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Research Article

The Damage and Gain Threshold of *Meloidogyne arenaria* on Faba Bean Favors the Use of a Safe Biological Control Over Chemical Nematicides

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Abstract | Root-knot nematodes (RKNs, *Meloidogyne* spp.) cause major agricultural losses worldwide. Some chemical nematicides are effective, but health and ecological issues are confronting their use. Biological nematicides are safe and promising alternatives. The present study examines *M. arenaria* damage on faba bean and presents effective control methods as Egypt is the world's largest importer of faba bean. Using gain thresholds, the study compares costs of a biological versus a chemical nematicide for *M. arenaria* control on faba bean. *Meloidogyne arenaria* was not detected at pre-planting soil samples of two consecutive field seasons. However, the potential of field weeds as hosts/reservoirs for *M. arenaria* to transfer from weeds and build-up on 'Giza 843' faba bean roots was apparent at harvest. Significant relations were established between the *M. arenaria* population levels at harvest and weights of faba bean pods. Consequently, the gain thresholds were calculated based on the combined costs of nematode sampling and control. Their calculated values demonstrated more costs in applying the chemical (oxamyl) than the biological (Nemaless, bacterial strains of *Serratia marcescens*) nematicide; that is, the gain threshold was 0.78 versus 0.57 metric tons of pods feddan^{-1} (= 4200 m^{-2}), respectively. This comparison should serve as a favorable, forward-looking assessment for the economic and safe application of biological pest control. Applying the chemical (oxamyl) or biological (Nemaless) nematicide is justified for *M. arenaria* control but Nemaless is less costly. Growers should be familiar with these biologicals to boost their use while offering economic and safe control of the nematodes. Cultural practices such as weed control should be strictly utilized for RKN control.

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Introduction

Faba bean or broad bean (*Vicia faba* L.) is one of the most important grain legume crops as food for human consumption and as feed for raising farm animals and poultry (Crepon *et al*., 2010). Yet, Egypt now is the world's largest importer of faba bean with its annual requirement of a half million tons accounting for over half of global imports (GRDC, 2016). The International Center for Agricultural Research in the Dry Areas (ICARDA) offered a recommended technology package (ICARDA, 2017) which increased grain yield and reduced production costs of faba bean, but more efforts to optimize and increase its production are still direly needed. Faba bean production is often affected by several factors such as susceptibility to various diseases, the effects of parasites, weed infestation, and competition with other crops. So, ICARDA scientists have developed improved varieties of faba bean which are adapted to target specific biotic and abiotic stresses. Early maturing faba bean genotypes were developed. They had low water requirement and are also resistant to both chocolate spot disease caused by *Botrytis fabae* and broomrape (*Orobanche crenata*). The yield of new varieties significantly outweighs that of the old varieties (ICARDA, 2017). Among these varieties, 'Giza 843' is a very common one, resistant to broomrape and tolerant to foliar diseases. It is a cross between ICARDA genetic resources and landraces collected in Egypt (ICARDA, 2017). Like other faba bean varieties, e.g., Misr 3, El-Nubariya-1, and El-Nubariya-3, Giza 843 is susceptible to plant-parasitic nematodes (PPNs), especially root-knot nematodes (RKNs) *Meloidogyne* spp. (Göldi) (Tylenchida: Heteroderidae) (Hammam *et al*., 2017; Korayem *et al*., 2018). Although *M. incognita* (Kofoid and White), *M. arenaria* (Neal), *M. javanica* (Treub), and *M. artiellia* (Franklin) can attack faba bean in the tropics/subtropics, only the first three species are commonly found in Egypt (Ibrahim, 1985). Faba bean damage caused by RKNs has also been reported from many countries; e.g., Italy, Sicily, Zimbabwe, Malawi, East Africa, Libya and Iraq (Sikora *et al*., 2018).

Newly reclaimed areas in Egypt assumes the danger of growing crops in light or sandy soils where RKNs can readily multiply and seriously damage many yields. There are few reports about the effect of RKNs on the faba bean plant (Osman and Kheir, 1978; Korayem *et al*., 2018) or their control (El-Zawahry, 2000; El-Nagdi and Youssef, 2004). No information is available about field losses and gain thresholds due to any natural RKN infestation of Giza 843. Moreover, chemical nematicides, used to control RKNs and reduce field losses, are confronting health and environmental issues. Admittedly, hazards of chemical pesticides have boosted interest in using biocontrol agents and their bioactive products. Contrary to using synthetic chemical pesticides, sustainable agricultural systems for food production rank high by exploring economical, safe, and effective biological pesticides. In this respect, grasping the relationship between crop yield/value and RKN numbers is basic to utilize quantitative rationale to management decisions relevant to these nematicides.

