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Timing of Plant Extracts Application in the Management of *Meloidogyne incognita* on Tomato Plants

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Abstract: *Meloidogyne incognita*, a widespread and damaging plant parasite, reduces crop yields. Chemical treatments are common but pose health and environmental risks, leading to a search for safer alternatives. Plant extracts with secondary metabolites, like those from *Maerua angolensis* and *Tabernaemontana elegans*, show promise for nematode control, though their efficacies vary. This study aimed to investigate how the timing of applying *T. elegans* and *M. angolensis* extracts influenced the population densities of *M. incognita* and the growth of tomato (*Solanum lycopersicon* L.) plants. The experiment was a factorial design with two plant extracts applied at 5 g per plant and three different timings of application relative to nematode inoculation. Additionally, the experiment included positive (chemical standard (Nemacur® 10 GR)) and negative (plants inoculated with nematodes only) controls, alongside naturally grown plants. The results indicate that applying plant extracts before the nematode inoculation or simultaneously with the inoculation reduced the total nematode populations as effectively as the Nemacur positive control. Plants treated with extracts showed improved growth variables compared with those treated with Nemacur® and the natural growing conditions. In conclusion, applying plant extracts before or simultaneously with nematode inoculation effectively suppressed the nematodes and enhanced the plant growth variables. These findings suggest that such plant extracts could be adopted as part of integrated nematode management strategies in agricultural settings.

Keywords: *Maerua angolensis*; *Tabernaemontana elegans*; *Meloidogyne incognita*; Nemacur®; application; inoculation

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1. Introduction

Tomato (*Solanum lycopersicon* L.) is a widely cultivated vegetable in South Africa and is essential to a healthy diet globally, serving both as a food source and a cash crop [1]. However, its productivity is significantly hindered by various root-knot nematodes, which infest its roots, causing substantial yield losses [2]. These nematodes pose a significant threat to agriculture globally, directly impacting crop productivity and thereby jeopardizing food security [3]. Estimates indicate that these nematodes can reduce *S. lycopersicon* yields by 26 to 68% [4], contributing to an annual global economic loss of around USD 100 billion [5]. *Meloidogyne incognita* in particular is notorious for its broad crop host range and ability to induce root galling, which leads to nutrient depletion; reduced water uptake; stunted growth; and ultimately, decreased yields [6].

The management of nematode infestations often relies on chemical nematicides, but concerns over the financial cost, environmental pollution, toxicity, and resistance development in nematode populations have prompted the search for safer alternatives [7]. These chemicals pose risks to human health through exposure during application, residue on harvested produce, or the contamination of water sources. Prolonged exposure can result in respiratory problems; skin irritations; and potential long-term health impacts, such as cancer or reproductive disorders. Environmentally, these chemicals can persist in soil and

water systems, impacting non-target organisms and disrupting ecosystems [8]. Their accumulation in the soil may affect soil health and microbial communities essential for nutrient cycling [9]. Financially, the costs associated with purchasing, applying, and managing these chemicals are significant for farmers, making them inaccessible to many small-scale *S. lycopersicon* growers in peri-urban and rural areas [8,9]. Moreover, the need for regulatory compliance, environmental monitoring, and potential cleanup further escalates expenses. The toxicity of synthetic nematicides is a critical concern, as they can bioaccumulate in the food chain, and, in turn, pose risks to wildlife and aquatic organisms, disrupting natural ecosystems [2]. Resistance development in nematodes is another consequential issue stemming from the prolonged, continuous, and intensive use of these chemicals. Over time, nematodes can evolve resistance mechanisms, rendering the chemicals less effective and necessitating higher application rates or the development of new, potentially more toxic formulations. This cycle of escalating chemical use contributes to a vicious cycle of resistance development and increased environmental and health risks. Many pesticides have now been withdrawn from use, and thus, there is a need to develop a new, safe, pollution free, and effective option.

