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Fruit traits associated with resistance to fruit pests of hot pepper

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Abstract

Thirty-seven local and fourteen exotic hot pepper (*Capsicum* spp.) genotypes were screened under natural field conditions for resistance to two quarantine fruit pests; the fruit fly (Diptera: Tephritidae) and the false coddling moth (Lepidoptera: Tortricidae) at Makerere University Research Institute Kabanyolo for two seasons. The genotypes were grown in a randomised complete block design with three replications. Data on pest occurrence and damage; and fruit traits (fruit weight, length, width, flesh penetrability, and fruit wall thickness) were subjected to analysis of variance. The 51 genotypes showed variation in pest infestation and fruit traits. Five local genotypes (UG-WE02-1014, UG-WE02-0711, UG-EA06-0515 and UG-WE02-1608) and one exotic (CAP0408-12) showed resistance to fruit fly infestation. Fruit fly infestation correlated highly with fruit weight (r=0.59, p<0.001) and width (r=0.63, p<.001), among others. Similarly, FCM infestation positively correlated to fruit weight (r=0.50, p<0.001) and width (r=0.50, p<0.001). The identified hot pepper genotypes with resistance to fruit fly and FCM can be used in hot pepper improvement programs.

Key words: False coddling moth, fruit fly, fruit traits, morphological

Introduction

Hot pepper belongs to the genus *Capsicum* that comprises 35 species of which, only five species *C. annuum*, *C. frutescens*, *C. chinense*, *C. baccatum* and *C. pubescens* are domesticated; *C. annuum* being the most widely cultivated (Fonseca *et al.,* 2008; Bozokalfa *et al.,* 2009). Hot peppers are used as vegetables, spices, beverages and condiments; constituents of many foods, adding flavour, and colour (Arimboor *et al.*, 2014) and they are a rich source of carotenoids and vitamins C (Pawar *et al.*, 2011). The capsaicinoids, responsible for the pungency of hot peppers, exert multiple pharmacological and physiological effects including pain relief, and treatment of fevers, arthritis, hernia, migraines, colds and constipation alleviation (Palevitch and Craker, 1995; Bosland, 1996; Tabuti *et al.*, 2003; Dagnoko *et al.*, 2013).

Hot pepper dominates the world spice trade in the tropics and is thus an important cash crop for smallholder farmers in developing countries (Bozokalfa *et al.,* 2009; Lin *et al.*, 2013). In Uganda, hot pepper is designated high value, produced for export though it is also consumed locally (Karungi *et al.*, 2011; Acaye and Odongo, 2018). However, its production and profitability is hampered by infestations of fruit flies and the invasive false coddling moth (FCM). These fruit damaging pests are of quarantine importance and stringent restrictive regulations are imposed by importing countries in respect to these pests (Barnes *et al.*, 2015; Besigye, 2015). In fact, a loss of about 67% equivalent to USD 1.17 m of export revenue was registered in Uganda in 2014 due to the FCM alone (PARM, 2017; UBOS, 2017). Fruit flies are also capable of causing fruit yield losses of 100% particularly in absence of control measures (Kakar *et al.*, 2014).

Farmers in an effort to protect their produce resort to conventional pesticides, albeit in most cases inappropriately (Karungi *et al.,* 2013). This increases the likelihood of rejection of export produce at the international market due to the failure to meet acceptable maximum pesticide residue levels (UIA, 2009). More still, fruit flies and FCM are internal fruit feeders (Yahia *et al.*, 2011), making pesticide control inadequate (Haque, 2012). Alternatively, such pests can be cost effectively managed by exploiting host plant resistance, which is envisaged as sustainable (Mundt, 2014) and can easily be used alongside other pest management practices. Therefore, host plant resistance can potentially reduce the intensity of conventional pesticides usage at farm-level and as well as offer environmental and human health protection from the chemicals (Stout, 2014).

The objective of this study was to identify hot pepper genotypes with appreciable resistance to fruit fly and false codling moth infestation, and establish the morphological fruit traits that are associated with the resistance to the fruit pests' infestation.

Materials and methods

A countrywide survey was conducted in 14 districts of Uganda to collect local hot pepper germplasm from farmer fields and homestead gardens. The districts included: Kabale, Kisoro, Ntungamo, Kasese, Mbarara, Ibanda, Lira, Kole, Gulu, Omoro, Mayuge, Mukono, Buikwe and Wakiso. Other genotypes were sourced from Embrapa Horticalis, Brazil (Table 1).

The selected hot pepper germplasm (37 local and 14 exotic) were screened under natural conditions for resistance to fruit flies and the false coddling moth (FCM) at the Makerere University Research Institute, Kabanyoro (MUARIK) in 2016 and 2017. MUARIK is located at 0º28'N, 32º27'E; at an altitude of 1204 m. The climate of this area is sub-humid with moderately well distributed bimodal rainfall. Average rainfall of 15.4 mm was received in the first season (between December 2016 and June 2017) and an average temperature of 24.6°C. In second season of the trial, an average rainfall of 19.4 mm and mean temperature of 23.5°C were registered (Table 2). The soils at MUARIK are deep, highly drained red soils classified as latisols. Soils have a pH of 5.6 (Karungi *et al*., 2006).

Seeds of each genotype were sown in sterilised soil medium in pots. Three weeks after, single seedlings of each genotype were potted in polythene sleeves consisting of soil and compost in a ratio of 3:1. An organic foliar NPK fertiliser, Vegimax (at a rate of 35 mls per 15 litres) was applied twice weekly for two weeks from potting. The seedlings were hardened at 6 weeks from sowing and transplanted to the field at 8 weeks.

Study design

A complete randomised block design consisting of a single row of each of the 51 genotypes was used. Each row comprised 10 plants spaced at 45 cm and 80 cm between rows. The genotypes (treatments) were replicated in three blocks separated by 2 m alleys. Guard rows of beans were planted around the experiment. Pesticides were not used and weeding was done manually.

