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ORIGINAL PAPER

Reactions of provitamin-A-enriched maize to foliar diseases under field conditions in Nigeria

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Abstract

Maize is a major staple food in Sub-Saharan Africa (SSA). Vitamin A deficiency index is high in Africa and could be reduced through the consumption of provitamin-A-enriched maize. However, foliar diseases such as maize streak virus, northern corn leaf blight and common rust constrain maize production in SSA. The cultivation of host-resistant varieties is the most effective approach to mitigate their effects. Therefore, maize synthetics improved for PVA carotenoids, their selection cycles and crosses as well as a commercial disease-resistant check were assessed for resistance to maize streak virus, northern corn leaf blight and common rust at hotspots in Nigeria. The foliar diseases' effects on the agronomic performance and carotenoid content of the maize genotypes were assessed. The Genotypes differed for most agronomic traits and foliar disease resistance. Stepwise regression revealed that, although the agronomic traits determined 93% of the grain yield, each foliar disease had effect on the yield. A unit increase in maize streak virus score increased plant aspect and husk cover scores by 0.6 and 0.4, respectively, whereas an increase in common rust score decreased plant height by 16.2 cm and increased plant aspect score by 0.7. Maize streak virus and common rust decreased genotypic variability for lutein by 36.7 and 18.7%, respectively, while northern corn leaf blight decreased genotypic variability for provitamin A by 27.1%. Most of the genotypes exhibited moderate susceptibility to northern corn leaf blight. However, three selection cycles and three crosses exhibited high tolerance to maize streak virus and moderate tolerance to common rust, thus can serve as sources of PVA-enriched, maize streak virus and common rust tolerant lines.

Keywords Common rust · Carotenoids · Maize streak virus · Northern corn leaf blight · Tolerance

Introduction

Maize is one of the world's leading cereals grown annually in over 166 countries on approximately two hundred million hectares (FAOSTAT 2021). In Sub-Saharan Africa (SSA), it is a major food staple, providing carbohydrates, protein, fat, minerals, and vitamins. Provitamin A (PVA) maize is enriched with vitamin A carotenoids and can be deployed to combat vitamin A deficiency (VAD) which is prevalent in SSA. An estimated 42.2% of children less than 5 years old and 15.3% of pregnant women in SSA are deficient in vitamin A (WHO 2009). This is primarily because millions of people in the region feed on crops deficient in nutrients due to the high cost of meat, dairy products and other food supplements which are major sources of vitamin A (Pfeiffer and McClafferty 2007; Bouis et al. 2011). Vitamin A deficiency retards physical growth and cognitive development, depresses immune function, causes visual disorders

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in children and adults and poor lactation in women (WHO 2009; Wurtzel et al. 2012). The cultivation and consumption of PVA-enriched maize is one of the strategies to deliver affordable source of vitamin A to combat VAD in the region, especially among poor rural populace (Bouis and Saltzman 2017). However, maize production in SSA is constrained by biotic stresses such as weeds, insects and a myriad of foliar diseases. Of particular importance among these foliar diseases are Maize Streak Virus (MSV), Northern Corn Leaf Blight (NCLB) and Common Rust (CR).

Maize streak disease is caused by MSV, genus *Mastrevirus* and transmitted by *Cicadulina* leafhoppers which are widespread in maize-producing agro-ecological zones of SSA (Sime et al. 2021). The epidemics of MSV are noted to be frequent in the tropics primarily due to the successive cropping of maize which serves as a host, and the presence of alternate hosts such as wild grasses (Mesfin et al. 1995). MSV Symptoms manifest only on leaves produced after infection of plants, while older leaves remain healthy. Susceptible maize genotypes develop severe streaking, interveinal necrosis, stunting, less vigour, smaller grains and ears, and sometimes eventual death of plants, particularly if infection occurs at an early stage of plant growth (Thottappilly et al. 1993). In general, yield losses due to MSV depend on the time of infection and genotypic resistance. Under natural infestation and farmers' field conditions, yield reductions range from as low as 2% to as high as 100% (Alegbejo et al. 2002).

Northern corn leaf blight disease is a fungal disease caused by *Exserrohilum turcicum* (Pass). NCLB is widespread and more prevalent in cool, humid zones and areas of high altitudes. Northern corn leaf blight was known to be localized in the high altitude of Nigeria and Cameroon but has now spread to the lowland areas, limiting maize production in West and Central Africa (Badu-Apraku et al. 2021). Observable symptoms include water-soaked portions on the leaf surface which elongate to form necrotic lesions. The lesions begin with lower leaves and spread to all leaves and husks with secondary infection (Akinwale and Oyelakin 2018). Yield losses attributable to NCLB have been reported to range from 15 to over 60% in the tropics and subtropics (Abdelsalam et al. 2022).

Common rust caused by the fungus *Puccinia sorghi* Schwein is widely distributed in the temperate, subtropical, and tropical regions and is endemic in SSA (Vivek et al. 2010; Bekeko 2019). Common rust develops pustules on the leaves, particularly at the flowering stage of the plant or a little later. The infection caused by *P. sorghi* decreases photosynthetic leaf areas, causing chlorosis, premature leaf senescence, and reduced photosynthesis and photoassimilates, resulting in poor grain filling, low grain quality, and yield (Roelfs and Bushnell 1985). The timing of disease development and its severity determines the extent of yield loss (Jackson-Ziems 2014). Grain yield losses ranging from 12 to 75% have been reported in different maize genotypes (Dey et al. 2012).

