Research Article

Assessing the Efficacy of Potassium Silicate Individually and in Sequencing with Nematicides for Managing *Meloidogyne* sp. on *Solanum lycopersicum*: A Suggested Approach for Sustainable Agricultural Practices

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Abstract | Integrated pest management (IPM) programs are depending on several tactics to manage the pests. Synthetic nematicides are one of the available options to farmers in IPM programs against plant parasitic nematodes. But in the same time the environmental protocol for sustainable agricultural practices states to reduce the usage of these chemicals. Therefore, in this investigation we examined the nematicidal impact of potassium silicate (PS) against root-knot nematode, *Meloidogyne* sp. and to improve the tomato growth. Potassium silicate (H-SILICAT® 42.5%), azadirachtin (Oikos® 3.2% EC) and oxamyl (Oxametod 24 % SL) applied as soil drench singly and in sequence (double or triple treatments). The obtained consequences indicated that potassium silicate at 2, 3 and 4L/ feddan alone gave the modest reductions in soil population (19.33 to 32.83%) and root gall index (14.29 to 23.81%). Meanwhile the sequences of potassium silicate at different rates with azadirachtin or oxamyl exhibited high reductions reaching 81.55% in soil population and 76.19% in gall index with triple treatments. The most applied treatments increased the tomato biometric indices significantly. The tomato root weight was the most respond plant parameter which recorded augmentation ranging from 21.85 to 199.13 %. On the other hand, approximately all the double treatments recorded additive effect, except for the sequence of PS (2L) + OXA which exhibited potentiation interaction effect.

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Introduction

Tomatoes are a rich source in vitamins, minerals and anti-oxidants (Bhowmik *et al*., 2012). Egypt is one of the biggest tomato producers globally with about 6.8 million metric tons (FAOSTAT, 2020). Root-knot nematodes, *Meloidogyne* spp. are one of the most devastating genera of plant parasitic nematodes (PPNs) that attacking the roots of tomato plants (Moens *et al*., 2009; Kantor *et al*., 2022). The available management practices are not enough to control root-knot nematodes (*Meloidogyne* spp.). The majority of farmers in Egypt are adoption the strategy of using chemical nematicides (Khalil and Alqadasi, 2019; Lian *et al*., 2022). Furthermore, the Egyptian list of non-fumigant nematicides are very limited and included; oxamyl, ethoprophos, imicyafos, fosthiazate, azadirachtin, abamectin and fluopyram (Khalil, 2021). Also, nematicides are one of the highest prices in the Egyptian markets in compared with other group of pesticides.

Silicon (SI) plays an advantageous role in defense against both biotic and abiotic stresses in plants (Zargar *et al*., 2019). Moreover, silicon could be a valuable tool for maintaining sustainable agriculture, using environmentally friendly strategies for the management of plant diseases and pests (Verma *et al*., 2021). Potassium silicate is consisting of blend of highly soluble potassium and silicon. It has several potential benefits; consequently its sufficient supply is required for healthy growth and plant productivity (Wissa, 2017). Potassium silicate can be used as an alternative tool against plant- parasitic nematodes to avoid environment pollution from pesticides. In the same time, no published investigations mentioned if potassium silicate is carcinogenic and mutagenic or toxic to human or other wild lives (El-Sherif *et al*., 2016). Limited investigations clarified the nematicidal activity of silicone compounds including silicone dioxide, sodium siliconate, sodium metasilicate, potassium silicate and calcium silicate (Zhan *et al*., 2018; Bicalho *et al*., 2021; El-Ashry *et al*., 2022).

On the other side, there are many large botanical families which have several pesticidal impacts. These plant species have increasingly focused the attention of researchers and stakeholders (Ntalli and Caboni, 2012; D'Addabbo *et al*., 2014). One of these plant species is the neem tree (*Azadirachta indica*, Aturs) which was widely distributed in India and some regions of Asia, Africa and Australia (Khalil, 2013). Neem has several beneficial plant protective properties such as repellent, anti-feedant, anti-molting, anti-fungal (Schmutterer, 1988; Khalil, 2013) and anti-nematodal (Nile *et al*., 2017; Yadav *et al*., 2018). Some extracts of neem seeds contain alkaloids, saponins, flavonoids, steroids and terpenes that have nematicidal properties (Sambo *et al*., 2024). Very little attempts have carried out to study the effect of interaction between different nematicides or nematicides with different substances to increase the nematicidal activity against different genera of the plant parasitic nematodes (Radwan *et al*., 2011; El-Deriny *et al*., 2022). Therefore, this study aimed to investigate the impact of potassium-silicate individually and in sequence with oxamyl or azadirachtin, as a suggested approach for sustainable agricultural practices against the root-knot nematodes (*Meloidogyne* sp.) on tomato plants.

