

Research Article

Damage function model in two cucumber cultivars infected by *Meloidogyne javanica* under greenhouse conditions

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Abstract: Root-knot nematodes (RKNs) hold global economic importance. Predicting the potential crop damage caused by a specific level of nematode population is crucial for developing effective nematode management strategies. This study aimed to investigate the effect of increasing the initial population density (Pi) of *Meloidogyne javanica* on the final population densities of the nematode and its impact on cucumber yield, to determine the damage functions for shoot fresh and dry weight as well as fruit weight in two selected cucumber cultivars (IRQS-22 and WGR-225) in response to the nematode. For this purpose, cucumber seedlings were inoculated with a specific density of J2s of *M. javanica* (0, 2, 4, 8, 16 J2s g⁻¹ soil), and the mentioned parameters were investigated. The findings indicated a negative correlation between the initial nematode inoculum level, the height and weight of the plant shoot, and the yield. However, the root response varied in relation to the level of nematode inoculum. The Pearson correlation coefficients among gall index and egg mass with plant growth parameters were negatively related. The yield responses to Pi were fitted properly by polynomial regression equations and Seinhorst's model. The tolerance limits were estimated at 5.708 and 1.808 J2s g⁻¹ soil for the WGR225 and IRQS22 cultivars for shoot fresh weight. The shoot dry weight tolerance limits were calculated as 2.107 and 3.081 J2s g⁻¹ soil for the WGR225 and IRQS22 cultivars. The maximum nematode reproduction factor was 12.55 and 23.03 in the WGR225 and IRQS22 cultivars, respectively, at an initial population density of 2 J2s g⁻¹ soil. These results can be used as a basis for the efficient management of the nematode.

Keywords: *Cucumis sativus*, Damage function, Host-parasitic relationship, Inoculum Levels, Seinhorst model

Introduction

Plant-parasitic nematodes are significant pests that cause substantial economic and social impacts by damaging crops (Nicol *et al.*, 2011).

Root-knot nematodes (RKNs), *Meloidogyne* spp., are the most destructive plant-parasitic nematodes. Their annual losses are around \$173 billion for planted crops worldwide (Gamalero and Glick, 2020). The reduction of crop yields

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due to root-knot nematodes has been frequently reported in various plants, for example, in bell peppers (Moosavi, 2015), finger millet (Waweru *et al.*, 2023), watermelon, and zucchini (Giné *et al.*, 2014; López-Gómez *et al.*, 2015). Nematode invasion disrupts root tissues, including the epidermis, cortex, endodermis, pericycle, and vascular cylinder, during penetration, female establishment, and giant cell formation (Anwar and McKenry, 2012). In addition, the feeding activities of nematodes interfere with plant physiological functions, such as photosynthesis, as well as increase the respiratory rate and disrupt the balance between catabolism and anabolism in the plant (Paez *et al.*, 1976; Carneiro *et al.*, 2002). The mentioned waste, as well as toxic enzymes, is sequestered by nematodes in the roots (Ami and Shingaly, 2020), resulting in a decrease in plant growth parameters. The reduction in plant yield depends on the *Meloidogyne* species and strains, the initial nematode population density at planting, and the host plant species and cultivar (Gullino *et al.*, 2019; Chen *et al.*, 2022). Understanding soil biology and nematode population dynamics at the time of sowing is critical for developing effective management strategies. Accurate prediction of damage levels is essential for deciding whether to cultivate specific crops or cultivars. Therefore, it is essential to investigate the response of major plant cultivars of each area to indigenous populations of nematodes to obtain the most precise correlation (Nadeem *et al.*, 2023).

Models of nematode populations and crop yields are derived from the integration of mathematical theories and computer programs that represent a portion of the presumptive actuality. These models rely on historical data to forecast future outcomes, with the primary goal of estimating crop yield based on nematode population density and other relevant factors (Jamali *et al.*, 2012). Previous studies have been conducted to determine the correlation between nematode-plant interactions and the loss threshold or tolerance limit. The results of these studies provided several experimental models for nematode population dynamics and yield loss in crops, and specific predictive models for

estimating nematode damage in different crops were developed (Seinhorst, 1965; Jamali *et al.*, 2012; Karimipour Fard *et al.*, 2018).

The Seinhorst's model provided valuable insights into the correlation between crop yield and nematode population (Seinhorst, 1965). Based on the Nicholson competition curve (Nicholson, 1933), this model predicts crop yield in nematode-affected fields by analyzing data on nematode population densities. The model has two components: tolerance limit (T) and minimum yield (m). The 'tolerance limit' is defined as a population density of nematodes below which no crop loss occurred, and 'm' is the minimum relative yield when nematode population density is at its highest level (Seinhorst, 1965). The Seinhorst model has been widely applied to plant parasitic nematodes, including root-knot nematodes (*Meloidogyne* spp.), potato cyst nematode (*Globodera pallida*), and *Aphelenchoides besseyi* (Phillips *et al.*, 1991; Ehwaeti *et al.*, 2000; Poudyal *et al.*, 2005; Norshie *et al.*, 2011; Jamali *et al.*, 2012; Sasanelli *et al.*, 2013; Heve *et al.*, 2015; Moosavi, 2015). Despite its widespread use, some studies have reported inconsistencies between observed data and the Seinhorst model's predictions (Gharabadiyan *et al.*, 2013). Alternative models, such as linear or sigmoid functions, have been proposed as suitable in some instances, depending on the nature of nematode damage, initial population density, crop tolerance, and environmental conditions (Haji-Hassani *et al.*, 2010; Karimipour Fard *et al.*, 2018; Gharabadiyan *et al.*, 2013).

In Iran, greenhouse cucumbers play a crucial role in the agricultural economy, contributing significantly to food production, employment, and export income. However, root-knot nematodes represent a serious biotic threat to the sustainability and profitability of this industry. Therefore, the present study aimed to: i) investigate the relationships between the population density of *M. javanica* and the growth and yield of the two commonly cultivated cultivars WGR-225 and IRQSP22 in Iran; ii) compare the damage functions of *M. javanica* on the cucumber cultivars to develop a

predictive model for crop losses based on nematode population density; *iii*) evaluate the tolerance limit using the Seinhorst model study.