The co-occurrences of these pathogens in maize fields cause multiple infestations on the plants reducing the photosynthetic efficiency and net assimilate rate, resulting in poor grain quality and yields. The combined effect of foliar diseases on maize production in SSA is high and predicted to cause significant economic impact by 2050 due to climate change (Ramirez-Cabral et al. 2017). If the effects are not mitigated, it will further incapacitate the region's efforts to achieve maize sufficiency, which is already at a deficit. Several methods have been suggested and used to control foliar diseases of maize, including the use of fungicides, foliar fertilizer, biocontrol agents, and the cultivation of resistant varieties. However, the development and deployment of resistant maize genotypes is the most cost-effective and ecologically friendly approach to minimize the effects of MSV, NCLB, and CR (Sserumaga et al. 2020).

In crop improvement programmes, routine screening of germplasm under artificial or natural infestations of disease pathogens is a strategy for assessing and selecting genotypes that are resistant or tolerant to the prevailing diseases. Common rust, NCLB, *Curvularia* leaf spot (CLS) caused by *Curvularia lunata,* and corn smut caused by *Ustilago maydis* are endemic in the humid rainforest zone of Nigeria characterized by high and prolonged rainfall and relative humidity, while MSV, NCLB, Southern corn leaf blight and CLS are endemic to the Guinea Savannah zone of the north with moderate rainfall, relative humidity and high temperature. Therefore, assessments of PVA-enriched maize germplasm developed at the International Institute for Tropical Agriculture (IITA) for prevailing foliar diseases at natural hotspots will be a cost-effective strategy for identifying PVA maize genotypes that are tolerant to these diseases. The concentrations of PVA and other carotenoids in maize have been reported to be influenced by the growing conditions and stress interactions, such as drought and low soil nitrogen (Ortiz-Covarrubias et al. 2019). Postharvest handlings and storage conditions of grains have also been identified as factors that affect carotenoid content in maize (Pixley et al. 2013). Suwarno et al. (2019) reported that aflatoxin contamination had a negative genetic correlation with β-cryptoxanthin, β-carotene, and PVA. However, information on the effects of foliar diseases on PVA content and other carotenoids of maize is lacking. Therefore, the objectives of this study were to:

1. Assess the performance of provitamin-A-enriched maize synthetics, their selection cycles, and varietal-cross hybrids for tolerance to maize streak virus, northern corn leaf blight, and common rust.

2. Assess the effects of maize streak virus, northern corn leaf blight, and common rust on the grain yield, agronomic performance and provitamin A content of the maize genotypes

Materials and methods

Genetic materials and description of experimental sites

The genetic materials comprised three selection cycles (C0, C1, and C2) each of two maize synthetics (HGA and HGB), nine crosses derived from the hybridizations of the selection cycles, and a commercial open-pollinated variety (PVASYN13) as check (Supplementary Table S1). The procedure for the development of the genetic materials was previously described in Iseghohi et al. (2020). In the present study, the genotypes were evaluated for some agronomic traits and reactions to foliar diseases at four locations in the 2018 and 2019 rainy seasons. The locations were Ikenne, Ogun State, Mokwa, Niger State, Saminaka, and Zaria, Kaduna State (Figure S1).

Ikenne is a hotspot for common rust, corn smut, and NCLB. Ikenne lies 60 m above sea level (asl) and is located in the tropical rainforest agro-ecological zone of Nigeria with an annual temperature range of 17–36 °C and average rainfall and relative humidity of 1636 mm and 86%, respectively. Mokwa is located in the southern Guinea savannah of Nigeria and is endemic to NCLB, MSV, and *Cercospora* leaf spots. It is 457 m asl with an annual temperature range of 20–45 °C and average rainfall and relative humidity of 1002 mm and 84%, respectively. Saminaka and Zaria are located in Nigeria's northern Guinea savannah zone. Saminaka lies 760 m asl with an annual temperature range of 10–44 °C and annual rainfall and relative humidity of 838 mm and 84%, respectively, whereas Zaria is 622 m asl with a temperature range of 14–44 °C and annual rainfall and relative humidity of 782 mm and 83%, respectively.

Field evaluation

Before land preparations, soil samples were randomly augered to depths of 30 cm at each location for the analysis of soil's physical and chemical properties. The trials were arranged in a 4 × 4 incomplete block design with four replicates. Plots consisted of four rows of 5 m long with inter- and intra- row spacing of 0.75 and 0.5 m, respectively. The plot size was 5 × 3 m (15 m^2). Each field trial comprised 64 plots. Three seeds were sown per hill and seedlings thinned to two per hill two weeks after planting (2 WAP). Fertilizer application was based on the recommendations of Chude et al. (2012) following the results of the soil tests at each location. Weeds were managed with the applications of 500 g/L of atrazine and 200 g/L of paraquat as pre-and post-emergence herbicides, respectively, which were complemented with hand weeding at regular intervals to keep the plots weed-free.