Therefore, this relationship was accurately investigated herein via assigning pod yield to nematode count on the same/whole faba bean plant to avoid sampling errors, especially those frequently arising from nematode aggregated distribution in the field (Abd-Elgawad, 2021). Moreover, our goal was also determining faba bean gain thresholds to *M. arenaria* in relation to costs. Following the procedure of Abd-Elgawad *et al*. (2016), the calculated costs herein included those related to both nematode sampling and management. Finally, we aimed at comparing these thresholds in terms of economic cost of a chemical versus a biological nematicide product in order to examine additional merit of a safe bionematicide.

Materials and Methods

Two seasons-field experiments

Faba bean variety Giza 843 was obtained from Egyptian Ministry of Agriculture (Field Crops Research Institute) and cultivated in a sandy loam (69.8% sand, 26.7% silt, 3.5% clay; organic matter= 3.17%, pH = 7.9) soil at El-Nubariya district, Northwest Egypt during 2016-2017 and 2017-2018 seasons. Nematode identification of the targeted area previously (Hammam *et al*., 2017; Korayem *et al*., 2018) indicated that the soil and faba bean plants were naturally infested with *Meloidogyne arenaria* which was confirmed herein at season-end via perineal patterns morphology of ten random females (Taylor and Sasser, 1978) and esterase phenotypes of six individual egg-laying females extracted from faba bean infected roots (Esbenshade and Triantaphyllou, 1985) at each season. Pre-plant sampling included five composite soil samples, each consisted of three subsamples, from 3 field sites. They were collected in a systematic zigzag pattern each season just before faba bean planting (250 gm soil/sample).

Following harvest of maize (*Zea mays* L.) variety Single Hybrid 10, about five feddans (= 2.1 ha, feddan= 4200 m^2) of area was delimited and prepared for planting faba bean in rows of 50 cm width and

6 m long; the length of the plot with four rows. No nematicide was used in the field. The faba bean seeds were planted in holes on 5 November, 2016 at rate of 2 seeds per hole; 25 cm between two consecutive plants on both sides of a row. All agronomic practices were carried out as recommended (Anonymous, 2012). At harvest, on 8 May, 2017, 40 plants were randomly selected, to represent all plots, and dug out to examine the relation between their growth parameters/yields and nematode densities. Their roots were washed gently so as not to wash away any soil that might have been attached to nematode females and/or egg masses before their extraction from the fibrous roots. The vermiform stages of RKN in the rhizosphere soil were extracted using the centrifugal-flotation technique and counted (Jenkins, 1964). Roots were stained in hot acid fuchsin-lactophenol, cleared with lactophenol and nematode galls and egg masses on the whole plant fibrous roots were counted (Taylor and Sasser, 1978). In 2017-2018 season, after harvest of peanut (*Arachis hypogaea* L.) variety Giza 6 and fallowing, only two feddans (0.84 ha) of the same area was delimited and similarly prepared for planting the same bean variety on 7 November, 2017. Rotating peanut with faba bean for the previous two seasons gave rise to fallowing, left unseeded area, apparently due to heavy RKN infestation. So, faba bean was planted after fifty days of fallowing. At harvest, on 12 May, 2018, 15 plants were similarly selected, in proportion to the cultivated area of the previous season, and also examined for number of the nematode juveniles in soil, and galls and egg masses on roots.