Materials and Methods

Nematode inoculum

In this study, *M. javanica* RKN was used. A single egg mass was selected from a tomato greenhouse in the Varamin district of Tehran, Iran, to establish a pure culture of the nematode. The species was identified using morphological approaches based on females and J2s (Jepson, 1987; Eisenback and Triantaphyllou, 1991) and confirmed species-specific primers (Zijlstra *et al.*, 2000). A mass population of the nematode was propagated by inoculating the Rutgers tomato cultivar. Egg suspension was prepared by soaking infected tomato roots with 0.05% (v/v) NaOCl for 3 min (Hussey and Barkers, 1973). The eggs were incubated at 25 °C in Baermann trays, and hatched J2s were collected for use in the experiment.

Plant culturing

Seeds of two cucumber (*Cucumis sativus*) cultivars, IRQS-22 and WGR-225 were planted in the seedling tray containing cocopeat. At the 2–4 leaf stage, seedlings were transferred to 2 kg plastic pots containing a sterile mixture of sand, soil, and leaf mold (2:1:1). Each pot contained one seedling. Plants were grown in a phytotron (Noor Sanat Ferdous Co., Iran) with a 16-h light and 8-h dark photoperiod at a temperature of 25 °C.

Nematode inoculation to plants

Cucumber seedlings were inoculated with a specific density (P_i) of J2s of *M. javanica* (0, 2, 4, 8, 16 J2s g⁻¹ soil) by making holes around the plant. The J2s nematode inoculum was added to the soil and then covered with sterilized soil. For each initial population level, four replications were considered, and the experiment was repeated twice. The pots were kept in the phytotron under the specified conditions. The pots were watered gently to avoid washing away the J2s, and the moisture level was maintained at a constant level throughout the experiment. To record the data, plants were carefully uprooted four months after

sowing. The harvested roots were washed to remove adhered soil, and plant growth parameters, as well as pathological parameters, were recorded.

Data collection

Plant growth and nematode pathological parameters were recorded. Growth parameters included shoot length, fresh weight of shoot, dry weight of shoot, fresh weight of root, number of fruits, and fruit weight. Pathological parameters included the number of galls, egg masses, eggs, and juveniles in the root system, as well as eggs and juveniles in the soil, final nematode population density (Pf), and reproduction factor (RF). For estimating the final nematode population (Pf), eggs and other developmental stages were extracted from the roots of individual plants (Hussey and Barker, 1973). The J2s were extracted from the soil of each pot using the Whitehead and Hemming tray method (Whitehead and Hemming, 1965). The Pf in each pot was determined by summing nematodes recovered from soil and roots. The reproduction factor (RF) was calculated by dividing the final population (Pf) by the initial one (P_i) (Sasser *et al.*, 1984).

Statistical analysis and modeling

The experiment was conducted using a completely randomized factorial design with two factors: cultivars (WGR225 and IRQS22) and nematode density (with five levels: 0, 2, 4, 8, and 16 J2s g⁻¹ soil). There were 10 treatments in total, each with four replicates. Nematode pathological data were normalized before analysis by transforming them into $\log(X + (\min(X) / 2))$. Data were analyzed using analysis of variance (ANOVA) in SAS version 9.3, with means compared using Fisher's protected least significant difference (LSD) test at $p = 0.05$. The Pearson correlation coefficient was used to assess the correlation between the measured parameters. The relationship between initial nematode population density (P_i) and plant yield (estimated by fresh and dry shoot weight and total fruit weight) was analyzed through regression analysis, fitting the data to the Seinhorst model using SPSS software version 15 and statGraph. In all assessments, the goodness of fit was estimated using the coefficient of determination, R^2 . The

tolerance limit was quantified via Seinhorst's equation: $y = m + (1-m) \times 0.95(P_i/T-1)$ for $P_i > T$, and $y = 1$ for $P_i < T$ (Seinhorst, 1965, 1970, 1986). In this model, y represents the relative yield defined as the ratio between plant growth in an initial population density of the nematode (P_i) and the value obtained in the control plant; m is the minimum yield value (y at a very high initial nematode population density); P_i is the initial nematode population density; and T is the tolerance limit.

Results

Relationship between the initial population density and the pathological parameters

All initial population densities (P_i) of *M. javanica* harmed plant growth parameters in both cucumber cultivars, IRQS-22 and WGR-225 (Tables 1 and 2). The values of the investigated traits decreased as the initial nematode inoculum increased in both studied cultivars. Pathological parameters, including the number of galls, egg mass per root system, final nematode population (P_f), and reproduction factor (RF), were investigated at 120 days after inoculation as well (Tables 1 and 2).

Statistical analysis revealed that the amount of nematode inoculum had a significant impact on various infection parameters, such as the number of root galls, egg masses, eggs, and nematode stages in the roots. Additionally, it affected the nematode population density in the soil, as well as the final nematode population density and the nematode reproduction factor. The lowest infection parameter values were recorded in the first level of infestation, with 2 J2s g^{-1} soil. Subsequently, the values of the infection parameters began to increase, with the highest values observed at a level of 16 J2s g^{-1} soil. Correspondingly, the severity of root galling of cucumber roots increased with the increase in the initial nematode population. The data trend revealed similarities between the two cultivars studied. The reproduction factor of *M. javanica* was inversely related to the initial population densities. The nematode had a higher maximum reproduction factor of 23.03 on the IRQS22 cultivar compared to 12.55 on the WGR225 cultivar showing the susceptibility of both cultivars to *M. javanica*. The highest RF occurred when there was an initial population density of two J2s g^{-1} soil in both of the studied cultivars.

Table 1 Analysis of variance of effects of density (J2s g^{-1} dry weight soil) of *Meloidogyne javanica* on the growth and yield of cucumber cultivars WGR225 and IRQS22 and the nematode pathological parameters.

