Genetics of Resistance to *Fusarium oxysporum* f. sp. *melonis* Races 0 and 2 in Muskmelon Cultivars Honey Dew, Iroquois, and Delicious 51

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ABSTRACT

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In artificial inoculation studies, muskmelon (*Cucumis melo*) cultivars Honey Dew, Iroquois, and Delicious 51 were resistant to races 0 and 2 but susceptible to races 1 and 1-2 of *Fusarium oxysporum* f. sp. *melonis*. Segregation ratios of F_1, F_2, and BC_1 populations of crosses between resistant Honey Dew, Iroquois, and Delicious 51 and susceptible Top Mark indicated that resistance to races 0 and 2 of Fusarium wilt is conferred by a single dominant gene. In allelism tests, resistance was determined to be controlled by the gene (*Fom 1*) or an allele of this gene.

Fusarium oxysporum Schlechtend.:Fr. f. sp. *melonis* W. C. Snyder & H. N. Hans., the cause of Fusarium wilt of muskmelon (*Cucumis melo* L.), was first reported in New York in 1930 (3,4). In 1931, Fusarium wilt of muskmelon was found in Minnesota, and the following year a severe outbreak was found in muskmelon plantings of several market gardens near Minneapolis (11). Leach and Currence (5,12,13) initiated a breeding program in 1932 and found resistant plants in the cultivars Honey Dew, Casaba, Persian, and Honey Ball. From a chance hybrid between Honey Dew and the cultivar Bender, Golden Gopher was selected and released as resistant by the Minnesota Agricultural Experiment Station (AES) in 1939 (1). A line resistant to Fusarium wilt from the Minnesota AES was crossed with the cultivar Bender by the New York AES. The resistant cultivar Iroquois was selected from this cross and released in 1943 (16). Iroquois was crossed with the susceptible cultivar Delicious, and four backcrosses to Delicious were made, selecting for resistance after each one. Delicious 51 was released as resistant to Fusarium wilt in 1951 by the New York AES (17).

The genetic basis for resistance to Fusarium wilt has not been definitely determined for Iroquois and Delicious 51 (18). The inheritance of resistance in Honey Dew has not been reported, but it seems likely that few genes are involved because of the relative ease of transferring resistance into several commercial cultivars.

The purposes of this paper are to report on a reliable artificial inoculation and testing procedure for the evaluation of the reaction of Honey Dew, Iroquois, and Delicious 51 to *F. o. melonis* races 0, 1, 2, and 1-2; the reaction of Honey Dew, Iroquois, and Delicious 51 to *F. o. melonis* races 0, 1, 2, and 1-2; the mode of inheritance of resistance in Honey Dew, Iroquois, and Delicious 51 to *F. o. melonis* race 2; the genetic relationship between these sources of resistance; and the genetic relationship of Honey Dew, Iroquois, and Delicious 51 to the cultivar Doublon, resistant to *F. o. melonis* races 0 and 2.

MATERIALS AND METHODS

Standard hybridization techniques for muskmelon (23) were used to make crosses between the homozygous cultivars resistant to *F. o. melonis* races 0 and 2 (Honey Dew, Iroquois, and Delicious 51) and a cultivar (Top Mark) susceptible to *F. o. melonis* races 0, 1, 2, and 1-2 to determine the mode of inheritance of resistance. A second series of crosses was made between resistant Honey Dew, Iroquois, and Delicious 51. These cultivars also were crossed with Doublon, which is resistant to *F. o. melonis* races 0 and 2, to identify alleles for resistance.

Two different seed sources for each cultivar were used in the inheritance studies. Iroquois and Delicious 51 seed was obtained from H. M. Munger, Cornell University, and represents the fourth generation from the original release. A second source of Iroquois and Delicious 51 seed was obtained from Harris Seed Company, Rochester, NY. Honey Dew seed was obtained from Asgrow Seed Company, Kalamazoo, MI, and from Moran Seed Company, Salinas, CA. All seed lots were screened for resistance to *F. o. melonis* race 2 (seedling test), and selected resistant plants were self-pollinated. Progenies from these resistant mother plants (homozygous resistant) were used as parents for crosses in the genetic studies.