The search for environmentally friendly, human-safe, and animal-safe methods for sustainable nematode control has increasingly focused on natural alternatives, like botanical and bio-based nematicides [2]. These approaches have garnered significant attention and popularity, as they offer effective means of managing nematodes while minimizing harm to the ecosystem, promoting biodiversity, and reducing reliance on synthetic chemicals [8]. By integrating these natural control methods into agricultural practices, there is a growing movement toward more sustainable and responsible farming that prioritizes the health of the environment, people, and animals alike. Plants are the important sources of naturally occurring pesticides that may contain many compounds with nematicidal activity, known as botanical pesticides. Plant-derived secondary metabolites have the potential to disrupt nematode life cycles and reduce their populations [10,11]. Plant extracts have long been considered as natural substitutes for synthetic chemicals in nematode control [2]. These pesticides with plant origins are generally considered to be non-persistent under field conditions, as they are readily transformed by light, oxygen, and microorganisms into less toxic products. Therefore, no residues are expected on the products or in the environment. The extracts contain bioactive compounds, such as saponins, alkaloids, tannins, flavonoids, terpenoids, steroids, and phenols with nematicidal properties that can either kill or repel nematodes [2,12]. However, their effectiveness has been variable, influenced by factors such as the extract origin, stability, seasonal variations, extraction methods, application rates, and timing of application [13]. These inconsistencies have hindered the widespread adoption of plant-extract-based nematode management strategies. The incorporation of organic material (plant parts and plant products) into the soil reduces *M. incognita* densities, resulting in an increase in *S. lycopersicon* yield [2].

The timing of applying plant extracts in nematode management is crucially important because proper timing plays a critical role in maximizing the efficacy of these natural compounds against nematode populations while minimizing the plant extract's impact on the environment and crops [14]. Applying plant extracts at key stages of the crop's growth cycle, especially during critical periods, like early development or peak nematode activity, enables growers to effectively protect plant roots from infestation [12]. Understanding the life cycle of the target nematode species is essential; for instance, applying extracts during the egg-hatching or juvenile penetration stages can disrupt nematode development and reduce the subsequent damage to crops. Moreover, seasonal considerations, such as temperature and moisture levels, influence the nematode activity and susceptibility, necessitating adjustments in application timing to align with optimal environmental conditions [15]. Proper timing also ensures that plant extracts persist long enough in the soil to exert their nematicidal effects, thereby reducing the need for frequent re-applications and minimizing the overall input costs [16]. Ultimately, by carefully timing the application of plant

extracts, growers can enhance their effectiveness in nematode management, contributing to improved crop health, increased yields, and sustainable agricultural practices.

Unlike synthetic chemicals, which have undergone extensive research on optimal application strategies, much remains to be understood about the effective use of plant extracts for nematode management. This study aimed to investigate the impact of the application timing of extracts from *Maerua angolensis* and *Tabernaemontana elegans* on *M. incognita* population densities, addressing the need for more precise application methods to enhance the efficacy and adoption rates. Therefore, the authors hypothesized that the application of plant extracts before nematode inoculation will reduce *M. incognita* population densities.

2. Materials and Methods

2.1. Study Site

This research was carried out under greenhouse conditions at the University of Mpumalanga (25.4365° S, 30.9818° E), Nelspruit, South Africa. The greenhouse temperatures were set between 25 °C and 30 °C, with thermostatically activated fans and wet walls at opposite ends.

2.2. Growth Condition and Inoculum

The plant extract was a leaf powder of *M. angolensis* and *T. elegans* collected from the Agricultural Research Council–Institute for Tropical and Subtropical Crops (ARC-ITSC) in Nelspruit, South Africa. The leaf parts were chopped into 5 cm pieces and oven dried for 4 days at 52 °C prior to grinding in a Wiley mill and passing the material through a 1 mm aperture. The plant extracts powder was bulk stored separately in marked, air-tight glass containers at room temperature in the dark until used in the experiments. A population of *M. incognita* race 2, of which the identification was confirmed by sequence-characterized amplified regions–polymerase chain reaction (SCARPCR) [17], was obtained from the ARC–Grain Crops Institute, Potchefstroom, SA, and multiplied for a period of 2 months in a glasshouse on susceptible *S. lycopersicon* plants cv. 'Floradade'.