Materials and Methods

The experimental treatments

1. Single treatments
   - Azadirachtin (Oikos 3.2%EC) applied at the recommended rate of 400 ml/ feddan (AZA).
   - Oxamyl (Oxametod 24 % SL) applied at the rate of 3L/ feddan (OXA).
   - Potassium-silicate (H- SILICAT® 42.5%) contained silicon (27.5%) + potassium (15%) applied at the recommended rate of 2 and 3L, as well as a suggested rate of 4L/ feddan. (PS 2, 3 and 4L/Fed).
2. Double treatments
   - Potassium silicate (PS) was applied at 2, 3 and 4L / feddan + azadirachtin (AZA) applied at the rate of 400 ml/ feddan (PS 2, 3 and 4L/Fed +AZA).
   - Potassium silicate (PS) was applied at 2, 3 and 4L / feddan + oxamyl (OXA) applied at the rate of 3L/ feddan (PSA 2, 3 and 4L/Fed +OXA).
   - The application of azadirachtin or oxamyl was done as soil drench after the application of potassium silicate by an hour.
   - The mixture of oxamyl and azadirachtin was done by the half of the recommended dose of each. (AZA+OXA "0.5 R").
3. Triple treatments
   - Potassium silicate was applied at 2, 3 and 4L / feddan + azadirachtin applied at the half rate + oxamyl applied at the half rate (PS 2, 3 .4L/Fed +AZA+OXA "0.5R").
   - The application of azadirachtin + oxamyl was done as soil drench after an hour of potassium silicate (2, 3 and 4L) application rate (PS2, 3.4L+AZA+OXA (0.5R)).

The root-knot nematodes inoculation

The plant samples were collected from eggplants field at Nagib Mahfouz village, EL-Behaira Governorate, Egypt to extract root-knot nematode eggs by the technique of Hussey and Barker (1973). The obtained eggs were collected on a 500-mesh sieve, and then the 2nd stage juveniles (J_2) were hatched by using Baermann plate technique (Ayoub, 1980) and only the freshly hatched J_2s (48 h old) were used in the experiment.

The experimental design

A pot trial was implemented to assess the impact of azadirachtin, oxamyl and potassium silicate alone and in double or triple sequences against root-knot nematode (*Meloidogyne* sp.). All the treatments were applied as soil drench. Four week- old of tomato plants (*Solanum lycopersicum* L. cv. Elissa) were transplanted into 2 kg plastic pots filled with autoclaved loamy sand soil (pH= 8, OM= 0.65 %, sand: silt: clay= 85:9:6%). One week after transplanting, each pot was inoculated with approximately 1200 newly hatched juveniles (J_2s) of *Meloidogyne* sp. into 3- cm deep holes around the root system of each plant. Fifteen treatments were applied and each treatment was replicated five times. Infected plants with 2nd stage juveniles served as positive control and not inoculated served as healthy plant (negative control). The tomato plants were carefully uprooted, 55 days after the inoculation. The roots were gently washed with tap water to be free of soil and dried. The shoot height and root length (cm), in addition to shoot and root fresh weight (g) were recorded. Furthermore, the J_2s were extracted from the soil using the sieving and Baermann technique (Ayoub, 1980), while counted using a stereo microscope (magnification x40). The root gall index was determined in scale from 0 to 10 according to the method of Bridge and Page (1980).

The co-toxicity factor and the mixtures interaction

The co-toxicity factor is usually used to classify the consequences into three categories; the positive factor (+20) or more was considered a potentiation action, a negative factor (-20) or more was considered an antagonism action and intermediate values between (– 20 and + 20) were considered an additive action. The co-toxicity factor equation was given by Mansour *et al*. (1966) as follows:

$$\text{Co} - \text{toxicity factor} = \frac{\text{Observed effect (\%)} - \text{Expected effect (\%)}}{\text{Expected effect (\%)}} \times 100$$

The expected effect was compared with the actual effect (observed) obtained experimentally for mixture. The expected effect of mixtures was estimated by using Limpel´s formula reported by Richer (1987) as follows:

$$E = X + Y - (XY/100)$$

Where; E= the expected additive effect of the mixture; X= the effect due to component A alone; Y= the effect due to component B alone.

Statistical analysis

The results of the experiment were subjected to one-way analysis of variance (ANOVA) using a computer Costat Program Version 6.303 (2005). The used experimental design was completely randomized (CRD). Statistically significant differences among the means were compared using the least significant differences (LSD) and *P*-values at 0.05 probabilities.

