0.0078
3LYR24	112	98	325	5.1	66.25	0.0151
WZY2	109	73	293	4.9	51.08	0.0447
WITA 4 (C)	111	83	279	3.2	0.00	
Hybrid mean	104	93	248	2.6	1.59	
Check mean	109	88	301	2.5		
Hybrid S.E.	6	16	72	0.9		
Check S.E.	2	6	29	0.3		
			(b) Wushishi 2010 Wet Season			
GSR-H-0141	85	104	17	11.5	35.50	0.144
WZY2	84	114	11	9.2	9.08	0.392
GXY3169	92	126	12	9.2	8.84	0.395
IIyou623	96	112	13	8.9	4.83	0.442
TY8022	77	114	12	8.7	2.12	0.475
Huayou7109	79	118	12	8.5	0.59	0.493
WITA 1 (C)	103	146	15	8.5	0.00	
Hybrid mean	84	117	11	6.8	17.12	
Check mean	99	119	15	5.8		
Hybrid S.E.	16	7	4	2.7		
Check S.E.	7	3	2	1.2		

Table 5. Grain traits and milling properties of promising rice hybrids and cultivar check (C) Sahel 108 after harvest in Ndjaye, Senegal during 2009 wet season.

Hybrid	Brown Rice Length (mm)	Grain Length	Grain Shape	Total Milling (%)	Alkali-Spreading Value	Gelanization Temperature (GT)
QY 1	6.3	Medium	Medium	68	5.67	Low
HAN F1-47	6.4	Medium	Medium	69	4.00	Intermediate
HS 706	6.2	Medium	Slender	70	4.58	Intermediate
HAN F1-39	6.3	Medium	Medium	66	3.67	Intermediate
HAN F1-36	6.8	Long	Slender	67	3.50	Intermediate
PLY 1108	6.1	Medium	Medium	70	5.67	Low
QY 3	6.4	Medium	Medium	66	4.00	Intermediate
ERHAO	6.1	Medium	Slender	70	6.67	Low
HAN F1-26	6.7	Long	Slender	69	3.50	Intermediate
HAN F1-31	6.6	Long	Medium	69	3.33	Intermediate
YX 9	6.9	Long	Medium	68	5.33	Intermediate
WZY 2	6.0	Medium	Medium	72	4.67	Intermediate
HAN F1-10	6.4	Medium	Medium	70	3.42	Intermediate
GXY–207	6.9	Long	Slender	69	3.50	Intermediate
CNY 549	6.1	Medium	Medium	72	3.50	Intermediate
HAN F1-9	6.2	Medium	Medium	70	4.42	Intermediate
IL YOU Z2	5.8	Medium	Medium	71	4.25	Intermediate
Sahel 108 (C)	6.1	Medium	Slender	65	3.33	Intermediate

3.3. Host Plant Resistance

Most of the 122 hybrids evaluated at a paddy screen house in Ibadan 2009 were highly susceptible to AfRGM. Only four hybrids (Han F1-21, YG 206, HS 33, and YG 17) were moderately susceptible to this insect pest (Table 6a), while the hybrid FFY66 showed partial resistance (5.9% tiller infestation) to AfRGM under natural infestation during the 2010 wet season at Edozhigi (Table 6b). Among hybrids, FFY66 had the lowest mean plant damage and could be described as possessing an acceptable level of resistance to the pest. The hybrid FFY66 needs to be further evaluated at Edozhigi to confirm its stability and acceptability as possessing desirable or appreciable level of host plant resistance to AfRGM. The population structure of AfRGM in different rice farming systems in West Africa revealed that the biotype at Edozhigi is a virulent type—hence, the high susceptibility of the hybrids to this pest. The percent tiller infestation reduced at 63 days because of other parasites in the fields.

Table 6. Host plant resistance of most promising rice hybrids plus resistant and susceptible check cultivars to African rice gall midge after artificial infestation in screen house at (**a**) Ibadan 2009 wet season and (**b**) Edozhigi 2010 wet season.

Cultivar	Tiller Infestation (%) at 45 DAT ^{z}	Tiller Infestation (%) at 70 DAT	Mean Tiller Infestation (%)	Host plant Resistance Rating ^{y}
		(a) Ibadan 2009 Wet Season		
Han F1-21	7.5	16.1	11.8	MS
YG 206	20.5	17.1	18.8	MS
HS 33	12.3	26.4	19.4	MS
YG 17	21.0	18.1	19.6	MS
ITA 306 (S)	32.1	54.0	43.1	HS
TOS14519 (R)	0.3	0.3	0.3	R
		(b) Edozhigi 2010 Wet Season		
FFY66	5.9	4.4	5.3	MR
Hanyou3	10.0	4.5	7.2	MS
HuF1-8	11.2	3.4	7.3	MS
FFY366	7.7	8.5	8.1	MS
EYH2	11.9	5.5	8.7	MS
QS2	12.7	4.9	8.8	MS
Huhan7A/07ZR15	11.0	7.2	9.1	MS
HLYR24	10.9	8.9	9.9	MS
CXY6	14.8	5.8	10.3	MS
CXY2	15.4	5.4	10.4	MS
HuF1-18	16.5	4.4	10.4	MS
Huhan9A/07ZR15	16.6	4.4	10.5	MS
ITA 306 (S)	20.7	14.9	17.8	S
TOS 14519 (R)	1.0	0.9	1.0	R

^{z} Days after transplanting, ^{y} R: resistant, MS: moderately susceptible, HS: highly susceptible (after [20]).

