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Experts' opinion on the sustainable use of nematicides in Mediterranean intensive horticulture

Miguel Talavera[1], María D. Vela[2] and Manuel Arriaza[3,*]

[1] IFAPA Centro Alameda del Obispo, Av. Menéndez Pidal s/n, 14004 Córdoba, Spain.
[2] IFAPA Centro Rancho de la Merced, Ctra. Cañada de la Loba CA-3102, Km. 3,1, 11471 Jerez de la Frontera (Cádiz), Spain.
[3] WEARE-Water, Environmental and Agricultural Resources Economics Research Group, Universidad de Córdoba, Puerta Nueva s/n, 14002 Córdoba, Spain.

***Correspondence** should be addressed to Manuel Arriaza: es1arbam@uco.es

Abstract

Aim of study: Root-knot nematodes are considered a common limiting factor to reaching premium quality and economically viable yields in horticultural crops. Soil disinfestation with agrochemical fumigants has been the main nematode control method until their recent ban due to environmental and social concerns. This paper explores farmers and agricultural advisors' opinion and preferences on the sustainable use of available nematode control methods, considering sustainability as an integration of nematicidal effectiveness, reduction of environmental harmful effects and preservation of human health.

Area of study: This study has been carried out between farm advisors of intensive horticultural crop areas in Southern Spain.

Material and methods: Farm advisors' opinion and preferences on the use of nematicides was evaluated following an opinion survey and the Analytic Hierarchy Process (AHP) method. The analysis done was exploratory.

Main results: Providing that current available control methods give enough nematicidal effectiveness to get a profitable yield, the group of farm advisors showed a great consciousness on the use of sustainable alternatives for nematode control in intensive horticultural crops, prioritizing biosolarization as the first option, followed by biopesticides and fumigant nematicides in third place. The use of ozone and non-fumigant nematicides with high toxicity profiles were considered the last options, but new generation nematicides with lower ecotoxicity profiles are also considered as an important tool in sustainable nematode management.

Research highlights: These results provide a prediction of farmers' responses to the sustainable use of nematicides promoted by the European Union when agrochemical fumigants are banned.

Additional key words: biosolarization; soil disinfestation; AHP; *Meloidogyne*.

Abbreviations used: AHP (Analytic Hierarchy Process); CI (Consistency Index); EHI (Environmental Hazard Index); EU (European Union); ICC (Intraclass Correlation Coefficient); IPM (Integrated Pest Management); RKN (Root Knot Nematodes).

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Introduction

In southern Spain, intensive horticulture is a crucial agricultural business that contributes up to 40% of the gross domestic product in some regions (Egea et al., 2018). There are about 40,000 hectares of protected vegetable crops, under plastic greenhouses or macro-tunnels, producing over 4,000,000 tons of high-value solanaceous, cucurbitaceous and berry crops that are shipped for fresh consumption in European markets with a yearly commercial value of approximately €3 billion (MAPAMA, 2020).

Plant parasitic nematodes are one of the most significant pests limiting global vegetable production (Nicol et al., 2011; Singh et al., 2015). In southern Spain intensive horticultural crops, root-knot nematodes (RKN: *Meloidogyne* spp.) prevalence ranges 20-70% and are viewed as the most common limiting factor to reaching premium quality and economically viable vegetable yields (Talavera et al., 2012, 2019).

Since nematode-caused yield losses are directly proportional to nematode soil densities at planting (Seinhorst, 1965), nematode management strategies have primarily focused on reducing nematode soil inocula prior to planting. Conventionally, RKN management in intensive crops has relied on fumigant chemical nematicides to disinfest soil. Fumigants are biocides with a broad spectrum that are most effective at reducing RKN soil populations but have adverse side effects on beneficial soil organisms (Jacobsen & Hjelmsø, 2014). The environmental impact of plant protection products is becoming increasingly relevant from both an ecological and political standpoint.