Results

The performance of potassium silicate at different rates (2, 3 and 4L/feddan), oxamyl and azadirachtin as well as, their double or triple interactions led to reductions in the soil population density (Figure 1A, B) and root gall index (Figure 2A, B) of root-knot nematodes (*Meloidogyne* spp.) on tomato. The treatments demonstrated varying degrees of success in reducing the soil population of *Meloidogyne* spp. in compared to the positive control. Potassium silicate (PS) alone exhibited relative minimization in the nematicidal activity, with reduction percentages increasing modestly with concentration, from 19.33 (PS at 2L) to 32.83% (PS at 4L). However, the single applications of Azadirachtin (AZA) and Oxamyl (OXA) were significantly more effective, achieving reductions of 61.51 and 72.52%, consecutively. Meanwhile, double treatment sequences improved efficacy compared to single treatments. The double treatments between PS at 2, 3 and 4L and AZA recorded suppression in soil population by 56.23, 60.88 and 67.30%, whilst the sequence with OXA recorded reductions by 58.97, 67.13 and 70.57%, consecutively. The combination of AZA + OXA (0.5 R) was also highly effective, achieving a 71.70% reduction. In respect to the triple treatments the sequence among potassium silicate at 2, 3 and 4L and both AZA + OXA in the half rates (0.5 R) yielded the most substantial reductions in soil populations. Application of PS at 2, 3 and 4L sequentially with the AZA + OXA (0.5 R) combination recorded reductions estimated by 72.54, 75.14 and 81.55%, respectively.

On the other hand, the reduction in root gall index, indicating the severity of root damage caused by root-knot nematodes. Single applications of PS

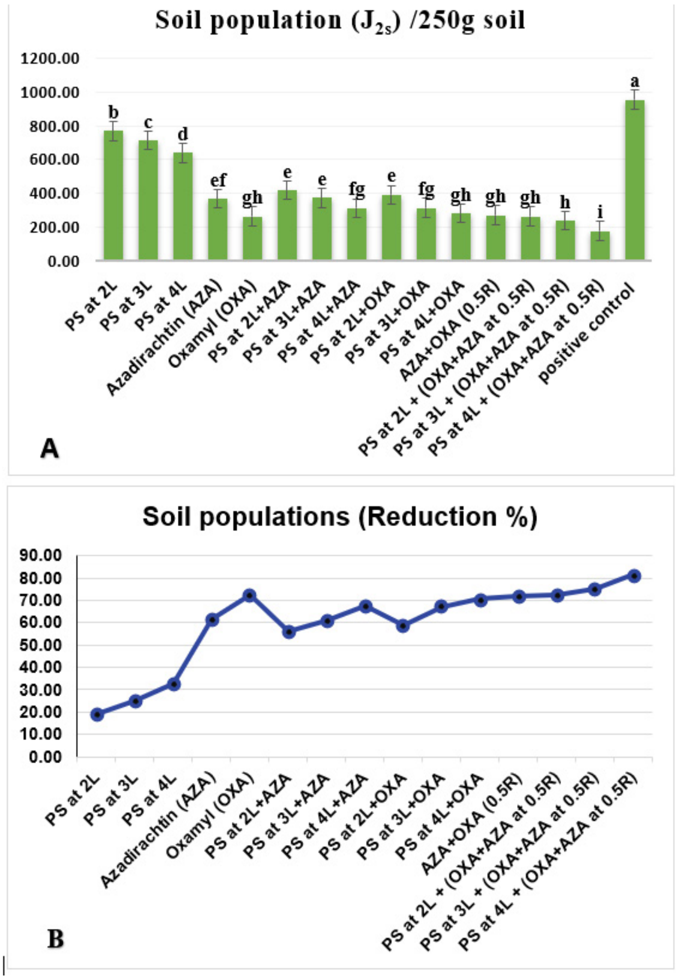

Figure 1: *The efficacy of potassium-silicate (PS), azadirachtin (AZA) and oxamyl (OXA) alone or in sequences (double and triple treatments)on the mean numbers of the root-knot nematodes (Meloidogyne sp.) in soil (A) and soil population reduction% (B) on tomato plants. (Means in each column followed by the same letter(s) are not significantly different according to LSD (p = 0.05), values are means ± SDM).*

showed limited efficacy, with reductions ranging from 14.29% (PS at 2L) to 23.81% (PS at 4L). AZA alone provided a moderate reduction of 38.10%, while OXA was more effective (47.62%). Double treatments exhibited improving over PS alone. PS sequenced with AZA resulted in reductions between 47.62% (PS at 2L+AZA) and 59.52% (PS at 4L+AZA). The sequence of PS with OXA were even more effective, which recorded reductions ranging from 54.76 (PS at 2L+OXA) to 69.05% (PS at 4L+OXA). The blend of AZA + OXA (0.5 R) achieved a 57.14% reduction in root galling. Similar to the soil population results, the triple treatments demonstrated the highest efficacy in reducing root gall index. The sequential application of PS + OXA + AZA (0.5 R) recorded gradual increasing with the increment of PS rates. The treatment of PS at 4L+ OXA+AZA (0.5 R) achieved the greatest reduction in root gall index at 76.19%. Meanwhile, application of PS at 2 and 3L in sequence with OXA+AZA (0.5 R) recorded 59.52 and 66.67% reductions, consecutively. This highlighted the superior performance of the triple combinations, particularly with PS 4L, in mitigating the physical damage caused by nematode infestation on the root system.