Table 7. Percentage of rice hybrids showing host plant resistance to *Rice Yellow Mottle Virus* strains Ng-01 and Ng-40.

Days after Inoculation	Isolate	Number of Lines Per Cluster	Host Plant Resistance ^{z}	Hybrid Resistance (%)
21	Ng-01	36	R	35.3
		0	MS	0.0
		66	S	64.7
	Ng-40	26	R	25.5
		31	MS	30.4
		45	S	44.1
42	Ng-01	5	R	4.9
		25	MS	24.5
		72	S	70.6
	Ng-40	0	R	0.0
		28	MS	27.5
		74	S	72.5

^{z} R: resistant, MS: moderately susceptible.

The hybrids were in four clusters according to their host plant resistance to blast when comparing them to known resistance and susceptible standard cultivars and NIL. We noted that two NIL bearing the same resistant gene (IRBLzt-IR56/CO and C104PKT) were in two contrasting clusters. This result could be due to either a non-detected additional major gene or minor sensitive resistant genes [24,25]. The highly resistant cluster included 49 hybrids, while there were 28 hybrids showing partial resistance, 23 hybrids were susceptible, and the remaining 22 hybrids were rated as highly susceptible.

There were 23% and 32% of the hybrids showing host plant resistance to isolates Ng-40 and Ng-01 after two weeks from inoculation (Table 6). With the epidemic progression, none of the hybrids showed host plant resistance to Ng-40 as the resistant check, but 18% hybrids were moderately susceptible. There were five hybrids rated as resistant, as the resistant check to isolate Ng-01 (Table 7).

4. Discussion

Hybrid rice seed technology was developed in China more than 35 years ago. Many of the released rice hybrids have shown between 15% and 20% grain yield advantage over inbred cultivars in Asia, South America, and Egypt [26,27]. These results encouraged some to test hybrid rice in sub-Saharan Africa. Our previous research indicated that the grain yield of IRRI-bred hybrids was similar to that of check cultivars in Senegal [28]. This research shows, however, that there was a high yield potential of hybrid rice bred in China after testing them in Mali, Nigeria, and Senegal. The grain yield of the most promising hybrids was higher than that of the best local inbred check cultivar. The hybrids exhibited a wide range grain yield, which was affected by the testing location and growing season.

The genotype × environment interactions (G × E) were highly significant for both sets of the hybrids and their respective cultivar checks across the three countries; i.e., their performances were different across sites from country to country. There was not the same hybrid or check cultivar showing superiority over others across the sites used in these three countries. This result may be due the soil characteristics, fertilizer applications, and weather conditions in the sites used for testing. The results of this study exhibited the high potential of these hybrids under the optimum conditions (Mali and Senegal), while the yield affected by RYMV and AfRGM stresses (in Nigeria). This finding suggests developing different hybrids for each region. In West Africa, high rice grain yields are often associated with high solar radiation, high maximum temperature, intermediate air humidity, multiple split nitrogen (N) fertilizer applications, high frequency of weeding operations, the use of certified seeds, and well-leveled fields in the irrigated lowland system [29]. Local cultivars with host plant resistance to pathogens and pest may be used to develop new hybrids with high adaptability to stress-prone African sites.

The most promising hybrids across the testing locations had 20% more grain yield than the best check cultivars. This additional grain yield advantage may encourage some African farmers to grow hybrid rice cultivars. Testing sites in Mali and Senegal have irrigated areas with higher solar radiation than the Nigerian testing site [30], which could be optimum environments for rice hybrids to show their heterosis for grain yield. The most promising hybrids also showed a good plant type and other interesting attributes. For example, most of them had medium or slender grain shape and higher milling recovery than the preferred check cultivar. Likewise, two hybrids had low GT, thereby needing less energy inputs for their cooking.

A major shortcoming of most of the hybrids bred in China is their susceptibility to both AfRGM and RYMV. Host plant resistance to both of them needs to be bred or incorporated into the parental lines of the hybrid rice germplasm before their release to West African farmers. In order words, indigenous parental lines such as traditional African (*O. glaberrima*) and Asian (*O. sativa*) rice-derived cultivars grown already in West Africa are proven useful sources of resistance to AfRGM and RYMV. They should be used in developing hybrids for farmers in West Africa. The levels of resistance shown in *O. glaberrima* gene pool are better than those of found in *O. sativa*. TOG7106 and TOS14519 were rated highly stable and highly resistant to AfRGM [31]. Crossing should be made with donors that possess multiple tolerance to biophysical stresses, and off-sites should be used to select appropriate lines from segregating generations [32]. Recently the major QTL of AfRGM were located and validated [11], being the QTL with major effect (qAfRGM4) on chromosome 4. They could be easily incorporated into the parental lines of the promising hybrids through marker-aided backcrossing [33]. Knowledge on the distribution of virulent RYMV populations across different target sites will also help to deploy safely rice hybrids in sub-Saharan Africa. It was interesting to note that in excess of 60% of the hybrids were either partially resistant (with slight symptoms) or highly resistant (without any symptom) to blast. Moreover, multi-environment testing will be still necessary to assess whether their host plant resistance will remain across space and time. Microsatellite-aided screening for fertility restoration genes *Rf* may further facilitate hybrid development with high adaptability in West Africa [34]. Preliminary results are promising: some adapted breeding lines and cultivars had high grain yield per plant with cytoplasmic male sterility lines and may be used as fertility restorers.

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