All isolates of *F. o. melonis* used in these studies were obtained from T. Gordon, University of California, Berkeley, and are representative of the race system of Risser et al (20). Three isolates from American Type Culture Collection (ATCC), 28856, 28857, and 28858, represent races 0, 1, and 1-2, respectively. Isolate P-2 described by Jacobson and Gordon (9) represents race 2. One isolate was used for each race. Inoculum of races 0, 1, 2, and 1-2 consisted of a mixture of macroconidia and microconidia prepared from potato-dextrose agar (PDA) slant cultures grown for 10 days at 20–24 C under continuous illumination. The spores were washed from the agar surface with distilled water and the suspension was filtered through two layers of cheesecloth. A hemacytometer was used to quantify inoculum. The filtrate was diluted with distilled water to obtain the desired inoculum concentration.

Resistance to races 0, 1, 2, and 1-2 was tested at an inoculum concentration of 0.05×10^6 spores per milliliter on 14-day-old (first to second true leaf) plants. The inoculum concentration study was also done on 14-day-old plants with race 2 at concentrations of 0.06×10^6, 0.12×10^6, 0.25×10^6, 0.5×10^6, and 1.0×10^6 spores per milliliter. The study on the interaction of plant age at time of inoculation and inoculum concentration was tested on 7-day-old (first true leaf) plants and 28-day-old (third to fifth true

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leaf) plants with race 2 at inoculum concentrations of 0.1×10^6, 0.5×10^6, and 1.0×10^6 spores per milliliter. The same inoculum preparation was used for both plant ages by adjusting the planting dates. The inoculum concentration used in the genetic studies was 0.05×10^6 spores per milliliter and the plants were approximately 21 days old (second to fourth true leaf).

Seeds of plants to be assayed for disease reaction were treated with 5% $Ca(OCl)_2$ for 5 min, rinsed in water, and planted into cell-type (two seeds per 55-ml cell) plastic growing trays filled with a pasteurized potting mix of peat and vermiculite (1:1, v/v). Each tray containing seeds was placed on top of a flat that was also full of potting mix. Each cell of the tray had an enlarged drainage hole that allowed seedling roots to grow into the lower flat of soil. Seedlings in the cotyledon stage of growth were thinned to one plant per cell. When the plants were at the desired age for inoculation, the upper tray was lifted from the lower flat. Ruptured roots protruding from the drainage holes in the cell bottoms were rinsed with a fine spray of water before the entire tray was placed in a cafeteria tray ($52 \times 38 \times 1.5$ cm) containing 1 L of inoculum. The tray was allowed to remain in the spore suspension until all of the inoculum was absorbed (approximately 45 min) and then placed back on the lower flat. Control plants were dipped in water only. To hasten inoculum absorption into the soil, seedling trays were not watered the day before inoculation. Inoculated seedlings were kept in a greenhouse at 20–27 C. The differential cultivars Doublon, CM 17-187, and Charentais T (20), as well as the parents of the cross being studied, were included in each test to monitor for any changes in pathogen virulence or race.

Plants were examined at 2- to 3-day intervals. Symptoms first appeared 7–18 days after inoculation. The number of infected plants as evident by stunting, wilting, or death was recorded. However, by the final assessment at 28 days post-inoculation, the population under test fell into two classes. Plants were either dead or free of wilt symptoms. Dead plants were classified as susceptible and those that were free of symptoms were classified as resistant.

RESULTS

Reaction to races 0, 1, 2, and 1-2. Twenty seedlings of Honey Dew, Iroquois, Delicious 51, and Top Mark and 10 seedlings of the differential cultivars Charentais T, Doublon, and CM 17-187 were inoculated with races of *F. o. melonis*. All Honey Dew, Iroquois, and Delicious 51 plants were resistant to races 0 and 2 and all were susceptible to races 1 and 1-2. Charentais T and Top Mark were susceptible to all races. Doublon and CM 17-187 were resistant to races 0 and 2, and 0 and 1, respectively, and susceptible to all other races (Table 1).