2.3. Treatment and Experimental Design

Thirty-centimeter diameter plastic pots were filled with a mixture of steam-pasteurized (250 °C for 4.5 h) loam soil and river sand at 1:3 (*v*/*v*) and placed with 0.3 m intra- and inter-row spacings on greenhouse benches. Two Floradade tomato seedlings were transplanted in each pot. Two weeks after transplanting, the seedlings were thinned to one healthy seedling per pot before inoculating with 5000 *M. incognita* eggs and second-stage juveniles (J2s) using a 20 mL plastic syringe by putting them on cardinal stem points in a 2.5 cm deep hole. The experiment was a 2 × 3 factorial arrangement laid out in a randomized complete block design with 5 replications per treatment. The first factor involved two plant extracts (*M. angolensis* and *T. elegans*) applied at a rate of 5 g per plant, while the second factor included three different application and inoculation timings: applying the plant extract before the nematode inoculation, inoculating with nematodes before applying the plant extract, and applying the plant extract and inoculating with nematodes simultaneously. Additionally, the experiment included a positive (chemical standard (Nemacur® 10 GR)) and negative (plants inoculated with nematodes only) controls and plants with no application of extracts and no inoculation of nematodes.

2.4. Data Collection

2.4.1. Plant Variables

At 56 days after the inoculation, the plant height was measured from the soil level to the end of the flag leaf; the plants were then cut at the soil line, and the stem diameter was measured at 3 cm above the cut end using a manual vernier caliper (model no: 464-9952, RS PRO, Midrand, South Africa). The chlorophyll meter was used to determine the amount of chlorophyll on the mature topmost leaves (Minolta spad-502, Hangzhou, China). The plant shoot mass was determined by drying the shoots in a 70 °C oven for 72 h and weighing them. The root systems were extracted from the soil, washed to remove any soil particles, and weighed.

2.4.2. Nematode Variables

Using the maceration and blending procedure, nematodes were extracted from the entire root system [17]. Each pot's soil was thoroughly mixed, and 250 mL of the soil sample was taken for the nematode extraction. Nematodes were extracted from the soil using a sugar floatation and centrifugation method [17], while nematodes from the roots were extracted using the blending and maceration procedure [17]. A 1 mL aliquot of each sample was counted under a stereomicroscope at 25× magnification (Olympus Corporation Tokyo (Japan) 163-0914, CX23 RTFS2) for the eggs and second-stage juveniles (J2s) from the roots and J2s from the soil. The total eggs and J2s from the root system were added to the total J2s from the soil to compute the final nematode population density (Pf). The reproductive potential (RP) was computed using the formula RP = total eggs and J2s in the root/fresh root mass, while the reproductive factor (RF) was computed using the formula RF = final nematode population (Pf) divided by the initial nematode inoculated (Pi). Both RP and RF are indicators of the nematode's ability to reproduce.

2.4.3. Data Analysis

Statistix 10 software was used to perform a two-way analysis of variance (ANOVA) on the plant growth and nematode variables data. Prior to ANOVA, the Shapiro–Wilk normality test was used to determine the normality of the data distribution. Non-continuous nematode and plant growth variables data were transformed to homogenous variance using $\log_{10}(x + 1)$. The Fisher's least significant difference (LSD) test was used to separate the means at the 0.05 level.

3. Results

3.1. Plant Growth Variables

The first-order interactions between the application time and the different plant extracts were not significant ($p > 0.05$) for all plant growth variables (Table 1). Significant differences were observed in all the measured plant growth variables. The plants treated with the plant extracts produced a higher dry shoot mass compared with all the plants that were not treated. Significant differences in the plant height were observed in all the plants that were treated with the plant extracts and the plants that were not treated, with treated plants producing the highest plant height. The plant extract treatment produced more fruit of bigger fruit mass compared with the natural-growing plants and chemical-treated plants. The plants treated with the plant extract before the nematode inoculation and the plant extract application simultaneous with the nematode inoculation produced the biggest stem diameters. All the plant extract treatments, except the plants treated with the plant extract before the nematodes, produced the highest chlorophyll content compared with all treatments. The plants that were treated with *M. angolensis* produced the highest chlorophyll content compared with the plants treated with *T. elegans*. The plant extracts were not phytotoxic to *S. lycopersicon* tomato plants; rather, they caused increased plant growth, vigor, and yield in the presence of nematodes.