Traits	Cultivar (A)	Treatment (B)	A × B	Error	Coefficient of variation
Degree of freedom	1	4	4	27	-
Stem height	552.79**	387.61**	16.84*	5.27	3.87
Number of fruits at harvest time	5017.60**	226.79**	5.66 ^{ns}	4.23	7.54
Total weight of fruits	556016.4**	37289.6**	1671.1**	258.7	5.3
Average weights of fruits	1.35 ^{ns}	4.83**	4.32**	0.65	7.25
Aerial fresh weight	599.85**	960.08**	274.55**	3.59	3.89
Aerial dry weight	25.92**	23.52**	1.39**	0.26	5.59
Root fresh weight	42.23**	25.24**	5.94*	1.63	8.09
Galls per root gram	1.60 ^{ns}	129211.54**	253.66 ^{ns}	422.52	10.10
Egg masses per root gram	297.02 ^{ns}	120258.46**	44.84 ^{ns}	230.36	7.67
Eggs and J2 per root gram	33732832.2**	70482949.0**	3476294.7**	568664.2	15.9
Eggs and J2 per 100 g soil	896723772**	104045159**	100689352**	477064	14
Egg masses per root system	1110055.8*	25704707.3**	99521.9 ^{ns}	196496.2	15.0
Galls per root system	635821.4 ^{ns}	27615494.0**	135768.8 ^{ns}	241350.9	16.1
Eggs and J2 per root system	10666030960**	15076154518**	880730068**	148981448	17
Eggs and J2 from 2 cm ³ soil	2209936619**	256414756**	248144516**	1175703	14
Final population density	22586014415**	19072360674**	1954651963**	154471758	16
Reproduction factor	220.78**	371.74**	33.25**	1.12	13.43

*, ** and ns indicate significant difference $p < 0.05$, significant difference $p < 0.01$ and non-significant, respectively.

Table 2 Effects of initial population density (J2s g⁻¹ dry weight soil) of *Meloidogyne javanica* on the growth and yield of cucumber cultivars WGR225 and IRQS22 and the nematode pathological parameters.

Traits	Initial nematode population (J2s.g ⁻¹ dry weight soil)				
	0	2	4	8	16
WGR225					
Stem height (cm)	62.75c	59.68d	54.32e	52.12f	48.95g
Number of fruits at harvest time	22.75f	18.00g	17.00h	12.00i	10.75j
Total weight of fruits (gr)	309.00f	188.25g	165.25h	131.50i	124.00i
Average weights of fruits (gr)	13.58a	10.45e	9.79f	11.00cd	11.61b
Aerial fresh weight (gr)	64.10a	63.75a	63.32a	36.50f	35.00g
Aerial dry weight (gr)	10.50c	8.38e	8.12f	7.22h	7.00h
Root fresh weight (gr)	16.52c	14.45ef	14.38ef	14.30f	14.25f
Galls per root gram	0.00f	188.50e	218.50c	297.75b	314.00a
Egg masses per root gram	0.00f	178.75e	209.25d	284.00c	303.25b
Eggs and juveniles per root gram	0.0i	3480.0h	4107.5g	5568.5e	5912.5d
Eggs and J2s per 100 g soil	0.0i	37.8h	78.0g	103.3f	153.3e
Egg masses per root system	0.0g	2586.3f	3011.0e	4061.2c	4319.0b
Galls per root system	0.0e	2724.7d	3142.9d	4258.7c	4472.6b
Eggs and juveniles per root system	0g	50139f	59088e	79729d	84566d
Eggs and juveniles from 2 L soil	0.0i	59.3h	122.4g	162.1f	240.6e
Final population density (individuals g ⁻¹ soil)	0i	50198h	59210g	79891f	84807e
Reproduction factor	0.00i	12.55c	7.40e	4.99g	2.65h
IRQS22					
Aerial length (cm)	73.80a	68.00b	62.00c	59.25d	51.95f
Fruits at harvest time	46.75a	41.00b	38.00c	35.75d	31.00e
Total weight of fruits (gr)	505.25a	465.25b	403.50c	371.00d	352.00e
Average weights of fruits (gr)	10.87d	11.35bc	10.64de	10.38e	11.36bc
Aerial fresh weight (gr)	59.50b	44.38c	42.50d	39.12e	38.45e
Aerial dry weight (gr)	12.7a	11.00b	9.58d	8.40e	7.55g
Root fresh weight (gr)	21.12a	17.50b	15.65d	14.92e	14.98e
Galls per root gram	0.00f	188.00e	200.00d	303.00b	325.75a
Egg masses per root gram	0.00f	182.50e	213.25d	290.75c	316.00a
Eggs and juveniles per root gram	0.0i	4767.5f	6420.0c	7576.8b	9487.5a
Eggs and juveniles per 100 g soil	0.0i	6025.0d	9180.0c	13915.0b	18600.0a
Egg masses per root system	0.0g	3201.3d	3330.7d	4370.4b	4741.0a
Galls per root system	0.0e	3298.3c	3119.9c	4551.4b	4890.0a
Eggs and juveniles per root system	0g	82679d	100491c	111568b	142079a
Eggs and juveniles from 2 L soil	0.0i	9458.4d	14411.3c	21844.6b	29199.4a
Final population density (individuals g ⁻¹ soil)	0i	92137d	114902c	133413b	171278a
Reproduction factor	0.00i	23.03a	14.36b	8.34d	5.35f

Means within a column followed by the same letter are not significantly different (LSD test, $p \leq 0.05$).

Correlation coefficients between nematode pathological parameters and cucumber growth traits for WGR-225 and IRQS-22 are presented in Tables 3 and 4, respectively. The number of galls and egg masses was inversely related to stem height, number and weight of fruits at harvest, shoot fresh weight, shoot dry weight, and root fresh

weight. However, fruit weight was not significantly correlated with nematode pathological parameters. No statistical correlation was observed between growth parameters and reproduction factor. Indeed, we found that the number and weight of fruits at harvest strongly correlate with shoot fresh and dry weight. As expected, Root fresh

weight showed no significant correlation with other growth parameters. Based on this analysis, we focused further on the shoot fresh and dry weight for modeling.