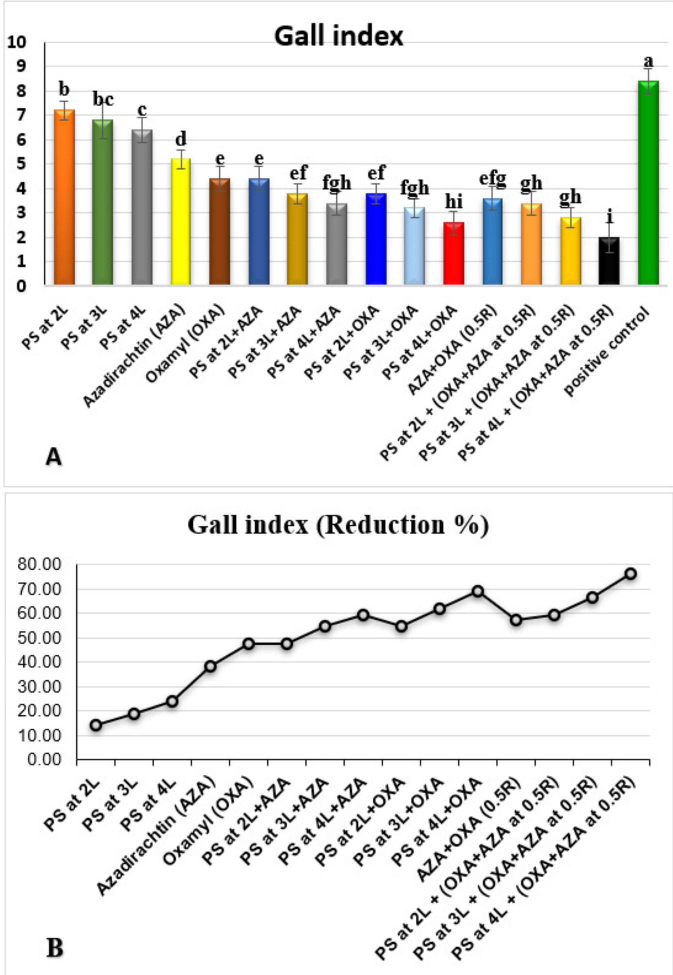

Figure 2: *The efficacy of potassium-silicate (PS), azadirachtin (AZA) and oxamyl (OXA) alone or in sequences (double and triple treatments)on the mean numbers of the root-knot nematodes (Meloidogyne sp.) galls (A) and gall index reduction % (B) on tomato plants. (Means in each column followed by the same letter(s) are not significantly different according to LSD (p = 0.05), values are means ± SDM).*

The provided data of tomato growth indices such as shoot height, root length, shoot and root weights were summarized the results of the pots experiment. Healthy plants (untreated uninfected treatment) showed augmentation in shoot height (29.87%), root length (33.93%), shoot weight (53.71%) and root weight (193.32%). The applied treatments exhibited varied impacts on the tomato shoot height augmentation (Table 1, Figure 3A). The single application of PS showed a rate -dependent response with 4L yielding the highest increase (38.64%), significantly greater than PS at 2L (14.29%) and PS at 3L (27.60%). The individual application of AZA and OXA resulted in moderate increases of 15.58 and 22.08%, respectively. The sequence of PS at 2, 3 and 4L with AZA particularly was effective and recoded 30.84, 31.82 and 46.10% augmentation, respectively. Also, the sequence between PS at 2, 3 and 4L with OXA enhanced shoot height by 25.65, 33.44 and 38.31%, respectively. OXA+AZA (0.5 R) recorded 14.94% increase over positive control (inoculated plants). The triple treatments showed increment by 20.45, 23.05 and 38.96% with PS at 2, 3 and 4L +AZA + OXA (0.5R), respectively.