Table 1. Effects of the plant extracts of *Maerua angolensis* and *Tabernaemontana elegans*, Nemacur® as the positive control and water as the negative control, and the application time on the plant growth and development.

Treatment	Chlorophyll Content	Dry Shoot Mass (g)	Root Mass (g)	Plant Height (cm)	Shoot Mass (g)	Fruit Mass (g)	Number of Fruit	Stem Diameter (cm)
Negative control	[x] 8.400 [b]	4.7100 [b]	1.2067 [c] (15.438) [y]	64.500 [b]	1.3358 [b] (21.009)	0.7046 [a] (13.013)	0.1505 [ab] (0.5000)	0.1944 [b] (0.5650)
Natural treatment	9.880 [b]	5.2110 [b]	1.3595 [b] (22.952)	74.110 [b]	1.3503 [b] (21.954)	0.0726 [b] (0.4320)	0.0301 [bc] (0.1000)	0.1981 [b] (0.5790)
Positive control	9.680 [b]	5.1040 [b]	1.3186 [b] (20.281)	71.750 [b]	1.3912 [b] (23.839)	0.0000 [b] (0.0000)	0.0000 [c] (0.0000)	0.1957 [b] (0.5710)
Nematodes first	13.660 [a]	8.7900 [a]	1.5381 [a] (34.566)	93.220 [a]	1.6407 [a] (43.159)	0.5349 [ab] (9.1990)	0.1556 [ab] (0.6000)	0.1970 [b] (0.5750)
Plant extract first	9.350 [b]	9.8840 [a]	1.4938 [a] (31.588)	85.330 [a]	1.6441 [a] (43.515)	0.8418 [a] (17.019)	0.1505 [ab] (0.5000)	0.2158 [a] (0.6450)
Simultaneous application and inoculation	14.340 [a]	9.0970 [a]	1.4980 [a] (31.974)	86.520 [a]	1.6301 [a] (42.132)	0.6562 [a] (9.9400)	0.1857 [a] (0.7000)	0.2048 [ab] (0.6040)
p value	0.0004	0.0000	0.0000	0.0000	0.0000	0.0144	0.0554	0.0515
LSD value	2.9366	1.2023	0.1108	10.253	0.0695	0.5544	0.0708	0.0150
F value	5.77	31.30	10.99	9.04	39.88	3.23	2.36	2.41

[x] Column means followed by the same letters were not significantly different at $p \leq 0.05$ according to Fisher's least significant difference. [y] Values in brackets are untransformed means [$\log_{10}(x + 1)$].

3.2. Nematode Variables

The first-order interactions between the application time and the different plant extracts were not significant ($p > 0.05$) for all nematode variables measured (Table 2). There were significant differences in all the measured nematode variables (Table 2). The time of the plant extract application had no significant difference in the gall rating, juveniles in the soil, and juveniles in the roots. The different times of the plant extract application reduced the nematode's population densities. The plant extract application before the nematode inoculation and simultaneous plant extract application and nematode inoculation reduced the total nematodes similar to Nemacur. *Maerua angolensis* and *T. elegans* were toxic to *M. incognita*. The negative control recorded the highest percentage of egg hatches; this was due to the fact that the normal life cycle and activities of the nematode did not interfere with the way the plant extracts acted. There were no differences in the reproductive potentials of all the plant extract treatments. There were significant differences in the reproductive potentials and reproductive factors between the treatments, with the negative control having an RF greater than one (Table 3).

Table 2. Effects of the plant extracts of *Maerua angolensis* and *Tabernaemontana elegans*, Nemacur® as the positive control and water as the negative control, and the application time on the nematode population densities.