Modeling the effect of nematode population densities on cucumber yield

Linear regression models failed to describe the relationship between shoot fresh weight and Pi accurately. However, the second-degree polynomial regression equations successfully depicted the relationship between shoot fresh weight and nematode initial density (Fig. 1). The Seinhorst model was also appropriately defined to represent the connection between the initial population density of nematodes and the fresh weight of the shoots. The IRQS22 cultivar showed better results with this model (Fig. 2).

The shoot dry weight was correlated to the nematode initial population using polynomial regression analysis up to order 3 (Fig. 3). The Seinhorst model similarly provided a robust fit for shoot dry weight in both cultivars (Fig. 4).

The Seinhorst model determined tolerance limits (T) of 5.708 and 1.808 J2s g⁻¹ soil for the WGR225 and IRQS22 cultivars, respectively, for shoot fresh weight. Tolerance limits for the shoot dry weight of WGR225 and IRQS22 cultivars were established as 2.107 and 3.081 J2s g⁻¹ soil, respectively. Based on this equation, the WGR225 and IRQS22 cultivars had minimum shoot fresh weights (m) of 0.546 and 0.652, respectively, compared to unaffected plants. The minimum relative values (m) for shoot dry weight of the WGR225 and IRQS22 cultivars were 0.677 and 0.592, respectively.

Table 3 Pearson correlation coefficients of different traits of cucumber cultivar “WGR225” grown in soil inoculated with different densities (0, 2, 4, 8 and 16 J2s g⁻¹ dry weight soil) of *Meloidogyne javanica*.

Traits	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Stem height	1.00	0.90**	0.83**	0.24	0.80**	0.82**	0.55	-0.90**	-0.90**	-0.86**	-0.95**	-0.88**	-0.88**	-0.85**	-0.95**	-0.85**	0.08
2 No. of fruits at harvest time		1.00	0.92**	0.27	0.88**	0.91**	0.60**	-0.94**	-0.93**	-0.92**	-0.93**	-0.92**	-0.92**	-0.91**	-0.93**	-0.91**	-0.05
3 Total weight of fruits			1.00	0.62**	0.69**	0.96**	0.74**	-0.97**	-0.97**	-0.97**	-0.87**	-0.96**	-0.96**	-0.95**	-0.87**	-0.95**	-0.34
4 Average weights of fruits				1.00	0.00	0.54*	0.58**	-0.50*	-0.50*	-0.54*	-0.29	-0.50*	-0.50*	-0.54*	-0.29	-0.54*	-0.66**
5 Aerial fresh weight					1.00	0.73**	0.37	-0.75**	-0.75**	-0.74**	-0.84**	-0.74**	-0.74**	-0.73**	-0.84**	-0.72**	0.32
6 Aerial dry weight						1.00	0.71**	-0.96**	-0.96**	-0.95**	-0.89**	-0.96**	-0.96**	-0.94**	-0.89**	-0.94**	-0.28
7 Root fresh weight							1.00	-0.69**	-0.69**	-0.66**	-0.55*	-0.62**	-0.63**	-0.60**	-0.55*	-0.60**	-0.40
8 Galls per root gram								1.00	0.99**	0.98**	0.91**	0.99**	0.99**	0.97**	0.91**	0.97**	0.28
9 Egg masses per root gram									1.00	0.98**	0.92**	0.99**	0.99**	0.97**	0.92**	0.97**	0.27
10 Eggs and juveniles per root gram										1.00	0.91**	0.98**	0.98**	0.99**	0.91**	0.99**	0.28
11 Eggs and juveniles per 100 g soil											1.00	0.91**	0.90**	0.90**	1.00**	0.90**	-0.07
12 Egg masses per root system												1.00	0.99**	0.98**	0.91**	0.98**	0.28
13 Galls per root system													1.00	0.98**	0.90**	0.98**	0.29
14 Eggs and juveniles per root system														1.00	0.90**	1.00**	0.29
15 Eggs and juveniles from 2 cm ³ soil															1.00	0.90**	-0.07
16 Final population density																1.00	0.29
17 Reproduction factor																	1.00

* and ** indicate significant difference $p < 0.05$ and significant difference $p < 0.01$, respectively.

Table 4 Pearson Correlation coefficients of different traits of cucumber cultivar “IRQS22” grown in soil inoculated with different densities (0, 2, 4, 8 and 16 J2s g⁻¹ dry weight soil) of *Meloidogyne javanica*.

Traits	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Stem height	1.00	0.87**	0.89**	-0.05	0.82**	0.89**	0.74**	-0.87**	-0.88**	-0.89**	-0.94**	-0.82**	-0.82**	-0.86**	-0.94**	-0.88**	0.04
2 No. of fruits at harvest		1.00	0.92**	-0.29	0.82**	0.85**	0.70**	-0.85**	-0.86**	-0.87**	-0.88**	-0.80**	-0.79**	-0.85**	-0.88**	-0.87**	-0.05
3 Total weight of fruits			1.00	0.12	0.86**	0.92**	0.83**	-0.86**	-0.88**	-0.92**	-0.91**	-0.80**	-0.79**	-0.88**	-0.91**	-0.90**	0.01
4 Average weights of fruits				1.00	0.02	0.10	0.24	0.03	0.02	-0.03	0.02	0.07	0.08	0.01	0.02	0.01	0.11
5 Aerial fresh weight					1.00	0.90**	0.85**	-0.95**	-0.97**	-0.93**	-0.88**	-0.94**	-0.92**	-0.93**	-0.88**	-0.93**	-0.39
6 Aerial dry weight						1.00	0.85**	-0.92**	-0.92**	-0.92**	-0.95**	-0.85**	-0.85**	-0.88**	-0.95**	-0.90**	-0.04
7 Root fresh weight							1.00	-0.79**	-0.81**	-0.86**	-0.77**	-0.69**	-0.68**	-0.78**	-0.77**	-0.79**	-0.26
8 Galls per root gram								1.00	0.99**	0.92**	0.95**	0.96**	0.98**	0.92**	0.95**	0.94**	0.23
9 Egg masses per root gram									1.00	0.94**	0.95**	0.98**	0.97**	0.95**	0.95**	0.96**	0.25
10 Eggs and juveniles per root gram										1.00	0.93**	0.88**	0.86**	0.98**	0.93**	0.98**	0.23
11 Eggs and juveniles per 100 g soil											1.00	0.90**	0.90**	0.91**	1.00**	0.94**	-0.01
12 Egg masses per root system												1.00	0.99**	0.93**	0.90**	0.94**	0.33
13 Galls per root system													1.00	0.91**	0.90**	0.92**	0.31
14 Eggs and juveniles per root system														1.00	0.91**	0.99**	0.32
15 Eggs and juveniles from 2 cm ³ soil															1.00	0.94**	-0.01
16 Final population density																1.00	0.27
17 Reproduction factor																	1.00

* and ** indicate significant difference $p < 0.05$ and significant difference $p < 0.01$, respectively.