Currently, six non-fumigant nematicides (abamectin, azadirachtin, dazomet, fosthiazate, fluopyram, and oxamyl), two botanical pesticides (based on garlic extract and terpenes from essential oils) and two biological control agents (*Bacillus firmus* and *Purpureocillium lilacinum*) are registered and approved for use in the European Union (EU) against plant parasitic nematodes (Sasanelli et al., 2021). In addition, some other products, categorized as biostimulants or soil improvers, such as amino acids, humic and fulvic acids, plant growth promoting rhizobacteria, arbuscular mycorrhizae fungi, *Trichoderma* spp. and other plant extracts or essential oils, have been reported as partial suppressors of RKN diseases in vegetables and are used occasionally by farmers to improve yields in nematode-infested soils. Alternative physical and cultural nematode management strategies, such as biosolarization or the use of ozone as ozonated water to disinfest soil are also available (Forghani & Hajihassani, 2020).

Farmers in southern Europe have considered soil chemical fumigation, as the most effective method for controlling RKN diseases in intensive horticultural crops, since the efficacy of other nematode control methods has not proven consistent enough when high RKN soil infestations occur (Talavera et al., 2012, 2019; Greco et al., 2020). Soil fumigation has been used regularly by 83-90% of the farmers in these intensive horticultural crops (Talavera et al., 2012, 2019; Greco et al., 2020), but owing to rising social awareness of the environmental concerns associated with agrochemicals' usage, most soil fumigants have been banned or heavily restricted in EU, as part of the European Green Deal and the 'farm to fork strategy'. Therefore, in a new scenario without fumigants farmers will have to use more complex strategies based on the integration of multiple control methods (IPM: Integrated Pest Management) to reach sufficient efficacies in reducing high RKN soil inocula (Sasanelli et al., 2021). IPM aims to limit the use of pesticides to economically and ecologically justifiable levels that reduce the risks to human health and environment. According to the EU policies, sustainable biological, physical, and other non-chemical methods must be favored over chemical methods if they provide adequate pest control.

Programming activities designed to implement any IPM system for nematode management should ideally account for both agricultural properties of an IPM system and farmer's decision-making process. However, due to the lack of data on the specific systems to be implemented a great deal of uncertainty exists as to how growers will deal with high nematode infestations in intensive horticulture. This lack of information makes predictions of farmers' responses to the sustainable use of nematicides imprecise at best (Nagesh et al., 2023).

This paper examines farm advisors' preferences on the use of currently available methods for RKN control in the EU according to the opinion of a group of experts in nematode control: field nematologists and agricultural advisors, who are employed by the co-operatives in which farmers associate to sell their production and are in charge of dealing with RKN diseases in most fields.

Material and methods

Source of data

Information on nematicidal efficacies of soil disinfestation treatments against plant parasitic nematodes in intensive horticultural crops was collected from the literature (Talavera et al., 2019; Talavera-Rubia et al., 2022) and expressed as reduction rates in nematode soil densities after the treatment application.

Information on toxicity of nematicides on human health and environment were collected from the EU and USA pesticide databases (EC, 2023; USEPA, 2023), safety data sheets and information provided on their labels. The toxicity of a pesticide is its capacity to cause injury or illness to human health or other living organisms in the environment. There are two types of toxicity, acute (from a single exposure) and chronic (from a prolonged exposure). Toxicities refer to the product concentration required to kill 50% of animals in a test population (LC50) and are determined by examining the dermal toxicity, inhalation toxicity, and oral toxicity. In addition, eye and skin irritation are also examined. Based on their relative acute toxicity, pesticides are categorized as either highly toxic (category I), moderately toxic (category II), slightly toxic (category III), or relatively nontoxic (category IV). Besides the Environmental Hazard Index (EHI), a weighted index designed to classify pesticides according to their non-desirable toxicological and environmental effects, was included as an integrated measure of pesticide sustainability (Sánchez-Moreno et al., 2009).

Assessing the experts' opinion on nematode control methods

To obtain data on the perception of the relative effectiveness and environmental sustainability of nematode control methods, what drives the decision-making process on the use of a particular nematicidal treatment, as well as their sustainability, a survey was designed and oriented to experts with experience in soil disinfestation against plant parasitic nematodes.

Forty experts were selected from the group of farm advisors dealing with nematode control in the intensive vegetable-growing areas of southern Spain. Farm advisors are qualified agronomists that deal with vegetable crop pests and diseases in commercial fields daily, thus providing a valuable source of accumulated local knowledge.

A survey involving a self-administered questionnaire (see Appendix [suppl]) distributed by email was carried out in October 2021. To select the nematode control methods and to assess the general structure of the questionnaire, a discussion group, composed of six experts, was conducted. The questionnaire was divided into two parts, first assessing five nematode control methods in terms of (i) effectiveness in suppression of nematode diseases, (ii) environmental impact, and (iii) side effects on human health; and second, an overall appraisal of the contribution of these criteria to the sustainability of nematode control strategy.