Setting regression models

Growth and yield parameters (g/plant) in terms of weights of pods, and shoot and root systems were recorded. Each of such parameters were measured and regressed against each of the counted RKN J_2, galls, and egg masses to construct 40 plotted points for each of nine regression lines. Likewise, yield parameters for each of weight of seeds and pods, and number of pods per plant were also regressed against each of the counted nematode parameters to construct fifteen plotted points for each of nine regression lines in the second season. The mean numbers of RKN J2, galls, and egg masses were compared between the two seasons by the two-tailed Student's *t*-test. The data were combined together for the two seasons. So, weights of faba bean pods were regressed against actual or transformed counts for each of RKN J2, galls, and egg masses to construct 55 plotted points for each of six regression lines. Since obvious correlations were found between the pod yield and J_2 counts in single and combined seasons, a quadratic damage function model was also constructed. Transformation of nematode counts was based on the index of nematode dispersion (I) or variance-to-mean ratio calculated as: $I = S^2/\bar{x}$(i), where S^2 = sample variance and $\bar{x}$ = sample arithmetic mean. The significance of departures from unity was assessed by reference to table of chi-square (χ^2) values (Pearson and Hartley, 1966).

Calculation of gain thresholds

The standard error to mean ratio (E) was used to derive optimum sample size (n) in faba bean field from the equation: $n = S^2/\bar{x}^2(E^2)$ where S^2 and $\bar{x}$ are sample variance and mean, respectively according to Karandinos (1976). The cost of sampling (to collect, process and count the nematodes) ranged from €15 to €21 per sample (Abd-Elgawad *et al*., 2016). The cost of RKN control, including the price of government recommended nematicides at 20 l of Nemaless (twice) per feddan (0.42 ha) or 4 l of oxamyl 24% SL (twice) per 0.42 ha for faba bean fields in Egypt (Anonymous, 2012) plus application costs for faba bean plants 0.42 ha^{-1}, ranged from €25 to €35 and €220 to €260 0.42 ha^{-1}, respectively. The price to growers of 1 kg of faba bean pods ranged from €0.8 to €1.2. We used the following averages of the costs for calculation: €30 and 240 for Nemaless and oxamyl, respectively; sampling cost = €18 × 30 samples 0.42 ha^{-1} of faba bean; €1.0 (kg pods)$^{-1}$. This calculation scheme is similar to that of citrus (Abd-Elgawad *et al*., 2016).

The costs of nematode problems are usually reported based on either nematode management (Sorribas *et al*., 2008) or sampling (Goodell and Ferris, 1981) but how the combination of these costs might influence the actual procedure is considered herein. The nematicide oxamyl is considered effective against RKN on faba bean (Stoddard *et al*., 2010). Also, Nemaless (a bionematicide containing strains of *Serratia marcescens*) was compared to oxamyl and significantly reduced the population density of RKN *M. incognita* on faba bean with an increase in plant growth (El-Nagdi and Youssef, 2004). Neither nematicides nor other RKN control measures were used in the present study but recommended rates and costs of oxamyl and Nemaless were utilized herein to estimate the gain thresholds based on costs of both nematode sampling and management. Therefore, nematode counts were used to determine spatial distribution patterns and optimum sample size to assess sampling costs (Abd-Elgawad *et al*., 2016). Nematode damage functions were derived herein to confer a biological idea about the yield loss of a plant corresponding to a given plant infestation degree of the same plant.

Results and Discussion

Field experiments

Although RKNs were not detected at pre-planting soil samples of faba bean preceded by maize or fallow, RKN galls were observed on some field weeds. These weeds included *chenopodium album* L., *C. murale* L., *Portulaca oleracea* L., *Amaranthus viridis* L., *Solanum nigrum* L., *Convolvulus arvensis* L., and *Dactyloctenium aegyptium* (L.) Willd. *Meloidogyne arenaria* were extracted from all soil samples of faba bean as the most common nematode species at the two season-ends. Other species related to the genera *Tylenchorhynchus*, *Helicotylenchus*, *Criconemoides*, *Xiphinema* and *Pratylenchus* were also found and accounted for < 0.7% of the total nematode community of the two seasons. Their numbers were too few to be analyzed.