Data collection

Agronomic data were collected from the two middle rows of each plot. Days to anthesis (DA) and days to silking (DS) were recorded as the number of days from planting to when 50% of the plants in a plot shed pollen and had emerged silks, respectively. Anthesis-silking interval (ASI) was calculated as the difference between DS and DA. Plant height (PHT) and ear height (EHT) were measured in cm as the distance from the base of the plant to the first tassel branch and the node bearing the upper ear, respectively. Plant aspect (PASP) was scored on a 1–5 scale as described by Badu-Apraku et al. (2012); where 1 represented uniform, clean, vigorous, and good overall phenotypic appeal, while 5 represented weak, diseased and poor overall phenotypic appeal. Husk cover (HC) was scored 3 weeks before harvest on a scale of 1–5, where 1 represented husks tightly arranged and extended beyond ear tip, while 5 represented loose and exposed husk tip. All ears were harvested and dehusked. Ear aspect (EASP) was scored on a scale of 1–5, where 1 represented clean, well-filled, uniform, and large ears, while 5 represented diseased, poorly filled, variable, and small ears. Samples of ears harvested were shelled and grain moisture content of grains was determined using a portable Dickey-John® moisture tester. Grain yield was adjusted to 15% moisture content. Clean ears harvested from the two outer rows were quantified for carotenoids using High Performance Liquid Chromatography (HPLC) (Iseghohi et al. 2020). Weather data comprising rainfall, temperature, relative humidity, and solar radiation were recorded throughout the growing seasons

Disease severity score

Natural disease pressure was relied upon for disease infestations. Visual Symptoms were scored on a year-location basis as observed at each hotspot. In the two years of evaluation, the maize streak virus was scored at Mokwa, Saminaka, and Zaria, while NCLB was scored at the four locations in 2018, and Saminaka in 2019. CR was scored at Ikenne for two years and Mokwa in 2018. All disease scorings were done 3–4 weeks after silking. Symptom severities of the diseases were scored on a plot basis on a scale of 1–5 (Vivek et al. 2010; Badu-Apraku et al. 2012). For MSV, scoring was based on the proportion of the ear leaf that was covered by lesions; where 1 = slight infection (i.e. less than 10% of the ear leaf covered by lesions) and

5 = very heavy infections (76–100% of ear-leaf covered by lesions). NCLB was rated based on the number, size, and position of lesions, where 1 = slight infection (few lesions on the lower leaves of the plants) and 5 = very heavy infections (high number of lesions on all leaves, premature leaf/plant death, light ears). For CR, score 1 means no rust, and 5 means severe rust infestation.

Statistical analyses

Each year-location combination was considered as an environment. A combined analysis of variance (ANOVA) was done using the PROC GLM in SAS 9.4 software (SAS Institute, Cary, NC). Entry was considered as a fixed effect, while environment, environment × entry interaction as random effect. Significantly different means of entry were separated using LSD at $p \leq 0.05$. Using the Restricted Maximum Likelihood Method (REML) and Best Linear Unbiased Prediction (BLUPs), the variance components were estimated in META-R (Version 6.0). Phenotypic variance (σ^2_p), Genotypic Coefficient of Variation (GCV), Phenotypic Coefficient of Variation (PCV) and broad-sense heritability (H^2) were each estimated as follows:

$$\sigma^2_p = \sigma^2_g + \sigma^2_e$$

$$\text{GCV} = \frac{\sqrt{\sigma^2_g}}{\overline{X}} \times 100$$

$$\text{PCV} = \frac{\sqrt{\sigma^2_p}}{\overline{X}} \times 100$$

$$H^2 = \frac{\sigma^2_g}{\sigma^2_g + \sigma^2_{ge}/\text{nEnvs} + \sigma^2_e/(\text{nEnvs} \times \text{nreps})}$$

where σ^2_g is the genotypic variance, σ^2_e is the residual variance, $\sigma^2_{\underline{ge}}$ is variance due to genotype × environment interaction, $\overline{X}$ is the grand mean, nEnvs is the number of environments.

To determine the environmental covariates (rainfall, solar radiation, minimum and maximum temperature and relative humidity) that contributed to the GEI for HC and MSV score, factorial regression analyses were done in GEA-R (Version 4.1). The stepwise regressions of agronomic traits on grain yield as well as those of foliar disease scores on grain yield, agronomic traits, and carotenoid contents were done in R version 4.1.3 (R Core Team 2022). Scatterplots were generated in R using the ggplot functions.

Results

Soil and climatic conditions of the study sites

The soil in the four study sites was slightly acidic with low organic carbon and total nitrogen contents. The textural class of soil at Ikenne and Zaria were loamy sand and loam, respectively, whereas Mokwa and Saminaka were sandy loam (Table S1). Rainfall and relative humidity were highest at Ikenne in the two years of field evaluations with a monthly average of 274.32 mm and 90.0%, respectively, while the least average monthly rainfall and relative humidity of 184.1 mm and 75.82% were recorded at Saminaka (Supplementary Figures S2 and S3). The average day temperature was highest at Mokwa (29.7 °C), while the night temperature was lowest at Saminaka (19.9 °C).

