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Original article (Orijinal araştırma)

The effect of weed control strategies on *Meloidogyne* spp. Göldi, 1897 (Tylenchida: Heteroderidae) and *Helicotylenchus* spp. Steiner, 1945 (Tylenchida: Hoplolaimidae) in banana under water stress[1]

Yabancı ot kontrol stratejilerinin su stresi altındaki muzda *Meloidogyne* spp. Göldi, 1897 (Tylenchida: Heteroderidae) ve *Helicotylenchus* spp. Steiner, 1945 (Tylenchida: Hoplolaimidae) üzerine etkisi

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Abstract

This study was conducted to evaluate the effects of different weed control practices on the nematode populations in the banana greenhouse of Alata Horticultural Research Institute, Mersin, Southern Türkiye, during the years 2022-2024. The greenhouse experiment was conducted under two irrigation regimes: Full (100%) and Deficit (50%) irrigation, with a split-plot design and three replications for treatments per irrigation. Weed control treatments, including herbicide combinations pre-planting (indaziflam, oxyfluorfen, pendimethalin) and post-planting (glyphosate, diquat), were applied to subplots. Additionally, geotextile mulching and mowing were compared to control plot (weedy) with herbicide combinations. Nematode densities were measured in relation to weed coverage for *Helicotylenchus*, *Meloidogyne* and total nematodes. Irrigation regimes had no significant effect on weed control but did affect nematode populations, particularly in the second year. Based on weed coverage, herbicide combinations (indaziflam, oxyfluorfen+glyphosate and pendimethalin+glyphosate) were effective in suppressing nematodes during the first 6 months, with diquat herbicide also helping before harvest. Geotextile mulching suppressed weeds and affected nematode populations. The results showed that weed control was more effective in reducing nematode densities in the first year, while in the second year nematode populations differed as a function of weed coverage. This highlights the importance of managing weed hosts to control nematodes in banana production.

Keywords: Density, host weeds, indirect control, irrigation, nematodes

Öz

Bu çalışma, farklı yabancı ot mücadele uygulamalarının 2022-2024 yıllarında Alata Bahçe Kültürleri Araştırma Enstitüsü, Türkiye'nin güneyi, Mersin'deki muz serasında nematod popülasyonları üzerindeki etkilerinin değerlendirilmesi amacıyla yürütülmüştür. Sera denemesi iki sulama rejimi altında: Tam (%100) ve Kısıtlı (%50) sulama, bölünmüş parsel deneme tasarımında ve her sulamada uygulamalar üç tekerrür olacak şekilde kurulmuştur. Dikim öncesi (indaziflam, oxyfluorfen, pendimethalin) ve dikim sonrası (glyphosate, diquat) herbisit kombinasyonlarını içeren yabancı ot kontrol uygulamaları alt parsellere uygulanmıştır. Ayrıca, jeotekstil malçlama ve biçme, herbisit kombinasyonları ile kontrol parseliyle (yabancı otlu) karşılaştırılmıştır. Nematod yoğunlukları, *Helicotylenchus*, *Meloidogyne* ve toplam nematodlar yabancı ot kaplama alanları ile ilişkili olarak ölçülmüştür. Sulama rejimlerinin yabancı ot kontrolü üzerinde önemli bir etkisi olmamıştır, ancak özellikle ikinci yılda nematod popülasyonlarını etkilemiştir. Yabancı ot kaplama alanlarına bağlı olarak, herbisit kombinasyonları (indaziflam, oxyfluorfen+glyphosate ve pendimethalin+glyphosate) ilk 6 ay boyunca nematodları baskılamada etkili olmuş, diquat herbisiti de hasattan önce baskılamayı sürdürmüştür. Jeotekstil malçlama yabancı otları baskılamış ve nematod popülasyonlarını etkilemiştir. Sonuçlar, yabancı ot kontrolünün ilk yılda nematod yoğunluklarını azaltmada daha etkili olduğunu, ikinci yılda ise nematod popülasyonlarının yabancı ot kaplama alanına göre farklılık gösterdiğini ortaya koymuştur. Bu durum, muz üretiminde nematodları kontrol etmek için yabancı ot konukçularını yönetmenin önemini vurgulamaktadır.