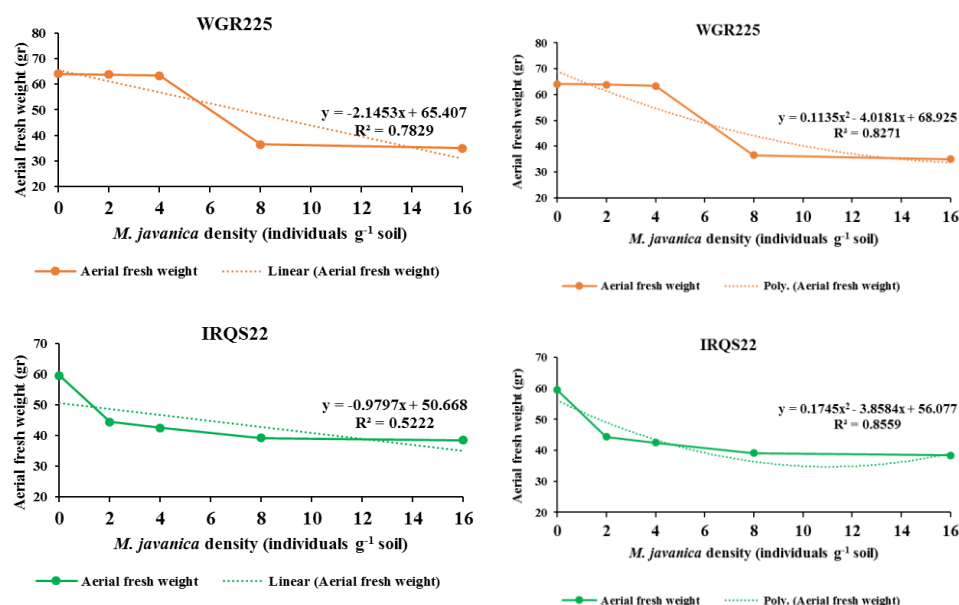


Figure 1 Simple and second-degree polynomial linear regression equations for estimating aerial fresh weight (gr) of cucumber cultivars (WGR225 and IRQS22) via density (J2s g⁻¹ dry weight soil) of *Meloidogyne javanica*.

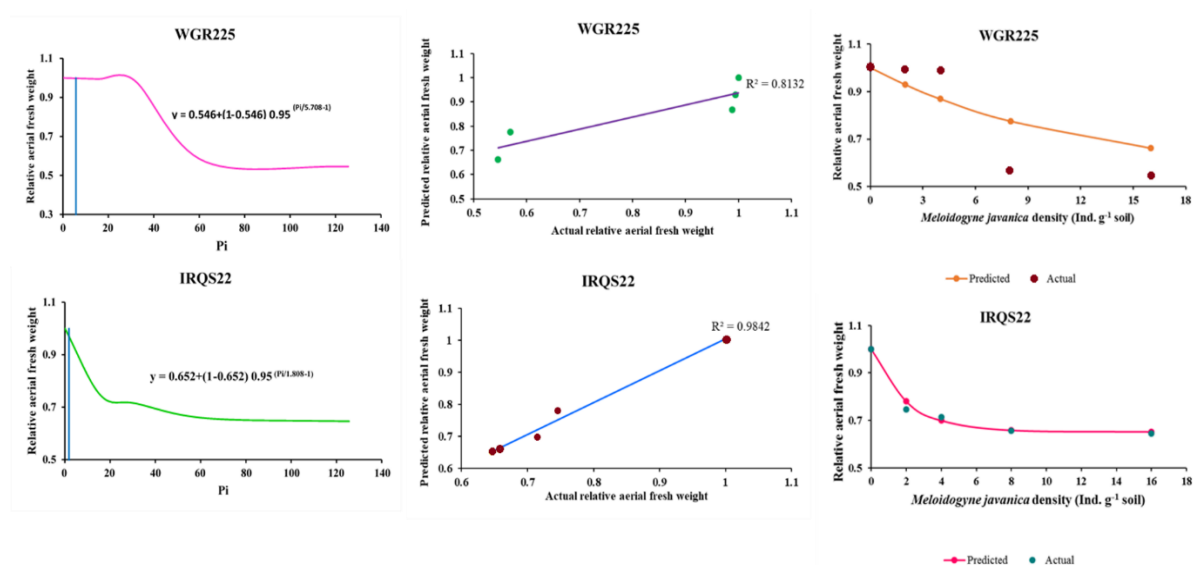


Figure 2 A) Seinhorst damage function model $y = m + (1-m) 0.95^{(P_i/T-1)}$, where y is relative aerial fresh weight, m is the minimum relative aerial fresh weight, P_i is *Meloidogyne javanica* initial population density per 100 cm³ soil and T is the tolerance limit of cucumber cultivars (WGR225 and IRQS22). B) Scatter plot of actual data against predicted values of relative aerial fresh weight of cucumber using Seinhorst damage function models $y = 0.546 + (1-0.546) 0.95^{(P_i/5.708-1)}$ and $y = 0.652 + (1-0.652) 0.95^{(P_i/1.808-1)}$ for WGR225 and IRQS22, respectively. The solid line shows a fitted simple regression line on scatter points.