Genotypic and environmental variations for agronomic traits and foliar diseases resistance

In the combined analysis of variance, the environment differed for all the agronomic traits and foliar disease scores (Table 1). The genotypic effect was significant for most traits, except ear height. The GEI effect was significant for husk cover and maize streak virus (MSV) scores. Factorial regression result revealed that solar radiation and relative humidity contributed 30.89 and 21.65% to the variability in GEI for husk cover score, respectively, while minimum temperature contributed the greatest proportion (50.74%) to the variability in GEI for MSV severity score (Tables S3 and S4).

Variance components and heritability estimates for agronomic traits and foliar diseases resistance

The genotypic variance (σ^2_G) and environmental variance (σ^2_E) were significant for most of the traits, whereas the genotype × environment variance component was only significant for plant height, husk cover score and MSV score (Table 2). The Phenotypic Coefficient of Variation (PCV) was higher than the Genotypic Coefficient of Variation (GCV) for all the traits. The heritability estimates ranged from moderate (≥ 0.45) to high (0.96) for the foliar disease scores and agronomic traits, except for husk cover score (Table 2).

Agronomic performance and foliar diseases resistance of provitamin A maize genotypes

The average grain yield of maize genotypes across the test environments was 5334.4 kg/ha, ranging from 4515.2 to

Table 1 Mean squares from analysis of variance of agronomic traits and foliar disease scores of sixteen maize genotypes evaluated across multiple environments in Nigeria

Source of variation	DF	Plant height	Ear height	Husk cover	Grain yield	DF	Maize streak disease	DF	*Turcicum* leaf blight	DF	Common rust
ENV	7	10,297.18***	7644.73***	3.53***	84,177,612.2***	5	11.60***	4	18.77***	2	2.21***
REP (ENV)	24	1222.50***	666.37***	0.13	1,839,457.4***	18	0.22**	15	0.46**	15	0.16
BLK (ENV × REP)	96	266.68*	296.99***	0.18***	714,173.6**	72	0.11*	60	0.21	30	0.20
GENOTYPE	15	559.70**	207.23	0.25**	10,445,892.9***	15	0.43**	15	0.30*	15	0.28*
ENV × GENOTYPE	105	244.81	137.36	0.15*	545,134.3	75	0.16**	60	0.20	30	0.14
ERROR	264	193.71	178.45	0.11	480,460.0	198	0.10	165	0.19	99	0.17

*,**,***Significant at 0.05, 0.01, and 0.001 probability levels, respectively

6415.2 kg/ha (Table 3) while the average plant height, ear height and husk cover score were 212.51 cm, 112.73 cm and 2.24, respectively. Across the test environments, NCLB was the most severe with an average severity score of 3.12, followed by CR (2.70), and MSV was the least severe (1.68). The grain yield of the resistant check variety (5454.32 kg/ha) was significantly higher than those of the selection cycles, but five of the crosses had grain yields (6155.49–6415.20 kg/ha) significantly higher than the check (Table 3). The five crosses also had low MSV score (< 2.0) and moderate (2.50–2.79) scores for common rust (Table 3).

Three selection cycles (PVASYNHGAC2, PVASYNHGBC0 and PVASYNHGBC2) and three varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC2 and PVASYNHGBC2/PVASYNHGAC2) had MSV severity score significantly lower than the check and comparable rust tolerance levels with the commercial check variety (Table 3).

Effects of foliar diseases on grain yield, agronomic traits and carotenoid content

The stepwise regression of agronomic traits and foliar diseases on grain yield revealed that agronomic traits contributed 93% to the variability of grain yield, while foliar diseases accounted for 7% (Table 4). Among the agronomic traits, husk cover had the highest direct effect on grain yield, accounting for 57% of its variability followed by plant aspect score accounting for 26.6% of the grain yield variability. Although foliar diseases contributed a meager 7% to grain yield variability, it was, however, significant (Table 4).

The regressions of each foliar disease on plant height, plant aspect and husk cover scores revealed that MSV had significant effects on plant aspect and husk cover scores, but not on plant height (Fig. 1a, b, c), whereas common rust had marked effects on plant height and plant aspect score (Fig. 2a, b). The effect of NCLB was not significant on the agronomic traits. Based on the regression model, a unit increase in the MSV score of the maize genotypes increased plant aspect and husk cover scores by 0.6 and 0.4, respectively (Fig. 1a, b), while a unit increase in common rust increased plant aspect score by 0.7, and decreased plant height by 16.2 cm (Fig. 2a, b).

Among the three foliar diseases, NCLB had a significant negative effect on provitamin A causing a 27.1% decrease in its variability (Table 5). Maize streak virus caused 11.5% variability in provitamin A but was not significant. Nevertheless, MSV caused significant decreases in lutein and total carotenoid, while the effect of common rust markedly increased lutein by 18.7%. Although the effects of MSV and NCLB decreased β-carotene, it was, however, not significant (Table 5).