Anahtar sözcükler: Yoğunluk, konukçu yabancı otlar, dolaylı mücadele, sulama, nematodlar

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Introduction

Banana production is a key player in the global economy, providing essential food and serving as a major export product, particularly in Latin America, Asia, and Africa (Uddin et al., 2002; Dassou et al., 2024). The industry highlights its broad economic and social impact, supporting millions of jobs in sectors ranging from agriculture to distribution (Dassou et al., 2024). Furthermore, sustainable banana farming practices can improve soil health and biodiversity, contributing to environmental conservation (Subba et al., 2023; Swafo & Dlamini, 2023). The sensitivity of banana plants to climate change highlights the need for adaptive and sustainable practices to ensure the long-term viability of this important crop.

The interaction between biotic factors (like plants and pests) and abiotic factors (such as soil and climate) is essential in influencing crop-weed dynamics, ultimately affecting productivity, sustainability, and pest population control within agroecosystems (Yeates et al., 1993; Koenning et al.,1999). In systems like long-term monoculture farming, variations in plant biodiversity and population density can trigger shifts in pest populations (Goodey et al., 1965; Quénéhervé et al., 2006). These interactions are heavily influenced by crop management practices, which affect both plant-pest dynamics and overall biodiversity (Govaerts et al., 2007a). In such environments, weeds often become key hosts for pests, particularly when cultivated crops are not present (Goodey et al., 1965; Siddiqui et al., 1973). Weeds in many cases act as alternative hosts for plant-parasitic nematodes, thereby intensifying pest-related challenges (Bélair & Benoit, 1996; Castillo et al., 2008). This highlights the importance of integrated pest management strategies that consider both weed control and the broader ecological context.

Plant-parasitic nematodes are obligate parasites that rely on host plants to fulfill their entire life cycle (Yeates et al., 1993; Koenning et al.,1999). Weeds play a critical role in supporting nematode populations by serving as alternative hosts, allowing nematodes to thrive and maintain their viability, even in the absence of cultivated crops (Egunjobi & Bolaji, 1979). This perpetuates nematode populations and increases the damage to cultivated plants (Goodey et al., 1965; Siddiqui et al., 1973). Effective weed control has been demonstrated to lower nematode populations and reduce yield losses in crops (Quénéhervé et al., 2006; Rich et al., 2008; Singh et al., 2010; Kokalis-Burelle & Rosskopf, 2012; Mendes et al., 2020).

Studies, conducted in Türkiye, have reported the relationship between root-knot nematodes, *Meloidogyne* spp. Göldi, 1897 (Tylenchida: Heteroderidae) and weed species in banana production areas, particularly in the Mediterranean region of Türkiye. A survey covering 2% of banana cultivation areas identified several weed species frequently contaminated by root-knot nematodes, including *Amaranthus retroflexus* L. (Caryophyllales: Amaranthaceae) (46.34%), *Portulaca oleracea* L. (Caryophyllales: Portulacaceae) (40.63%), and *Solanum nigrum* L. (Solanales: Solanaceae) (37.84%). Molecular analyses further identified numerous weed species-such as *Abutilon theophrasti* Medic. (Malvales: Malvaceae), *Amaranthus* spp., *Cucumis melo* var. *agrestis* Naudin. (Cucurbitales: Cucurbitaceae), *Erodium cicutarium* (L.) L'Hér. (Geraniales: Geraniaceae), *Kickxia commutata* (Bernh. ex Rchb.) Fritsch (Lamiales: Plantaginaceae), *Malva* spp. (Malvales: Malvaceae), *Mercurialis annua* L. (Malpighiales: Euphorbiaceae), *P. oleracea*, *S.nigrum*, and *Sonchus oleraceus* L. (Asterales: Asteraceae) as suitable hosts for root-knot nematodes (*Meloidogyne javanica* and *M. incognita*) (Dinçer et al., 2024). It indicates that certain weeds in banana fields can sustain nematode populations, which could damage subsequent crops. The presence of weeds in banana cultivation areas has been demonstrated to be a contributing factor to the problem of nematodes, which may result in substantial yield and quality losses (Özarslandan & Elekcioğlu, 2010; Özarslandan & Dinçer, 2015). In addition, numerous plant species are known to host the major parasitic nematodes affecting bananas (Isaac et al., 2007; Fongod et al., 2010; Dinçer et al., 2024). Studies like these highlight the importance of adopting effective weed management strategies to control nematode populations and reduce their negative impact on banana production.