Data collection

Ripe fruits were harvested four consecutive times on a biweekly basis in season A and six times in season B per genotype. The fruits were weighed and graded into marketable and non-marketable fruits. Non-marketable fruits; fruits with oviposition marks and those rotting were considered damaged (modified from the methodology of Nath *et al*., 2017). The external damage (oviposition and entry marks) of fruits by both fruit flies and FCM are similar and many marks were observed on the fruits.

Table 1. Characteristics of hot pepper germplasm used in the study

Germplasm code	Collection site	Type
NSR0105-01	USA	Habanero
NSR0105-02	USA	Habanero
BRS-M205-03	Brazil	Calabrian
BRS-M205-04	Brazil	Biquinho
OHA0306-05	Mexico	Habanero
HAP-W305-06	USA	Habanero
RHA-T305-07	USA	Habanero
OHA-C309-08	USA	Habanero
OHA-T305-09	USA	Habanero
OHA-B305-10	USA	Habanero
RHA0307-11	USA	Habanero
CAP0408-12	China	Cayenne
PBA-CPT-10	Brazil	De cheiro
PDC-CPT-11	Brazil	Biquinho
UG-CE01-0401	Mukono	Habanero
UG-WE02-1802	Ntungamo	Habanero
UG-WE03-0503	Kisoro	Scotch bonnet
UG-NO04-2004	Omoro	Bird eye chili
UG-CE01-0805	Mukono	Habanero
UG-NO07-0606	Kole	Bird eye chili
UG-WE05-0607	Mbarara	Scotch bonnet
UG-WE02-1608	Ntungamo	Cayenne
UG-WE02-1909	Ntungamo	Habanero
UG-WE02-0711	Ntungamo	Bullet chili
UG-WE02-0513	Ntungamo	Habanero
UG-WE02-1014	Ntungamo	Cayenne
UG-EA06-0515	Mayuge	Bird eye chili
UG2-WE0106-01	Kisoro	Cayenne
UG2-WE0102-02	Kisoro	Bullet chili
UG2-WE0119-03	Kisoro	Habanero
UG2-WE0103-05	Kisoro	Bullet chili
UG2-NO0210-06	Gulu	Bird eye chili
UG2-NO0214-07	Gulu	Bird eye chili
UG2-NO0215-08	Gulu	Bird eye chili
UG2-NO0211-09	Gulu	Bullet chili
UG2-NO0211-10	Gulu	Bird eye chili
UG2-NO0217-11	Gulu	Bird eye chili
UG2-NO0212-12	Gulu	Bird eye chili
UG2-NO0203-13	Gulu	Bird eye chili
UG2-WE0307-14	Ibanda	Bird eye chili

Table 1. Contd.

Germplasm code	Collection site	Type
UG2-WE0318-15	Ibanda	Habanero
UG2-WE0402-16	Kasese	Bird eye chili
UG2-WE0419-17	Kasese	Scotch bonnet
UG2-WE0405-18	Kasese	Bird eye chili
UG2-WE0502-20	Kabale	Bird eye chili
UG2-WE0507-21	Kabale	Serrano
UG2-WE0511-22	Kabale	Bird eye chili
UG2-WE0505-23	Kabale	Bullet chili
UG2-EA0604-24	Buikwe	Cayenne
UG2-CE0706-25	Mukono	Scotch bonnet
UG2-WE0808-26	Ntungamo	Unidentified

Table 2. Monthly weather data for Makerere University Agricultural Research Institute Kabanyolo for the hot pepper experimental period

Month	Rainfall (mm)	Minimum temperature ºC	Maximum temperature ºC	Mean. temperature ºC
Season A				
December 2016	25.2	17	36	26.5
January 2017	17.8	16	35	25.5
February 2017	30.2	16	33	24.5
March 2017	12.8	17	32	24.5
April 2017	7.0	17	32	24.5
May 2017	7.8	18	30	24.0
June 2017	7.0	15	31	23.0
Mean	15.4	16.6	32.7	24.6
Season B				
September 2017	6.4	17	31	24.0
October 2017	57.0	17	32	24.5
November 2017	34.0	16	31	23.5
December 2017	0.0	17	32	24.5
January 2018	0.2	16	29	22.5
February 2018	0.0	16	28	22.0
March 2018	38.6	16	31	23.5
Mean	19.4	16.4	30.6	23.5

Notes: Season A (December 2016-June, 2017), Season B (September 2017-March, 2018)

This made external differentiation of fruit pest damage difficult. Therefore, all fruits with marks associated with oviposition or larval entry were considered damaged.

The damaged fruits were then opened to reveal presence of internal damage and larvae (Nath *et al.*, 2017). The fruits that had fruit fly larvae were considered infested and the number of larvae recovered per fruit was recorded (Rossetto *et al.*, 2006). The proportion of fruits infested by fruit flies was calculated as:

$$\text{Fruit fly infestation (\%)} = \frac{\text{Number of fruits with fruit fly larvae}}{\text{Total number of damaged fruits}} \times 100$$

FCM infestation was determined by consideration of the presence of frass in the hot pepper fruit following Ostojá-Starzewski *et al.* (2017).

$$\text{FCM infestation (\%)} = \frac{\text{Number of fruits with frass or larvae}}{\text{Total number of damaged fruits}} \times 100$$

Fruit traits; weight, length, width, wall thickness and penetration force were measured from 10 randomly selected fruits per replicate in the second harvest. Marketable and non-marketable fruit weight were determined using an electronic weighing scale (HK122BB-G, Zhongshan Xinfu Household Electronic Co., Ltd, Guangdong, China). Fruit length, width and thickness were measured using a digital caliper following IPGRI *et al.* (1995). Fruit penetration force i.e., force required to penetrate the fruit was taken from three points along the fruit center with force gauge (Ametek, Mansfield & Green products, Somerset Drive, USA) using the 1mm pin. The readings were from kilograms to newtons (N). The average gauge readings for the three points were calculated.

