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The Use of Botanical Extracts for the Control of *Meloidogyne incognita* (Kofoid and White) in Yellow Pitahaya

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Abstract: *Meloidogyne incognita*, a widely distributed plant parasite that is considered one of the most devastating species for various crops, has traditionally been controlled through the use of synthetic products. However, the risks associated with these products for human health and the environment have prompted a search for more sustainable alternatives. In this context, plant extracts rich in secondary metabolites, such as those of *Tagetes zypaquirensis* and *Dysphania ambrosioides*, have shown potential for nematode management, although their efficacy varies. This study aimed to evaluate the effect of extracts of *T. zypaquirensis*, *Lonchocarpus urucu*, *D. ambrosioides*, *Urera laciniata*, and *Ricinus communis* on the population of *M. incognita* in *Selenicereus megalanthus* under controlled greenhouse conditions. A completely randomized block experimental design was used with three replicates per treatment and six yellow pitahaya (or dragon fruit) plants per experimental unit. A total of 10 g of extract per plant was applied at two application times: 7 days before nematode inoculation and 7 days after. In addition, two controls were included: an absolute control, with no extract application and no nematode inoculation, and an inoculated control, consisting of plants exposed only to nematodes. The results showed that the preventive application of *T. zypaquirensis* and *D. ambrosioides* extracts 7 days before nematode inoculation significantly reduced *M. incognita* populations compared to the inoculated control. At 60 days, both extracts were able to reduce nematode populations and the number of nodules on roots, with reproductive factors close to 1 (1.47 and 1.50), indicating efficient control. Moreover, plants treated with these extracts showed superior growth compared to the other treatments and the inoculated control. In conclusion, the preventive application of *T. zypaquirensis* and *D. ambrosioides* extracts had a positive influence on the control of *M. incognita* and caused an improvement in plant growth variables. These results suggest that these botanical extracts could be adopted within integrated nematode management strategies in agriculture, contributing to sustainability and a reduction in the use of chemicals.

Keywords: nematodes; botanical control; *Tagetes zypaquirensis*; *Lonchocarpus urucu*; *Dysphania ambrosioides*; *Urera laciniata*; *Ricinus communis*

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1. Introduction

Yellow pitahaya, scientifically known as *Selenicereus megalanthus*, stands out as an economically important fruit tree worldwide, and is part of the extensive Cactaceae family [1,2]. However, various pests and diseases, especially plant-parasitic nematodes (PPNs), are considered a significant threat to its cultivation, negatively affecting yield and quality [3–5].

All soil pathogens, including PPNs, exert a significant impact on agricultural products across the world [6]. Among PPNs, the most detrimental are divided into four categories: (I) ectoparasites, (II) semi-endoparasites, (III) migratory endoparasites, and (IV) sedentary endoparasites [7]. Particularly, endoparasite nematodes of the genus *Meloidogyne* spp. cause significant damage to plants worldwide, reducing yield by 10–25% [3,8,9], with *M. incognita* (Kofoid and White) Chitwood being the species considered the most devastating within this genus [10]. However, other species such as *M. javanica*, *M. arenaria*, *M. enterolobii* and *M. hapla* also have a high incidence in crops of economic importance [11,12]. Root-knot nematode (*M. incognita*) eggs develop to the first juvenile stage (J1), molt to mobile juveniles of the second stage (J2), and begin to infect the root system, affecting vascular tissues and forming nodules or galls and giant feeding cells, permanently altering the host plant's ability to absorb water and nutrients [10,13].

Research carried out in the Ecuadorian Amazon has determined that the most frequent nematodes affecting pitahaya crops are *Meloidogyne* spp., representing between 50% and 81% of incidences, and *Helicotylenchus dihystera*, affecting between 82% and 100% [8,11]. In Palora canton, where the largest extension of pitahaya cultivation is located, it has been shown that 97% of the cultivation areas are infected by *M. incognita* and *H. dihystera*, while only 3% are affected by *Tylenchus* spp. [5,14]. *M. incognita* causes the formation of nodules on the roots, which cause significant losses in crop yield, reaching up to 87% [6,8,9]. Currently, the use of chemical products to combat pests and diseases is common practice [15]. Among these products, chemically synthesized nematicides, such as Fenamiphos, Oxamyl, Fosthiazate, and Fluopyram, are often chosen to control PPNs, due to their high efficacy [16,17]. However, most of these products also lead to a decrease in the abundance of free-living nematodes and the development of resistance to nematicides, in turn leading to significant risks to human health and the environment [17,18]. This scenario has prompted the need to search for new strategies and methods of defense against PPNs in order to find more secure and sustainable solutions for agriculture.

Scientists are searching for sustainable methods to develop botanical nematicides using natural active substances, such as plant extracts [19–21], bacteria, fungi [22–24], and marine biomolecules [25]. Plant extracts, known as botanical pesticides, have been considered as potential alternatives to synthetic nematicides due to their low persistence in the field and lower side effects on non-target organisms and the environment [19,26,27]. Plants synthesize a variety of secondary metabolites that play an important role in their defense against pathogens, herbivores, and other environmental stress factors [21,27,28]. Secondary metabolites have been shown to possess a wide range of biological activities, such as fungicidal, nematicide, antiviral, antibiotic, antibacterial, and other properties [29]. Their extracts contain bioactive compounds, such as saponins, alkaloids, tannins, flavonoids, terpenoids, steroids, and phenols, with nematicide properties, making them capable of killing or repelling PPNs [19,20,27,30]. These compounds act by interfering with the life cycle of nematodes, by affecting either their development, reproduction, or ability to infect the roots of host plants [27,28,30].

Plant extracts such as *Chrysanthemum* spp. and *Eupatorium* spp. have shown strong nematicide activity against root-knot nematodes. Perez et al. [17,31] demonstrated that *C. coronarium* essential oils significantly reduced the hatching of *M. artiellia* during in vitro studies. In addition, the amendment of infested soils with flowers, leaves, roots, or seeds

of *C. coronarium* and other species such as *C. maritima* reduced the population biomass of these nematodes by 83.0–95.9%. Other studies have confirmed the efficacy of extracts such as those of *Mentha rotundifolia* and *Syzygium aromaticum*, which immobilized *Meloidogyne* larvae and inhibited nodule formation [32–34].

Other plant species have been shown to be effective against phytoparasitic nematodes. Extracts of *Allium tuberosum*, containing carboxylic acids, glycosides, ketones, and organic sulfides, have been observed to act as a nematicide against *M. incognita*, significantly reducing root nodules in crops such as tomato and cucumber [35,36]. Likewise, extracts of *Tulbaghia violacea* were effective in reducing *M. incognita* populations in infested soils [37]. Furthermore, *Tagetes patula* flower extracts showed high efficacy, with mortality rates of 50–100%, on *Heterodera zeae* after a 24 h treatment at 5% concentration, highlighting their potential as an alternative for the biological control of plant-parasitic nematodes [29,38].

Unlike synthetic nematicides, whose application dynamics and efficacy have been studied, much remains to be understood about the efficient use of botanicals for PPN management. This study aimed to evaluate the efficacy of extracts of *T. zypaquirensis*, *Lonchacarpus urucu*, *Dysphania ambrosioides*, *Urera laciniata*, and *Ricinus communis* on the population of *M. incognita* in *S. megalanthus* under controlled greenhouse conditions.

2. Materials and Methods

2.1. Experimental Site Characteristics

The study was carried out under controlled conditions in the greenhouse at the Amazon Research Site (EECA) of the National Institute of Agricultural Research (INIAP), located in the canton of La Joya de los Sachas, province of Orellana (Figure 1), with coordinates 20°27″ N latitude and 87°40″ E longitude, an altitude of 250 m above sea level. Inside the greenhouse, the average temperature was 35 °C, and a relative humidity of 70% was maintained [39].

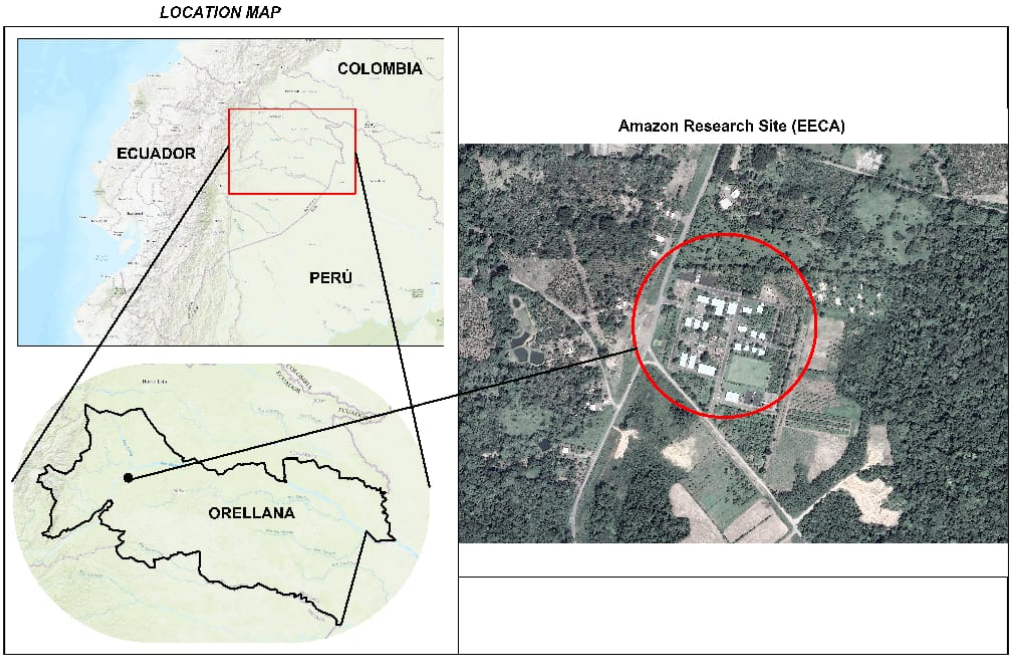

Figure 1. Location of experimental site, Amazon Research Site.