The goal of this study was to evaluate the effects of chemical and alternative weed control methods on nematode populations under two irrigation types (Full 100% and Deficit 50%) in a banana greenhouse. To achieve this aim, we evaluated the effectiveness of various herbicide combinations, including Indaziflam, Oxyfluorfen, Pendimethalin, Glyphosate, and Diquat, as well as alternative methods such as Geotextile mulching and mowing in controlling weeds that serve as hosts for nematodes. Specifically, the effects of these weed management practices on the densities of *Helicotylenchus* spp. Steiner, 1945 (Tylenchida: Hoplolaimidae), *Meloidogyne* spp. and total nematode populations were observed. Potential relationships between weed management strategies and weed-nematode dynamics were also investigated. The aim is to determine how different weed control approaches affect nematode populations in banana, *Musa* spp. (Zingiberales: Musaceae), so that pest management strategies can be proposed to improve banana production systems.

Materials and Methods

Study area, treatments and irrigation

This experimental study was conducted between 2022 and 2024 in a newly established banana greenhouse (cv. Alata Azman) at the Alata Research Directorate of Agricultural Experiment Management in Mersin, Türkiye. The experiment used a split-plot design with two main factors: irrigation levels (main plot factor) and weed control treatments (subplot factor). The two irrigation levels, full irrigation (100%) and deficit irrigation (50%), were assigned to the main plots with three replications per level in a randomised per block design. Seven weed control treatments were tested, consisting of four chemical herbicide combinations (indaziflam, oxyfluorfen, pendimethalin, glyphosate and diquat), two alternative methods (geotextile mulching and mowing) and weedy control plot. These treatments were randomly assigned to subplots, except for the Geotextile mulch, resulting in six randomly assigned plots per block (three total blocks at one irrigation). Each main plot was divided into seven subplots where different weed control treatments were applied. The linear mixed-effects model employed for the analysis was μ: Overall average, αi: Irrigation level effect (fixed), βj: Effect of weed control method (fixed), (αβ)ij: Irrigation×Weed control interaction (fixed), ρk: Block effect (random), and ϵijkl: Error term (random) (Equation 1).

$$Yijkl=\mu+\alpha i+\beta j+(\alpha\beta)ij+\rho k+\epsilon ijkl \qquad \text{(Equation 1)}$$

The objective of the experiment was to evaluate two irrigation methods: full (IR100) and deficit (IR50) irrigation using a drip irrigation system consisting of a fertilizer tank, header, water distribution pipes, and 16 mm drippers with a 4 L h^{-1} flow rate. Initially, all plants received equal water for the first 120 days. After this period, irrigation levels were adjusted according to the data from a Class A evaporation pond, regulated by a coefficient Kcp (0.45-1.2) (Liu et al., 2008). Irrigation was performed every two days with full irrigation (IR100) providing adequate water for banana cultivation as recommended by previous studies (Carr, 2009; Arantes et al., 2018). From April 14, 2022 to March 12, 2024, the total water applied was 3301 mm for IR100 and 1727 mm for IR50, across 178 irrigation events. Daily evaporation rates were tracked using a Class A pan evaporimeter, following US Weather Service standards to accurately calculate evaporation (Epan) (Eid & Maklad, 2019). Key variables included irrigation (IR in mm), plant spacing (Sp in m), row spacing (Sl in m), cumulative evaporation (Epan), crop coefficient (Kc: 1.0 for IR100, 0.5 for IR50), plant cover (P), and irrigation efficiency (Ea, %) (Equation 2).