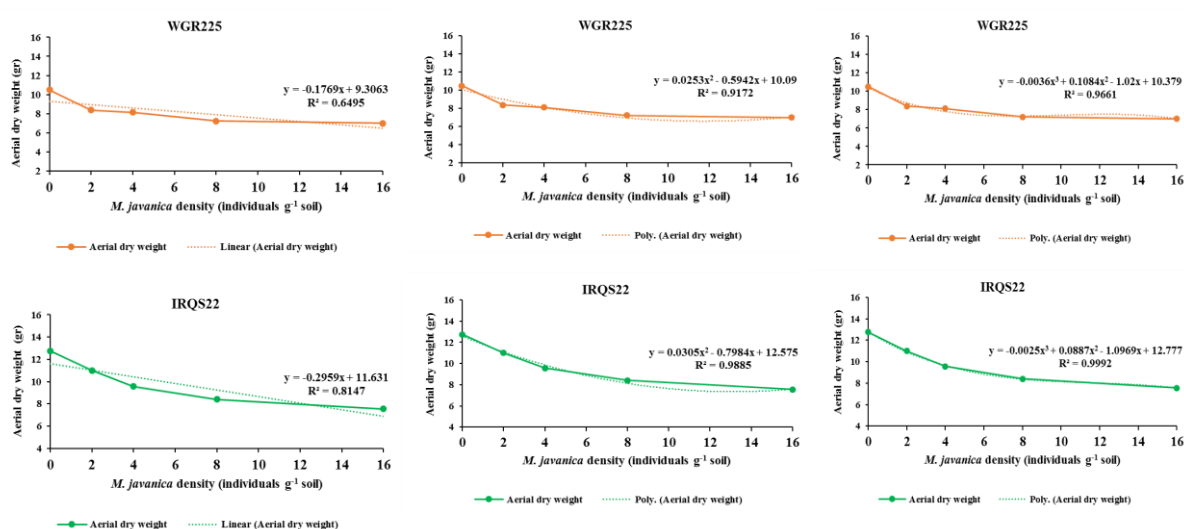


Figure 3 Simple and second-degree polynomial linear regression equations for estimating aerial dry weight (gr) of cucumber cultivars (WGR225 and IRQS22) via density (J2s g⁻¹ dry weight soil) of *Meloidogyne javanica*.

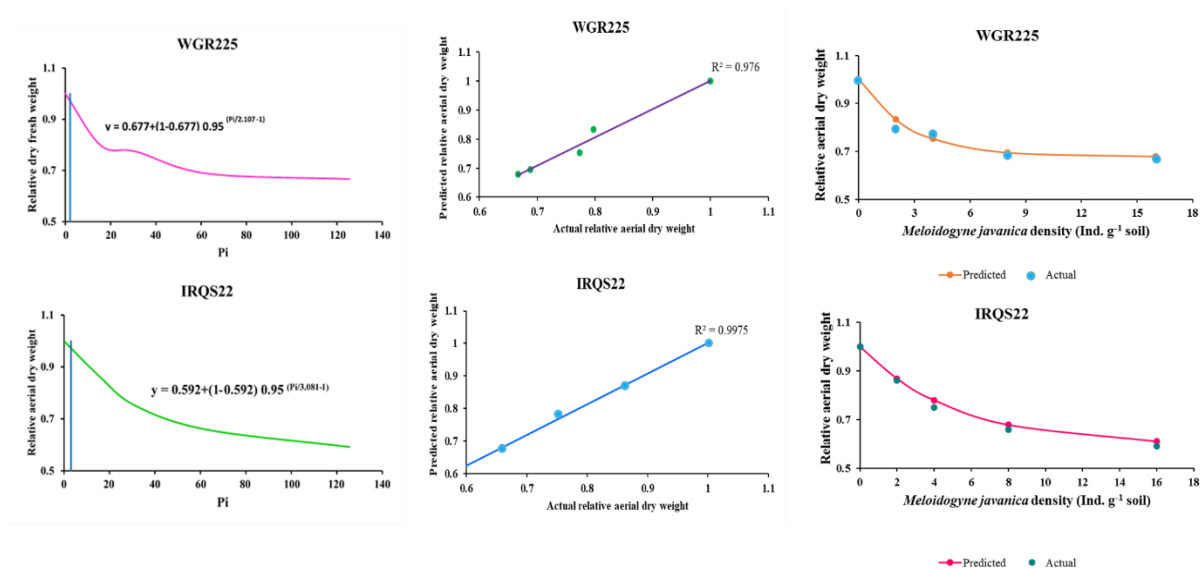


Figure 4 A) Seinhorst damage function model $y = m + (1-m) 0.95^{(Pi/T-1)}$, where y is relative aerial dry weight, m is the minimum relative aerial dry weight, Pi is *Meloidogyne javanica* initial population density per 100 cm³ soil and T is the tolerance limit of cucumber cultivars (WGR225 and IRQS22). B) Scatter plot of actual data against predicted values of the relative aerial dry weight of cucumber using Seinhorst damage function models $y = 0.677 + (1-0.677) 0.95^{(Pi/2.107-1)}$ and $y = 0.592 + (1-0.592) 0.95^{(Pi/3.081-1)}$ for WGR225 and IRQS22, respectively. The solid line shows a fitted simple regression line on scatter points.