Table 2 Variance components and heritability estimate for agronomic traits and disease resistance of PVA-enriched maize synthetics evaluated in Nigeria

Trait	Genotypic variance (σ^2_G)	Environmental variance (σ^2_E)	Genotype × environment variance (σ^2_{GE})	Residual variance (σ^2_e)	Phenotypic variance (σ^2_P)	Genetic coefficient of variation GCV (%)	Phenotypic coefficient of variation PCV (%)	Broad-sense heritability (H^2b)
Grain Yield (Kg/ha)	405,118.09***	1,285,237.13***	20,731.68	481,049.51	886,167.6	11.93	17.65	0.96
Plant height (cm)	28.51**	170.65**	41.42***	149.69	178.2	2.57	6.43	0.64
Ear height (cm)	15.39*	221.46***	0.00 ns	84.47	99.86	3.66	9.31	0.59
Husk cover (1–5)	0.00 ns	0.05*	0.01***	2.27	2.27	0.00	66.27	0.39
Maize streak virus (1–5)	0.04**	0.05**	0.02*	0.09	0.13	10.53	18.99	0.75
Turcicum blight (1–5)	0.01*	0.28***	0.01 ns	0.19	0.2	2.94	13.16	0.45
Rust (1–5)	0.03*	0.00 ns	0.00 ns	0.19	0.22	6.66	18.04	0.58

ns nonsignificance

*,**,***$p \leq 0.05$, 0.01, and 0.001, respectively

Table 3 Mean performance of maize genotypes for agronomic traits and foliar disease resistance evaluated across multiple environments in Nigeria

Pedigree	Grain yield, kg/ha	Plant height, cm	Ear height, cm	Husk cover (1–5)	Maize streak disease (1–5)	Blight (1–5)	Rust (1–5)
PVASYNHGAC0	4941.71	200.03	112.16	2.34	1.98	3.05	2.92
PVASYNHGAC1	4766.66	213.59	114.75	2.28	2.03	3.33	2.88
PVASYNHGAC2	4788.36	215.44	112.91	2.13	1.65	3.25	2.50
PVASYNHGBC0	4515.20	214.41	112.25	2.09	1.65	3.13	2.71
PVASYNHGBC1	5064.98	211.53	109.88	2.28	1.98	3.20	3.00
PVASYNHGBC2	4864.79	216.75	113.16	2.08	1.58	2.90	2.46
PVASYNHGBC0/PVASYNHGAC0	6162.45	213.19	114.78	2.31	1.68	2.98	2.63
PVASYNHGBC1/PVASYNHGAC0	5070.32	208.75	110.81	2.30	2.08	3.10	2.92
PVASYNHGBC2/PVASYNHGAC0	6415.20	215.94	111.28	2.25	1.80	3.13	2.75
PVASYNHGBC0/PVASYNHGAC1	6159.51	210.97	110.97	2.41	1.88	3.33	2.50
PVASYNHGBC1/PVASYNHGAC1	5256.30	204.53	111.72	2.34	1.88	3.18	2.96
PVASYNHGBC2/PVASYNHGAC1	6155.49	214.56	116.22	2.30	1.85	3.05	2.79
PVASYNHGBC0/PVASYNHGAC2	4573.50	211.88	108.56	2.11	1.60	3.23	2.71
PVASYNHGBC1/PVASYNHGAC2	6190.53	216.94	112.59	2.22	1.90	3.18	2.54
PVASYNHGBC2/PVASYNHGAC2	4970.83	214.75	112.13	2.20	1.60	3.13	2.54
PVASYN13	5454.32	216.97	120.47	2.25	1.90	2.85	2.46
Mean	5334.39	212.51	112.73	2.24	1.68	3.12	2.70
LSD (0.05)	341.2	6.85	6.58	0.16	0.18	0.27	0.33
CV (%)	12.99	6.55	11.85	14.55	18.53	13.92	15.41

LSD least significant difference, *CV* coefficient of variation

Table 4 Unstandardized partial regression coefficient (b-values), coefficients of determination (R^2) and R^2 change (ΔR^2) from stepwise multiple regression of agronomic traits and foliar diseases scores on grain yield of provitamin A maize genotypes evaluated across multiple environments in Nigeria

Trait	b-value	R^2	ΔR^2 (%)
Plant height (cm)	42.53	0.044	4.4
Ear height (cm)	−63.67	0.071	2.7
Husk cover (1–5)	3634.35	0.645***	57.4
Plant aspect (1–5)	−2655.21	0.911***	26.6
Ear aspect (1–5)	−222.19	0.928	1.8
Maize streak virus (1–5)	1294.66	0.965*	3.7
Turcicum blight (1–5)	−1012.13	0.989**	2.4
Common rust (1–5)	493.84	0.994*	0.5

*,**,***Significant at 0.05, 0.01, and 0.001 probability levels, respectively

Discussion

Maize Streak Virus (MSV), Northern Corn Leaf Blight (NCLB) and Common Rust are economic diseases of maize in Sub-Saharan Africa (SSA). Maize synthetics improved for provitamin A contents with characteristic high yield and host tolerance to these foliar diseases will be useful in breeding programmes for developing improved varieties for SSA. The present study gives insights into the causal effects of MSV, NCLB and CR on grain yield, agronomic traits, and carotenoid content of provitamin A maize synthetics, their selection cycles and crosses. The significant genotypic effect for grain yield, most agronomic traits and the foliar diseases scores indicated that there was sufficient variability among the genotypes for selection for these traits. The significant environment effect for all traits indicated that each test environment was unique for phenotyping these traits. The differences in the environments could be due to variations in the climatic conditions, soil type and nutrients status, topography, altitude, and disease pressure in each environment.