Treat	Gall Rating	Juveniles in Soil	Eggs in Roots	Juveniles in Roots	Total Nematodes in Soil	Total Nematodes in Roots	Total Nematodes in Pot
Negative control	0.4816 [c] (1.6000)	2.4557 [a] (330.00)	2.5228 [a] (380.00)	2.3152 [a] (360.00)	2.6050 [a] (460.00)	2.8578 [a] (840.00)	3.0667 [d] (8100.0)
Positive control	0.0301 [b] (0.1000)	1.3996 [b] (140.00)	2.4249 [ab] (350.00)	0.9012 [bc] (90.000)	1.6571 [b] (180.00)	2.5069 [abc] (440.00)	2.7161 [b] (620.00)
Nematodes first	0.2107 [a] (0.7000)	2.5458 [a] (450.00)	2.4344 [ab] (320.00)	1.3996 [ab] (140.00)	2.5871 [a] (490.00)	2.5723 [ab] (460.00)	2.9261 [a] (950.00)
Plant extract first	0.1505 [a] (0.5000)	2.6881 [a] (630.00)	1.9711 [bc] (190.00)	0.8137 [bc] (230.00)	2.7223 [a] (660.00)	2.1326 [c] (420.00)	2.7903 [b] (680.00)
Simultaneous application and inoculation	0.1505 [a] (0.5000)	2.1954 [a] (290.00)	1.7230 [c] (120.00)	1.4928 [ab] (110.00)	2.4636 [a] (340.00)	2.3085 [bc] (230.00)	2.7154 [b] (570.00)
p value	0.002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LSD value	0.0543	0.2746	0.2419	0.4689	0.2297	0.1877	0.0898
F value	6.30	28.08	31.29	5.52	42.19	61.41	343.43

Column means followed by the same letters were not significantly different at $p \leq 0.05$ according to Fisher's least significant difference. Values in brackets are untransformed means [$\log_{10}(x + 1)$].

Table 3. Effects of the plant extracts of *Maerua angolensis* and *Tabernaemontana elegans*, Nemacur® as the positive control and water as the negative control, and the application time on the reproductive potential and reproductive factor of *Meloidogyne incognita*.

Treatment	Reproductive Potential	Reproductive Factor
Negative control	1.6887 ^{a}	1.2930 ^{c}
Positive control	1.247 ^{b}	0.0496 ^{b}
Nematodes first	1.0937 ^{bc}	0.0741 ^{ab}
Plant extract first	0.8765 ^{c}	0.0806 ^{ab}
Simultaneous application and inoculation	0.8931 ^{c}	0.0465 ^{b}
F value	33.14	11.65
$LSD_{0.05}$	0.1373	0.0138
p value	0.0000	0.0000

Column means followed by the same letters were not significantly different at $p \leq 0.05$ according to Fisher's least significant difference.

4. Discussion

Khosa et al. [2] conducted field trials in South Africa to explore the efficacies of traditional medicinal plants, known locally as 'muti', against root-knot nematodes and their potential to enhance plant growth. These botanical medicines are usually prescribed by herbal healers to treat humans and domestic animals for various ailments [18]. They tested powders made from stems, leaves, and bulbs of various endemic plant species used in South African traditional medicine. Specifically, they found that extracts from *M. angolensis* (bead-bean tree) and *T. elegans* (toad tree), commonly available in South Africa, consistently reduced the population of root-knot nematodes (*M. incognita*) in *S. lycopersicon* roots compared with untreated controls. Their study, which employed the Curve-Fitting Allelochemical Response Dosage model, identified the low concentrations necessary for inhibiting nematode hatching and providing lethal doses in these plant extracts, indicating their potential as effective agents for managing *M. incognita* infestations [2].

4.1. Plant Growth Variables

Following environmental concerns that arise from chemical control measures against nematodes, extracts from indigenous plants have become important in recent years [19]. It is apparent from the results of this study that the plants treated with plant extract levels showed the best growth variables and development compared with the plants treated with Nemacur® and the plants that grew naturally without any application or inoculation. The results agreed with the work by Claudius-Cole et al. [20], who reported that extracts of *Ocimum gratissimum*, *Azadirachta indica*, *Vernonia amygdalina*, and *Moringa oleifera* promoted plant growth variables, vigor, and yield while decreasing nematode populations in cowpea. Khosa et al. [2] reported a higher shoot weight in plants treated with *M. angolensis* and *T. elegans* in the years 2008 and 2011, which agrees with the current results. However, El-Deeb et al. [21] observed an increase in the fresh and dry shoot weights of *S. lycopersicon* plants treated with Nemacur®, which contradicts the current results. Akpheokhai et al. [22] reported an increase in grain weight, fresh root weight, and the number of root nodules in soybean plants treated with plant extracts, such as *Tithonia diversifolia*, *A. indica*, *Zanthoxylum zanthoxyloides*, and *Datura metel*.