Based on *t*-test, the mean numbers of RKN J_2, galls, and egg masses in the first season were not significantly ($P \leq 0.05$) different from their corresponding values in the second season ($t = 0.90$, 1.67, and 1.93, respectively; $df = 53$). So, due to similar nematode data of the two seasons (Table 1), they were combined together. The mean numbers of RKN galls/plant, egg masses/plant, and J_2/ 250 g soil were 47, 19, and 272, respectively ($n = 55$). The variance of J_2 counts was significantly ($P < 0.05$) greater than the mean for both seasons singly or together ($n = 40$, 15, and 55). The same trend was also applicable for galls and egg masses but for the first season and combined seasons ($n = 40$, and 55 for each). Such significant differences suggested aggregated distribution of these nematode parameters which statistically validated their log transformations. The variance for each of galls and egg masses numbers was not significantly ($P < 0.05$) different from the mean for the second season only ($n = 15$ for each) which suggested that random distribution is limited only to these two nematode parameters in a single season. Based on these relationships $\log_{10}$, transformation could generally be chosen to place the data on a scale in which the variance is more stable (Table 2). It was clear that the nematode had adversely affected the yield of faba bean pods. The correlation coefficient between actual or transformed nematode J_2 in soil, galls, or egg masses on roots and pod weight was always negative with different values of probability levels (Table 2), respectively. In a column, means of the two seasons are not significantly ($P \leq 0.05$) different according to student's *t*-tests.

Table 1: *Meloidogyne arenaria population densities in faba bean field at harvest in May 2017 and 2018*.*

The growing season	J2 (250 g soil)$^{-1}$	Galls (plant)$^{-1}$	Egg masses (plant)$^{-1}$
2016-2017	260.8 ± 162.2	50.3 ± 29.4	17.8 ± 10.6
2017-2018	301.7 ± 109.9	37.5 ± 4.3	23.3 ± 6
Combined two seasons	272 ± 149.9	46.8 ± 25.7	19.3 ± 9.8

**Values are means ± standard deviation of 40 and 15 samples in the two consecutive seasons.*

The derived regression models and assessment of yield losses

For the combined two seasons, all correlation coefficients were significant ($P < 0.05$) indicating reduced yield with increasing numbers of galls, egg masses, or J_2. So, we calculated the regression lines of six linear equations for faba bean field from which nematode-yield loss could be derived across the two growing seasons:

Table 2: *Correlation coefficient (r) followed by probability level (P) of linear relation between Meloidogyne arenaria counts sampled from faba bean field and the pod weight (g plant^{-1}) at El-Nubariya district, Egypt in two separate or combined seasons.*

The growing season	Type of nematode count											
	Original of J_2/250 g soil		$\log_{10}$ of J_2/250 g soil		Original of galls/plant		$\log_{10}$ of galls/plant		Original of egg masses/plant		$\log_{10}$ of egg masses/plant	
	r	P	r	P	r	P	r	P	r	P	r	P
2016-2017	0.760	<0.001	0.571	<0.001	0.681	<0.001	0.447	0.004	0.699	<0.001	0.451	0.0035
2017-2018	0.361	0.022	0.292	0.068	0.001	0.995	0.014	0.932	0.144	0.375	0.150	0.356
Two seasons	0.556	<0.001	0.514	<0.001	0.277	0.041	0.273	0.044	0.618	<0.001	0.508	<0.001

J_2 = nematode-second-stage juveniles. All correlation coefficients had negative values.

Y = 460.23 - 10.489X, where Y is yield in g $plant^{-1}$ and X is no. egg masses $(plant)^{-1}$ (r = -0.618 and *P* = 0.5E-7; yield loss = 43.99%) ...(1)

Y = 570.81 - 261.08X, where Y is yield in g $plant^{-1}$ and X is log_{10} no. egg masses $(plant)^{-1}$ (r = -0.508 and *P* = 7.7E-5; yield loss = 58.8%) ...(2)

Y = 342.06 - 1.795X, where Y is yield in g $plant^{-1}$ and X is no. nematode galls (plant root $system)^{-1}$ (r = -0.277 and *P* = 0.041; yield loss = 24.56%) ....(3)

Y = 498.81 – 151.64X, where Y is yield in g $plant^{-1}$ and X is log_{10} no. nematode galls (plant root $system)^{-1}$ (r = -0.273 and *P* = 0.044; yield loss = 50.77%) ...(4)

Y = 425.91 - 0.617X, where Y is yield in g $plant^{-1}$ and X is no. J_2 (250 g $soil)^{-1}$ (r = -0.556 and *P* = 0.00001; yield loss = 39.4%; Figure 1) ...(5)

Y = 909.16 - 277.5X, where Y is yield in g $plant^{-1}$ and X is log_{10} no. J_2 (250 g $soil)^{-1}$ (r = -0.514 and *P* = 5.9E-5; yield loss = 74.32%) ...(6)