Reaction to race 2 inoculum concentrations. Forty seedlings of each cultivar were inoculated at six inoculum concentrations (including a water control). Honey Dew, Iroquois, and Delicious 51 were resistant at an inoculum concentration of 0.06×10^6 spores per milliliter. A proportion of the population was susceptible at concentrations of 0.12×10^6 and higher (Fig. 1). With each doubling of the inoculum concentration, the number of plants free of Fusarium wilt symptoms decreased. All plants of Doublon were resistant and all plants of Top Mark were susceptible to all concentrations and thus not included in Figure 1. All plants were free of wilt symptoms in the control treatment.

Interaction of plant age and race 2 inoculum concentration. Twenty plants each of Honey Dew, Iroquois, Delicious 51, Doublon, and Top Mark were inoculated at two ages and at four inoculum concentrations (including a water control). The level of resistance (proportion of population free of wilt symptoms) in Honey Dew, Iroquois, and Delicious 51 was lower, at a given inoculum concentration, in plants inoculated at 7 days old than plants inoculated at 28 days of age (Fig. 2). Honey Dew, Iroquois, and Delicious 51 symptom expression appeared earlier and was more severe in plants inoculated at 7 days old compared with plants inoculated at 28 days old. The level of resistance of Iroquois was generally lower than Honey Dew and Delicious 51. This may be associated with the relatively poor vigor of Iroquois plants compared with Honey Dew and Delicious 51 plants. Doublon was resistant and Top Mark was susceptible at all inoculum concentrations at the two ages of inoculation and, thus, were not included in Figure 2. All plants were free of wilt symptoms in the control treatments.

Inheritance of resistance to race 2. Crosses of resistant Honey Dew, Iroquois, and Delicious 51 with susceptible Top Mark produced F_1 progenies resistant to race 2. The segregation observed in the F_2 generation indicated simple inheritance (3:1) of the disease reaction, with resistance determined by a single

Table 1. Reaction of Honey Dew, Iroquois, Delicious 51, Top Mark, and the differential cultivars Charentais T, CM 17-187, and Doublon to races 0, 1, 2, and 1-2 of *Fusarium oxysporum* f. sp. *melonis*

	Number of plants resistant or susceptible to races of *F. o. melonis*[a,b]							
	0		1		2		1-2	
Cultivar	R	S	R	S	R	S	R	S
Honey Dew	20	0	0	20	20	0	0	20
Iroquois	20	0	0	20	20	0	0	20
Delicious 51	20	0	0	20	20	0	0	20
Top Mark	0	20	0	20	0	20	0	20
Charentais T	0	10	0	10	0	10	0	10
CM 17-187	10	0	10	0	0	10	0	10
Doublon	10	0	0	10	10	0	0	10

[a] R = number resistant, S = number susceptible.
[b] 14-day-old plants inoculated at a concentration of 0.05×10^6 spores per milliliter.