$$IR=(SpxSlxEpanxKcxP)/Ea \qquad \text{(Equation 2)}$$

Each subplot (6m²) contained three banana plants. The percentage (%) of weed coverage was recorded to assess the impact of treatments on weed growth. Weed species were identified using the Flora of Turkey (Davis, 1965-1988). Soil samples for nematode analysis were collected from around the base of three banana trunks per subplot using an auger (100 g per sample). The samples were processed using the 'Improved Baermann Funnel' method (Barker, 1985), and nematode populations were counted under a microscope. The reproductive rate (R0) of the nematodes was calculated by comparing the final population (Pf) at the end of the year with the initial population (Pi) at the start, using Equation 3. This experimental setup aimed to assess the impact of various weed control methods on nematode populations in banana cultivation under different irrigation conditions. For nematode identification, morphological characterization was conducted on the second stage juveniles recovered from the soil. The nematodes were vermiform, slender and annulated. The body of *Helicotylenchus* was short or medium in length, spiral as a result of fixation, the stylet was strong, and the median bulb was developed. The ovary was paired in females, and the female's tail was short, hemispherical, convex or conical. The tail of the male was short and conical. In *Meloidoyne*, the stylet was delicate, narrow, and sharply pointed, with small knobs. The excretory pore was distinct. The tail was conoid with a hyaline terminus distinctive in most species (Kepenekci & Ökten, 1996; Evlice & Bayram, 2016).

Nematode density: R0=Pf/Pi (Equation 3)

For chemical weed control in banana cultivation, the following herbicides were used: 500 g L^{-1} Indaziflam (100 ml ha^{-1}), 480 g L^{-1} Oxyfluorfen (400 ml ha^{-1}) and 455 g L^{-1} Pendimethalin (3000 ml ha^{-1}) were applied during pre-planting, and 441 g L^{-1} Glyphosate (3000 ml ha^{-1}) and 200 g L^{-1} Diquat (8000 ml ha^{-1}) was applied during post-planting. The purpose of the pre-planting applications in the first year was to avoid the damaging on young banana seedlings. In the second year, as the banana plants matured, herbicide applications were adjusted to avoid direct contact with plants, and they were tailored based on weed density. Additionally, Geotextile mulching combined with mowing was used as an alternative weed control method applied once. Weed population measurements, based on weed coverage percentage (10-15%), were taken by comparing herbicide-treated plots and alternative control plots with untreated weedy control plots (TAGEM, 2019). The timing of both chemical and mowing applications was recorded according to target weed densities. The experimental setup was established in April, in the light of the first 6-month observations in September and pre-harvest observations in March. During the first 6-months, under two irrigation regimes, the following combinations were applied: (1) Indaziflam, (2) Oxyfluorfen+Glyphosate, (3) Pendimethalin+Glyphosate, (4) Glyphosate+Glyphosate, and (5) Mowing (applied twice). An additional application was made during the pre-harvest period based on weed populations, involving such combinations as (1) Indaziflam+Diquat, (2) Oxyfluorfen+Glyphosate+Diquat, (3) Pendimethalin+Glyphosate+Diquat, (4) Glyphosate+Glyphosate+Diquat, and (5) Mowing (applied three times).

Statistical analysis

Analysis of variance-ANOVA was used to assess the significance of the main effects and their interactions. The fixed effects included irrigation, weed control treatments, and their interaction, while blocks were considered a random effect. Linear regression analysis was also used to show the interaction between weed coverage - *Helicotylenchus*, *Meloidogyne* and total nematode densities and graphs were presented. All statistical analyses were performed using JMP software (version 5.0.1, SAS Institute Inc., Cary, NC, USA), with residual diagnostics verifying the assumptions of normality and homogeneity of variances. Least Significant Difference (LSD) test was employed for pairwise comparisons to detect significant differences among treatment means at 5% and 1% significance levels.

Results

In the 2022-2024 banana greenhouse experiment, 25 weed species belonging to a total of 15 families were identified in the weed species observations made in accordance with the relevant practices to determine the effect of chemical and alternative weed control practices on nematode densities. These weed species were found to be hosts of *Helicotylenchus* and *Meloidogyne* nematodes, which are the other important pests (Table 1).