Data analysis

The general linear model of Genstat analysis software package (12^{th} Edition, Version 2; VSN International Ltd, 2010) was used to generate analysis of variance (ANOVA) with season and genotypes as fixed factors, and pepper types as the covariate. The response variables included pests, fruit, and yield parameters. Arcsine transformation was used for percentage pest infestations data while the square root transformation (“(X+1)) for pest counts. Fisher’s least significance difference test at 5% level was used to separate significant means; while Pearson correlation analysis was used to determine existent relationships between pest infestation and fruit traits.

Results

Hot pepper fruit damage

Hot pepper genotypes interacted significantly with season at P<.001 to influence fruit damage (Table 3). Genotypes PDC-CPT-11 (70.6%) and BRS-M205-04 (67.6%) had the highest fruit damage in season A. CAP0408-12 (4.9%) and UG-WE02-1014 (0.7%) registered the lowest damage. In season B, genotypes UG2-WE0808-26 (91.8%) and UG-WE02-1909 (89.3%) had the highest damage, while CAP0408-12 (16.1%) and UG-WE02-0711 (15.5%) registered the lowest damage (Table 4).

Fruit fly infestation and fruit fly larva per fruit

Fruit fly infestation significantly varied among the genotypes (P<0.001); between seasons (P<.001), and the genotypes*season interaction was significant for fruit fly infestation and fruit fly larva per fruit (P<.001) (Table 3). Genotypes registered higher fruit infestation in season A (20.1%) than in season B (7.6%). Genotypes NSR0105-01 (46.3%) and UG2-WE0419-17 (42.5%) had the highest mean infestations while UG2-WE0402-16 (2.4%) and UG2-WE0307-14 (1.3%) had the lowest in season A. In season B, genotypes UG-WE02-1909 (25.8%) and UG2-WE0318-15 (23.5%) had the highest mean infestation; whereas genotypes RHA0307-11, UG2-NO0211-10, UG2-NO0217-11, UG2-WE0307-14, UG2-WE0507-21, UG2-WE0511-22 and UG2-EA0604-24 had no fruit fly infestation. Genotypes, NSR0105-01, NSR0105-02, RHA-T305-07, OHA-T305-09, PDC-CPT-11, UG2-WE0318-15 and UG2-CE0706-25 consistently had high fruit damage. Meanwhile, genotypes CAP0408-12, UG-WE02-1014, UG-WE02-0711, UG-EA06-0515 and UGWE02-1608 had the least damage across seasons (Table 4).

Genotypes had a higher mean number of larvae per fruit (1.7) in season A than in season B (0.9). Genotypes, PBA-CPT-10 (3.1), NSR0105-01 and UG-WE02-0711 (3.0) had the highest mean numbers of larvae per fruit in season A, while UG2-WE0511-22 (0.8) and UG-WE02-1014 (0.0) had the lowest means. Similarly, in season B, the number of fruit fly larvae per fruit differed significantly among genotypes (P=0.001). Generally, there was decrease in the mean number of larvae per fruit among genotypes in season B from that in season A. NSR0105-02 (2.7) and RHA-T305-07 (2.5) had the highest numbers of larvae per fruit while UG2-EA0604-24, UG2-NO0211-10, UG2-NO0217-11, UG2-WE0307-14, UG2-WE0507-21 and UG2-WE0511-22 (0.0) had no fruits with larvae (Table 4).

Ranking of the reaction of hot pepper genotypes to fruit fly attack

Fruit damage (fruits with oviposition and rotting signs) was used to rank reaction of hot pepper genotypes to fruit fly attack as modified from Nath *et al.* (2017). Genotypes

Table 3. Pooled analysis of variance for pest infestation, fruit traits and yield for 48 hot pepper genotypes with pepper type as a covariate

Source of variation	Df	Pest infestation				Fruit traits				Yield	
		DF (%)	FFL (%)	FL/F	FCM (%)	PF (N)	FL (cm)	FW (cm)	Few (g)	Yield (t/ha)	MF (%)
Pepper type	1	5.627^{ns}	3.531 ^{ns}	0.112^{ns}	0.01 ^{ns}	0.01 ^{ns}	0.00 ^{ns}	0.01 ^{ns}	31.28 ^{ns}	362.96 ^{ns}	0.22 ^{ns}
Genotype	47	1378.31***	416.11***	1.337***	0.50***	0.70***	7.71***	3.81***	43.77***	2469.76***	1121.96***
Season	1	36.83 ^{ns}	9576.85***	42.029***	10.18***	0.48***	5.82***	3.94***	65.83***	48586.75***	17933.35***
Genotype x Season	47	742.21***	124.76**	0.884***	0.587***	0.19***	0.44***	0.05***	4.10***	1690.77***	512.87***
Error	189	48524.39	108858.4	0.3312	130.18	0.04	0.13	0.02	0.09	138.49	180.46

df = degrees of freedom, DF = damaged fruits, FFL = fruit fly infestation, FCM = false coddling moth infestation, PF = fruit penetration force, FL = fruit length, FW = fruit width, Few = fruit weight, MF = marketable fruits; ns = not significant; *significant ($P < 0.05$) ** highly significant ($P < 0.01$); *** highly significant ($P < 0.001$)

with fruit damage ranging from 1-10% were considered highly resistant, 11-20%, resistant, 21-50%, moderately resistant, 51-75%, susceptible and 76-100%, highly susceptible. There was variation in the reaction of hot pepper genotypes common to both seasons to fruit fly attack. Only one genotype (CAP0408-12) was highly resistant, four; UG-WE02-1014, UG-WE02-0711, UG-EA06-0515 and UG-WE02-1608 were resistant, 18 were moderately resistant, 24 susceptible, and only UG2-WE0808-26 was very susceptible (Table 5).

Fruit infestation by the false coddling moth (FCM) larvae was generally very low but was significantly influenced by the genotypes*season interaction (P<.001) (Table 3). The highest mean fruit infestation by FCM (0.5%) was registered in season A in which almost 50% of the genotypes had infestations. Among the genotypes infested, NSR0105-01 (2.0%) and NSR0105-02 (1.9%) had the highest infestation; while UG2-NO0211-09 and OHA-T305-09 (0.1%), the lowest. In season B, the pest infested only genotype OHA-T305-09 (Table 4).