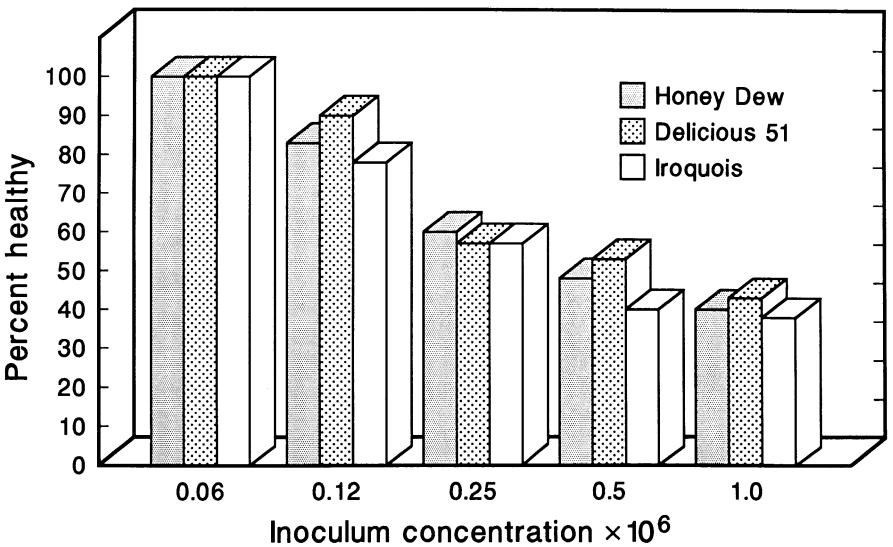

Fig. 1. The effect of inoculum concentration on the percentage of plants that remained free of wilt symptoms in cultivars Honey Dew, Delicious 51, and Iroquois after inoculation with *Fusarium oxysporum* f. sp. *melonis* race 2.

dominant gene (Table 2).

To verify the pattern of resistance, the F_1s were backcrossed to susceptible Top Mark. The BC_1 progenies of these crosses gave a good fit to a 1:1 ratio of resistant to susceptible plants. The F_1s backcrossed to resistant Honey Dew, Iroquois, and Delicious 51 resulted in all resistant progenies (Table 2). The segregation of the BC_1 progenies indicated that resistance is conferred by a single dominant gene. Honey Dew and Delicious 51 parents were resistant in the inheritance study, but three of the Iroquois plants showed stunting and wilting symptoms. The Top Mark parent was susceptible.

Allelism test. Crosses were made between Doublon, with the dominant gene *Fom 1* conferring resistance to races 0 and 2, and Honey Dew, Iroquois, and Delicious 51, shown to have a single dominant gene controlling resistance to races 0 and 2. Crosses also were made between Honey Dew, Iroquois, and Delicious 51. Self-pollinated F_1 plants from these crosses produced F_2 progenies that did not segregate (Table 3).

Progenies from the F_1 (Honey Dew × Iroquois, Honey Dew × Delicious 51, Honey Dew × Doublon, Iroquois × Delicious 51, Iroquois × Doublon, and Delicious 51 × Doublon) crossed to susceptible Top Mark did not segregate (Table 3). The lack of segregation indicates that the gene *Fom 1*, or an allele of this gene, confers resistance to races 0 and 2 in Honey Dew, Iroquois, and Delicious 51.

A total of 77 Honey Dew, 74 Iroquois, 73 Delicious 51, 46 Doublon, and 73 Top Mark plants were inoculated during the course of the allelism tests. Two Honey Dew plants, three Iroquois plants, and one Delicious 51 plant were observed with typical Fusarium wilt symptoms. None of the Doublon plants developed symptoms, and all of the Top Mark plants were susceptible. All plants were free of wilt symptoms in the control treatment.

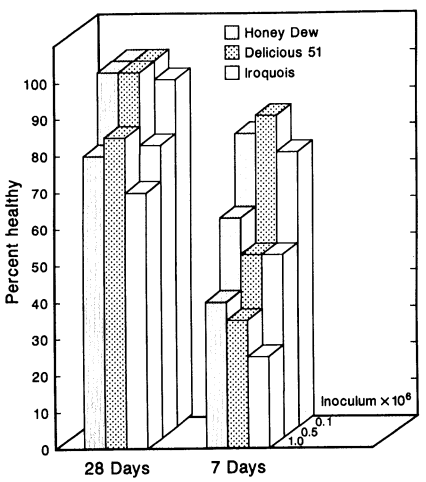

Fig. 2. The effect of age of plants at inoculation with *Fusarium oxysporum* f. sp. *melonis* race 2 and inoculum concentration on the percentage of plants free of wilt symptoms in cultivars Honey Dew, Delicious 51, and Iroquois.