The improvement in plant growth variables in plants treated with *M. angolensis* and *T. elegans* can be explained mostly using three phenomena. First, the ability of plant extracts to suppress nematodes results in plants growing in a pest-free environment, hence better performance [23]. The second phenomenon is that the addition of plant extracts improves the soil conditions around the plants' rhizosphere [24]. The improvement in soil conditions has received extensive attention in the agronomic studies of organic amendments and disease suppression [24]. The third concept, which is quickly gaining attention, is the induction of resistance and/or defense reactions by compounds produced by plant extracts in treated plants [25]. The concept of induced resistance is well studied in plant fungal and

bacterial diseases, with elicitors being identified as inducers of such resistance [25]. Induced plant resistance has been defined as the enhancement of a plant's defense against pests through extrinsic physical or chemical stimuli, where these stimuli could be a pathogen, insect herbivore or wounding, beneficial microbe, or chemical agent [26]. A further study needs to be conducted to comprehensively explain the relationship between *S. lycopersicon* plants, *M. angolensis*, and *T. elegans*.

4.2. Nematode Variables

The earlier studies also showed that many plants and their derived phytochemicals are known to possess nematicidal potential against a broad range of phytoparasitic nematodes. Several research groups are attempting to develop phytochemical-based strategies for nematode control. According to Mashela et al. [27], the nematicidal mechanisms of medicinal plants as nematicides are unclear. Many plant extracts used in these studies have yet to be fully characterized, making it difficult to identify the active compounds that could help explain their mode of action. These compounds may disrupt nematode cell membranes, impair their metabolism, or interfere with their reproductive systems, although the exact mechanisms require further exploration [28]. *T. elegans* has not yet been fully characterized. While it is known to have medicinal uses, no detailed study has been conducted to identify its active nematicidal compounds. Future research will focus on isolating and characterizing the bioactive components in *T. elegans* to better understand its mechanism of action in nematode control. This characterization is crucial to comprehensively explain the phytochemical interactions responsible for the observed nematicidal effects. In contrast, *M. angolensis* extract has been reported to harbor secondary metabolites, like alkaloids, phenols, saponins, flavonoids, and tannins, which are known to exhibit nematicidal properties [29].

When organic matter decomposes, it releases phytochemicals that have been reported to be toxic to RKN [27]. The involvement of phenolic compounds absorbed systemically by the roots of *S. lycopersicon* plants exposed to *M. angolensis* and *T. elegans* might have induced tolerance against nematodes. Phenolics inhibited *M. incognita*-induced gall formation in greenhouse or micro-plot studies in cotton [29]. Chin et al. [28] recently found that flavonoids induce quiescence by slowing down the movement of nematodes and modifying their migration toward the roots by repelling them and killing them. D'Addabbo et al. [30] and Ogwudire [31] reported that saponins inhibit root galling by *M. incognita*. The presence of the phytochemicals might be the reason why the plant extracts managed nematodes better/the same as the Class I nematicides control.

From the current study, the systemic action of curative applications of *M. angolensis* and *T. elegans* extracts on the development of nematodes was comparable with the systemic action of Nemacur®. Similarly, it showed that *M. angolensis* and *T. elegans* induced defense mechanisms within plants, which were subsequently able to delay the development of the nematodes. This study indicates that if *M. angolensis* and *T. elegans* extracts are applied as a protective treatment to plants before transplanting (in the greenhouse) they might provide a better nematode management strategy.