The Analytic Hierarchy Process (AHP) was developed as a decision-making aid tool to handle complex problems by using a hierarchical framework (Saaty, 1980; Vaidya & Kumar, 2006). Briefly, in each level, the relative importance (or weightings) of its elements with respect to the higher level was obtained by a series of pairwise comparisons that determine which option is preferred and for how much, using, among other options, the linear scale proposed by Saaty (1980) that ranges from 1 (equally importance) to 9 (absolutely preferred over the other). In our study, the hierarchical structure had three levels: (a) at the top the overall goal, that is, finding the most sustainable nematode control strategy; (b) in the intermediate level the sustainability criteria (nematicidal efficacy, environmental impact, and human health risk); and (c) at the lowest level, the nematicidal treatments alternatives (Fig. 1). The hierarchical structure of the AHP method means that the weightings obtained at each level add up to one, therefore, the normalized importance that the decision maker assigns to alternative *i* to the goal, , is calculated as follows:

$$w_i^* = \sum_{j=1}^{3} w_{ij} * w_j$$

where w_{ij} is the weighting of alternative *i* with respect to criterion *j* and w_j is the weighting assigned to criterion *j*.

Although AHP assumes evaluation consistency by the decision makers, perfect consistency is rare, therefore, a consistency index (CI), must be calculated to avoid exceeding a predefined value (Dodd et al., 1993). Once the individual experts' judgements were calculated, before the aggregation, we assessed the degree of agreement between the experts' weightings using the intraclass correlation coefficient (ICC), with 1 indicating perfect agreement and 0 only random agreement (Hallgren, 2012). Since the 40 experts, viewed as random effects, rated all the five nematicidal methods the model of choice is a 2- two-way mixed-effects model. Additionally, we were interested in the reliability of the mean in terms of consistency, therefore, we used the ICC3k coefficient (Koo & Li, 2016). Finally, once the experts' consistency was assessed, we followed the Forman and Peniwati aggregation procedure (Forman & Peniwati, 1998), using the geometric mean to obtain the group decision-making.

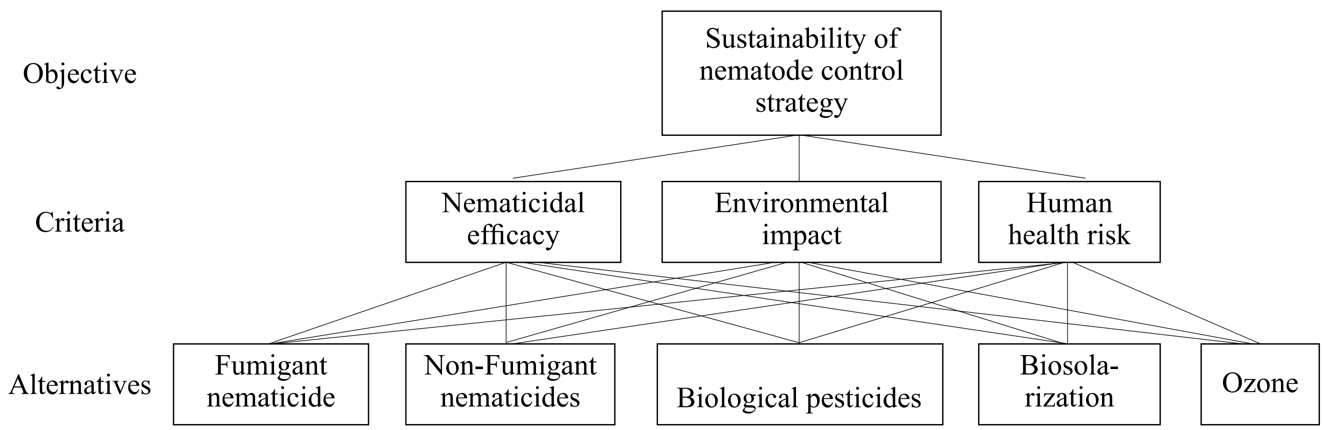

Figure 1. The AHP's hierarchical structure for evaluating nematicidal treatments.