Quadratic damage function model was tried resulting in the equation:

Y = -431.66 X^2 + 1649.4 X – 1195.2 where Y is yield in g $plant^{-1}$ and X is no. J_2 (250 g $soil)^{-1}$ (r = -0.567 and *P* = 0.00001; Figure 2) ...(7)

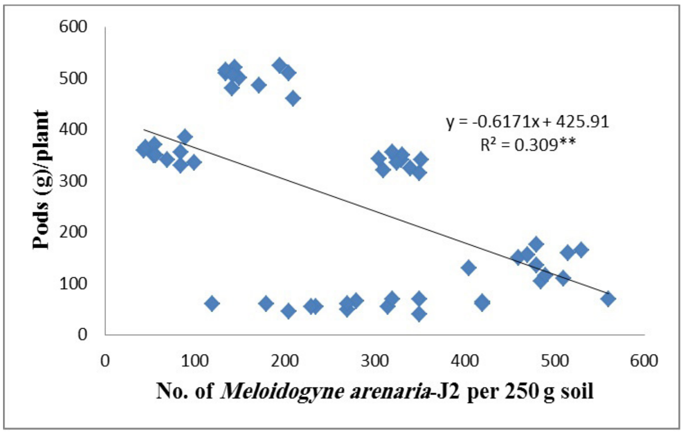

Figure 1: *Relationship of Meloidogyne arenaria J2 to pod yield of faba bean of combined two consecutive seasons in reclaimed sandy soil, Egypt (P = 0.00001).*

Clearly, the most obvious loss in the faba bean field occurred when the pod yield of the two seasons singly or combined had strong correlation to J_2 counts resulting in three high probability levels (*P* ≤ 0.022; Table 2). Therefore, considering the relevant equation 5 (Y = 425.91 - 0.617X), the yield loss of pod weight was estimated (Table 3). Five distinct clusters of data points were generally found in plotting the above-mentioned equations.

Calculating the thresholds

The variance to mean relationship in the obtained data suggests that to achieve a standard error to mean ratio of 0.20 in sampling this faba bean field with a mean of 272 J_2/ 250 g soil, 8 samples should be randomly collected. When sampling accuracy is raised in terms of achieving a standard error to mean ratio of 0.10, 30 samples should be randomly taken. The latter sample size was adopted herein to calculate the gain thresholds.

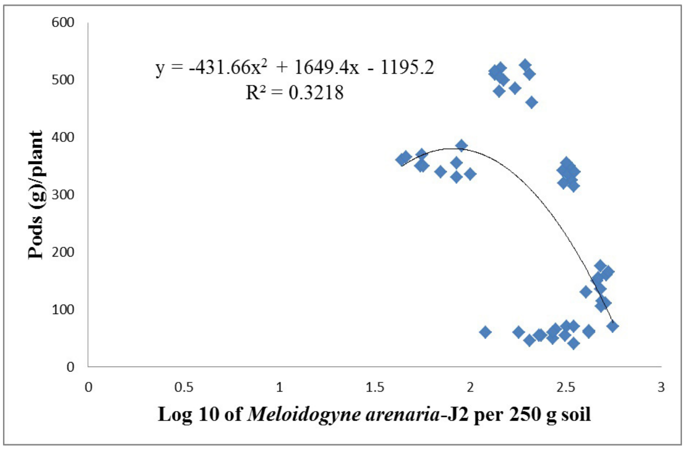

Figure 2: *Quadratic relationship of Meloidogyne arenaria J2 (log10) to pod yield of faba bean of combined two consecutive seasons in reclaimed sandy soil, Egypt (P < 0.001).*

Table 3: *Predicted marketable pod losses in faba bean (Vicia faba) at increasing number of Meloidogyne arenaria-second stage juveniles (J_2)*.*

Nematode number (J_2/250 g soil)	Predicted pod weight (g $plant^{-1}$)	Predicted pod loss (g $plant^{-1}$)	Pod loss (metric tons 0.42 ha^{-1})	Percentage loss
0	425.91	0	0	0
10	419.74	6.17	0.864	1.4
100	364.21	61.70	8.638	14.5
200	302.51	123.40	17.276	29
300	240.81	185.10	25.914	43.5
400	179.11	246.80	34.552	57.9
450	148.26	277.65	38.871	65.2

* *The yield losses were calculated according to* Abd-Elgawad et al. (2016).