Table 1. Weed species in the experimental area of the banana greenhouse (2022-2024)

Plant family	Weed species	Greenhouse First year (2022-2023)	Greenhouse Second year (2023-2024)	Examples of hosts for nematode species* (*Helicotylenchus* spp. and *Meloidogyne* spp.)
Amaranthaceae	*Amaranthus* spp.	✓	✓	*Helicotylenchus* sp., *Meloidogyne javanica* Treub,1885
Asteraceae	*Capsella bursa-pastoris (*L.) Medik.	✓	✓	*Meloidogyne* sp.
	Sonchus spp.	✓	✓	*M. incognita* Kofoid&White,1919
Boraginaceae	*Heliotropium europaeum* L.	✓	✓	*Meloidogyne* sp.
Brassicaceae	*Cardamine occulta* Hornem.	✓	✓	*Meloidogyne* sp.
	Malva spp.	✓		*Helicotylenchus multicinctus* (Cobb,1893) Golden,1956, *M. incognita*
Caryophyllaceae	*Stelleria media* (L.) Vill.	✓	✓	*M. incognita*
Convolvulaceae	*Convolvulus arvensis* L.	✓	✓	*M. javanica*
Cyperaceae	*Cyperus rotundus* L.	✓	✓	*H. dihystera* (Cobb,1893) Sher,1961, *M. javanica*
Euphorbiaceae	*Chrozophora tinctoria (*L.) A.Juss.	✓		*Meloidogyne* sp.
	Euphorbia spp.	✓	✓	*M. arenaria* Neal,1889
	Mercurialis annua L.	✓	✓	*Meloidogyne* sp.
Lamiaceae	*Lamium amplexicaule* L.	✓	✓	*M. hapla* Chitwood,1949, *M. incognita*
Musaceae	*Musa* spp. (Banana)	Crop	Crop	*H. dihystera, H. multicinctus, M. arenaria, M. enterolobii* Yang&Eisenback,1983, *M. hapla, M. incognita, M. javanica*
Oxalidaceae	*Oxalis* spp.	✓	✓	*M. arenaria*, *M. hapla, M incognita, M. javanica*
Plantaginaceae	*Veronica* spp.	✓		*M. incognita*, *M. javanica*
Poaceae	*Digitaria sanguinalis (*L.) Scop.	✓	✓	*H. dihystera*, *M. arenaria*, *M incognita, M javanica*, *M. naasi* Franklin,1965
	*Eleusine indica (*L.) Gaertn.	✓	✓	*Helicotylenchus* sp., *M. arenaria*, *M. incognita*, *M. javanica*
	Setaria spp.	✓	✓	*H. dihystera*, *M. arenaria*, *M. hapla*, *M. incognita*, *M javanica*
	Sorghum halepense (L.) Pers.	✓	✓	*H. dihystera, M. arenaria*, *M. enterolobii, M. incognita*, *M. javanica*
Portulacaceae	*Portulaca oleracea* L.	✓	✓	*H. multicinctus, M. arenaria*, *M. enterolobii*, *M. hapla*, *M. incognita*, *M. javanica*
Solanaceae	*Physalis* spp.	✓		*M. arenaria, M. hapla, M incognita, M javanica*
	Solanum nigrum L.	✓		*M. arenaria, Meloidogyne chitwoodi* Golden et al.,1980, *M. hapla, M incognita, M. javanica*
Urticaceae	*Parietaria judaica* L.		✓	-
	Pilea microphylla (L.) Liebm.		✓	*M. incognita*
	Urtica spp.	✓	✓	*M. hapla, M. incognita*

* The reference data used as example host were from Goodey et al. (1965), Caveness (1967), Davidson & Townshend (1967), Stoyanov (1967), Siddiqui et al. (1973), Dabaj & Jenser (1990), McKenry (1992), Powers & Pitty (1993), Queneherve et al. (1995), Levin et al. (2005), Kaur et al. (2007), Rich et al. (2008), Singh et al. (2010), Kokalis-Burelle & Rosskopf (2012), Mendes et al. (2020).