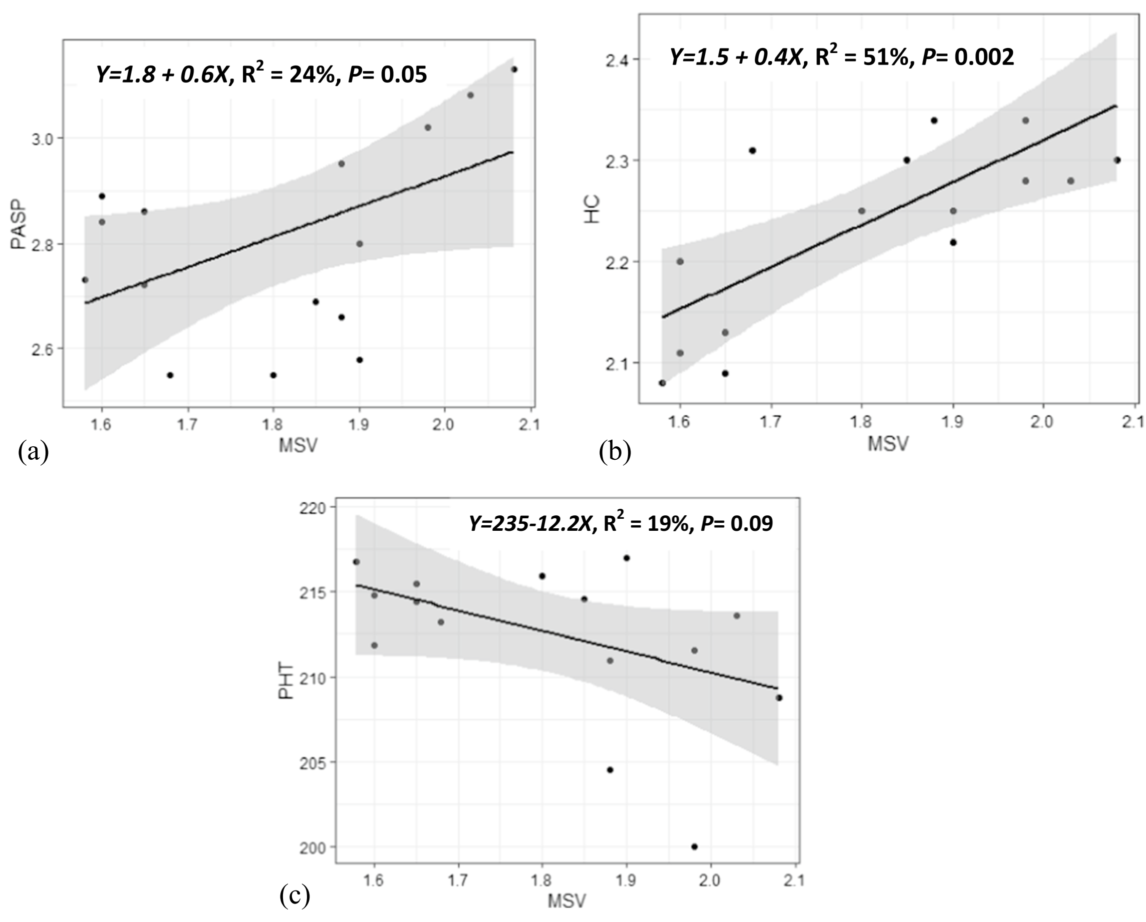

Fig. 1 Scatter plots of the regression of maize streak virus (MSV) score on (a) plant aspect (PASP) score, (b) husk cover (HC), and (c) plant height of provitamin A maize genotypes evaluated across multiple environments in Nigeria

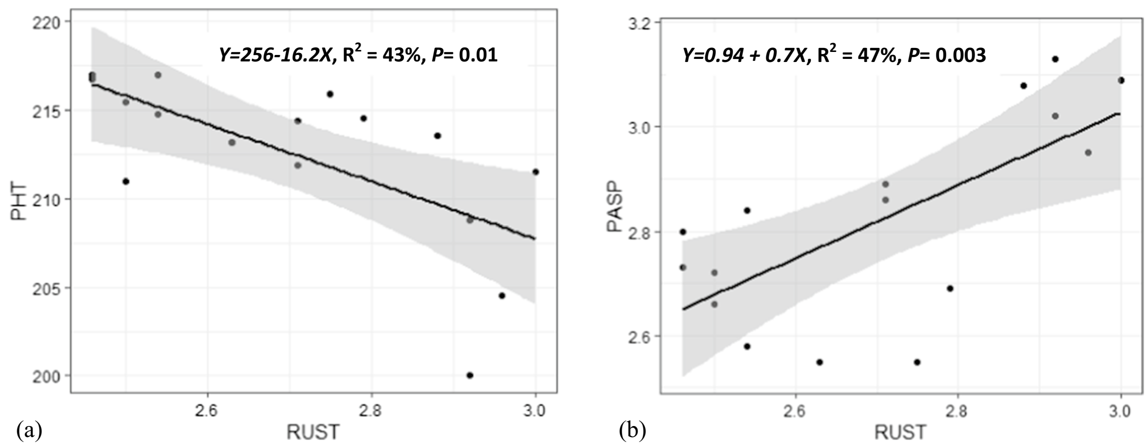

Fig. 2 Scatter plots of the regression of common rust on (a) plant height (PHT) and (b) plant aspect (PASP) score of provitamin A maize genotypes evaluated across multiple environments in Nigeria