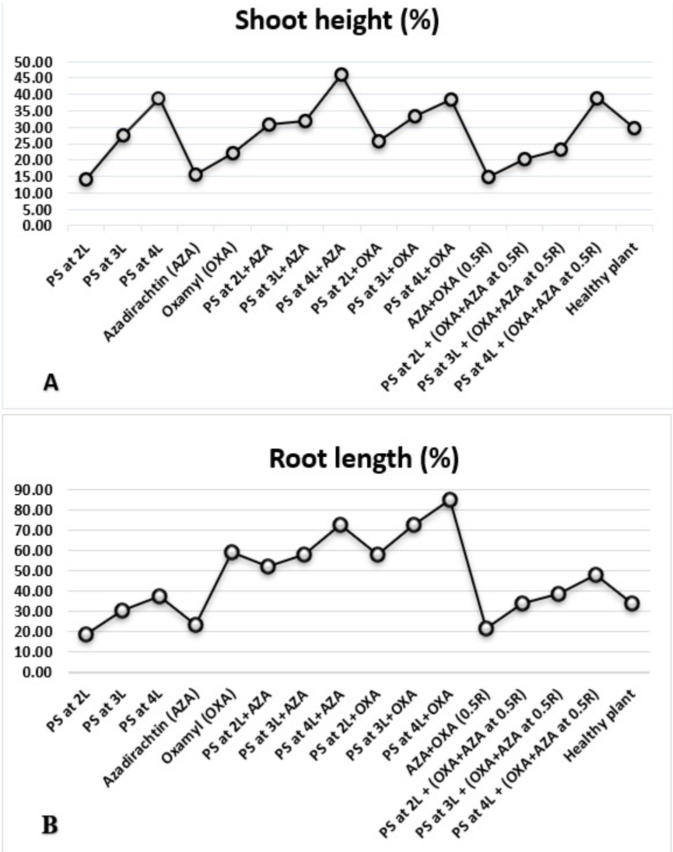

Figure 3: *The impact of potassium-silicate (PS), azadirachtin (AZA) and oxamyl (OXA) alone or in sequences (double and triple treatments) on the growth of infected tomato plants with the root-knot nematode (Meloidogyne sp.). (A) increase (%) in the shoot height and (B) increase (%) in the root length.*

Root length was significantly influenced by the single treatments yielding substantial increases of 18.75, 30.36 and 37.50% with PS at 2, 3 and 4L, consecutively (Table 1, Figure 3B). AZA alone provided the modest increase of 23.21%, however, OXA alone demonstrated a strong impact of 58.93%. The series of double treatment applications increased the root length by 51.79% (PS at 2L+AZA), 57.59% (PS at 3L+AZA) and 72.32% (PS at 4L+AZA). Furthermore, sequencing of PS at 2, 3 and 4L with OXA recorded 58.04, 72.32 and 84.82% increase, respectively. While the combination of AZA+OXA (0.5R) gave 21.43% increase. The triple treatments of sequenced PS at 2, 3 and 4L with AZA + OXA (0.5R) achieved 33.93, 38.39 and 47.77% increases, respectively, with no significant differences.

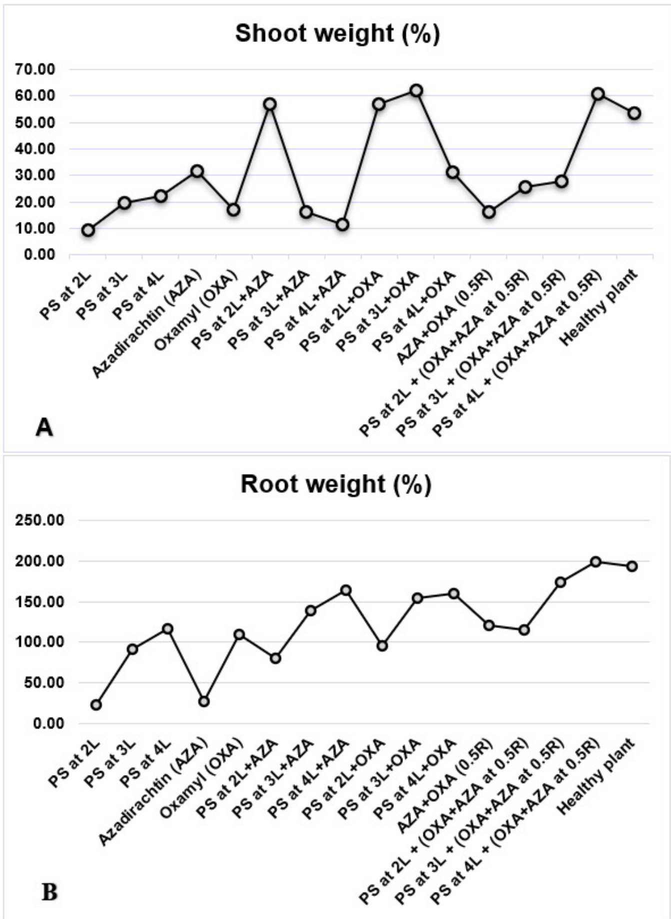

Figure 4: *The impact of potassium-silicate (PS), azadirachtin (AZA) and oxamyl (OXA) alone or in sequences (double and triple treatments) on the growth of infected tomato plants with the root-knot nematode (Meloidogyne sp.). (A) increase (%) in the shoot weight and (B) increase (%) in the root weight.*

The tomato shoot weight was increased at range of 9.25% with PS at 2L to 21.99% with PS at 4L. AZA alone yielded a notable increment by 31.82%, whereas OXA recorded 17.16% (Table 1, Figure 4A). No significant differences were noticed among single treatments. The double treatments of PS at 2, 3 and 4L with AZA produced augmentations by

Table 1: *The impact of potassium-silicate alone or in sequence with azadirachtin on the tomato biometric indices in the presence of the root-knot nematode (Meloidogyne sp.) on tomato plants.*