2.2. Treatments and Experimental Design

The study was implemented under greenhouse conditions, using 40 cm long yellow pitahaya cuttings, which were planted in a 12 × 18 cm perforated nursery bag containing

5000 g of sterilized soil. The cuttings were planted at a depth of 5 to 10 cm [5]. Previous studies have shown that the use of 35 to 45 cm long cuttings for propagation favors a greater development in the length and fresh weight of the roots [5,40], observing this effect 30 days after planting. The experiment was carried out using a randomized complete block design, with three replicates per treatment and six yellow pitahaya plants per experimental unit. The first factors under study were five plant extracts: T1 (*T. zypaquirensis*), T2 (*L. urucu*), T3 (*D. ambrosioides*), T4 (*U. laciniata*), and T5 (*R. communis*). The two controls consisted of T6 (absolute control, i.e., *no extract application and no nematode inoculation*) and T7 (plants inoculated *only with nematodes*). The second factor included two moments of inoculum application: the extract was applied 7 days before the inoculation of nematodes and 7 days after.

2.3. Specific Handling of Experiment

2.3.1. Botanical Extracts

The identification of the plant species (botanical extracts) was carried out through a literature review, through which a detailed description of the morphological and taxonomic characteristics of each species was found (*D. ambrosioides* [41], *T. zypaquirensis* [42], *U. laciniata* [43,44], *R. communis* [45], and *L. urucu* [46]).

For the preparation of botanical extracts, leaves, stems, and flowers (5 kg) of the species *D. ambrosioides*, *U. laciniata*, *R. communis*, and *T. zypaquirensis* were used, while for *L. urucu*, the root (5 kg) was used. The samples were washed, cut into fragments of approximately 4 cm, and placed in a lyophilizer (Telstar, LyoQuest-85, Terrasa, Spain). The lyophilizer was calibrated at −85 °C, and a vacuum pressure of 1 Pa, for 72 h. The dehydrated material was pulverized in a mill (Willey, Tecnal, Mexico D.F., Mexico). Subsequently, 10 g of each species was weighed and placed in 100 mL of distilled water, and then stirred at 60 rpm, using a magnetic stirrer (C-MAG HS 7, IKA, Staufen im Breisgau, Germany), for one hour, until a homogeneous emulsion was obtained. The solution (16 mL/plant) was applied by root irrigation, ensuring a uniform distribution around the roots of the plants. The botanical extracts were applied 7 days before and 7 days after inoculation with *M. incognita*.

2.3.2. Preparation of Nematode Inoculum

Infected roots were obtained from yellow pitahaya plants, and extracted using the blender method described by Hussey and Barker [47]. The roots were washed, cut into approximately 1 cm sections, and blenderized with 100 mL of water for 20 s, in two intervals, with five seconds of rest. The contents of the mixer were filtered through a set of nested sieves with apertures of 250, 150, and 25 µm (60, 100, and 500 mesh, respectively). The residues retained on the 250 and 150 µm sieves were rinsed with water for 1 min, and the sediment accumulated on the No. 25 µm sieve was collected in a graduated cylinder and adjusted to 100 mL with distilled water, obtaining second-instar juveniles (J2) for subsequent multiplication [48,49]. The J2 obtained were inoculated on 20-day-old tomato plants (*Lycopersicon esculentum* Mill.). The inoculated plants were maintained under controlled conditions (35 °C and a relative humidity of 70%) for 30 days to allow the development of new nematode populations. Subsequently, nematodes were extracted from tomato roots using the liquefier method and counted with an inverted trinocular microscope (IM-5, OPTIKA, Bergamo, Italy), equipped with LWD IOS objectives, X-LED illumination for optimal visibility, and EWF10X/22mm eyepieces.

For inoculation on pitahaya plants, a nematode suspension adjusted to 1200 J2/plant was prepared [24,48]. This suspension was applied by drilling four 5 cm deep holes around the base of the stem of each plant, into which the J2 suspension was deposited. Finally, the holes were closed to ensure incorporation of the J2 into the soil.

2.4. Variables

2.4.1. Plant Variables

At 30, 60, and 90 days after inoculation, root fresh weight, shoot fresh weight, and shoot dry weight were taken using a precision analytical balance (BPS 51 PLUS, BOECO, Hamburg, Germany), with a measuring capacity of up to 4500 g and readability of 0.01 g. The shoot diameter was measured using a precision digital vernier caliper (CD-15AX, Mitutoyo, Tokyo, Japan), with a measuring range of 0 to 150 mm and a resolution of 0.01 mm. A flexometer (Global Plus ¾, Stanley, Shenzhen, China) was used for shoot length.

2.4.2. Nematode Variables

To determine the nematode population, 10 g was extracted from the root system using the blender method. The extraction of *M. incognita* in the soil was carried out using the Chamlaty funnel technique [50], which consists of placing 100 mL of soil on a filter paper suspended in a funnel with water, and allowing it to settle for 48 h. Subsequently, 100 mL of the filtered sample of soil and roots was collected separately in a beaker, from which an aliquot of 1 mL was taken for J2 quantification using an inverted trinocular microscope (IM-5, OPTIKA, Bergamo, Italy). The reproductive factor (RF) was calculated using the following formula: RF = Final population (FP)/Initial population (IP) [19,51].

2.4.3. Statistical Analysis

Statistical analysis was performed using three replications, with a total of six experimental units. Each treatment consisted of 42 plants. A destructive evaluation was carried out on two randomly selected plants at the different times of application and days of evaluation, with a total of 252 plants. Statistical analysis was performed with R software (version 4.2.3). Analysis of variance (ANOVA) and Tukey's test with a significance level of 0.05 were used to identify significant differences between means.

3. Results

3.1. Plant Growth Variables

3.1.1. Effects of Botanical Extracts on Growth and Shoot Biomass Variables Before Inoculation

At 7 days before the inoculation with *M. incognita*, significant interactions were identified between the time of application and botanical extracts, in terms of their effect on growth and shoot biomass variables (Table 1). At 30 days, *T. zypaquirensis* and *D. ambrosioides* stood out in length (44.00 and 43.83 cm) and diameter (5.23 and 4.16 cm), exceeding the absolute control (36.96 cm, 4.16 cm) and the inoculated control (17.90 cm, 2.15 cm). In shoot biomass, *D. ambrosioides* showed higher fresh and dry weights (57.23 g, 6.74 g), followed by *T. zypaquirensis* (54.47 g, 6.56 g), which was comparable to the absolute control (63.15 g and 7.69 g), while the inoculated control was the lowest (17.98 g, 3.02 g).

At 60 days, the analysis showed significant differences in the interaction between the time of application and botanical extracts for different shoot biomass variables, and no interaction was found between shoot length and diameter variables. For shoot biomass, *D. ambrosioides* presented the highest values in fresh (71.18 g) and dry (7.74 g) weight, followed by *T. zypaquirensis* (70.85 and 7.56 g, respectively), both of which were comparable to the absolute control (73.93 g and 7.69 g) and surpassed the inoculated control, which presented the lowest values in fresh (29.63 g) and dry (3.02 g) weight.

At 90 days, a significant interaction was observed between botanical extracts and shoot growth and biomass variables. In length, *T. zypaquirensis* (76.79 cm), *D. ambrosioides* (78.58 cm), and the absolute control (75.33 cm) reached the greatest lengths, surpassing the inoculated control (27.46 cm). In diameter, *T. zypaquirensis* (3.75 cm), *D. ambrosioides*

(3.20 cm), and the absolute control (3.23 cm) stood out against the inoculated control (1.42 cm). In shoot biomass, the absolute control obtained the highest values in fresh weight (116.80 g) and dry weight (11.99 g), followed by *D. ambrosioides* (92.98 g and 10.16 g) and *T. zypaquirensis* (89.95 g and 8.30 g), while the inoculated control showed the lowest values in fresh weight (35.37 g) and dry weight (2.22 g).