Table 5 Unstandardized partial regression coefficient (b-values), coefficients of determination (R^2) and R^2 change (ΔR^2) from stepwise regression of foliar disease scores on provitamin A and other carotenoids of maize genotypes evaluated across multiple environments in Nigeria

Trait	Provitamin A			β-carotene			Lutein			Total carotenoid		
	b-value (%)	R^2	ΔR^2	b-value (%)	R^2	ΔR^2	b-value (%)	R^2	ΔR^2	b-value (%)	R^2	ΔR^2
Maize streak virus (1–5)	−1.80	0.12	11.5	−3.14	0.18	17.7	−10.98	0.37**	36.7	−6.50	0.28*	28.3
Blight (1–5)	−3.27	0.39*	27.1	−2.84	0.31	13.5	−1.63	0.37	0.1	−6.29	0.45	16.8
Common rust (1–5)	0.96	0.42	3.3	1.88	0.41	10.1	5.75	0.55*	18.7	1.74	0.47	1.80

*,**Significant at 0.05 and 0.01 probability levels, respectively

The genotype × environment interaction effect for MSV indicated that the maize genotypes responded differently to MSV in the test environments, consistent with previous findings (Asare-Bediako et al. 2020). Among the environmental covariables, the significant contribution of solar radiation (30.89%) to GEI variability for husk cover score suggested differential effects of the covariate on the maize genotypes in the different test locations. In a recent study, following the wide occurrence of barbell ears and short husks in many corn fields in the western and central corn belt of the US, it was reported that extreme weather, occasioned mainly by solar radiation was responsible for the abnormally (Ortez et al. 2022). In the tropics, high solar radiation couple with high relative humidity can split husks of maize giving way for pests attack and disease infestation. The significant contribution (50.74%) of the minimum temperature to the variability of GEI for MSV score signified that low/night temperature was mainly responsible for the variation of GEI for the trait. This is consistent with the result of Reynaud et al. (2009) who reported that 63 to 80% of MSV variability was due to the vector number and temperature. The epidemiology of MSV is primarily governed by environmental influences on its vector, the leafhopper (Fajemisin and Shoyinka 1976; Shepherd et al. 2010).

The relatively higher PCV over the GCV for all traits indicated that the environment played important role in the phenotypic expression of the traits. However, the moderate heritability estimates for ear height, NCLB and CR resistance signified that these traits were partly influenced by the genetic and environmental components, respectively. Meanwhile, the high heritability estimates for GY, PHT and MSV resistance indicated that the trait expressions were predominantly governed by the genetic components of the PVA-enriched maize genotypes.

The average grain yield of 5334.4 kg/ha of the maize genotypes is comparable to the average global yield (5300 kg/ha) of maize. However, the relatively high grain yields (6155.49–6415.20 kg/ha) of the top five crosses is significantly higher than the 1600 kg/ha that is usually obtained in the farmers' fields under West Africa growing conditions. This indicated that the crosses derived from the maize synthetics were outstanding. Although the yield of hybrid maize is often reported to be more than those of maize synthetics in Central and West Africa (Ewool et al 2016; Tshiabukole et al. 2017), but some maize synthetic varieties have been found to have higher yields than some maize hybrids (Manasseh et al. 2016). In addition to relatively high yield, Open-Pollinated Varieties (OPVs) such as maize synthetic is advantageous to the poor-resourced farmer in SSA in that they are resistant to major prevailing foliar diseases and abiotic stresses (Kamara et al. 2004), cheap and can be re-used for more than one growing season unlike hybrids (Kutka et al. 2011).

The low average MSV score of the provitamin-A-enriched maize genotypes across the test environments suggested that the genotypes were highly tolerant of the disease. IITA has invested a lot of resources in improving maize for streak resistance and carries out routine screening of its germplasm (Kim et al. 1988; Sime et al. 2021). The source germplasm used to develop these PVA-enriched maize genotypes must have been improved for MSV tolerance. This is important because studies have shown that breeding for streak resistance more than doubled grain yield under streak pressure while the streak resistant varieties performed equally with or better than the non-streak resistance counterparts under streak-free environments (Efron et al 1989; Fakorede et al 1993). The range of MSV scores obtained in this study was similar to those obtained by Akinwale and Oyelakin (2018) among MSV tolerant early and extra-early maize inbred lines developed for the humid agro-ecological zone of Nigeria, but lower than those reported by Vivek et al. (2010) in a diallel study involving 12-parent lines evaluated across six environments in East Africa. On the contrary, the relatively high average score (3.12) of northern corn leaf blight (NCLB) among the PVA-enriched maize genotypes indicated that most of the genotypes were moderately susceptible to the fungal disease, except PVASYNHGBC2, PVASYNHGBC0/PVASYNHGAC0, and the commercial check variety which had moderate tolerance scores. This suggested that the PVA-enriched germplasm used in this study were less tolerant to NCLB and this disease poses a greater risk to maize productivity in these maize-growing regions. Raymundo and Hooker (1981) reported yield reductions of up to 60% in susceptible germplasm while Akinwale and Oyelakin (2018) reported that 9 (22.5%) of 40 tropical maize genotypes evaluated in the rainforest ecology of Nigeria were susceptible to NCLB. A 74% susceptibility rate was reported among 87 temperate maize genotypes (Kistner et al. 2022), suggesting that NCLB has a wide effect on diverse maize germplasm. The initial breeding sources of high PVA carotenoids were selected from temperate regions (Pixley et al. 2013; Menkir et al. 2017) and may have been less resistant to NCLB. The disease which was previously reported to be restricted to the mid-altitudes of West and Central Africa has over the last decade become endemic in the lowland agro-ecologies of SSA (Akinwale and Oyelakin 2018; Badu-Apraku et al. 2021). To optimize the benefit of the PVA-enriched maize synthetics and their selection cycles, there is a need to improve them for tolerance/resistance to NCLB through recurrent selection.