Treatments	No. of mixed treatments	Shoot height	Root Length	Shoot weight	Root weight
		Means (cm)	Means (cm)	Means (g)	Means (g)
PS at 2L	Single treatments	70.40cd	26.60gh	18.03bc	4.89 f
PS at 3L		78.60bc	29.20defg	19.72bc	7.65de
PS at 4L		85.40ab	30.80cdefg	20.13bc	8.70cde
Azadirachtin (AZA)		71.20cd	27.60fgh	21.75b	5.08f
Oxamyl (OXA)		75.20bc	35.60abc	19.33bc	8.40cde
PS at 2L+AZA	Double treatments	80.60abc	34.00bcde	25.91a	7.20e
PS at 3L+AZA		81.20abc	35.30bcd	19.17bc	9.59bcd
PS at 4L+AZA		90.00a	38.60ab	18.38bc	10.58abc
PS at 2L+OXA		77.40bc	35.40bcd	25.87a	7.83de
PS at 3L+OXA		82.20abc	38.60ab	26.75a	10.22abc
PS at 4L+OXA		85.20ab	41.40a	21.66b	10.40abc
AZA+OXA (0.5R)		70.80cd	27.20fgh	19.19bc	8.84cde
PS at 2L + (OXA+AZA at 0.5R)	Triple treatments	74.20bc	30.00cdefg	20.74b	8.61cde
PS at 3L + (OXA+AZA at 0.5R)		75.80bc	31.00cdefg	21.08b	11.00ab
PS at 4L + (OXA+AZA at 0.5R)		85.60ab	33.10bcdef	26.55a	12.00a
Healthy plants		80.00abc	30.00cdefg	25.36a	11.76a
Positive control		61.60d	22.40h	16.50c	4.01f

Means (mean of five replicates) in each column followed with the same letter are not significantly different according to LSD test (P< 0.05). PS = potassium-silicate; AZA+OXA (0.5R) = blend in the half rates.

Table 2: *The co-toxicity factor and type of interaction among potassium-silicate (PS), azadirachtin (AZA) and oxamyl (OXA) on the soil population of Meloidogyne sp.*

Treatments	Efficacy (%) for soil population (J_2s)			
	Observed (%)	Expected (%)	Co-toxicity factor	Type of interaction
PS at 2L+AZA	56.23	67.40	-18.45	Additive
PS at 3L+AZA	60.88	69.99	-14.50	Additive
PS at 4L+AZA	67.30	72.31	-9.24	Additive
PS at 2L+OXA	58.97	38.38	50.21	Potentiation
PS at 3L+OXA	67.13	47.77	17.88	Additive
PS at 4L+OXA	70.57	62.48	15.30	Additive
OXA+AZA (0.5R)	71.70	89.42	-19.82	Additive

PS = potassium-silicate; azadirachtin (AZA); oxamyl (OXA) and AZA+OXA (0.5R) = blend in the half doses.

57.03, 16.21 and 11.42%, respectively. However, the effect of increase PS rates was not consistently liner. Conversely, the sequence between PS + OXA showed high increases for PS at 2L (56.79%) and PS 3L (62.13%), but a lower increase for PS at 4L (31.30%) was noticed. The combination between AZA+ OXA (0.5R) recorded 16.32% increase in shoot weight. The triple treatments of PS at 2, 3 and 4L with AZA+OXA (0.5R) achieved augmentation estimated by 25.67, 27.75 and 60.88%, respectively. Meanwhile, no significant differences were noticed between PS at 2L and PS at 3L with AZA+OXA (0.5R).

The most dramatic increases in tomato growth indices were achieved in the root weight (Table 1, Figure 4B). The single treatments exhibited 21.85, 90.87 and 116.96% augmentation with PS at 2, 3 and 4L, respectively. Application of AZA alone had a relatively small effect (26.63%), whereas OXA alone recorded 109.38%. The sequence of PS at 2, 3 and 4L with AZA exhibited 79.50, 139.10 and 163.94% increases, respectively. Meanwhile, PS at 2, 3 and 4L with OXA recorded augmentation by 95.21, 154.81 and 159.30%, consecutively. The blend of AZA+ OXA (0.5R) yielded a significant increase of 120.50%.

The triple sequenced treatments demonstrated the most potent efficacy, particularly PS at 4L with AZA+OXA (0.5R) which resulted in the highest overall root weight by 199.13%. The sequence of PS at 2 and 3L with AZA+OXA (0.5R) recorded 114.69 and 174.29% increase, respectively.

On the other hand, the co-toxicity factor for the sequence of PS at 2, 3 and 4L + AZA treatments exhibited additive interaction at range of -9.24 to -19.45 (Table 2). However, the interaction between PS at (2L) and OXA exhibited a potentiation interaction with co-toxicity factor of 50.21, while the rest treatments (PS at 3 and 4L + OXA) recorded additive interaction. Also, the blend of AZA+OXA in the half of recommended rate showed additive interaction with co-toxicity factor of -19.82.