Table 1. Effect of botanical extracts on shoot growth and biomass variables at different times after inoculation.

Plant Growth Variable	Time of Botanical Extract Application	Botanical Extract	Day of Evaluation		
			30	60	90
Length (cm)	7 days before	*T. zypaquirensis*	44.00 ± 0.31 a	62.35 ± 1.22 ab	76.79 ± 0.43 a
		L. urucu	37.33 ± 0.33 b	59.82 ± 0.45 ab	59.96 ± 0.34 abc
		D. ambrosioides	43.83 ± 0.56 a	64.97 ± 1.32 ab	78.58 ± 0.33 a
		U. laciniata Juss	32.00 ± 0.01 bc	61.79 ± 1.34 ab	65.89 ± 0.49 ab
		R. communis	26.63 ± 0.44 cd	57.58 ± 1.23 ab	65.82 ± 0.84 abc
		Inoculated control	17.90 ± 0.38 ef	19.47 ± 0.43 ef	27.46 ± 0.43 e
		Absolute control	36.96 ± 0.67 ab	69.83 ± 1.54 a	75.33 ± 0.34 a
	7 days after	*T. zypaquirensis*	26.36 ± 0.36 cde	50.58 ± 1.32 bc	68.64 ± 0.24 ab
		L. urucu	17.83 ± 0.12 ef	29.12 ± 0.32 cd	56.67 ± 0.12 bc
		D. ambrosioides	23.48 ± 0.43 cde	51.86 ± 1.42 bc	72.67 ± 0.37 ab
		U. laciniata	20.69 ± 0.35 def	39.88 ± 1.77 cd	46.83 ± 0.53 cd
		R. communis	19.42 ± 0.42 def	36.61 ± 0.54 cd	32.75 ± 0.72 de
		Inoculated control	16.08 ± 0.06 f	12.81 ± 0.43 f	31.83 ± 0.57 de
		Absolute control	23.25 ± 0.43 def	60.66 ± 0.43 ab	79.28 ± 0.38 a
Diameter (cm)	7 days before	*T. zypaquirensis*	5.23 ± 0.03 a	2.70 ± 0.11 ab	3.75 ± 0.45 a
		L. urucu	2.78 ± 0.05 cde	1.52 ± 1.32 b	2.45 ± 0.28 c
		D. ambrosioides	4.16 ± 0.07 ab	2.67 ± 0.34 ab	3.20 ± 0.18 ab
		U. laciniata	2.98 ± 0.32 cde	2.30 ± 0.30 bc	2.40 ± 0.13 c
		R. communis	2.86 ± 0.54 cde	1.91 ± 0.32 cd	2.73 ± 0.24 bc
		Inoculated control	2.15 ± 0.08 ef	1.75 ± 0.44 def	1.42 ± 0.42 de
		Absolute control	4.16 ± 0.16 ab	2.63 ± 0.12 ab	3.23 ± 0.14 ab
	7 days after	*T. zypaquirensis*	3.05 ± 0.05 cd	1.93 ± 0.33 cd	1.23 ± 0.03 e
		L. urucu	2.62 ± 0.03 cdef	1.80 ± 0.38 de	1.04 ± 0.04 e
		D. ambrosioides	3.11 ± 1.03 c	1.79 ± 0.40 de	1.36 ± 0.03 e
		U. laciniata	2.16 ± 0.16 ef	1.73 ± 0.56 def	1.02 ± 0.04 e
		R. communis	2.23 ± 0.04 def	1.49 ± 0.57 ef	1.04 ± 0.04 e
		Inoculated control	1.87 ± 0.01 f	1.37 ± 0.37 f	1.05 ± 0.02 e
		Absolute control	3.10 ± 0.12 c	2.55 ± 0.54 ab	2.15 ± 0.25 cd
Fresh weight (g)	7 days before	*T. zypaquirensis*	54.47 ± 0.47 ab	70.85 ± 1.12 a	89.95 ± 1.55 abc
		L. urucu	32.75 ± 1.23 cd	31.98 ± 1.77 d	38.88 ± 1.23 ef
		D. ambrosioides	57.23 ± 0.45 ab	71.18 ± 1.45 a	92.98 ± 1.34 ab
		U. laciniata	42.67 ± 1.32 b	57.62 ± 1.67 ab	49.85 ± 0.77 def
		R. communis	49.93 ± 0.58 b	56.57 ± 0.54 ab	33.23 ± 0.33 f
		Inoculated control	17.98 ± 0.32 e	29.63 ± 0.33 d	35.37 ± 0.43 ef
		Absolute control	63.15 ± 1.15 a	73.93 ± 0.46 a	116.80 ± 1.42 a
	7 days after	*T. zypaquirensis*	36.00 ± 0.45 c	46.20 ± 0.51 bc	61.68 ± 0.29 cde
		L. urucu	23.52 ± 0.43 d	33.32 ± 0.32 cd	44.83 ± 0.23 def
		D. ambrosioides	34.73 ± 0.73 c	48.88 ± 1.24 b	62.53 ± 0.54 cde
		U. laciniata	31.27 ± 0.39 cd	26.07 ± 0.20 d	43.03 ± 1.33 def
		R. communis	22.77 ± 0.56 d	39.00 ± 0.65 bcd	45.05 ± 0.05 def
		Inoculated control	17.52 ± 0.08 e	29.64 ± 0.43 d	31.47 ± 0.32 f
		Absolute control	61.72 ± 0.72 ab	70.41 ± 0.45 a	83.30 ± 0.30 bc

Table 1. *Cont.*

Plant Growth Variable	Time of Botanical Extract Application	Botanical Extract	Day of Evaluation		
			30	60	90
Dry weight (g)	7 days before	*T. zypaquirensis*	6.56 ± 1.33 a	7.56 ± 1.33 a	8.30 ± 0.30 ab
		L. urucu	3.39 ± 0.24 cd	3.39 ± 0.24 cd	3.42 ± 0.32 de
		D. ambrosioides	6.74 ± 0.34 a	7.74 ± 0.34 a	10.16 ± 0.18 a
		U. laciniata	4.55 ± 1.21 b	6.55 ± 1.21 ab	4.62 ± 0.44 cd
		R. communis	4.08 ± 0.77 bc	5.08 ± 0.77 bc	7.53 ± 0.24 c
		Inoculated control	3.02 ± 0.08 d	3.02 ± 0.08 d	2.22 ± 0.22 i
		Absolute control	7.89 ± 1.13 ab	7.69 ± 1.13 a	11.99 ± 0.49 a
	7 days after	*T. zypaquirensis*	5.14 ± 0.33 bc	5.14 ± 0.33 bc	6.60 ± 0.30 ef
		L. urucu	3.85 ± 0.22 cd	3.85 ± 0.22 cd	3.71 ± 0.12 ghi
		D. ambrosioides	5.33 ± 0.12 bc	5.04 ± 0.12 bc	6.25 ± 0.25 ef
		U. laciniata	3.05 ± 0.10 d	3.05 ± 0.10 d	4.27 ± 0.17 gh
		R. communis	2.61 ± 0.34 d	2.61 ± 0.34 d	4.37 ± 0.29 bcd
		Inoculated control	2.89 ± 1.23	2.89 ± 1.23	2.47 ± 0.44 hi
		Absolute control	7.01 ± 0.32 ab	7.01 ± 0.32 ab	8.21 ± 0.23 bcd

Different letters in the same column indicate significant differences between treatments ($p < 0.05$).

3.1.2. Effects of Botanical Extracts on Shoot Growth and Biomass Variables After Inoculation

At 7 days after inoculation with *M. incognita*, significant interactions were identified between the time of application and botanical extracts for shoot growth and shoot biomass variables (Table 1). All treatments showed a decrease in length, diameter, and fresh and dry weight compared to the values taken 7 days before inoculation. However, the absolute control had a natural and continuous development, showing the highest averages in all variables. At 30 days, *T. zypaquirensis* (26.36 cm in length, 3.05 cm in diameter) and *D. ambrosioides* (23.48 cm, 3.11 cm, respectively) exceeded the inoculated control (16.08 cm, 2.15 cm), but did not reach the values of the absolute control (23.25 cm, 3.10 cm), which showed the best results, due to natural development. In shoot biomass, *T. zypaquirensis* (36.00 g fresh weight, 5.14 g dry weight) and *D. ambrosioides* (34.73 g, 5.33 g) stood out among the treatments, although the absolute control presented the highest values (61.72 g fresh weight, 7.01 g dry weight), surpassing the inoculated control (17.52 g, 2.89 g).

At 60 days, the analysis showed significant differences in the interaction between the time of application and botanical extracts for shoot biomass variables, and no interaction was found between shoot length and diameter variables. Regarding biomass, *T. zypaquirensis* (46.20 g fresh weight, 5.14 g dry weight) and *D. ambrosioides* (48.88 g, 5.04 g), stood out for their higher values among the treatments, surpassing the inoculated control (29.64 g, 2.89 g), but lagging behind the absolute control (70.41 g fresh weight, 7.01 g dry weight), which presented the best results, due to natural development.