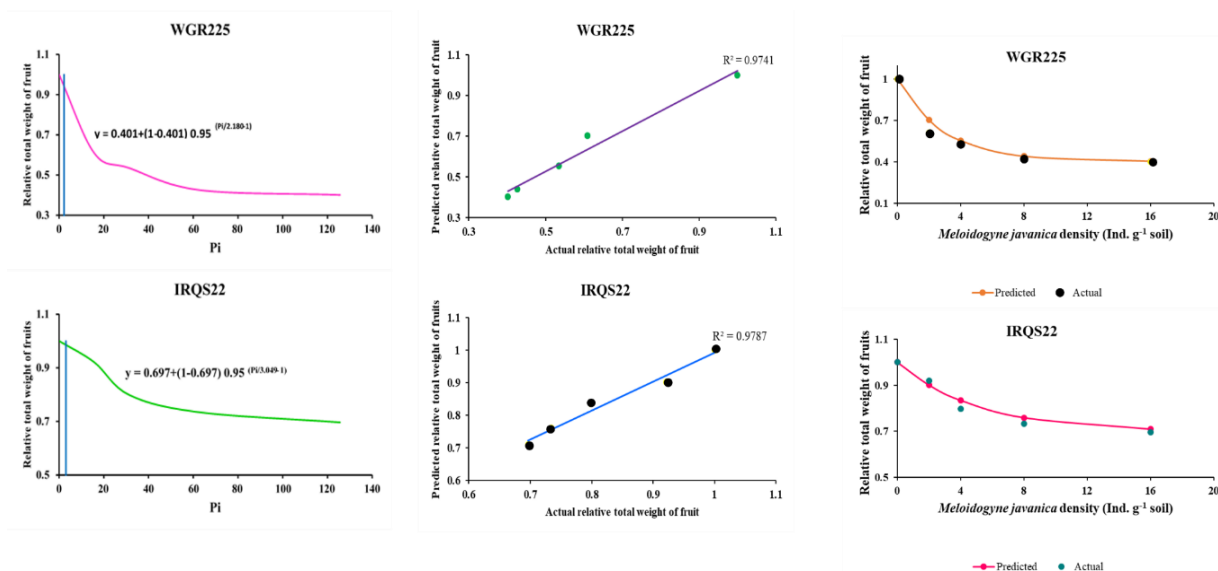


Figure 5 A) Seinhorst damage function model $y = m + (1-m) 0.95^{(Pi/T-1)}$, where y is relative total weight of fruits, m is the minimum relative aerial fresh weight, Pi is *Meloidogyne javanica* initial population density per 100 cm³ soil and T is the tolerance limit of cucumber cultivars (WGR225 and IRQS22). B) Scatter plot of observed data against predicted values of the relative total weight of fruits of cucumber using Seinhorst damage function models $y = 0.401 + (1-0.401) 0.95^{(Pi/2.180-1)}$ and $y = 0.697 + (1-0.697) 0.95^{(Pi/3.049-1)}$ for WGR225 and IRQS22, respectively. The solid line shows a fitted simple regression line on scatter points.

Since the tolerance limits for shoot fresh and dry weight showed contrasting results for the two studied cultivars. Therefore, the Seinhorst equation was also established for the total weight of fruits (Fig. 5). For the total weight of fruits, the tolerance limits were determined as 2.180 and 3.049 J2s g⁻¹ soil for the WGR225 and IRQS22 cultivars.

Discussion

Understanding the applicable principles and assessing damage functions under specific conditions for various crops are essential prerequisites for determining nematode damage threshold values and identifying potential management approaches (Ravichandra, 2014a). The present study was conducted to investigate the relationship between the population densities of *M. javanica* and the crop yields of the cucumber cultivars WGR225 and IRQS22.

The obtained data indicated that the initial population densities of the nematode had negative impacts on yield and plant growth characteristics of both cultivars. This study found that the extent of yield and shoot growth decreased with an increase in the inoculum level of *M. javanica* in both cucumber cultivars under investigation. A similar correlation was observed between the initial population density of *Meloidogyne* spp. and their host plants (Seinhorst, 1965, 1970; Al-Sabie and Ami, 1989; Schomaker and Been, 2006; Russo *et al.*, 2007; Greco and Di Vito, 2009; Hussain *et al.*, 2011; Charegani *et al.*, 2012; Gharabadiyan *et al.*, 2013; Moosavi, 2014; Wesemael *et al.*, 2014; Kankam and Adomako, 2014; Nadeem *et al.*, 2023).

The data we gathered showed that as the inoculum levels of the nematode increased, the severity of root gall occurrence and egg mass also increased. However, we observed a negative correlation between the initial population densities of *M. javanica* and the reproduction factor. In line with our results, numerous prior studies repeatedly reported that, unlike other nematode population indices, the

reproduction rate is inversely related to the initial inoculum levels of the nematode (Charegani *et al.*, 2012; Maleita *et al.*, 2012; Moosavi, 2014, 2015; Ami and Shingaly, 2020; Nadeem *et al.*, 2023). The decrease in nematode reproduction factor as inoculum levels increase is due to the competition of root-knot nematodes for space, food, and penetration (Ibrahim, 2002; El-Sharif *et al.*, 2007; Joymatidevi, 2009; Hussain *et al.*, 2011; Kumar *et al.*, 2011; Charegani *et al.*, 2012). This competition reduces the efficiency of females in egg production (Sumita, 2014) and results in an increase in the number of males in the root (David and Triantaphyllou, 1967).

In assessing plant tolerance, selecting appropriate growth parameters is crucial (Willig *et al.*, 2023). The strong correlation between fruit number, fruit weight, and shoot fresh and dry weight justified focusing on shoot biomass for modeling. The present data showed a clear inverse correlation between the number of galls and the yield, suggesting that the root damage caused by RKN will likely be highly detrimental to the plants. However, no correlation was observed between root weight and other plant growth parameters. As a result, we decided to focus our modeling efforts on the fresh and dry weight of shoots as a key factor.

The analysis showed that the polynomial regression equations outperformed the linear regression in explaining the relationship between yield (shoot fresh and dry weight) and initial nematode density in the cucumber cultivars under study. The most suitable damage function equation for each parameter was determined using the coefficient of determination. The data were also suitably fitted to the Seinhorst model.

The Seinhorst equation models the nematode density–plant yield relationship as an inverted sigmoid curve, where the decrease in yield at a certain time point is a derivative function of the damage. The yield stays consistent until it reaches a specific nematode density, known as the tolerance limit, after which it decreases rapidly, eventually reaching the lowest yield level at the highest nematode density. The

tolerance limit is the first measurable inhibition of plant growth caused by pathogen infection (Seinhorst, 1986). The Seinhorst model facilitates the comparison of tolerance limits for a specific pathogen across different crop varieties. The tolerance limit and the steepness of the reduction in yield over increasing nematode densities are agronomically important features (Pagan and Garcia-Arenal, 2020). In this study, based on the Seinhorst model, the tolerance limits were determined as 5.708 and 1.808 J2s g⁻¹ soil for the WGR225 and IRQS22 cultivars, respectively, in terms of shoot fresh weight. For the shoot dry weight, tolerance limits for the WGR225 and IRQS22 cultivars were determined as 2.107 and 3.081 J2s g⁻¹ soil, respectively.