Efficacy of tests. A total of 577 resistant parent plants (Honey Dew, Iroquois, and Delicious 51) were inoculated with *F. o. melonis* race 2 in the study on the reaction to races, inheritance test, and allelism test. Thirteen plants, 2.25% of the population, developed wilt symptoms. Of the 212 inoculated susceptible parent plants (Top Mark), none were free of wilt symptoms.

DISCUSSION

The isolates of *F. o. melonis* used in the Minnesota AES and New York AES breeding programs in the 1930s to 1950s were from diseased muskmelon plants in each respective state. A race could not be assigned to these isolates because the existence of physiologic races in muskmelon was first shown in 1965 (21).

Jacobson and Gordon (9) reported that isolates of *F. o. melonis* from California, Indiana, Michigan, New York, and Ontario, Canada, are race 2, and race 0 was identified in isolates from Maryland and Texas. The proximity of Indiana, Michigan, New York, and Ontario to Minnesota suggests that race 2 is the prevalent race in Minnesota. The reaction of Honey Dew, Delicious 51, and Iroquois to the races of *F. o. melonis* indicates that these cultivars have race-specific resistance (resistant to races 0 and 2 and susceptible to races 1 and 1-2).

Table 2. Segregation in progenies from crosses between resistant (R) cultivars Honey Dew, Iroquois, and Delicious 51 and susceptible (S) cultivar Top Mark after inoculation with race 2 of *Fusarium oxysporum* f. sp. *melonis*

Parents and crosses	Expected ratio	Observed reaction[a] (no. of plants) R	S	χ^{2b}	*P*
Honey Dew[c] (HD[c])	All R	48	0	...	...
Top Mark (TM)	All S	0	20	...	...
F_1 HD[c] × TM	All R	50	0	...	...
TM × HD[c]	All R	47	0	...	...
F_2 (HD[c] × TM)	3:1	75	21	0.50	0.50–0.30
BC_1 (HD[c] × TM) × TM	1:1	53	42	1.27	0.03–0.20
BC_1 (HD[c] × TM) × HD[c]	All R	95	0	...	...
Honey Dew[d] (HD[d])	All R	46	2	...	...
Top Mark	All S	0	20	...	...
F_1HD[d] × TM	All R	51	0	...	...
TM × HD[d]	All R	46	0	...	...
F_2 (HD[d] × TM)	3:1	78	20	1.01	0.50–0.30
BC_1 (HD[d] × TM) × TM	1:1	49	42	0.54	0.50–0.30
BC_1 (HD[d] × TM) × HD[d]	All R	97	0	...	...
Iroquois[e] (I[e])	All R	48	1	...	...
Top Mark (TM)	All S	0	19	...	...
F_1 I[e] × TM	All R	48	0	...	...
TM × I[e]	All R	45	0	...	...
F_2 (I[e] × TM)	3:1	59	26	1.41	0.30–0.20
BC_1 (I[e] × TM) × TM	1:1	52	45	0.50	0.50–0.30
BC_1 (I[e] × TM) × I[e]	All R	92	0	...	...
Iroquois[f] (I[f])	All R	46	2	...	...
Top Mark (TM)	All S	0	20	...	...
F_1 (I[f] × TM	All R	50	0	...	...
TM × I[f]	All R	47	0	...	...
F_2 (I[f] × TM)	3:1	74	19	1.04	0.50–0.30
BC_1 (I[f] × TM) × TM	1:1	46	51	0.26	0.70–0.50
BC_1 (I[f] × TM) × I[f]	All R	96	0	...	...
Delicious 51[e] (D51[e])	All R	50	0	...	...
Top Mark (TM)	All S	0	20	...	...
F_1 D51[e] × TM	All R	49	0	...	...
TM × D51[e]	All R	20	0	...	...
F_2 (D51[e] × TM)	3:1	67	28	1.01	0.50–0.30
BC_1 (D51[e] × TM) × TM	1:1	45	49	0.17	0.70–0.50
BC_1 (D51[e] × TM) × D51[e]	All R	97	0	...	...
Delicious 51 (D51[f])	All R	46	2	...	...
Top Mark	All S	0	20	...	...
F_1 D51[f] × TM	All R	50	0	...	...
TM × D51[f]	All R	51	0	...	...
F_2 (D51[f] × TM)	3:1	71	27	0.34	0.70–0.50
BC_1 (D51[f] × TM) × TM	1:1	54	43	1.24	0.30–0.20
BC_1 (D51[f] × TM) × D51[f]	All R	95	0	...	...