The average severity score (2.70) for common rust indicated that the provitamin-A-enriched maize genotypes were moderately tolerant to the disease, and can be improved to serve as source populations for resistance to common rust. The development of adapted maize germplasm with tolerance to multiple foliar diseases is important, as projections showed that common rust will expand within SSA with the increasing effects of climate change (Sserumaga et al. 2020). The tolerance to common rust exhibited by the PVA-enriched maize genotypes was higher than the one reported by Akinwale and Oyelakin, (2018) for early and extra-early maturing tropical maize inbred lines evaluated in Nigeria, but lower than that reported by Vivek et al. (2010) among tropical inbred lines adapted to East Africa ecology. The tolerance level obtained in this study is similar to the moderate resistance reported for bi-parental double haploid tropical maize populations (Ren et al. 2021).

In the present study, the three selection cycles (PVASYNHGAC2, PVASYNHGBC0 and PVASYNHGBC2) identified to be highly tolerant to MSV and moderately tolerant to common rust can be used as donor parents to improve provitamin A, MSV and common rust resistance. Also, the varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC2/PVASYNHGAC0, PVASYNHGBC2/PVASYNHGAC1, PVASYNHGBC0/PVASYNHGAC2 and PVASYNHGBC2/PVASYNHGAC2) with high tolerance to MSV and moderate tolerance to common rust can be used as source populations for maize inbred line development.

The large contribution of agronomic traits to grain yield variability is consistent with previous report (Badu-Apraku et al. 2014) as agronomic traits are the key determinants of grain yield in most crops. The combined direct effect of the three foliar diseases on grain yield was significant, suggesting the need to incorporate screening for foliar diseases tolerance in maize varietal development in SSA. The significant increase in plant aspect and husk cover scores due to MSV suggested that the disease decreased the phenotypic appeal of the plant. The maize streak virus is characterized by chlorotic spots and stripes along the leaf veins, thus reducing the photosynthetic efficiency of the plant (Shepherd et al. 2010). The non-significant reduction in plant height caused by the MSV confirmed the tolerance of the maize genotypes to the disease, as MSV is known to cause stunting, especially if infection occurs at the early stage of plant life. Nevertheless, the marked reduction in height and the significant increase in plant aspect score occasioned by common rust confirmed that the maize genotypes should be improved for tolerance to the disease.

The effects of foliar diseases on grain carotenoids of maize have not been established. Suwarno et al. (2019) reported significant negative genetic correlations between aflatoxin contamination and βcryptoxanthin, βcarotene, and PVA in maize hybrids. In the present study, the significant decrease in PVA variability due to NCLB and the marked increase in lutein attributable to common rust suggested that these fungal diseases could alter carotenoid content in maize. The predicted significant decline in lutein and total carotenoid of the maize genotypes due to MSV is an indication that this foliar disease could affect the carotenoid content of the maize genotypes.

Conclusions

Foliar diseases such as maize streak virus (MSV) northern corn leaf blight (NCLB) and common rust (CR) are major biotic production constraints of maize. Our assessment of their effects on the agronomic performance and carotenoid contents of provitamin A (PVA)-enriched maize synthetics, their selection cycles, hybrids and a commercial variety indicated that the three foliar diseases had significant effects on grain yield, while MSV increased plant aspect and husk cover scores of the maize genotypes. Common rust caused a decrease in plant height by 16.2 cm and increased plant aspect score by 0.7. The effects of MSV and CR were not significant on PVA content but decreased lutein variability by 36.7% and 18.7%, respectively. Also, NCLB decreased the variability among the genotypes for PVA content. Most of the genotypes exhibited moderate susceptibility to NCLB but three selection cycles (PVASYNHGAC2, PVASYNHGBC0 and PVASYNHGBC2) and three varietal-cross hybrids (PVASYNHGBC0/PVASYNHGAC0, PVASYNHGBC0/PVASYNHGAC2 and PVASYNHGBC2/PVASYNHGAC2) had high tolerance to MSV and moderate tolerance to CR. These genotypes were identified as potential source materials for the development of PVA-enriched, MSV and CR tolerant lines.

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Data availability Data presented in this study are available in this article or in the supplementary material.

Declarations

Conflict of interest The authors have no competing interests.

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