At 90 days, a significant interaction was observed between botanical extracts and shoot growth and biomass variables. *T. zypaquirensis* (68.64 cm length, 1.23 cm diameter) and *D. ambrosioides* (72.67 cm, 1.36 cm) outperformed the inoculated control (31.83 cm, 1.05 cm), reflecting a limited capacity to mitigate the effects of the nematode. The absolute control had a length of 59.28 cm and diameter of 2.15 cm. In biomass, *T. zypaquirensis* (61.68 g fresh weight, 6.60 g dry weight) and *D. ambrosioides* (62.53 g, 6.25 g) outperformed the inoculated control (31.47 g, 2.47 g), although the absolute control (83.30 g, 8.21 g) outperformed all treatments, with significantly higher values for both variables.

3.2. Nematode Variables

3.2.1. Effects of Botanical Extracts on Nematode Variables Prior to Inoculation

At 7 days prior to inoculation with *M. incognita*, significant interactions were observed between the time of application and botanical extracts in the variables related to nematodes (Table 2). At 30 days, the analysis showed significant differences in the interaction between the time of application and botanical extracts for the nematode variables, and while no interaction was observed for root fresh weight, it was observed for the treatment factor. For root fresh weight, *T. zypaquirensis* and *D. ambrosioides* showed the highest values (144.55 g and 142.42 g, respectively), which were lower than that of the absolute control (160.55 g) and higher than that of the inoculated control (72.21 g). In terms of infestation, *T. zypaquirensis* and *D. ambrosioides* significantly reduced the nodules (492.00 and 451.00, respectively), the nematodes in 100 mL of soil (57.00 and 54.00), the nematodes in 10 g of root (95.00 and 75.00), and the reproductive factor (0.13 and 0.11), compared to the inoculated control, which reached 1172.00 nodules, 164.00 nematodes in 100 mL of soil, 1033.00 nematodes in 10 g of root, and a reproductive factor of 1.00.

Table 2. Effect of botanical extracts on *M. incognita* populations in soil and roots at different times after inoculation.

Plant Growth Variable	Times of Botanic Extract Application	Botanical Extract	Day of Evaluation		
			30	60	90
Root fresh weight (g)	7 days before	*T. zypaquirensis*	144.55 ± 1.88 ab	90.88 ± 0.77 ab	40.93 ± 1.23 b
		L. urucu	108.00 ± 1.77 bcd	65.83 ± 0.17 cd	22.67 ± 0.44 d
		D. ambrosioides	142.42 ± 1.87 ab	87.78 ± 0.19 ab	42.21 ± 0.21 b
		U. laciniata	124.57 ± 2.34 bc	58.25 ± 0.27 de	22.57 ± 1.24 d
		R. communis	124.50 ± 1.43 bc	82.50 ± 0.45 bc	24.37 ± 0.27 cd
		Inoculated control	72.21 ± 1.72 e	32.93 ± 1.43 f	6.23 ± 1.13 f
		Absolute control	160.55 ± 1.44 a	105.37 ± 1.44 a	68.47 ± 1.33 a
	7 days after	*T. zypaquirensis*	85.98 ± 1.56 cde	42.97 ± 0.32 ef	23.87 ± 0.33 c
		L. urucu	88.83 ± 1.22 de	29.34 ± 0.65 f	19.60 ± 0.44 e
		D. ambrosioides	84.98 ± 1.78 cde	42.60 ± 0.14 ef	29.60 ± 0.30 c
		U. laciniata	79.05 ± 1.45 de	29.77 ± 0.07 f	10.23 ± 0.17 ef
		R. communis	89.50 ± 1.28 de	29.45 ± 0.43 f	6.52 ± 0.32 f
		Inoculated control	61.67 ±1.32 e	28.19 ± 0.19 f	9.87 ± 0.18 ef
		Absolute control	155.17 ± 1.34 ab	98.23 ± 0.55 ab	63.64 ± 0.54 a
Number of nodules	7 days before	*T. zypaquirensis*	492.00 ± 1.44 b	75.00 ± 0.32 g	52.00 ± 0.78 cd
		L. urucu	650.00 ± 1.56 b	292.00 ± 0.44 ef	222.00 ± 1.45 abc
		D. ambrosioides	451.00 ± 0.78 b	94.00 ± 0.02 g	80.50 ± 1.32 bcd
		U. laciniata	744.00 ± 1.52 b	458.00 ± 0.22 bcd	253.00 ± 1.34 ab
		R. communis	727.00 ± 2.54 b	227.00 ± 0.34 f	244.00 ± 1.59 ab
		Inoculated control	1172.00 ± 2.43 a	399.00 ± 0.44 cde	32.00 ± 1.45 d
		Absolute control	-	-	-
	7 days after	*T. zypaquirensis*	521.00 ± 1.45 b	328.00 ± 0.53 def	22.00 ± 0.56 d
		L. urucu	1197.00 ± 1.82 a	534.00 ± 1.44 ab	78.00 ± 1.45 bcd
		D. ambrosioides	558.00 ± 1.57 b	287.00 ± 2.32 ef	76.00 ± 1.34 bcd
		U. laciniata	689.00 ± 1.79 b	634.00 ± 1.43 a	76.00 ± 0.99 bcd
		R. communis	1133.00 ± 2.64 a	463.00 ± 0.32 bc	37.00 ± 0.54 cd
		Inoculated control	1197.00 ± 2.96 a	531.00 ± 1.77 abc	47.00 ± 0.23 cd
		Absolute control	-	-	-

Table 2. *Cont.*

Plant Growth Variable	Times of Botanic Extract Application	Botanical Extract	Day of Evaluation		
			30	60	90
Nematodes in 100 mL of soil	7 days before	*T. zypaquirensis*	57.00 ± 1.32 e	945.00 ± 1.44 cd	1709.00 ± 2.72 bc
		L. urucu	122.00 ± 1.21 cd	1487.00 ± 1.32 c	3176.00 ± 1.65 bc
		D. ambrosioides	54.00 ± 0.32 e	957.00 ± 0.55 cd	3711.00 ± 2.45 abc
		U. laciniata	105.00 ± 1.23 d	1961.00 ± 1.67 c	5967.00 ± 1.77 ab
		R. communis	119.00 ± 0.13 cd	1650.00 ± 2.32 c	6186.00 ± 2.34 ab
		Inoculated control	164.00 ± 0.34 a	4075.00 ± 0.56 b	6722.00 ± 3.56 ab
		Absolute control	-	-	-
	7 days after	*T. zypaquirensis*	110.00 ± 0.34 cd	1641.00 ± 1.77 c	4110.00 ± 2.34 abc
		L. urucu	126.00 ± 0.96 cd	1699.00 ± 1.42 c	4034.00 ± 1.45 abc
		D. ambrosioides	114.00 ± 1.21 cd	1907.00 ± 1.44 c	3160.00 ± 1.44 bc
		U. laciniata	131.00 ± 0.44 bc	7082.00 ± 0.56 a	4932.00 ± 2.88 abc
		R. communis	124.00 ± 0.45 cd	5181.00 ± 0.44 b	1595.00 ± 1.32 bc
		Inoculated control	152.00 ± 0.12 ab	4802.00 ± 1.23 b	6836.00 ± 3.45 ab
		Absolute control	-	-	-
Nematodes in 10 g of roots	7 days before	*T. zypaquirensis*	95.00 ± 0.32 fg	818.00 ± 0.47	69.00 ± 1.34 cd
		L. urucu	341.00 ± 0.44 cde	1341.00 ± 2.89 de	169.00 ± 1.04 bcd
		D. ambrosioides	75.00 ± 1.2 g	960.00 ± 1.03 de	60.00 ± 0.56 cd
		U. laciniata	218.00 ± 0.31 ef	1729.00 ± 1.76 de	434.00 ± 1.58 abcd
		R. communis	318.00 ± 2.12 de	7914.00 ± 1.44 a	101.00 ± 1.23 bcd
		Inoculated control	1033.00 ± 1.32 a	5179.00 ± 2.34 abc	534.00 ± 2.54 ab
		Absolute control	-	-	-
	7 days after	*T. zypaquirensis*	389.00 ± 0.45 cd	957.00 ± 0.89 de	78.00 ± 1.55 cd
		L. urucu	574.00 ± 1.23 b	2790.00 ± 2.44 cde	493.00 ± 1.78 abc
		D. ambrosioides	398.00 ± 1.44 cd	1560.00 ± 2.45 de	194.00 ± 1.39 bcd
		U. laciniata	598.00 ± 2.32 b	5860.00 ± 1.67 ab	338.00 ± 1.23 bcd
		R. communis	475.00 ± 1.48 bc	3784.00 ± 3.31 bcd	139.00 ± 1.09 bcd
		Inoculated control	1064.00 ± 2.56 a	6321.00 ± 2.46 ab	576.00 ± 1.34 ab
		Absolute control	-	-	-
Reproductive factor	7 days before	*T. zypaquirensis*	0.13 ± 0.01 g	1.47 ± 0.12 d	1.48 ± 0.21 cd
		L. urucu	0.39 ± 0.02 de	2.36 ± 0.36 cd	2.79 ± 0.34 cd
		D. ambrosioides	0.11 ± 0.01 gh	1.70 ± 0.10 d	3.14 ± 0.10 bcd
		U. laciniata	0.27 ± 0.01 f	3.08 ±0.32 c	5.34 ± 0.34 abc
		R. communis	0.37 ± 0.02 ef	7.97 ± 0.97 b	5.24 ± 0.89 abc
		Inoculated control	1.00 ± 0.01 a	7.71 ± 0.71 b	7.39 ± 1.32 ab
		Absolute control	-	-	-
	7 days after	*T. zypaquirensis*	0.42 ± 0.02 de	2.17 ± 0.34 cd	3.49 ± 0.12 bcd
		L. urucu	0.58 ± 0.03 bc	3.74 ± 1.23 c	3.78 ± 0.34 abcd
		D. ambrosioides	0.43 ± 0.02 de	2.39 ± 0.39 cd	2.79 ± 1.07 cd
		U. laciniata	0.61 ± 0.01 b	10.79 ± 0.79 a	4.39 ± 0.54 abc
		R. communis	0.50 ± 0.03 cd	7.47 ± 1.47 b	1.77 ± 0.43 cd
		Inoculated control	1.01 ± 0.04 a	9.27 ± 1.23 ab	8.07 ± 1.34 a
		Absolute control	-	-	-