Genotype fruit traits

Even when pepper type was included in the analysis as a covariate, fruit weight, fruit length and width still differed significantly among genotypes (P<0.001). Fruit weight differed highly and significantly (P<.001) among genotypes and between seasons (P<.001) as was the interaction genotype*season. Genotypes generally had heavier fruits (3.5 g) in season A than in season B (2.8 g). Genotypes NSR0105-01 (10.8 g) and UG-WE05-0607 (10.3 g) were the heaviest in season A while UG2-NO0215-08 (0.3 g) and UG-EA06-0515 (0.2 g) were the lightest. For season B, UG2-WE0318-15 (9.8 g) and UG2-WE0419-17 (9.2 g) had the heaviest fruits while UG2-WE0402-16 (0.1 g) and UG2-NO0217-11 (0.1 g) had the lightest fruits (Table 6).

Fruit length differed significantly among the hot pepper genotypes (P<.001) and between seasons (P<.001). Genotypes had longer fruits (3.2 cm) in season A than in season B (3.0 cm). Genotypes UG-WE02-1608 (7.5 cm) and BRS-M205-03 (6.6 cm) had the longest fruits in season A; while UG2-WE0307-14 (1.6 cm) and UG-EA06-0515 (0.9 cm) had the shortest fruits (Table 6). In season B, BRS-M205-03, CAP0408-12 (5.3 cm) and UG-WE02-1608 (5.1 cm) had the longest fruits; while UG2-WE0307-14 (1.4 cm) and UG-EA06-0515 (1.3 cm) had the shortest fruits (Table 6).

Fruit width like fruit length differed significantly among the genotypes at P<.001 and between seasons (P<.001). Fruits were generally wider in season A (1.7 cm) than in season B (1.4 cm). Genotypes NSR0105-02, UG2-WE0318-15, UG2-WE0419-17, NSR0105-01 and RHA-T305-07 had the widest fruits (3.2 cm) in season A.

Table 4. Damage and infestation by fruit pests of hot pepper genotypes evaluated in Makerere University Agricultural Research Institute Kabanyolo, Uganda in season A and season B

Genotype	Fruit fly damage (%)		Fruit fly infestation (%)		Mean number of larvae per fruit		FCM infestation (%)	
	Season A	Season B	Season A	Season B	Season A	Season B	Season A	Season B
NSR0105-01	56.4	54.1	46.3	12.7	3.0	1.3	1.9	0.0
NSR0105-02	62.7	62.5	31.9	11.1	1.7	2.7	2.0	0.0
BRS-M205-03	53.6	74.8	29.3	10.5	2.8	0.9	0.0	0.0
BRS-M205-04	67.6	20.4	17.3	13.4	1.5	1.6	0.2	0.0
OHA0306-05	58.5	-	23.7	-	1.8	-	1.1	-
HAP-W305-06	52.1	62.8	42.3	14.5	1.1	1.3	1.5	0.0
RHA-T305-07	57.3	56.0	28.4	22.5	1.9	2.5	0.8	0.0
OHA-C309-08	59.3	87.4	12.7	5.4	1.9	1.1	1.1	0.0
OHA-T305-09	56.4	52.8	28.3	14.9	2.2	0.9	0.1	0.0
OHA-B305-10	55.0	48.5	23.1	4.2	1.8	1.1	1.2	0.0
RHA0307-11	47.8	28.7	32.2	0.0	2.0	0.3	0.7	0.0
CAP0408-12	4.9	16.1	5.4	0.9	1.3	0.5	0.0	0.0
PBA-CPT-10	55.9	63.1	24.4	13.8	3.1	0.7	0.6	1.0
PDC-CPT-11	70.6	69.2	12.2	4.4	1.3	1.1	0.0	0.0
UG-CE01-0401	51.2	67.4	32.3	18.5	1.9	1.9	0.0	0.0
UG-WE02-1802	48.2	59.8	27.3	18.0	1.7	1.6	1.0	0.0
UG-WE03-0503	56.5	47.8	28.9	15.2	1.3	1.1	0.3	0.0
UG-NO04-2004	22.8	61.0	13.1	1.6	1.2	0.7	0.0	0.0
UG-CE01-0805	48.6	69.0	35.9	16.6	1.9	1.3	1.5	0.0

Table 4. Contd.

Genotype	Fruit fly damage (%)		Fruit fly infestation (%)		Mean number of larvae per fruit		FCM infestation (%)	
	Season A	Season B	Season A	Season B	Season A	Season B	Season A	Season B
UG-NO07-0606	34.0	27.3	4.5	14.2	1.4	0.7	0.0	0.0
UG-WE05-0607	47.8	67.3	30.1	15.4	2.1	1.3	1.3	0.0
UG-WE02-1608	6.6	32.5	11.4	0.3	1.8	0.7	0.0	0.0
UG-WE02-1909	44.5	89.3	40.7	25.8	2.1	1.4	1.6	0.0
UG-WE02-0711	20.7	15.5	8.2	2.8	3.0	0.5	0.0	0.0
UG-WE02-0513	62.7	-	27.8	-	1.8	-	1.6	-
UG-WE02-1014	0.7	23.6	0.0	2.5	0.0	0.3	0.0	0.0
UG-EA06-0515	9.0	28.1	9.8	0.2	0.9	1.3	0.0	0.0
UG2-WE0106-01	52.5	40.3	23.3	2.4	2.0	0.3	0.0	0.0
UG2-WE0102-02	62.9	48.4	14.9	5.8	1.2	1.1	0.0	0.0
UG2-WE0119-03	48.9	79.8	39.6	13.0	1.8	1.4	0.0	0.0
UG2-WE0103-05	53.4	39.2	15.8	1.7	1.8	0.4	0.0	0.0
UG2-NO0210-06	54.0	20.9	6.0	7.3	1.4	0.8	0.0	0.0
UG2-NO0214-07	43.8	39.1	10.4	1.2	1.4	0.7	0.0	0.0
UG2-NO0215-08	41.1	77.6	14.4	0.9	1.4	0.8	0.0	0.0
UG2-NO0211-09	66.6	40.6	19.8	3.1	1.6	1.4	0.1	0.0
UG2-NO0211-10	13.8	54.7	11.0	0.0	1.2	0.0	0.0	0.0
UG2-NO0217-11	40.9	41.2	5.0	0.0	1.3	0.0	0.0	0.0
UG2-NO0212-12	55.1	52.1	15.3	2.5	1.5	0.7	0.0	0.0
UG2-NO0203-13	49.6	17.4	14.6	3.7	1.4	0.5	0.0	0.0

Table 4. Contd.