Nematode densities of *Helicotylenchus* and *Meloidogyne* populations were assessed in soil samples which were taken from the banana trial plots of the two key observation points: after 6-months (1st observation) and pre-harvest (2nd observation). The results revealed that the weed control applications at the 6-month mark led to higher nematode densities compared to those observed just before harvest. This change was likely due to the increasing number of weed control treatments, higher water application, and the absence of a sufficient developmental period for nematodes to build populations (Table 2). Nematode densities, on the other hand, were generally lower under full irrigation across all weed control treatments. Herbicide treatments, particularly Indaziflam and the combination of Oxyfluorfen+Glyphosate, effectively reduced nematode populations when compared to the weedy control plots, which had the highest nematode densities. This reduction pattern persisted across both the 6-month and pre-harvest observation periods. However, under deficit irrigation, nematode populations increased, particularly in the weedy control plots emphasizing the detrimental effects of water stress in the absence of weed management. Even under deficit irrigation, herbicide treatments still managed to reduce nematode populations compared to untreated plots. The differences observed between irrigation regimes may have resulted from the interactions between soil moisture, weed management, and nematode ecology. In addition, soil moisture plays a critical role in nematode survival, mobility, and reproduction. While excessive moisture can limit nematode activity due to oxygen depletion, moderate moisture levels can enhance nematode movement and infectivity.

Table 2. Nematode density (number 100 g soil^{-1}) of weed control treated plots in greenhouse banana (2022-2024)

Irrigation	Treatments	Total		*Helicotylenchus*		*Meloidogyne*	
		2022-2023	2023-2024	2022-2023	2023-2024	2022-2023	2023-2024
	1st Observation (6-months)						
Full irrigation (100%)	Indaziflam	6.18	0.64	5.70	11.00	6.86	0.10
	Oxyfluorfen+Glyphosate	4.16	1.41	3.27	10.67	10.67	0.25
	Phendimethalin+Glyphosate	1.76	1.14	1.71	6.00	1.91	0.58
	Glyphosate+Glyphosate	2.83	4.27	3.43	19.33	1.25	0.50
	Geotextile mulching	-	-	-	-	-	-
	Mowing (2 times)	2.00	2.33	3.08	7.33	0.38	1.08
	Weedy control	11.69	2.07	7.58	19.17	22.86	0.56
Deficit irrigation (50%)	Indaziflam	3.07	2.18	2.70	18.33	6.33	0.24
	Oxyfluorfen+Glyphosate	3.68	3.81	3.00	24.33	9.33	1.25
	Phendimethalin+Glyphosate	2.71	4.64	1.64	34.67	11.67	0.55
	Glyphosate+Glyphosate	10.32	1.47	7.00	15.67	28.00	0.18
	Geotextile mulching	-	-	-	-	-	-
	Mowing (2 times)	2.39	2.44	1.42	25.67	7.40	0.19
	Weedy control	16.25	6.64	2.62	24.67	75.33	1.73
	Average	5.59	2.75	3.60	18.07	15.17	0.60
	2nd Observation (Pre-harvest)						
Full irrigation (100%)	Indaziflam+Diquat	5.06	0.21	8.20	4.33	0.57	0.00
	Oxyfluorfen+Glyphosate+Diquat	4.44	0.74	4.50	6.67	4.00	0.00
	Phendimethalin+Glyphosate+Diquat	2.23	0.76	2.24	6.67	2.18	0.08
	Glyphosate+Glyphosate+Diquat	5.00	0.87	4.24	4.33	7.00	0.00
	Geotextile mulching	1.62	1.18	1.35	8.67	4.33	0.00
	Mowing (3 times)	3.05	1.60	3.25	7.67	2.75	0.08
	Weedy control	3.81	0.46	3.26	4.67	5.29	0.09
Deficit irrigation (50%)	Indaziflam+Diquat	1.60	3.29	1.26	26.33	4.67	0.52
	Oxyfluorfen+Glyphosate+Diquat	0.59	1.89	0.46	13.00	1.67	0.50
	Phendimethalin+Glyphosate+Diquat	1.71	2.56	1.60	21.33	2.67	0.00
	Glyphosate+Glyphosate+Diquat	2.42	1.22	2.63	14.33	1.33	0.03
	Geotextile mulching	5.42	1.03	5.43	19.33	5.33	0.05
	Mowing (3 times)	1.32	1.62	1.27	17.33	1.60	0.10
	Weedy control	4.31	5.21	3.15	21.00	9.33	0.91
	Average	3.04	1.62	3.06	12.55	3.77	0.17