Different letters in the same column indicate significant differences between treatments ($p < 0.05$).

At 60 days of evaluation, the analysis showed significant differences in the interaction between the time of application and botanical extracts with respect to the variables related to nematodes. Extracts of *T. zypaquirensis* and *D. ambrosioides* showed effective control against *M. incognita*, presenting lower nematode populations in soil (945.00 and 957.00) and roots (818.00 and 960.00), as well as fewer nodules (75.00 and 94.00), reduced reproductive factors (1.47 and 2.10), and higher root fresh weights (90.88 and 87.78 g). In comparison, the inoculated control presented high values of nematodes in the soil (4075.00) and roots (5179.00), together with a higher number of nodules (399.00), a high reproductive factor (7.71), and a lower root weight (32.93 g), evidencing the negative impact of infestation without the intervention of the extracts.

At 90 days of evaluation, a significant interaction was observed for root fresh weight, while the nematode variables measured were not significant for the interaction. Treatments with *T. zypaquirensis* (40.93 g) and *D. ambrosioides* (42.21 g), applied 7 days before the inoculation, produced higher root fresh weights compared to the inoculated control (6.23 g), highlighting the efficacy of the botanical extracts in promoting root development.

3.2.2. Effects of Botanical Extracts on Nematode Variables After Inoculation

At 7 days after inoculation with *M. incognita*, all variables related to the nematode population, such as the number of nematodes in the soil and roots, showed a significant increase compared to the evaluation 7 days before inoculation (Table 2). At 30 days, the inoculated control showed the highest following values: 1197.00 nodules, 152.00 juveniles in 100 mL of soil, 1064.00 juveniles in 10 g of roots, and a reproductive factor of 1.01. Extracts of *T. zypaquirensis* and *D. ambrosioides* significantly reduced infestation, with the following values: 521.00 and 558.00 nodules, 110.00 and 114.00 juveniles in 100 mL of soil, 389.00 and 398.00 juveniles in 10 g of root, and reproductive factors of 0.42 and 0.43, respectively. However, the effect of the extracts was less efficient at this point in time compared to the results obtained before inoculation.

At 60 days of evaluation, after inoculation with *M. incognita*, the extracts of *T. zypaquirensis* and *D. ambrosioides* showed an effective control of the nematode infestation, evidenced by a significant reduction in the variables associated with the nematode population. The extracts generated a decrease in the number of nodules (328.00 and 287), nematodes in 100 mL of soil (1641 and 1907), and nematodes in 10 g of root (957 and 1560). They also produced a reduction in the reproductive factor (2.17 and 2.39) compared to the inoculated control, which presented the highest values of nematodes in soil (4802.00), roots (6321.00), and nodules (531.00), together with a high reproductive factor (9.27). In addition, the extracts promoted an increase in root fresh weight (42.97 and 42.60 g) compared to the inoculated control (28.19 g).

At 90 days of evaluation, a significant interaction was observed for root fresh weight, while the variables associated with the nematode population showed no significant differences. The extracts *T. zypaquirensis* (23.87 g) and *D. ambrosioides* (29.60 g) recorded higher root fresh weights, significantly exceeding that of the inoculated control (9.87 g), thus highlighting the effectiveness of the botanical extracts in promoting root development.

4. Discussion

Previous research has shown that several plants and their derived phytochemicals possess nematicide properties with a wide range of PPNs [52]. Currently, various research groups are working on the development of management strategies based on the use of these plant compounds [52,53]. Several isolated plant compounds involved in plant nematode interactions have been categorized according to their function as attractants, repellents, inhibitors, or hatching promoters, as well as toxic agents for nematodes [53,54]. In this context, botanical pesticides are gaining attention for their broad control action and lower environmental impact.

4.1. Plant Growth Variables

Nematode management strategies are a central focus of plant pathological studies, due to their significant impact on agriculture [17]. In response to the environmental damage associated with the use of chemical control measures against PPNs, indigenous plant extracts have gained importance in recent years as sustainable and environmentally friendly alternatives [19]. The present study shows that the use of botanical extracts of *T. zypaquirensis* and *D. ambrosioides* constitutes an effective alternative for the management of

M. incognita on *S. megalanthus*. These plant genera have been reported to contain secondary metabolites, such as EOs (Z)-ascaridole, E-ascaridole, p-cymene, α-terthienyl, and bithenyl, with nematicidal properties [31,38,55] (Figure S1). The results show that plants treated with these extracts had similar values for fresh weight and root development compared to plants grown naturally without inoculation, and higher values than the inoculated control. The results are in agreement with the work of Mnyambo et al. [19], who found that extracts from plants such as *Maerua angolensis* and *Tabernaemontana elegans* promoted the growth variables of *Solanum lycopersicon*. In addition, Walia et al. [16,56] reported higher fresh weights in *S. quitoense* plants treated with *T. zypaquirensis* extracts, in agreement with the results of this study. These findings also align with previous studies, such as that of Mnyambo et al. [19], who demonstrated that vegetal extracts not only reduce nematode populations, but also promote plant development. Applications made prior to nematode inoculation enabled better performance, suggesting that the preparation of the rhizosphere environment plays a key role in nematode damage.

However, the results obtained show that the extracts of *T. zypaquirensis* and *D. ambrosioides*, although effective in the early stages (30 and 60 days), were significantly less efficient by 90 days. This is in agreement with the results reported by Mwamula et al. [31], who attribute this reduction to factors such as the degradation of bioactive compounds by adverse environmental conditions, or the ability of nematodes to adapt to the active substances. Studies by Mnyambo et al. [19] showed that botanical extracts applied for up to 56 days were effective in controlling nematode populations and promoting proper plant development. These findings support the results obtained in this study, where plants treated with *T. zypaquirensis* and *D. ambrosioides* showed similar vegetative development to the absolute control in the evaluations carried out at 30 and 60 days.

The improvement in the growth variables of plants treated with *T. zypaquirensis* and *D. ambrosioides* can be explained mainly by three factors. The first factor is the plant extracts' ability to control PPNs, which allows plants to develop in a pest-free environment, thus favoring optimal yield [54]. The second factor lies in the fact that the application of plant extracts improves soil conditions in the rhizosphere, creating a more favorable environment for plant development [17]. This aspect has been extensively studied in agronomic research related to organic amendments and disease control [17,54,57]. The third factor is the ability of compounds present in plant extracts to combat changes in both biotic and abiotic environmental factors to induce resistance responses in treated plants [29,58].

4.2. Nematode Variables

Mnyambo et al. [19] found that bioactive compounds in botanical extracts alter the metabolism of nematodes, which can inhibit their reproductive and colonization capacity. Various chemical compounds produced by plants, such as phenols, flavonoids, and saponins, have been reported to be efficient for nematode control [31]. Phenolic compounds have been reported to inhibit gall formation induced by *M. incognita* and *Heterodera glycines* in cotton and soybean studies [59,60]. Recent studies, such as those of Chin et al. [61] and Ogwudire et al. [62], suggest that flavonoids induce quiescence in nematodes, reducing their mobility and modifying their migration to roots by repelling and subsequently killing them. Saponins inhibit nodule formation in nematode roots [62,63]. The phenolic compounds released by *T. zipaquirensis* and *D. ambrosoides*, once systematically absorbed by the roots of *S. megalanthus* plants, favor the activation of defense mechanisms against *M. incognita* [26,56,64]. The presence of the phytochemical compounds in the plant extracts could be the reason for their greater or equal effectiveness compared with the control treatment.