Genotype	Fruit fly damage (%)		Fruit fly infestation (%)		Mean number of larvae per fruit		FCM infestation (%)	
	Season A	Season B	Season A	Season B	Season A	Season B	Season A	Season B
UG2-WE0307-14	57.5	24.2	1.3	0.0	1.1	0.0	0.0	0.0
UG2-WE0318-15	59.6	55.4	28.0	23.5	2.0	2.3	1.0	0.0
UG2-WE0402-16	41.0	51.3	2.4	0.2	1.2	0.7	0.0	0.0
UG2-WE0419-17	49.9	43.1	42.5	7.6	2.0	0.4	1.4	0.0
UG2-WE0405-18	44.6	58.2	6.3	4.8	1.2	0.3	0.0	0.0
UG2-WE0502-20	49.3	-	6.9	-	1.3	-	0.0	-
UG2-WE0507-21	60.6	36.7	17.5	0.0	2.0	0.0	0.2	0.0
UG2-WE0511-22	43.1	20.1	2.6	0.0	0.8	0.0	0.0	0.0
UG2-WE0505-23	61.7	23.9	17.2	5.7	1.6	1.1	0.0	0.0
UG2-EA0604-24	58.8	23.3	20.5	0.0	1.8	0.0	0.0	0.0
UG2-CE0706-25	57.8	55.7	38.1	10.9	2.6	1.5	1.8	0.0
UG2-WE0808-26	64.3	91.8	23.8	11.0	1.5	0.8	0.0	0.0
Mean	48.00	48.30	20.00	7.60	1.70	0.92	0.46	0.02
LSD (5%)	18.30	29.88	14.9	12.02	0.80	1.04	1.16	0.40
P-value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	0.505

- The genotypes were not planted in the second season because of poor germination

UG-WE02-1014, UG2-NO0217-11 and UG-EA06-0515 had the narrowest fruits (0.5 cm). In season B, RHA-T305-07 (3.1 cm), UG2-WE0419-17 and UG2-WE0318-15 (3.0 cm) had the widest fruits. The narrowest fruits belonged to genotypes UG2-NO0217-11 (0.4 cm) and UG-EA06-0515 (0.3 cm) (Table 6).

Fruit wall thickness measurements were only taken in season B and it differed significantly among the genotypes (P<.001). Genotypes UG2-WE0507-21 (2.0 mm) and UG2-CE0706-25 (1.8 mm) had the thickest fruit wall whereas UG-NO04-2004 and UG-EA06-0515 (0.2 mm) had the thinnest fruits (Table 6).

The penetration force of the fruit skin and flesh differed highly significantly among genotypes (P<.001) and the genotype*season interaction was also significant (Table 3). Genotypes RHA0307-11 (2.2N) and PDC-CPT-11(1.9N) fruits required the highest penetration force in season A; while UG-EA06-0515, UG-NO04-2004 and UG2-NO0212-12 fruits required the least penetration force of 0.5N. In season B, BRS-M205-03 (2.1N) and UG2-WE0507-21(2.0N) had the toughest fruits while UG2-WE0808-26, UG2-NO0215-08 and UG2-NO0217-11 had the softest fruits at 0.5N (Table 6).

Correlation of fruit parameters and pest infestation

Results of a two tailed Pearson correlation test revealed that fruit fly infestation correlated positively and significantly with number of fruit fly larvae, fruit weight, fruit length, fruit width, and penetration force (r=0.56, r=0.59, r=0.30, r=0.63, and r=0.24, respectively). While false coddling moth infestation similarly correlated to fruit weight, fruit length, fruit width (r=0.50, r=0.17, r=0.50, respectively), but had no significant relationship with penetration force (Table 7).

Discussion

Fruit damage due to fruit flies varied highly by genotypes and seasons. Varying levels of fruit fly damage among genotypes have been observed in other crops such as tomatoes (Balagawi *et al*., 2005), bitter gourd (Nath *et al*., 2017) and in mangoes (Nankinga *et al*., 2014). The variation in damage may be attributed to the innate morphological and biochemical profiles that vary among plants within the same species (Diatta *et al*., 2013; Pedigo and Rice, 2014). Fruit traits such as size, colour and total soluble solids do vary among genotypes, and have been reported to determine oviposition preference, and larval growth and development (Dhillon *et al*., 2005; Aluja and Mangan, 2008; Gogi *et al*., 2010). In consequence, the number of fruit fly larvae per fruit significantly varied among hot pepper genotypes in this study. Fruit traits such as fruit weight, length, width, fruit wall thickness, colour and flesh

Table 5. Pooled fruit damage, number of fruit fly larva per fruit and reaction of hot pepper genotypes common to both seasons to fruit fly attack evaluated at Makerere University Agricultural Research Institute Kabanyolo, Uganda