The host status of a plant to nematodes is usually determined by any or both of the following indicators: reproductive potential and reproductive factor [29]. When the reproductive factor on a particular host is less than one, it indicates that the nematode cannot reproduce on that host; hence, that plant is not a host [30]. If the reproductive factor is greater than one, the nematode has multiplied successfully on the host [31]. The reproductive factor (RF) is a basic indicator of nematode reproductive potential, and hence, gives a good indication of a plant's level of resistance [32]. According to Hussain et al. [33], one of the most important criteria for cultivar selection is a reproductive factor, and cultivars with a lower RF are deemed suitable against RKN. On the other hand, the reproductive potential (RP) indicator uses the ratio of nematodes in the roots as a function of the total fresh root mass [29]. The reproductive potential of a nematode can be used as an indicator of whether a plant is susceptible, tolerant, or resistant to the presence of nematodes.

Susceptible plants are those that will be affected by the presence of nematodes and result in plant growth failure, while a tolerant plant is able to withstand the presence of nematodes and continue to grow without being affected [9]. Resistant plants completely restrict the presence of nematodes; if nematodes are exposed to such plants, they will not feed at all [34].

M. incognita was able to penetrate and multiply in the negative control treatment. The reproduction potential of *M. incognita* was comparable in both the Nemacur® chemical and plant extract applications before the nematode inoculation, which is contradictory to the work by Khosa [2], who observed comparable reproductive potential between all plants treated with *M. angolensis* and Nemacur®. Plant extracts with lower reproductive factors will be appropriate for the management of root-knot nematodes [35]. Both the host status and the plant's reactions to nematode infection are used to describe the host sensitivity [33]. A susceptible host is one that allows for nematode reproduction but suffers growth or yield losses, whereas a tolerant host is one that does not suffer yield losses despite nematode reproduction [35]. The plant is termed to be resistant if reproduction is not allowed and there is no loss of growth or yield as a result [33].

On host sensitivity, the current study reports that nematodes did not affect the plant growth variables; however, the plants treated with *M. angolensis* and *T. elegans* performed better than the plants treated with Nemacur®. The lower RP and RF of nematodes on a susceptible *S. lycopersicon* plant might have been due to the *M. angolensis* and *T. elegans* extracts highly suppressing nematodes and making the plant grow in a nematode-free environment. This could have been due to the nematicidal effects that the *M. angolensis* and *T. elegans* extracts had, which acted on the nematode directly or indirectly, and thus, restricted the nematode from laying eggs and prevented reproduction. Tibugari et al. [36] reported that some nematicidal properties can cause the female-to-male ratio to decrease. The current results agree with Khosa et al. [2], who observed the suppression of *M. incognita* caused by *M. angolensis* and *T. elegans* similar to the suppression caused by Nemacur® in 2008 and 2009. Moreover, *M. angolensis* and *T. elegans* did not suppress nematode densities in 2011 [2], which contradicts the current findings. According to Claudius-Cole et al. [20], the negative control that recorded the highest percentage of total nematodes was because the normal life cycle and activities of the nematode did not interfere with the way the plant extracts acted.

The use of plant extracts for nematode control offers a promising, sustainable alternative to chemical nematicides, which often have harmful environmental effects. Extracts from plants like *M. angolensis* and *T. elegans* are biodegradable and pose minimal risk to non-target organisms, contributing to environmental sustainability. However, there are considerations regarding the cost effectiveness of this approach. The availability and large-scale production of plant extracts can be limited by factors such as the seasonal availability of plant materials and the costs associated with extraction and processing. To enhance the feasibility, further research is needed to optimize the extraction methods and explore the potential for cultivating these plants on a larger scale. Additionally, integrating plant extracts with other management strategies, such as crop rotation or organic amendments, could improve the overall cost-effectiveness in agricultural production. The sustainable use of these extracts may also require standardized formulations to ensure consistent efficacy across different environmental conditions.

5. Conclusions

Plant extracts offer an additional or alternate method of controlling nematode parasites on crops to chemicals. *M. angolensis* and *T. elegans* extracts have potential in crop management and can be used to reduce the deleterious impact of RKN on plants under greenhouse conditions. The results indicate that applying extracts from *M. angolensis* and *T. elegans* before planting as a preventive measure in greenhouses could offer a more effective strategy for managing nematodes compared with applying them later after planting for control purposes. Therefore, the hypothesis put forward was supported by these findings.

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