The present study showed that the systemic action of *T. zipaquirensis* and *D. ambrosoides* extracts on the development of the nematodes allowed a vegetative development similar to

that of the absolute control. In addition, it was demonstrated that *T. zipaquirensis* and *D. ambrosoides* induced defense mechanisms in plants, which helped to delay the development of *M. incognita*. These results suggest that the preventive application of *T. zipaquirensis* and *D. ambrosoides* extracts on *S. megalanthus* plants could provide a more effective strategy for nematode management. Salazar and Guzman [65] suggest that applying botanical extracts early on can prevent the spread of nematodes and reduce damage to the root system. The present results agree with those of Singh et al. [16,56], who tested the effects of essential oils of *T. zypaquirensis* on *Meloidogyne* spp. under greenhouse conditions, and observed that the oil presented the same nematicide action as carbofuran-treated soil in reducing *Meloidogyne* spp. populations. According to Mnyambo et al. [19], the reason why the nematode control had the highest percentage of nematodes was that the normal life cycle and activities of the nematode were not interfered with by the plant extracts, which underlines the effectiveness of these extracts as control agents.

In this study, it was observed that the characteristic symptoms associated with *M. incognita* infestation, such as the formation of nodules on the roots, began to be visible after 30 days of evaluation. Hernández et al. [66] mention that the time of symptom appearance depends on factors such as the initial population of the nematode, environmental conditions, and susceptibility of the host plant. Previous studies have indicated that J2 can penetrate roots in the first 24 to 48 h after inoculation, and establish feeding sites that induce galls from 5 to 10 days under optimal temperature conditions of 25–30 °C [66–68].

The host status of a plant against nematodes is determined by the RF [69,70]. If the RF on a host is less than one, the nematode cannot reproduce in that plant. Conversely, if the RF exceeds the value of one, the nematode has successfully reproduced in the host [19,71]. The present study showed the lowest RF of nematodes in *S. megalanthus* to be at 30 days of evaluation, which could be attributed to the ability of *T. zipaquirensis* and *D. ambrosoides* extracts to largely suppress the nematode population, creating a favorable environment for plant growth, an effect that decreases with time. This reduction in nematode population could be explained by direct or indirect nematicide effects of the extracts that inhibited nematode reproduction [26]. According to Mnyambo et al. [19], one of the fundamental criteria for the selection of botanical extracts is the RF; those with low RFs are considered suitable for combating plant-parasitic nematodes.

The use of plant extracts like *T. zypaquirensis* and *D. ambrosioides* represents a sustainable and biodegradable alternative to chemical nematicides, which contributes to the promotion of sustainable agriculture. However, their implementation faces challenges related to material availability, large-scale extraction costs [31], and technology adoption. To improve the feasibility of the application of this technology, further research is needed to optimize extraction processes, and also to integrate them with practices such as crop rotation or organic amendments [70,72]. The use of these extracts may also require standardized formulations that will be key to ensuring their efficacy under various environmental conditions [31].

5. Conclusions

The results showed that *T. zypaquirensis* and *D. ambrosioides* extracts were highly effective when applied 7 days before inoculation, with a reproductive factor close to 1 in the first 60 days, reflecting good control of the infestation. When the extracts were applied 7 days after inoculation, it was observed that the effectiveness was lower, which was reflected in a progressive increase in the nematode population, and a reproductive factor that was higher than 1 after 60 days. This suggests that control with botanical extracts is less effective once nematode infestation has advanced, reaffirming the importance of preventive application. Consequently, botanical extracts of *T. zypaquirensis* and *D. ambrosioides* could be

considered a promising treatment for reducing *M. incognita* infestation on yellow pitahaya, when applied as a preventative treatment. This approach contributes to the biological control of nematode populations in order to minimize the use of nematicides, highlighting the importance of early application in an integrated pest management strategy.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/horticulturae11030268/s1: Figure S1: Metabolites found in the chemical analysis of *T. zypaquirensis* and *D. ambrosioides* using the RAM methodology.

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References

1. Verona-Ruiz, A.; Urcia-Cerna, J.; Paucar-Menacho, L.M.; Verona-Ruiz, A.; Urcia-Cerna, J.; Paucar-Menacho, L.M. Pitahaya (*Hylocereus* spp.): Culture, Physicochemical Characteristics, Nutritional Composition, and Bioactive Compounds. *Sci. Agropecu.* **2020**, *11*, 439–453. [CrossRef]
2. Jiang, H.; Zhang, W.; Li, X.; Shu, C.; Jiang, W.; Cao, J. Nutrition, Phytochemical Profile, Bioactivities and Applications in Food Industry of Pitaya (*Hylocereus* spp.) Peels: A Comprehensive Review. *Trends Food Sci. Technol.* **2021**, *116*, 199–217. [CrossRef]
3. Guzmán-Piedrahita, Ó.A.; Zamorano-Montañez, C.; López-Nicora, H.D.; Guzmán-Piedrahita, Ó.A.; Zamorano-Montañez, C.; López-Nicora, H.D. Physiological interactions of plants with plant-parasitic nematodes: A review. *Bol. Cient. Cent. Mus. Mus. Hist. Nat.* **2020**, *24*, 190–205. [CrossRef]
4. Trindade, A.R.; Paiva, P.; Lacerda, V.; Marques, N.; Neto, L.; Duarte, A. Pitaya as a New Alternative Crop for Iberian Peninsula: Biology and Edaphoclimatic Requirements. *Plants* **2023**, *12*, 3212. [CrossRef]
5. Vargas Tierras, Y.B.; Pico, J.T.; Díaz, A.; Sotomayor Akopyan, D.A.; Burbano, A.; Caicedo, C.; Paredes Andrade, N.; Congo, C.; Tinoco, L.A.; Bastidas, S.; et al. *Manual del Cultivo de Pitahaya para la Amazonía Ecuatoriana*; INIAP: La Joya de los Sachas, Ecuador, 2020.
6. Phani, V.; Khan, M.R.; Dutta, T.K. Plant-Parasitic Nematodes as a Potential Threat to Protected Agriculture: Current Status and Management Options. *Crop Prot.* **2021**, *144*, 105573. [CrossRef]
7. Maqsood, A.; Wu, H.; Kamran, M.; Altaf, H.; Mustafa, A.; Ahmar, S.; Hong, N.T.T.; Tariq, K.; He, Q.; Chen, J.T. Variations in Growth, Physiology, and Antioxidative Defense Responses of Two Tomato (*Solanum lycopersicum* L.) Cultivars after Co-Infection of *Fusarium oxysporum* and *Meloidogyne incognita*. *Agronomy* **2020**, *10*, 159. [CrossRef]
8. Bačić, J.; Lalićević, I.; Širca, S.; Theuerschuh, M.; Susič, N.; Gerič Stare, B. Occurrence and Distribution of Root-Knot Nematodes *Meloidogyne* spp. in Serbia. *Agronomy* **2025**, *15*, 372. [CrossRef]
9. Desmedt, W.; Mangelinckx, S.; Kyndt, T.; Vanholme, B.A. Phytochemical Perspective on Plant Defense Against Nematodes. *Front. Plant Sci.* **2020**, *11*, 602079. [CrossRef]
10. Rani, K.; Devi, N.; Banakar, P.; Kharb, P.; Kaushik, P. Nematicidal Potential of Green Silver Nanoparticles Synthesized Using Aqueous Root Extract of Glycyrrhiza Glabra. *Nanomaterials* **2022**, *12*, 2966. [CrossRef]
11. Baniya, A.; Zayed, O.; Ardpairin, J.; Seymour, D.; Dillman, A.R. Current Trends and Future Prospects in Controlling the Citrus Nematode: Tylenchulus Semipenetrans. *Agronomy* **2025**, *15*, 383. [CrossRef]
12. Wu, C.; Wang, Y.; Chen, Y.; Wu, H. Effective Management of Meloidogyne Enterolobii Using Anaerobic Soil Disinfection Technique. *Sci. Hortic.* **2024**, *332*, 113215. [CrossRef]