Genotype	Damaged fruits (%)	Mean number of fruit fly larva per fruit	Hot pepper type	Ranking reaction to fruit fly attack (based on damaged fruits)
CAP0408-12	10.5	0.9	Cayenne	Highly resistant
UG-WE02-1014	12.1	0.2	Cayenne	Resistant
UG-WE02-0711	18.1	1.7	Cayenne	Resistant
UG-EA06-0515	18.5	1.1	Bird eye chili	Resistant
UG-WE02-1608	19.5	1.2	Cayenne	Resistant
UG-NO07-0606	30.6	1.1	Bird eye chili	Moderately resistant
UG2-WE0511-22	31.6	0.4	Bird eye chili	Moderately resistant
UG2-NO0203-13	33.5	1.0	Bird eye chili	Moderately resistant
UG2-NO0211-10	34.3	0.6	Bird eye chili	Moderately resistant
UG2-NO0210-06	37.4	1.1	Bird eye chili	Moderately resistant
RHA0307-11	39.4	1.2	Habanero	Moderately resistant
UG2-WE0307-14	40.8	0.5	Bird eye chili	Moderately resistant
UG2-EA0604-24	41.0	0.9	Bird eye chili	Moderately resistant
UG2-NO0217-11	41.0	0.7	Bird eye chili	Moderately resistant
UG2-NO0214-07	41.4	1.0	Bird eye chili	Moderately resistant
UG-NO04-2004	41.9	0.9	Bird eye chili	Moderately resistant
UG2-WE0505-23	42.8	1.3	Bullet chili	Moderately resistant
BRS-M205-04	43.9	1.5	Biquinho	Moderately resistant
UG2-WE0402-16	46.1	0.9	Bird eye chili	Moderately resistant
UG2-WE0103-05	46.3	1.1	Bullet chili	Moderately resistant
UG2-WE0106-01	46.4	1.1	Cayenne	Moderately resistant
UG2-WE0419-17	46.5	1.2	Scotch bonnet	Moderately resistant
UG2-WE0507-21	48.6	1.0	Serrano	Moderately resistant
UG2-WE0405-18	51.4	0.8	Bird eye chili	Susceptible
OHA-B305-10	51.7	1.4	Habanero	Susceptible
UG-WE03-0503	52.1	1.2	Scotch bonnet	Susceptible
UG2-NO0211-09	53.6	1.5	Bullet chili	Susceptible
UG2-NO0212-12	53.6	1.1	Bird eye chili	Susceptible
UG-WE02-1802	54.0	1.7	Habanero	Susceptible
OHA-T305-09	54.6	1.5	Habanero	Susceptible
NSR0105-01	55.2	2.2	Habanero	Susceptible
UG2-WE0102-02	55.6	1.2	Bullet chili	Susceptible
RHA-T305-07	56.7	2.2	Habanero	Susceptible
UG2-CE0706-25	56.8	2.1	Scotch bonnet	Susceptible

Table 5. Contd.

Genotype	Damaged fruits (%)	Mean number of fruit fly larva per fruit	Hot pepper type	Ranking reaction to fruit fly attack (based on damaged fruits)
UG2-WE0318-15	57.4	2.1	Habanero	Susceptible
HAP-W305-06	57.5	1.2	Habanero	Susceptible
UG-WE05-0607	57.5	1.7	Scotch bonnet	Susceptible
PBA-CPT-10	58.3	1.9	De cheiro	Susceptible
UG-CE01-0805	58.7	1.6	Scotch bonnet	Susceptible
UG-CE01-0401	59.3	1.9	Habanero	Susceptible
UG2-NO0215-08	59.3	1.1	Bird eye chili	Susceptible
NSR0105-02	62.6	2.2	Habanero	Susceptible
BRS-M205-03	64.2	1.8	Calabrian	Susceptible
UG2-WE0119-03	64.3	1.6	Habanero	Susceptible
UG-WE02-1909	66.9	1.8	Habanero	Susceptible
PDC-CPT-11	69.9	1.2	Biquinho	Susceptible
OHA-C309-08	73.3	1.5	Habanero	Susceptible
UG2-WE0808-26	78.1	1.2	Unidentified	Very susceptible

penetrability are among those documented to influence the number of larva per fruit (Aluja and Mangan, 2008).

False coddling moth infestation (FCM) was generally very low during the experimental period, nevertheless, it varied significantly among the hot pepper genotypes. The false coddling moth being a polyphagous pest (EPPO, 2013) may have preferred other hosts to hot pepper in this environment. Thus, the crop could be a secondary host of the moth, a situation most manifested in season B, which included the main crop growing period (March-June) when a wide range of crop species are in season. Low infestation of FCM on hot pepper was also reported on-farm in south western Uganda indicating prevailing low infestations in the country (Ssekkadde, 2021). The trend in FCM infestation on hot pepper genotypes was similar to that of the fruit fly in terms of incidence and larval infestation suggesting similar traits at play in determining host resistance.

The observed differences in fruit fly and FCM infestation among genotypes were dependent on season, and hence the registered variation in infestation can be partly explained by the prevailing environmental conditions. Environmental conditions such as drought or water stress are known to affect the physiological processes of plants

Table 6. Means of fruit quality traits for hot pepper genotypes evaluated at Makerere University Agricultural Research Institute Kabanyolo, Uganda in season A and season B

Genotype	Weight (g)		Length (cm)		Width (cm)		FWT (mm)		PF (N)		MF (%)	
	A	B	A	B	A	B	A	B	A	B	A	B
NSR0105-01	10.8	7.7	3.8	3.4	3.2	2.9		1.3	1.2	1.2	0.0	30.5
NSR0105-02	10.1	7.0	4.0	3.8	3.2	2.6		0.9	1.1	1.4	1.9	21.7
BRS-M205-03	7.5	4.3	6.6	5.3	1.4	1.2		1.0	1.9	2.1	4.0	16.6
BRS-M205-04	1.2	1.2	2.0	2.0	1.5	1.3		0.9	1.2	1.2	6.7	71.7
OHA0306-05	5.5	-	3.0	-	2.5	-		-	0.7	-	1.1	-
HAP-W305-06	7.4	3.8	3.4	3.2	2.5	2.0		1.2	1.3	1.4	28.3	27.0
RHA-T305-07	9.8	8.2	3.7	3.7	3.2	3.1		1.3	1.1	1.2	6.1	35.8
OHA-C309-08	6.1	2.5	3.1	2.6	2.5	2.0		1.1	1.6	1.3	1.6	9.1
OHA-T305-09	3.2	3.6	3.0	2.8	2.5	1.8		1.0	1.7	1.3	0.0	15.1
OHA-B305-10	6.7	4.6	3.0	3.5	2.7	2.2		1.2	1.1	1.3	10.8	35.9
RHA0307-11	3.1	3.6	2.7	3.0	2.3	2.3		1.4	2.2	1.8	5.6	41.5
CAP0408-12	1.3	1.5	5.2	5.3	0.8	0.7		0.3	1.3	1.4	42.2	30.6
PBA-CPT-10	3.9	4.6	4.7	3.9	2.6	2.0		1.4	1.8	1.6	0.0	23.4
PDC-CPT-11	1.2	1.0	1.7	1.9	1.5	1.1		1.2	1.9	1.9	0.9	21.8
UG-CE01-0401	6.3	5.1	4.2	3.4	2.8	2.4		1.3	1.2	1.5	0.6	20.9
UG-WE02-1802	9.7	8.4	4.7	4.5	2.6	2.6		1.5	1.5	1.2	4.1	28.3
UG-WE03-0503	4.5	2.8	3.3	3.3	2.0	1.6		0.9	1.3	1.4	1.5	44.2
UG-NO04-2004	0.3	0.3	2.6	1.8	0.8	0.5		0.2	0.5	0.7	23.5	31.2
UG-CE01-0805	9.8	6.4	4.3	3.6	2.9	2.6		1.0	1.2	1.3	3.9	22.6
UG-NO07-0606	0.7	0.4	2.2	1.9	0.8	0.6		0.4	1.2	1.0	44.4	64.4