The study evaluated the impact of weed control methods on nematode densities and weed coverage in a banana greenhouse, specifically after the first 6-months of treatment implementation. While no statistically significant effects were observed in the interaction between irrigation and treatment factors for total nematode density, some emerging differences were observed for *Helicotylenchus* spp., *Meloidogyne* spp., or weed coverage during the first 6-months of both study periods (2022-2023 and 2023-2024). In the first year, there was a statistically significant difference in the total nematode density and *Meloidogyne* density. In the second year, irrigation had a significant effect on total nematode and *Helicotylenchus* densities. Weed control treatments were very effective on weed coverage in both years. In addition, there was a parallel in both nematode densities and weed coverage, especially in the weedy control plots under different irrigation levels during in the first year. In contrast, weed control treatments resulted in a reduction in nematode densities in the second year (Table 3). The analysis of the average total nematode and *Meloidogyne* densities in the second year revealed that all of the treatments, except for the weedy control, significantly reduced nematode densities in the soil. This reduction was correlated with the weed population management, suggesting that effective weed control may indirectly influence nematode dynamics. Although no statistically significant difference was observed in the average density of *Helicotylenchus*, a significant effect on weed coverage was observed. The herbicide treatments (Indaziflam, Oxyfluorfen+Glyphosate, Pendimethalin+Glyphosate, and Glyphosate+Glyphosate) were the most effective ones in reducing weed coverage over the two years, while double mowing treatment had relatively little effect on weed control. In summary, the findings indicated that weed management practices significantly reduced both weed coverage and nematode densities within the first 6-months of application (Table 3).

Table 3. Initial observations (6-months) of total nematode, *Helicotylenchus*, *Meloidogyne*, and weed coverage in banana plants under two different irrigation levels (2022-2023)

Treatments	Irrigation	Total nematod (number)		*Helicotylenchus* (number)		*Meloidogyne* (number)		Weed coverage (%)	
1st Observation (6-months)	Year	1st	2nd	1st	2nd	1st	2nd	1st	2nd
IrrigationxTreatments factor									
Indaziflam	Ir100	700.00	260.00	380.00	220.00	320.00	40.00	5.00	1.00
	Ir50	613.00	407.00	487.00	367.00	127.00	40.00	11.70	6.00
Oxyfluorfen+Glyphosate	Ir100	693.00	253.00	480.00	213.00	213.00	40.00	8.30	3.70
	Ir50	687.00	687.00	500.00	487.00	187.00	200.00	4.30	2.70
Phendimethalin+Glyphosate	Ir100	493.00	220.00	353.00	120.00	140.00	100.00	12.70	2.00
	Ir50	507.00	773.00	273.00	693.00	233.00	80.00	6.00	5.70
Glyphosate+Glyphosate	Ir100	547.00	427.00	480.00	387.00	67.00	40.00	10.00	2.00
	Ir50	1307.00	353.00	747.00	313.00	560.00	40.00	10.00	2.70
Geotextile mulching									
Mowing (2times)	Ir100	267.00	233.00	247.00	147.00	20.00	87.00	18.30	55.00
	Ir50	493.00	553.00	247.00	513.00	247.00	40.00	15.00	43.30
Weedy control	Ir100	2027.00	510.00	960.00	383.00	1067.00	127.00	23.30	70.00
	Ir50	1733.00	620.00	227.00	493.00	1507.00	127.00	21.70	68.30
LSDirrigation		N.S	133**	N.S	117**	N.S	N.S	N.S	N.S
LSDtreatmens		729**	N.S	N.S	N.S	499**	N.S	7.2**	2.5**
LSDirrigationxtreatments		N.S	N.S	N.S	N.S	N.S	N.S	N.S	N.S
1st Observation (6-months)		Averages (2 year)							
Treatments factor									
Indaziflam		495.00a		363.34		131.67a		5.92a	
Oxyfluorfen+Glyphosate		580.00a		420.00		160.00a		4.75a	
Phendimethalin+Glyphosate		498.34a		360.00		138.34a		6.58a	
Glyphosate+Glyphosate		658.34a		481.67		176.67a		6.16a	
Geotextile mulching									
Mowing (2times)		386.67a		288.33		98.34a		32.92b	
Weedy control		1222.50b		515.83		706.67b		45.83c	
LSDtreatmens		421*		N.S.		256**		14.23**	