Discussion

Very few investigations in literature indicated the role of potassium silicate in management of plant- parasitic nematodes. There are various silicone compounds including silicone dioxide, silicone dioxide nano-particle, sodium siliconate, sodium metasilicate, potassium silicate, calcium silicate and nano-chelated silicon fertilizer were proved their activity as bio-control agents against different pathogens, especially root-knot nematodes (*Meloidogyne* spp.) in certain investigations (Khan *et al*., 2022; Ahamad and Siddiqui, 2021; Udalova *et al*., 2020; Mattei and Dias-Arieira, 2015).

According to our results the gradual increasing in potassium silicate application rates showed parallel augmentation in the reduction levels of soil population and root gall index. Moreover, the sequence treatments of the nematicides azadirachtin or oxamyl after utilizing the potassium silicate showed increment in the reduction percentages. Our results were supported by the findings of El-Sherif *et al*. (2015) who reported that using potassium silicate, calcium sulphate and moringa dry leaf powder either alone or mixed as double or triple applications or plus oxamyl showed strong nematicidal efficacy. Their results illustrated that application of single treatments recorded reductions in soil populations at range of 60 to 66% and tomato root galls at range of 65 to 75%. Meanwhile, the mixed treatments recorded soil population reductions at range of 75.26 to 91.29%, while root galls at range of 74.30 to 92.53%. The plant growth increased over control with all treatments.

Application of potassium silicate before and after inoculation with *M. incognita* reduced the reproduction factor (RF= final population/ initial population) by 74.1 and 79.5%, respectively. However, foliar application recorded 93.6, 85.6 and 69.3% after 1, 2 and 3 application times (one time per week), respectively. All the measured cucumber plant indices were increased significantly (El-Sherif *et al*., 2015). Silva *et al*. (2010) reported that coffee plants treated with silicon reduced the root penetration of *Meloidogyne exigua* by 25 and 77% at 5 and 10 days after inoculations, respectively.

The results of the present study were found in formity reported by Abo-Korah (2021) who found that using potassium silicate alone reduced *M. incognita* on ground cherry plants (*Physalis pruinosa* L.) by 39.4%, while in combination with furfural or albendazole recorded 58.9 and 53.4%, respectively. Furthermore, potassium silicate reduced females, egg masses and root gall index by 39.00, 51.10 and 33.30%, consecutively. All applied treatments recorded increasing in plant height, shoot weigh and root weights and fruit weight at range of 16.40 to 236.20%, over control.

The reduction in the soil population of root-knot nematodes (*Meloidogyne* spp.) on different crops such as sugarcane, horse bean and coffee was related to the enhancement in POD, phenylalanine ammonialyase (PAL), polyphenol oxidase (PPO) and lignin activity (Guimaraes *et al*., 2010; Dutra *et al*., 2004). Also, Zhan *et al*. (2018) and Yu *et al*. (2022) observed that lignin and phenolic compounds are released after 24 and 48 h post-inoculation with root knot nematodes in plants amended with silicon. Silicon applications helped plants to overcome different biotic or abiotic stresses by mechanical and physiological improvements (Zellner *et al*., 2021; Silva *et al*., 2010; Ma *et al*., 2006). Similarly, the treated cotton plants with potassium silicate became more resistance to the penetration of reniform nematode and this was because of the entry of silica into the structure of the cell walls became firmer (Gad, 2019).

Oxamyl is one of the most famous carbamate nematicides, insecticides which heavily utilized against plant parasitic nematodes in Egypt. Oxamyl is a non-fumigant, and systemic nematicide that inhibits acetyl cholinesterase, causing paralysis and

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death (Hassan *et al*., 2024). In a recent study by El-Deriny *et al*. (2022) found that oxamyl significantly controlled root- knot nematodes (*Meloidogyne* spp.) in soil and root galls of eggplants by 97.07 and 95.43% over control (under greenhouse conditions), respectively. Meanwhile, in the field, soil population and root galls were decreased by 90.00 and 73.75%, respectively. The plant growth parameters notably were increased significantly with oxamyl. The rest treatments included humic acid, selenium and NPK individually or in combinations recorded moderate reductions in soil population, galls, egg masses, developmental stages and females. El-Ashry *et al*. (2018) investigated the effects of bionematicides, plant oils, entomopathogenic nematodes and oxamyl on root galls and soil J2s of *Meloidogyne incognita*, as well as the fresh and dry shoot weights of different pepper (*Capsicum annuum* L.) cultivars (cv. 1515, Rima "Egypt" and Lama "Holland"). The results exhibited that oxamyl significantly reduced galls (ranged from 87.71 to 92.17%), egg masses (ranged from 75.59 to 85.11%) and soil population (ranged from 89.28 to 90.86%). Obviously, all applied treatments enhanced the plant growth parameters, however oxamyl showed the modest increment in fresh and dry shoot weights.