The pod yield had an average of 258.09 g $plant^{-1}$ for the two seasons. The gain threshold, *i.e.*, the value of harvested pods that equals the cost of *M. arenaria* sampling and control with Nemaless, was 0.570 metric ton 0.42 ha^{-1}. For oxamyl, the gain threshold was 0.780 metric ton 0.42 ha^{-1}.

Gain threshold encompasses, and is based on nematode damage to the plant. As it estimates the amount of yield loss that justify nematode management, several studies could harness gain thresholds for various functional goals rather than additional practical usage of nematicides. For example, Sorribas *et al.* (2008) calculated gain thresholds, without nematicidal application too, for comparison between two nematicides. Since the cost of *Tylenchulus semipenetrans* control by any of the nematicides registered in Spain for citrus varies greatly among these nematicides, they considered only the lower and upper treatment cost of those nematicides for estimating the gain thresholds as tools for decision making to assess the amount of yield gain (Sorribas *et al*., 2008). In another study, gain thresholds were used to compare between two very common but chemical nematicides (Abd-Elgawad *et al*., 2016). The present study used the same approach but to compare safe biological control with toxic chemical nematicide. Interestingly, we found that biological (Nemaless) nematicide is more economically justified for *M. arenaria* control than the chemical (oxamyl) nematicide. Furthermore, Nemaless is less expensive than other chemical nematicides (Abd-Elgawad 2020a, b).

Current progress for sustainable agriculture produced quite a number of PPN-biocontrol commercial products (Lamovšek *et al*., 2013; Abd-Elgawad and Askary, 2018). Among them, Nemaless is produced and recommended by the Egyptian Ministry of Agriculture against nematode pests especially RKNs (Anonymous, 2012). It contains bacterial strains of *Serratia marcescens* as natural and safe alternative to chemical nematicides. These bacteria have multiple mechanisms for antagonism against numerous pathogens (Chen *et al*., 2017) including RKNs on faba bean (El-Nagdi and Youssef, 2004). Furthermore, transferring chitinase gene(s) from *S. marcescens* to *Pseudomonas fluorescens* has enhanced the efficacy of the genetically engineered bacterium (*P. fluorescens*) for controlling RKN infecting cucumber roots under greenhouse conditions (Abdel-Razik *et al*., 2016). Our study demonstrated additional attractive economic aspect of *S. marcescens* as biocontrol agent.

Two methods are used for assessing crop losses caused by PPNs. Nematode populations have been decreased by nematicides/treatments and subsequent crop yields recorded. In this method, rhizosphere organisms (e.g., beneficial/harmful bacteria and fungi) as well as PPNs are affected which may bias the results. Alternatively, natural nematode infestation levels have been correlated to yields as adopted herein, the second method. Yet, a preliminary report (Hammam *et al*., 2017) indicated that the correlation coefficient between counts of each RKN parameter (galls, egg masses, or J_2) in soil/roots and its corresponding faba bean growth parameters was mostly insignificant. Negative correlation coefficients with significant values of probability levels could relate each of these RKN parameters with faba bean pods only. Therefore, we used the pod weights for sound correlations. Interestingly, such correlations are based on direct evidence from the field results. However, this relationship is sometimes complicated by other factors such as more than one nematode generations in the lifetime of the crop, the interaction between pest and other plant stresses, and by the range of RKN population densities (Abd-Elgawad *et al*., 2016). Hence, other worthy models could be used for such relationships. Clearly, the present study materializes biological meaning as it gives an idea about the yield loss corresponding to given plant infestation degree at harvest.

Under similar conditions, Korayem *et al.* (2018) found that *M. arenaria* significantly reduced both pod and dry seed yields of faba bean by 10.6% and 15.2%, respectively. Thus, the higher yield loss in our study reveals that the variety Giza 843 is possibly more vulnerable to *M. arenaria* damage than El-Nubariya-1 tested in the same area. However, the most (81-100%) root-galling was also reached in 2015-2016 season as reported by Korayem *et al.* (2018). More importantly, our study dedicated an example for a useful comparison between the two competing groups, i.e., biological and chemical pesticides. Various aspects of comparison between the two groups have been initiated such as their effectiveness (Abd-Elgawad and Askary, 2020), persistence (Timper, 2014; El-Nagdi *et al*., 2019), and interaction with other agricultural inputs (Laznik and Trdan, 2014). Nevertheless, the economic comparison presented herein is an indispensable factor to supplement these aspects. The study determined the gain thresholds as 0.570 and 0.780 metric ton of pods 0.42 ha^{-1} for a bio-nematicide and a chemical nematicide, respectively.