[a] R = number resistant, S = number susceptible.
[b] Chi-square test was used to determine goodness of fit to genetic ratios.
[c] Seed source Asgrow Seed Company.
[d] Seed source Moran Seed Company.
[e] Seed source Cornell University.
[f] Seed source Harris Seed Company.

Therefore, it appears that the Minnesota and New York *F. o. melonis* isolates used in the Minnesota AES and New York AES breeding programs probably were race 2.

Intermediate resistant cultivars have been shown to exhibit varying degrees of susceptibility when inoculated as seedlings in greenhouse studies (25). Furthermore, there are differences among cultivars in disease response at different concentrations of inoculum (2,7,24). The response of Honey Dew, Iroquois, and Delicious 51 to an inoculum concentration gradient and to the interaction of plant age and inoculum concentration is in agreement with previous reports (2,10, 14,22).

McKeen (14) cautioned that Iroquois may show losses from Fusarium wilt when direct-seeded because of susceptibility in the seedling state, but he based this on greenhouse tests rather than field observation. Few muskmelons are direct-seeded in the Midwest and the northeastern U.S. Because of the short growing season, 3- to 4-wk-old plants are transplanted into the field. Cultivars having the Minnesota AES source of resistance, such as Delicious 51, Golden Gopher, Harvest Queen, Iroquois, and Minnesota Honey, apparently have adequate resistance when transplanted into fields infested with *F. o. melonis* race 2. In the San Joaquin Valley of California, Honey Dew melons are direct-seeded in production areas with a history of *F. o. melonis* race 2. It is common to grow vigorous, symptom-free Honey Dew plants in fields where the previous year severe losses have occurred in susceptible Top Mark and PMR 45. Gordon et al (8) reported inoculum densities in a commercial field in the San Joaquin Valley naturally infested with *F. o. melonis* race 2 as 270 ± 50 colony-forming units per gram of soil. This level of inoculum density caused severe symptoms and losses in susceptible PMR 45 whereas Honey Dew remained free of symptoms.

Studies of the genetic basis of resistance in Iroquois and Delicious 51 were not conclusively determined by previous investigators (6,15,18). Dolan (6) concluded that resistant and susceptible muskmelon could be differentiated best in the greenhouse by injecting a spore suspension of *F. o. melonis* between the cotyledons of seedlings (injection method). However, he reported that a few susceptible plants survived this treatment and some resistant plants developed wilt symptoms. He found the F_1 progenies from the cross Iroquois × susceptible were all resistant, and three tests of F_2 progenies gave 87, 85, and 73% resistant plants. Of 32 F_3 progenies tested, 10 were nonsegregating and 22 segregated 3:1. Backcrosses of the F_1 to susceptible Delicious and to susceptible Seneca Bender gave 42 and 43% resistant plants, respectively. Despite the poor fit of two of the three F_2 tests to the expected ratio (3:1 resistant/susceptible), and a poor fit of the two backcross tests to the expected ratio (1:1 resistant/susceptible), Dolan concluded that his results could best be interpreted by assuming the Fusarium wilt resistance is attributable to a single dominant factor.