In comparison to the control plants, the WGR225 and IRQS22 cultivars demonstrated minimum shoot fresh weights (m) of 0.546 and 0.652, respectively. The minimum values (m) for shoot dry weight of the WGR225 and IRQS22 cultivars were 0.677 and 0.592, respectively. Previous research has documented the tolerance limit for *Meloidogyne* spp. at 0.65 J2 g⁻¹ soil for finger millet grain yield, 2.2 eggs and J2 g⁻¹ soil for African paddy rice (*Oryza glaberrima*), 0.18 eggs and J2 g⁻¹ soil for upland rainfed Asian rice, 0.50 eggs and J2 g⁻¹ soil for pepper, 0.19 eggs and J2 g⁻¹ soil for cantaloupe, 0.0002 J2 g⁻¹ soil for zucchini, 0.12 J2 g⁻¹ soil for cucumber, 0.5 egg and J2s g⁻¹ soil for bell pepper, and 0.74 eggs and juveniles cm⁻³ soil for bell pepper cultivar Yolo Wonder (Di Vito et al., 1996; Giné et al., 2014; López-Gómez et al., 2015; Moosavi, 2015; Waweru et al., 2023). Contrasts in tolerance limits and minimum yields of different studies can be due to variations in plant species and cultivar, nematode species and population, soil type, the way of utilizing the inoculum, and environmental conditions (Hussey and Janssen, 2002; Greco and Di Vito, 2009; Ravichandra, 2014b; Mekete et al., 2003; Moosavi, 2015). The tolerance limits for shoot fresh and dry weight showed contrasting results for the two studied cultivars. Therefore, the Sinnhorst equation was also established for the total

weight of fruits. For the total weight of fruits, the tolerance limits were determined as 2.180 and 3.049 J2s g⁻¹ soil for the WGR225 and IRQS22 cultivars. The main difference between the dry weight and fresh weight of a plant shoot lies in their water content. Dry weight reflects only the organic and inorganic matter, providing a precise measurement of biomass that is stable and less affected by external conditions. Dry weight is a more reliable measure for comparison of plant growth, biomass accumulation, or experimental treatments because it is not affected by fluctuating water content (Huang et al., 2019). The results of this study also showed close similarity in the tolerance limits for the shoot dry weight and the total weight of fruits.

Although IRQS-22 exhibited a higher reproductive factor (RF = 23.03) than WGR-225 (RF = 12.55), it demonstrated greater tolerance to *M. javanica*, as indicated by its higher tolerance index (T) for both shoot dry weight and total fruit weight. This finding highlights that tolerance and resistance are distinct traits that must be evaluated independently (Evans and Haydock, 1990; Teklu et al., 2022).

This research provides some key information on the resistance and tolerance levels of two cucumber cultivars (WGR225 and IRQS22). This information enhances our capacity to predict the extent of damage and yield reduction in the two cucumber cultivars as a function of initial *M. javanica* population density under greenhouse conditions, providing a practical foundation for designing targeted nematode management strategies.

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Statement of Conflicting Interests

The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

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بررسی مدل توابع خسارت در دو رقم خیار آلوده به نماتد *Meloidogyne javanica* در شرایط گلخانه‌ای

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چکیده: نماتدهای ریشه‌گرهی اهمیت اقتصادی جهانی دارند. جهت تعیین روش‌های مؤثر مدیریت نماتد، پیش‌بینی میزان خسارت بالقوه ناشی از سطوح مختلف جمعیت اولیه نماتد بسیار حائز اهمیت است. هدف از این پژوهش بررسی تأثیر میزان تراکم جمعیت اولیه نماتد *Meloidogyne javanica* بر میزان جمعیت نهایی نماتد و عملکرد خیار و تعیین توابع خسارت نماتد برای شاخص‌های وزن تر و خشک شاخساره و وزن میوه در دو رقم خیار IRQS-22 و WGR-225 در واکنش به آلودگی نماتد است. بدین‌منظور، گیاهچه‌های خیار با جمعیت‌های اولیه ۰، ۲، ۴، ۸ و ۱۶ لارو سن دوم نماتد در گرم خاک مایه‌زنی شدند و شاخص‌های ذکر شده مورد بررسی قرار گرفت. نتایج نشان داد که بین میزان تراکم جمعیت اولیه نماتد و طول و وزن شاخساره و عملکرد گیاه رابطه معکوس وجود دارد؛ ولی واکنش ریشه نسبت به میزان نماتد مایه‌زنی شده متفاوت بود. نتایج بررسی ضریب هم‌بستگی پیرسون بین شاخص‌های مورد مطالعه نشان داد که بین شاخص گال و توده تخم با شاخص‌های رشد گیاه رابطه منفی وجود دارد. معادلات رگرسیون چندجمله‌ای و مدل سین‌هورست جهت توصیف واکنش عملکرد گیاه به جمعیت اولیه نماتد، مناسب بودند. حد تحمل برای وزن تر شاخساره در ارقام WGR225 و IRQS22 به‌ترتیب ۵/۷۰۸ و ۱/۸۰۸ لارو سن دوم نماتد در گرم خاک بود. این شاخص برای وزن خشک شاخساره در ارقام ذکر شده به‌ترتیب ۲/۱۰۷ و ۳/۰۸۱ لارو سن دوم در گرم خاک بود. بالاترین میزان ضریب تولیدمثل نماتد برای هر دو رقم، در تراکم جمعیت اولیه دو لارو سن دوم نماتد در گرم خاک به‌دست آمد و در ارقام WGR225 و IRQS22 به‌ترتیب ۱۲/۵۵ و ۲۳/۰۳ بود. نتایج این پژوهش، می‌تواند به‌عنوان اطلاعات پایه‌ای برای مدیریت مؤثر نماتد مورد استفاده قرار گیرد.

واژگان کلیدی: *Cucumis sativus*، تابع خسارت، رابطه میزبان-پارازیت، سطح اینوکلوم، مدل سین‌هورست