Table 6. Contd.

Genotype	Weight (g)		Length (cm)		Width (cm)		FWT (mm)		PF (N)		MF (%)	
	A	B	A	B	A	B	A	B	A	B	A	B
UG-WE05-0607	10.3	6.5	3.6	2.9	3.1	2.8		1.3	1.1	1.3	2.1	26.2
UG-WE02-1608	2.0	1.5	7.5	5.1	1.0	0.8		0.6	1.1	1.3	76.1	42.6
UG-WE02-1909	9.3	5.8	4.3	3.8	2.8	2.8		1.4	1.7	1.8	4.0	9.6
UG-WE02-0711	1.6	1.3	3.1	3.5	1.0	0.8		0.4	0.8	1.3	64.9	64.0
UG-WE02-0513	4.1	-	2.9	-	2.4	-		-	1.7	-	0.8	-
UG-WE02-1014	1.5	1.1	3.6	4.4	0.5	0.6		0.3	1.4	1.0	37.7	20.6
UG-EA06-0515	0.2	0.2	0.9	1.3	0.5	0.3		0.2	0.5	0.8	53.0	21.6
UG2-WE0106-01	2.2	1.4	5.1	4.2	0.9	0.7		0.4	1.6	1.5	10.7	49.3
UG2-WE0102-02	1.3	0.7	2.6	2.2	0.9	0.8		0.4	1.0	0.9	15.5	39.7
UG2-WE0119-03	3.6	1.9	2.9	2.8	1.9	1.4		1.2	1.3	1.3	0.0	15.2
UG2-WE0103-05	1.4	1.8	2.5	3.0	1.0	1.0		1.0	1.0	1.0	31.1	52.0
UG2-NO0210-06	0.5	0.3	2.5	1.6	0.9	0.5		0.6	1.0	0.6	10.5	47.5
UG2-NO0214-07	0.5	0.4	2.3	2.0	0.8	0.5		0.8	0.8	0.8	13.2	34.1
UG2-NO0215-08	0.3	0.3	1.8	1.6	0.9	0.5		0.5	1.0	0.5	12.4	14.7
UG2-NO0211-09	1.7	1.4	3.0	2.8	1.0	1.0		0.7	0.7	0.7	15.9	57.6
UG2-NO0211-10	1.6	0.8	4.1	3.7	1.0	0.9		1.0	0.7	1.0	51.5	37.6
UG2-NO0217-11	0.4	0.1	2.4	1.7	0.5	0.4		0.5	0.9	0.5	31.5	32.8
UG2-NO0212-12	0.4	0.4	2.4	2.0	0.8	0.5		0.6	0.5	0.6	14.6	23.9
UG2-NO0203-13	0.4	0.4	2.3	1.9	0.9	0.6		1.0	1.1	1.0	7.3	42.8
UG2-WE0307-14	0.4	0.3	1.6	1.4	0.6	0.5		1.2	1.1	1.2	15.4	42.0
UG2-WE0318-15	5.6	9.8	4.0	4.3	3.2	3.0		1.4	1.3	1.4	0.2	30.9

Table 6. Contd.

Genotype	Weight (g)		Length (cm)		Width (cm)		FWT (mm)		PF (N)		MF (%)	
	A	B	A	B	A	B	A	B	A	B	A	B
UG2-WE0402-16	0.3	0.1	1.9	1.8	0.7	0.5		0.8	0.8	0.8	31.7	31.4
UG2-WE0419-17	6.8	9.2	3.6	4.0	3.2	3.0		1.1	1.5	1.1	0.0	40.1
UG2-WE0405-18	0.4	0.3	2.0	1.6	0.8	0.6		0.4	0.9	0.8	16.5	30.3
UG2-WE0502-20	0.7	-	2.0	-	0.7	-		-	1.1	-	25.2	-
UG2-WE0507-21	2.0	1.1	3.8	2.5	1.3	0.9		2.0	1.7	2.0	5.3	19.6
UG2-WE0511-22	1.0	0.7	2.2	2.1	0.8	0.8		1.6	1.8	1.6	21.3	48.3
UG2-WE0505-23	1.3	1.1	2.2	2.2	1.0	0.9		1.5	1.2	1.5	13.7	48.2
UG2-EA0604-24	2.6	1.0	4.8	3.7	1.0	0.7		1.3	1.3	1.3	12.8	30.3
UG2-CE0706-25	5.9	5.8	2.9	2.5	2.9	2.5		1.8	1.5	1.8	0.0	33.7
UG2-WE0808-26	1.4	1.2	2.8	2.4	1.5	1.0		0.5	0.7	0.5	0.2	5.2
Mean	3.50	2.80	3.20	3.00	1.70	1.40		0.96	1.21	1.18	15.4	33.09
LSD (5%)	1.84	1.51	0.29	0.33	0.13	0.14		0.20	0.256	0.246	11.7	26.81
P-value	<.001	<.001	<.001	<.001	<.001	<.001		<.001	<.001	<.001	<.001	<.001