13. Yigezu Wendimu, G. Biology, Taxonomy, and Management of the Root-Knot Nematode (*Meloidogyne incognita*) in Sweet Potato. *Adv. Agric.* **2021**, *2021*, 8820211. [CrossRef]
14. Delgado, A.; Pico, J.T.; Navia, D.; Suárez, C. Nemátodos fitoparásitos asociados al sistema radical del cultivo de pitahaya amarilla en el cantón Palora. In Proceedings of the IV Simposio en Fitopatología, Control Biológico e Interacciones Planta-Patógeno, Quito, Ecuador, 14–16 August 2019; USFQ Press: Galápagos, Ecuador, 2019.
15. Ravisankar, N.; Ansari, M.A.; Panwar, A.S.; Aulakh, C.S.; Sharma, S.K.; Suganthy, M.; Suja, G.; Jaganathan, D. Organic Farming Research in India: Potential Technologies and Way Forward. *Indian J. Agron.* **2021**, *66*, S142–S162.
16. Singh, Y.; Gupta, A.; Kannojia, P. *Tagetes erecta* (Marigold)—A Review on Its Phytochemical and Medicinal Properties. *Curr. Med. Drug Res.* **2020**, *4*, 201. [CrossRef]
17. Theofilidou, A.; Argyropoulou, M.D.; Ntalli, N.; Kekelis, P.; Mourouzidou, S.; Zafeiriou, I.; Tsiropoulos, N.G.; Monokrousos, N. Assessing the Role of Melia Azedarach Botanical Nematicide in Enhancing the Structure of the Free-Living Nematode Community. *Soil Syst.* **2023**, *7*, 80. [CrossRef]
18. Buralli, R.J.; Dultra, A.F.; Ribeiro, H. Respiratory and Allergic Effects in Children Exposed to Pesticides—A Systematic Review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2740. [CrossRef]
19. Mnyambo, N.M.; Rantho, L.P.; Dube, Z.P.; Timana, M. Timing of Plant Extracts Application in the Management of *Meloidogyne incognita* on Tomato Plants. *Int. J. Plant Biol.* **2024**, *15*, 1108–1117. [CrossRef]
20. Nikolova, M.; Lyubenova, A.; Yankova-Tsvetkova, E.; Georgiev, B.; Gavrilov, G.; Gavrilova, A. *Satureja kitaibelii* Essential Oil and Extracts: Bioactive Compounds and Pesticide Properties. *Agronomy* **2025**, *15*, 357. [CrossRef]
21. Makhubu, F.N.; Khosa, M.C.; McGaw, L.J. South African Plants with Nematicidal Activity against Root-Knot Nematodes: A Review. *S. Afr. J. Bot.* **2021**, *139*, 183–191. [CrossRef]
22. Benttoumi, N.; Colagiero, M.; Sellami, S.; Boureghda, H.; Keddad, A.; Ciancio, A. Diversity of Nematode Microbial Antagonists from Algeria Shows Occurrence of Nematotoxic *Trichoderma* spp. *Plants* **2020**, *9*, 941. [CrossRef]
23. Susič, N.; Žibrat, U.; Sinkovič, L.; Vončina, A.; Razinger, J.; Knapič, M.; Sedlar, A.; Širca, S.; Gerič Stare, B. From Genome to Field—Observation of the Multimodal Nematicidal and Plant Growth-Promoting Effects of *Bacillus firmus* I-1582 on Tomatoes Using Hyperspectral Remote Sensing. *Plants* **2020**, *9*, 592. [CrossRef] [PubMed]
24. Vargas, Y.; Pico, J.; Manobanda, N.; Garcia, A.; Sanmiguel, J. Biological Nematicides as an Alternative for Control of *Meloidogyne incognita* Populations in Yellow Pitahaya (*Selenicereus megalanthus*). *Bionatura J.* **2024**, *9*, 4. [CrossRef]
25. Ledchumanakumar, S.; Aruchchunan, N.; Kandiah, P.; Gunasingham, M. Root-Knot Nematode Management Using Chitin-Rich Fish Industry By-Product in Organic Brinjal Cultivation. *Biol. Life Sci. Forum* **2021**, *3*, 57. [CrossRef]
26. Barros, A.F.; Campos, V.P.; de Paula, L.L.; Oliveira, D.F.; de Silva, F.J.; Terra, W.C.; Silva, G.H.; Salimena, J.P. Nematicidal Screening of Essential Oils and Potent Toxicity of *Dysphania ambrosioides* Essential Oil Against Meloidogyne Incognita in Vitro and in Vivo. *J. Phytopathol.* **2019**, *167*, 380–389. [CrossRef]
27. Nasiou, E.; Giannakou, I.O. Nematicidal Potential of Thymol Against *Meloidogyne javanica* (Treub) Chitwood. *Plants* **2023**, *12*, 1851. [CrossRef] [PubMed]
28. Catani, L.; Manachini, B.; Grassi, E.; Guidi, L.; Semprucci, F. Essential Oils as Nematicides in Plant Protection—A Review. *Plants* **2023**, *12*, 1418. [CrossRef] [PubMed]
29. Kirgiafini, D.; Serafim, A.; Menkissoglu-Spiroudi, U.; D'Addabbo, T.; Tsiropoulos, N.; Ntalli, N. Nematicidal Trans-Anethole Blends Paralyzing *Meloidogyne incognita*. *Agriculture* **2024**, *14*, 889. [CrossRef]
30. D'Addabbo, T.; Argentieri, M.P.; Laquale, S.; Candido, V.; Avato, P. Relationship between Chemical Composition and Nematicidal Activity of Different Essential Oils. *Plants* **2020**, *9*, 1546. [CrossRef]
31. Mwamula, A.O.; Kabir, M.F.; Lee, D. A Review of the Potency of Plant Extracts and Compounds from Key Families as an Alternative to Synthetic Nematicides: History, Efficacy, and Current Developments. *Plant Pathol. J.* **2022**, *38*, 53–77. [CrossRef]
32. Sarri, K.; Mourouzidou, S.; Ntalli, N.; Monokrousos, N. Recent Advances and Developments in the Nematicidal Activity of Essential Oils and Their Components against Root-Knot Nematodes. *Agronomy* **2024**, *14*, 213. [CrossRef]
33. Catani, L.; Grassi, E.; Cocozza di Montanara, A.; Guidi, L.; Sandulli, R.; Manachini, B.; Semprucci, F. Essential Oils and Their Applications in Agriculture and Agricultural Products: A Literature Analysis through VOSviewer. *Biocatal. Agric. Biotechnol.* **2022**, *45*, 102502. [CrossRef]
34. Mwamba, S.; Kihika-Opanda, R.; Murungi, L.K.; Losenge, T.; Beck, J.J.; Torto, B. Identification of Repellents from Four Non-Host Asteraceae Plants for the Root Knot Nematode, *Meloidogyne incognita*. *J. Agric. Food Chem.* **2021**, *69*, 15145–15156. [CrossRef] [PubMed]
35. Izuogu, N.B.; Bello, O.E.; Bello, O.M. A Review on *Borreria verticillata*: A Potential Bionematicide, Channeling Its Significant Antimicrobial Activity against Root-Knot Nematodes. *Heliyon* **2020**, *6*, e05322. [CrossRef]
36. Faria, J.M.S.; Rusinque, L.; Cavaco, T.; Nunes, J.C.; Inácio, M.L. Essential Oil Volatiles as Sustainable Antagonists for the Root-Knot Nematode Meloidogyne Ethiopica. *Sustainability* **2023**, *15*, 11421. [CrossRef]