Results

Nematicidal efficacies and toxicity data

Information on nematicidal efficacies collected from the literature and side effects on human health and environment are shown in Table 1.

Consistency of intra-rater judgements

The experts' CI of a 5×5 matrix (we had 5 nematicidal treatments), for a 95% confidence level, should be lower than 0.28959 (Dodd et al., 1993). In this study, the maximum CI was 0.282 (Table 2), thus implying an acceptable experts' consistency of the AHP choices.

Inter-rater reliability

The ICC for the model was 0.98 (Table 3), which is considered excellent inter-rater reliability (Cicchetti, 1994; Koo & Li, 2016).

Experts' weightings

The aggregation of the 40 experts' weightings based on the geometric mean is shown in Table 4, including the importance of each treatment toward the three criteria, the criteria importance toward sustainability and the overall treatment sustainability.

Discussion

Conventionally farm advisors have recommended nematode management strategies according mainly to the nematicidal effectiveness and secondarily to a cost-benefit analysis of the treatment (Talavera-Rubia et al., 2022). For nematicidal efficacy, agricultural advisors consider that fumigant nematicides are the most efficient method for RKN control, followed by biosolarization and non-fumigant nematicides in third place, what agrees with previous reports about nematicide efficacies in most horticultural crops in Spain (Talavera et al., 2019, 2012).

However, our results indicate that the most important criterion among farm advisors for choosing nematicidal treatments is now the preservation of human health, followed by nematicidal efficacy and reduction of harmful environmental side effects, in that order. Biosolarization and biological pesticides were regarded as the two best ways for reducing environmental impacts and adverse effects on human health, in line with the ecotoxicological results observed for these group of treatments (Table 1). When compared to non-fumigant nematicides, which are classified as being highly toxic for the environment, biosolarization and biological pesticides have reportedly been found to be relatively non-toxic or slightly toxic (Table 1).

Considering the three criteria together, the most sustainable RKN control method for farm advisors was biosolarization,

Table 1. Efficacies, environmental and human health side effects of nematicidal treatments.

	Nematicidal efficacy[1]	Human health		Aquatic environment		EHI[2]
		Acute toxicity	Skin/Eye irritation	Acute toxicity	Chronic toxicity	
1.3-dichloropropene	80-90	III	II	I	I	5.66
Metam-Na/-K	46-56	IV	I	I	I	7.08
Abamectin	33-52	II	II	I	I	-
Azadirachtin	46-63	IV	II	I	I	-
Dazomet	45-62	IV	II	I	I	-
Fluopyram	58-69	III	II	I	I	-
Fosthiazate	40-66	III	II	I	I	10.58
Oxamyl	57-65	II	II	II	II	86.23
Garlic extract	25-56	II	II	II	-	-
Geraniol + Thymol	35-62	IV	I	II	II	-
Ozone	33-52	I	II	I	-	-
P. lilacinum	-	-	II	-	III	-
B. firmus	-	IV	II	-	-	-
Biosolarization	69-78	-	-	-	-	-

[1] Range of nematicidal efficacies expressed as percentage of reduction in soil nematode densities after the treatment applications in different field trials (Talavera et al., 2019; Talavera-Rubia et al., 2022). [2] EHI: Environmental Hazard Index (Sánchez-Moreno et al., 2009). - Not available information.

Table 2. Consistency index statistics of the Analytic Hierarchy Process (AHP) experts' evaluation.

	Nematicidal efficacy	**Environmental side effects**	**Human health side effects**
Mean	0.181	0.127	0.163
Min	0.048	0.023	0.026
Max	0.282	0.256	0.278

Source: Own elaboration from the experts' evaluation using the AHP method.

Table 3. Intraclass correlation coefficients (ICC).

	Type[1]	**ICC**	**F**	**df1**	**df2**	**p**	**Lower bound**	**Upper bound**
Single raters absolute	ICC1	0.57	55	4	195	7.7e-31	0.31	0.92
Single random raters	ICC2	0.57	55	4	156	1.0e-28	0.31	0.92
Single fixed raters	ICC3	0.57	55	4	156	1.0e-28	0.31	0.92
Average raters absolute	ICC1k	0.98	55	4	195	7.7e-31	0.95	1.00
Average random raters	ICC2k	0.98	55	4	156	1.0e-28	0.95	1.00
Average fixed raters	ICC3k	0.98	55	4	156	1.0e-28	0.95	1.00

Source: Output from R psych package based on the experts' judgements. [1] ICC1 = ICC(1,1) one-way random effects model, absolute agreement, single rater; ICC2 = ICC(2,1) two-way random effects model, absolute agreement, single rater; ICC3 = ICC(3,1) two-way mixed effects model, consistency, single rater; ICC1k = ICC(1,k) one-way random effects model, absolute agreement, multiple raters; ICC2k = ICC(2,k) two-way random effects model, absolute agreement, multiple raters; ICC3k = ICC(3,k) two-way mixed effects model, consistency, multiple raters.