Mortensen (15) reported F_1 progenies from the cross Iroquois × susceptible cultivars were resistant and F_2 progenies segregated 3:1 or 9:7 resistant/susceptible. Backcrosses segregated 1:1 and 3:1, respectively. The fact that both monohybrid and dihybrid F_2 ratios appeared suggests a two-gene hypothesis. However, this hypothesis did not fit all of his data. Mortensen then proposed that there is a principal dominant gene (R) for resistance, as Dolan (6) assumed. In addition to the (R) gene, there are two complementary genes, (A) and (B), which are expressed when the principal gene is in the homozygous recessive (rr) condition. The hypothetically resistant genotypes would include RAB, RAbb, RaaB, Raabb, and rrAB; susceptible ones would include rrAbb, rraaB, and rraabb. These proposed genotypes were based on results obtained by the injection method in the greenhouse and by placing wheat inoculum beneath plants at the time of transplanting in the field. However, neither method of inoculation gave a consistent reaction on resistant and susceptible parent cultivars. Little confidence can be placed on a hypothesis based on the results of these experiments.

In testing (injection method) successive backcross progenies involved in breeding Delicious 51, Munger and Newhall (18) reported that there was no difficulty in maintaining the same level of resistance found in Iroquois. This confirms the idea that resistance is completely dominant and simply inherited. However, they observed the proportion of BC_3 and BC_4 progenies showing segregation for Fusarium wilt resistance was consistently larger than expected if only one dominant gene was involved. There appear to be several possible explanations for this phenomenon: a partial failure of the injection method of inoculation; a reduced virulence of the *F. o. melonis* isolate used for inoculation; and a low inoculum concentration. Any one of these factors alone or in combination could contribute to the survival of a proportion of susceptible progenies and result in an excess of progenies in the resistant class. In Dolan's (6), Mortenson's (15), and Munger and Newhall's (18) studies, there is no reference to the concentration of inoculum used in the injection method.

The reaction to *F. o. melonis* races and genetic information reported here on the intermediate level of resistance in Honey Dew, Iroquois, and Delicious 51 was obtained by artificial inoculation using a tray-dip method. By adjusting the concentration of the inoculum and the age of plants at time of inoculation, a relatively consistent separation of resistant and susceptible parents was achieved. The segregation of F_1, F_2, and backcross progenies supports a single dominant gene hypothesis for resistance in Honey Dew, Iroquois, and Delicious 51. Allelism tests indicate that the intermediate resistance in Honey Dew, Iroquois, and Delicious 51 is controlled by *Fom 1*, the gene conferring a high level of resistance in Doublon (19), or an allele of the gene *Fom 1*. If *Fom 1* is the controlling gene in these intermediate resistant cultivars, then full expression of *Fom 1* appears to be reduced by a modifying gene or genes present in Honey Dew, Iroquois, and Delicious 51. However, if the gene controlling resistance is an allele of *Fom 1*, the intermediate resistant reaction to artificial inoculation suggests that this allele does not express as high a level of resistance as *Fom 1* does in the cultivar Doublon.

Table 3. Allelism test for the dominant gene *Fom 1* in Honey Dew, Iroquois, Delicious 51, and Doublon that confers resistance to race 2 of *Fusarium oxysporum* f. sp. *melonis*

Cross[a]	Expected ratio[b]	Observed reaction (no. of plants)[c]	
		R	S
F_2 (HD × I)	15:1	145	0
F_2 (HD × D51)	15:1	148	0
F_2 (HD × D)	15:1	144	0
F_2 (I × D51)	15:1	141	0
F_2 (I × D)	15:1	147	0
F_2 (D51 × D)	15:1	144	0
F_1 (HD × I) × TM	3:1	87	0
F_1 (HD × D51) × TM	3:1	97	0
F_1 (HD × D) × TM	3:1	94	0
F_1 (I × D51) × TM	3:1	92	0
F_1 (I × D) × TM	3:1	89	0
F_1 (D51 × D) × TM	3:1	145	0

[a] HD = Honey Dew, I = Iroquois, D51 = Delicious 51, D = Doublon, and TM = susceptible cultivar Top Mark. Seed sources I and D51, Cornell University and HD Asgrow Seed Co.
[b] If different genes confer resistance.
[c] R = number resistant, S = number susceptible.

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