A = season A, B = season B, FWT = fruit wall thickness, PF = penetration force, MF = marketable fruits, NMF = non-marketable fruits

Table 7. Correlation coefficients for the relationship between fruit pest infestation and hot pepper fruit traits pooled over the two seasons

	Damage (%)	FFL%	FCM%	No. L/F	Few	FL	FW	PF
Damage (%)	-							
FFL%	0.28***	-						
FCM%	0.09	0.50***	-					
No. L/F	0.27***	0.56***	0.31***	-				
Few	0.24***	0.59***	0.50***	0.43***	-			
FL	-0.03	0.30***	0.17**	0.28***	0.50***	-		
FW	0.34***	0.63***	0.50***	0.49***	0.89***	0.39***	-	
PF	0.26***	0.24***	0.11	0.17**	0.30***	0.29***	0.37***	-

Damaged% = damaged fruits, FFL% = fruits infested by fruit fly, FCM% = FCM infestation, No. L/F = number of fruit fly larvae per fruit, Few = average fruit weight, FL = fruit length, FW = fruit width, PF = penetration force; *significant ($P < 0.05$); ** highly significant ($P < 0.01$); *** highly significant ($P < 0.001$); the rest are non-significant

resulting in fewer and smaller fruits with quality drawbacks (Haldhar *et al.*, 2013), these in turn can influence fruit pest infestation. In this study, maximum temperatures and mean rainfall quantities showed variation between the seasons; and season B of the study was particularly characterised by three months of very low rainfall (Dec 2017, Jan-Feb, 2018); which may have negatively affected the measured fruit traits causing selection pressure on the fruit pests. As such, both the genotype and the environmental conditions influenced the fruit resource available on the plants to support pest build up. For instance, it has been documented that having fewer fruits increases competition for oviposition sites and may induce both intra and interspecific multiple fruit oviposition tendency in tephritid flies and hence increases fruit damage. However, due to the low nutritional quality of the fruits, the larval survival rate diminishes and hence lower numbers of larva per fruit (Aluja and Mangan, 2008).

Genotypes, CAP0408-12 (cayenne), UG-WE02-1014 (cayenne), UG-WE02-0711 (bullet chili), UG-EA06-0515 (bird eye chili) and UG-WE02-1608 (cayenne) showed resistance to fruit pest infestation. Genotypes OHA-C309-08, UG-WE02-1909 and UG2-WE0119-03 (habanero), UG-CE01-0805, UG-WE05-0607, and UG2-CE0706-25 (scotch bonnet) were more susceptible to fruit pest infestation and had the least marketable yield; yet, the habanero and scotch bonnet types contribute the largest portion of Uganda's fresh produce export volumes on the international hot pepper market. These results highlight the gravity of the challenges posed by fruit pests in the hot pepper industry, especially as they are designated as quarantine pests in importing countries.

The study showed that the fruit traits of fruit wall toughness as measured by penetration force, fruit length, fruit width and fruit weight were influenced by the genotype and season interaction. Subsequently, fruit weight, width, length, and fruit wall toughness were found to have a significant association to fruit fly infestation. Gogi *et al.* (2010) also reported significant positive correlations between fruit fly infestation in bitter gourd genotypes and fruit length and diameter (width). They also reported that fruit diameter and pericarp toughness were the major factors that influenced fruit fly infestation. Fruit flesh penetrability (pericarp toughness or firmness) usually negatively correlates with fruit fly infestation (Balagawi *et al*., 2005; Rattanapun *et al*., 2009; Gogi *et al*., 2010), however, the results of this study are to the contrary. Nufio *et al.* (2000) also reported that fruit toughness did not influence walnut fruit infestation by *Rhagoletis juglandis*. These exceptions could be due to the overarching influence of other fruit traits such as fruit size on fruit fly infestation. Factually, fruit flies prefer ripe fruits (Rattanapun *et al*., 2010) and penetration force measurements in this study were taken on the ripe fruits, which were already vulnerable to the attack.

Fruit length, width and fruit wall thickness had positive relationships with the number of fruit fly larva per fruit (Table 7). Generally, genotypes with bigger fruits and thicker fruit walls had more larva per fruit which is in agreement with the findings of Dhillon *et al*. (2005) and Haldhar *et al.* (2013) who reported that larval density (number of larva per fruit) was positively correlated with fruit length, diameter and flesh thickness. Large host size and thicker fruit wall are likely to offer more volumes of nourishment to the developing larva than smaller fruits with thin fruit walls.

With regard to FCM, fruit width and weight were the key traits that positively associated with false codling moth (FCM) infestation. FCM larva are voracious feeders and usually only one larva is found per fruit, though exceptions exist (Stotter, 2009). The larger the unit area of the host, the more substrate resources are available for pest growth and development. This may also explain the positive correlation between FFL and FCM infestation.

In crops where fruits are the economic product, enhanced fruit weight, length and width are often desirable attributes (Marimo *et al*., 2020). Fruit pests also overwhelming preferred genotypes with these attributes. As such, this has implications on field management of hot pepper since broad and heavy fruits fetch more revenue at the international market (Besigye, 2015). It is therefore crucial that agronomic practices that promote these traits are partnered with viable protection measures against the fruit pests. Judicious usage of insecticides for instance only deploying pesticides on areas where the pest has been trapped (Prokopy *et al*., 2003) can be part of a management strategy. In view of this, very susceptible genotypes as the case of OHA-C309-08 and UG2-WE0808-26 can be deployed as trap crops in fields of genotypes demanded by markets.

Conclusion

This study ranked CAP0408-12 (exotic) and four local genotypes UG-WE02-1014, UG-WE02-0711, UG-EA06-0515 and UG-WE02-1608 as resistant to fruit fly fruit damage and can be followed up for genetic improvement of the crop. Fruit length, width, weight and fruit wall thickness and firmness, traits, that were influenced by genotype and season contributed to the resistance.

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