37. Shokoohi, E. Plant Extracts and Their Effects on Plant-Parasitic Nematodes, with Case Studies from Africa. In *Sustainability in Plant and Crop Protection*; Chaudhary, K.K., Meghvansi, M.K., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 189–216.
38. Riaz, M.; Ahmad, R.; Rahman, N.U.; Khan, Z.; Dou, D.; Sechel, G.; Manea, R. Traditional Uses, Phyto-Chemistry and Pharmacological Activities of *Tagetes patula* L. *J. Ethnopharmacol.* **2020**, *255*, 112718. [CrossRef] [PubMed]
39. Climate Data Climate Province of Orellana Temperature, Weather Chart, Climate Table of Province of Orellana. Available online: https://en.climate-data.org/south-america/ecuador/provincia-de-orellana-63/ (accessed on 20 February 2025).
40. Trivellini, A.; Lucchesini, M.; Ferrante, A.; Massa, D.; Orlando, M.; Incrocci, L.; Mensuali-Sodi, A. Pitaya, an Attractive Alternative Crop for Mediterranean Region. *Agronomy* **2020**, *10*, 1065. [CrossRef]
41. Dagni, A.; Codruta Heghes, S.; Suharoschi, R.; Pop, O.L.; Fodor, A.; Vulturar, R.; Cozma, A.; Filali, O.A.; Vodnar, D.C.; Soukri, A.; et al. Essential oils from *Dysphania* genus: Traditional uses, chemical composition, toxicology, and health benefits. *Front. Pharmacol.* **2024**, *13*, 1024274. [CrossRef]
42. Luna-Florin, A.D.; Nole-Nole, D.A.; Rodríguez-Caballero, E.; Molina-Pardo, J.L.; Giménez-Luque, E. Ecological Characterization of the Flora in Reserva Ecológica Arenillas, Ecuador. *Appl. Sci.* **2022**, *12*, 8656. [CrossRef]
43. Cepero, V.C.; Huamán, L.A.; Soraluz, J.T.; Ventura, R.B.; Amez, S.B.; Aguiar, P.L.D.C.; Lerner, S.H.; Otiniano, A.J. *Manual de Malezas Asociadas al Cultivo del Café en la Selva Central del Perú*; Universidad Nacional Agraria La Molina: Lima, Peru, 2019.
44. Monro, A.K.; Rodríguez, A. Three New Species and a Nomenclatural Synopsis of *Urera* (Urticaceae) from Mesoamerica1. *Ann. Mo. Bot. Gard.* **2009**, *96*, 268–285. [CrossRef]
45. Solera-Steller, P.; Moreira-González, I.; Hernández-López, J.; Solera-Steller, P.; Moreira-González, I.; Hernández-López, J. Botanical descriptors to characterize germplasm of *Ricinus communis* from different areas of Costa Rica. *Rev. Tecnol. Marcha* **2015**, *28*, 37–46.
46. Avilés Bustamante, H.A. Caracterización Morfológica de las Escoespecies de Plantas de Gordolobo (*Lonchocarpus* sp.) of the Ventanas Canton Province of Los Ríos. Bachelor's Thesis, Universidad Técnica Estatatl de Quevedo, Quevedo, Ecuador, 2015.
47. Hussey, R.S.; Barker, K.R. A Comparison of Methods of Collecting Inocula of *Meloidogyne* spp., Including a New Technique. *Plant Dis. Rep.* **1973**, *57*, 1025–1028.
48. Hussey, R.; Janssen, G. Root-Knot Nematodes: Meloidogyne Species. In *Plant Resistance to Parasitic Nematodes*; Star, J.L., Cook, R., Bridge, J., Eds.; Cabi Publishing: Wallingford, UK, 2002; pp. 43–70.
49. Palacino, J. Interacción Entre *Glomus manihotis* y *Meloidogyne incognita* en Pitaya Amarilla y Roja Bajo Condiciones de Vivero. *Cenicafé* **1990**, *41*, 80–90.
50. Chamlaty-Fayad, Y.E. Identificación de Fitonematodos *Meloidogyne* sp. en Cafetos de La Finca "La Mata" en Coatepec. *Rev. Cient. Biol. Agropecu. Tuxpan* **2014**, *2*, 364–369. [CrossRef]
51. Pinheiro, J.B.; da Silva, G.O.; Pinto, T.J.; Cunha, D.F.; Rafael, F.S.; Santos, L.A.; Florentino, M.L.; Ragassi, C.F.; Carvalho, A.D.; Pereira, A.S. Reaction of Potato Genotypes to the Root-Knot Nematode *Meloidogyne* spp. in a Naturally Infested Field. *Hortic. Bras.* **2025**, *42*, e2535. [CrossRef]
52. Atolani, O.; Fabiyi, O.A. Plant Parasitic Nematodes Management Through Natural Products: Current Progress and Challenges. In *Management of Phytonematodes: Recent Advances and Future Challenges*; Ansari, R.A., Rizvi, R., Mahmood, I., Eds.; Springer: Singapore, 2020; pp. 297–315.
53. Ghareeb, R.Y.; Hafez, E.E.; Ibrahim, D.S.S. Current Management Strategies for Phytoparasitic Nematodes. In *Management of Phytonematodes: Recent Advances and Future Challenges*; Ansari, R.A., Rizvi, R., Mahmood, I., Eds.; Springer: Singapore, 2020; pp. 339–352.
54. Ntalli, N.; Bratidou Parlapani, A.; Tzani, K.; Samara, M.; Boutsis, G.; Dimou, M.; Menkissoglu-Spiroudi, U.; Monokrousos, N. *Thymus citriodorus* (Schreb) Botanical Products as Ecofriendly Nematicides with Bio-Fertilizing Properties. *Plants* **2020**, *9*, 202. [CrossRef]
55. Campos–Montiel, R.G.; Castro-Parra, L.; de Anda, F.R.G.; Velazquez, A.P.Z. Histopathological findings in Anisakidae nematodes exposed to aqueous plant extracts with nematicidal capacity in vitro. *Rev. MVZ Córdoba* **2024**, *29*, e3078. [CrossRef]
56. Walia, S.; Mukhia, S.; Bhatt, V.; Kumar, R. Variability in Chemical Composition and Antimicrobial Activity of Tagetes Minuta L. Essential Oil Collected from Different Locations of Himalaya. *Ind. Crops Prod.* **2020**, *150*, 112449. [CrossRef]
57. Paudel, R.; Waisen, P.; Wang, K.-H. Exploiting the Innate Potential of Sorghum/Sorghum–Sudangrass Cover Crops to Improve Soil Microbial Profile That Can Lead to Suppression of Plant-Parasitic Nematodes. *Microorganisms* **2021**, *9*, 1831. [CrossRef]
58. Monokrousos, N.; Argyropoulou, M.D.; Tzani, K.; Menkissoglou-Spiroudi, U.; Boutsis, G.; D'Addabbo, T.; Ntalli, N. The Effect of Botanicals with Nematicidal Activity on the Structural and Functional Characteristics of the Soil Nematode Community. *Agriculture* **2021**, *11*, 326. [CrossRef]
59. Mukhtar, T.; Hussain, M.A. Pathogenic Potential of Javanese Root-Knot Nematode on Susceptible and Resistant Okra Cultivars. *Pak. J. Zool.* **2019**, *51*, 1891–1897. [CrossRef]
60. Yates, P.; Janiol, J.; Li, C.; Song, B.-H. Nematocidal Potential of Phenolic Acids: A Phytochemical Seed-Coating Approach to Soybean Cyst Nematode Management. *Plants* **2024**, *13*, 319. [CrossRef] [PubMed]

61. Chin, S.; Behm, C.A.; Mathesius, U. Functions of Flavonoids in Plant–Nematode Interactions. *Plants* **2018**, *7*, 85. [CrossRef]
62. Ogwudire, V.E.; Agu, C.M.; Ewelike, N.C.; Ojiako, F.O.; Cookey, C.O.; Nwokeji, E. Assessment of *Jatropha curcas* L. as Alternative Nematicide for Root Knot Nematode (*Meloidogyne incognita*) Management. *Aust. J. Sci. Technol.* **2022**, *6*, 65–70.
63. D'Addabbo, T.; Argentieri, M.P.; Żuchowski, J.; Biazzi, E.; Tava, A.; Oleszek, W.; Avato, P. Activity of Saponins from Medicago Species against Phytoparasitic Nematodes. *Plants* **2020**, *9*, 443. [CrossRef]
64. Hooks, C.R.; Wang, K.-H.; Ploeg, A.; McSorley, R. Using Marigold (*Tagetes* spp.) as a Cover Crop to Protect Crops from Plant-Parasitic Nematodes. *Appl. Soil Ecol.* **2010**, *46*, 307–320. [CrossRef]
65. Salazar, W.; Guzman, T.J. Nematicidal effect of *Quassia amara* and *Brugmansia suaveolens* extracts on *Meloidogyne* sp. associated with tomato in Nicaragua. *Agron. Mesoam.* **2014**, *25*, 111–119. [CrossRef]
66. Hernández Ochandía, D.; Arias, Y.; Gómez, L.; Peteira, B.; Miranda, I.; Rodríguez, M.G. Elements of the Life Cycle of Cuban Population of *Meloidogyne incognita* (Kofoid and White) Chitwood on *Solanum lycopersicum* L. *Rev. Protección Veg.* **2012**, *27*, 188–193.
67. Ahuja, A.; Somvanshi, V.S. Diagnosis of Plant-Parasitic Nematodes Using Loop-Mediated Isothermal Amplification (LAMP): A Review. *Crop Prot.* **2021**, *147*, 105459. [CrossRef]
68. Escobar, C.; Barcala, M.; Cabrera, J.; Fenoll, C. Overview of Root-Knot Nematodes and Giant Cells. In *Advances in Botanical Research*; Escobar, C., Fenoll, C., Eds.; Academic Press: London, UK, 2015; pp. 1–32.
69. Kyndt, T.; Fernandez, D.; Gheysen, G. Plant-Parasitic Nematode Infections in Rice: Molecular and Cellular Insights. *Annu. Rev. Phytopathol.* **2014**, *52*, 135–153. [CrossRef]
70. Sivasubramaniam, N.; Hariharan, G.; Zakeel, M.C.M. Sustainable Management of Plant-Parasitic Nematodes: An Overview from Conventional Practices to Modern Techniques. In *Management of Phytonematodes: Recent Advances and Future Challenges*; Ansari, R.A., Rizvi, R., Mahmood, I., Eds.; Springer: Singapore, 2020; pp. 353–399.
71. Sikandar, A.; Gao, F.; Mo, Y.; Chen, Q.; Ullah, R.M.K.; Wu, H. Efficacy of *Aspergillus tubingensis* GX3' Fermentation against *Meloidogyne enterolobii* in Tomato (*Solanum lycopersicum* L.). *Plants* **2023**, *12*, 2724. [CrossRef]
72. D'Addabbo, T.; Avato, P. Chemical Composition and Nematicidal Properties of Sixteen Essential Oils—A Review. *Plants* **2021**, *10*, 1368. [CrossRef] [PubMed]

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