Table 4. Experts' weightings of nematicidal treatments toward criteria and overall sustainability.

	Nematicidal efficacy	**Environmental side effects**	**Human health side effects**	**Treatment sustainability[1]**
Criteria weighting	0.30	0.28	0.42	
Fumigants	0.48	0.04	0.03	0.17
Non fumigants	0.15	0.07	0.07	0.09
Biological	0.08	0.32	0.28	0.23
Biosolarization	0.24	0.43	0.47	0.39
Ozone	0.05	0.14	0.15	0.11
Sum	1.00	1.00	1.00	1.00

[1] The sustainability indicator of the fumigant nematicides is calculated as follows: 0.48*0.30 + 0.04*0.28 + 0.03*0.42 = 0.17.

followed by biological pesticides. Despite being the most effective, fumigant nematicides ranked third in terms of sustainability. Finally, according to these results, the less sustainable treatments were ozone and non-fumigant nematicides. The prioritizing criteria used by farm advisers to recommend nematode management techniques have changed, shifting away from the effectiveness side of these treatments toward environmental and health preservation.

Particularly interesting is the case of soil disinfestation with 1,3-dichloropropene. A cost-benefit analysis of soil disinfestation methods against RKN in Mediterranean intensive horticulture (Talavera-Rubia et al., 2022) showed that fumigation with 1.3-dichloropropene and biosolarization with chicken manure were the only treatments able to reduce high RKN soil inocula to levels below the nematode economic damage threshold, keeping profitability in the most susceptible crops as eggplant or cucumber. Other nematicidal treatments were not able to reduce RKN populations above 200-300 J2/100 cm^3 of soil below the economic thresholds. Therefore, when high RKN inocula occurs fumigant treatments with 1,3-dichloropropene could be still required since other options may not be profitable. Despite of 1,3-dichloropropene was included in the lowest toxicity group due to its low-medium persistence in the environment and its low EHI (Sánchez-Moreno et al., 2009), its use is currently banned in the EU, in contrast with other chemical nematicides with higher toxicities and thus higher EHI, whose use is still allowed within the EU. This apparently contradictory regulation could be explained considering the widespread use of 1,3-dichloropropene, and the great impact of banning one single agrochemical to easily get the objectives of reduction in the use of pesticides required by the EU.

However, in most cases, RKN soil densities in field are below the limits of 200-300 J2/100 cm^3 of soil and thus other RKN management options are feasible and will be recommended by farm advisors, prioritizing those with less side effects on human health and environment. Next generation nematicides as fluensulfone, fluopyram, and fluazaindolizine, which have a relatively high control efficacy with a low toxicity to non-target organisms are also a promising alternative tool in sustainable RKN management strategies (Lahm et al., 2017; Oka, 2020; Talavera et al., 2021).

Providing that current RKN available method give enough nematicidal effectiveness to get a profitable yield, the group of farm advisors show a great consciousness on the use of sustainable alternatives for RKN control in intensive horticultural crops. The first option as RKN control method for them, is biosolarization followed by biopesticides and fumigant nematicides in third place, due to their superior effectiveness in fields infested with high RKN soil inocula. The use of ozone and non-fumigant nematicides with high toxicity profiles were considered the last options.

The results of this study indicate that farm advisors are highly inclined to adjust their methods for managing plant-parasitic nematodes in intensive crops, with a preference for sustainability above effectiveness. Biosolarization and other environmentally friendly methods are expected to become more widely utilized in the next years, while the use of chemical nematicides is anticipated to decrease. Only in exceptional circumstances characterized by high nematode densities in soil at planting time, should the most effective chemical nematicides be utilized.

Supplementary material (Appendix) accompanies the paper on SJAR's website.

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