The Egyptian ministry of Agriculture has recently circulated (Anonymous, 2019) an alert not to plant Giza 843 in El-Nubariya district due to its low yield there without indicating the reasons for such a reduction. Our study shows that RKN may be a main reason for this yield loss. Although the nematodes can invade the cultivated land via organic fertilizers, plant materials, mulching by fertile soil from the Nile valley, and machinery, weeds seem to play a major role herein. As winter can loosely extent from November to February, most Egyptian soils are too cold to support RKN infection and/or development on winter-season crops like faba bean at early stage of the growing season. So, RKN populations resort to their weed hosts before and at planting winter crops. The aforementioned weeds encountered in our study have been reported as good hosts to RKNs in Egypt (Bakr *et al*., 2020). The nematodes overwinter primarily as eggs where typical soil assays cannot detect the eggs (Jagdale and Brewer, 2022). Strikingly, the remaining residue of the previous crop and associated weeds should have been destroyed instantly to eliminate nematode food sources. Unfortunately, delays in such a destruction could contribute to moving RKN from the weeds to the newly cultivated faba bean especially via irrigation. It is likely that RKN populations associated with weeds could transfer to and reproduce on faba bean at warm temperature which starts at mid of the growing season. Because of the nematodes' wide host range, variability in the RKN species, and unavailability of resistance genotypes of faba bean, care should also be taken in selecting rotation crops (Sikora *et al*., 2018).

The problem of infested fields in newly reclaimed areas should be alarming for: (i) assessing crop losses to relate productivity to all yield-forming and yield-reducing factors which would benefit sustainability evaluation in these areas; (ii) persuading growers to avoid mulching virgin soil with PPNs-infested soil from the Nile Valley and adopt all sanitary measures to block all means of nematode transfer; (iii) controlling weeds as imperative measure to alleviate PPN damage; (iv) motivating private/governmental sectors to develop elite faba bean cultivars; (v) fostering an integrated management strategy for PPNs and other pests; and (vi) alerting growers to the gain thresholds. Caution should also be exercised for these threshold values because many factors may affect the nematode-plant interactions in a given region. The prices of nematicides and faba bean pods are subject to fluctuation but the values investigated herein should be taken as benchmarks.

Conclusions and Recommendations

Despite the strenuous efforts to boost the productivity of faba bean in Egypt, there are still some pests that significantly reduce its yield. Strong relationships between the field yield of faba bean pods and natural *M. arenaria* population levels enabled assessing the considerable amount of RKN-pod weight losses. Furthermore, we economically compared a chemical nematicide (oxamyl) with another safe biological one (Nemaless) also known for its effectiveness in RKN control. The gain threshold of Nemaless was lower than that of oxamyl. This economic merit of Nemaless should enhance the interest in the benign strategies of RKN biocontrol. Therefore, agricultural extensions should raise awareness of farmers for using such biological products for RKN control to lower the adverse effects of chemicals while economizing the costs.

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Novelty Statement

The study realizes biological concept as it offers an idea about the yield loss corresponding to given plant infestation degree at harvest. Such a concept is especially practical when difficulty are found in sampling initial nematode population to assess damage and gain thresholds of the nematodes.

Author's Contribution

All authors equally participated in the development and implementation of the reviewing plan. Subsequently, they worked it out wrote the manuscript; the first author Mostafa Hammam wrote and discussed the different parts of the article with Moawad Mohamed and Mahfouz Abd-Elgawad and all together finalized the manuscript. All authors have read and approved the final manuscript.

Abbreviations

ICARDA, The International Center for Agricultural Research in the Dry Areas; RKNs, Root-knot nematodes; *r*, Correlation coefficient; *P*, Probability level; J_2, Nematode-second-stage juveniles; PPNs, Plant-parasitic nematodes.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Conflict of interests

The authors have declared no conflict of interest.

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