On the other hand, azadirachtin (Achook® 0.15% EC and Nimbecidine® 0.03% EC) recorded nematicidal activity towards *M. incognita* on tomato plants. Galls, egg masses and soil population were reduced by 69.31 and 64.48%, 62.25 and 40.37%, and 60.15 and 63.71%, with Achook® and Nimbecidine®, respectively (Khalil *et al*., 2012). Sivakumar and Gunasekaran (2011) found that the soil root-knot nematode (*M. incognita*) was diminished on tomato, chilli and brinjal post using of formulated neem oil as seed treatment and seedling root dip. Otherwise, it was reported that azadirachtin (Neem Azal-T 1% EC) relatively reduced females of *M. incognita*, egg masses and eggs by 63.33, 68.82, 35.25%, respectively (Metwally *et al*., 2019).

Abbas *et al*. (2020) observed suppression in root galls of *M. incognita* (65.62%), soil population (78.59%) and egg masses (67.44%) when cultivated soil with tomato treated with azadirachtin that reduced mobility of *M. incognita* by 36% after a one-day exposure (Lynn *et al*., 2010). Okra plants treated with azadirachtin at the first sign of galls was shown to be an economical and effective approach to manage *M. incognita* infestation (Khan *et al*., 2012). Also, applications of azadirachtin on infested tomato plants with *M. incognita* showed a lower amount of in galls (d'Errico et al., 2023). Under *in vitro* conditions, at 0.001% azadirachtin (NeemAzal-U®), the juveniles of *M. incognita* showed immobilization by 17% and decreased hatching and viability in pot trials (Meyer *et al*., 2012).

According to certain authors, azadirachtin has a systemic action (Larew, 1988; Osman and Port, 1990; Nisbet *et al*., 1993). Azadirachtin is the main active ingredient of neem seed kernel extract and a well-known nematicidal action (Nayak and Khandelwal, 2022). The decomposition of neem extract release ammonia, formaldehyde, phenols and fatty acids (Khan *et al*., 1974; Alam *et al*., 1980). Mojumder (2002) mentioned that neem extracted from seeds has a high nematicidal and nematostatic effects because of their active components like; nimbidin, thionemone, limonoide, epinimbin, salannin, deacetyl salannin, and azadirachtin. Moreover, azadirachtin has several possible actions such as; fecundity suppression, sterilization, direct toxicity, anti-feedant action, anti-mitotic activity, ovipositional repellency and anti-molting (Mulla and Su, 1999; Howard *et al*., 2009). Khalil (2013) suggested that the repellency effect of some neem components on plant parasitic nematodes may be attributed to the direct effects on chemoreceptors (Amphids and Phasmids), which are responsible for recognizing the host plant.

El-Deriny *et al*. (2022) demonstrated that binary and trinary mixtures of humic acid, NPK, vitamin E, vitamin C and selenium succeeded to reduce the population density of *Meloidogyne* spp. at range of 25.86 to 53.48%, over control on eggplants under field conditions. Also, plant growth parameters, yield, N, P and K contents% in leaves, and fruit quality of eggplant were increased significantly. In a study by Khalil *et al*. (2022) showed that the interaction between fluopyram or abamectin admixed with *Trichoderma album* recorded additive effect against *Meloidogyne incognita* on tomato plants with co-toxicity factor of -10.55 to -17.41. Radwan (2007) found that azadirachtin in combination with *Bacillus thuringiensis* recorded additive effect. Also, the binary mixtures between oxamyl and Bioarc®, Biozeid® and Algaefol® exhibited additive action with co-toxicity factor of -4.0, -3.9 and -9.7, respectively (Radwan *et al*., 2011).

Conclusions and Recommendations

The study concluded that the sequential triple treatments involving PS at 4L followed by a mixture of OXA + AZA (0.5 R) achieved the highest statistically significant reductions in both soil nematode population density and root gall index. Furthermore, a noticeable improvement in tomato plant growth indices was observed upon application of all treatment patterns (single, double and triple). The results indicated that root biomass was the most responsive parameter to the applied treatments, recording increases ranging from 21.85 to 199.13%. The calculated co-toxicity factors revealed that the sequences of double treatments predominantly exhibited an additive effect with the exception of PS at 2L + OXA which demonstrated potentiation effect. There are hundreds of registered pesticides including, insecticides, fungicides, herbicides and acaricides were marketed as blends, the development of effective double or triple nematicide mixtures was proposed as a promising strategy to overcome the plant parasitic nematodes (Youssef *et al*., 2023; El-Nagdi *et al*, 2024). Consequently, the study recommended the necessity of conducting further experimental research to verify the nematicidal efficacy of double or triple mixtures or sequential applications against plant parasitic nematodes.

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Novelty Statement

This investigation is an attempt to suggest approach for sustainable agricultural practices against the disease of root-knot nematode (*Meloidogyne* sp.) by using potassium silicate individually and in sequences with natural nematicide; azadirachtin and the popular non-fumigant nematicide; oxamyl.

Author's Contribution

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by M.S.K. and M.M.Z. The draft of the manuscript was written by M.S.K., and M.M.Z. reviewed the previous versions of the manuscript. The authors read and approved the final manuscript.

Generative AI or AI-assisted Technology Statement

The authors declare that no Genrative AI was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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