1) Separate letters indicate the differences between the averages. 2) N.S.:Not Significant,*p≤0.05,**P≤0.01.

The findings also revealed that the irrigation and weed control treatments had a significant effect on nematode densities and weed coverage, especially in the pre-harvest periods of both years. In the first year, a significant interaction between irrigation and treatments affected total nematode and *Helicotylenchus* densities. Specifically, under deficit irrigation (Ir50), herbicide combinations such as Oxyfluorfen+Glyphosate+ Diquat and mowing treatments (applied three times) were the most effective ones in reducing nematode densities. However, no significant effects were found in the second year. In addition, treatments such as Indaziflam+Diquat and Geotextile Mulching significantly reduced weed coverage, especially under both irrigation levels in the second year, while mowing and weedy treatments showed the highest weed coverage. In two years, full irrigation resulted in lower nematode densities and better weed control compared to deficit irrigation. The combination of higher soil moisture and herbicide treatments, such as Indaziflam+Diquat and Oxyfluorfen+Glyphosate induced the significantly reduced nematode populations, as moisture supports better herbicide efficacy and minimized nematode habitat by suppressing weed hosts (Table 4).

Table 4. Second observations (Pre-harvest) of total nematode, *Helicotylenchus*, *Meloidogyne*, and weed coverage in banana plants under two different irrigation levels (2023-2024)

Treatments	Irrigation	Total nematod (number)		*Helicotylenchus* (number)		*Meloodogyne* (number)		Weed coverage (%)	
2nd Observation (Pre-harvest)	Year	1st	2nd	1st	2nd	1st	2nd	1st	2nd
IrrigationxTreatments factor									
Indaziflam+Diquat	Ir100	573.00b-e	87.00	547.00bcd	87.00	26.70	0.00	2.00	4.30ab
	Ir50	320.00abc	613.00	227.00ab	527.00	93.30	86.70	1.00	2.30a
Oxyfluorfen+Glyphosate+Diquat	Ir100	740.00cde	133.00	660.00d	133.00	80.00	0.00	35.00	56.70d
	Ir50	110.00a	340.00	77.00a	260.00	33.30	80.00	17.00	18.30bcd
Phendimethalin+Glyphosate+Diquat	Ir100	623.00bcde	147.00	463.00bcd	133.00	160.00	13.30	25.00	48.30d
	Ir50	320.00abc	427.00	267.00abc	427.00	53.30	0.00	15.00	21.70c
Glyphosate+Glyphosate+Diquat	Ir100	967.00e	87.00	660.00d	87.00	37.30	0.00	21.00	30.00c
	Ir50	307.00abc	293.00	280.00abc	287.00	26.70	6.70	16.00	21.70c
Geotextile mulching	Ir100	367.00abc	173.00	280.00abc	173.00	86.70	0.00	0.00	0.00a
	Ir50	867.00de	407.00	760.00d	387.00	106.70	20.00	0.00	0.00a
Mowing (3times)	Ir100	407.00abc	160.00	260.00abc	153.00	160.00	6.70	63.30	90.00e
	Ir50	273.00ab	367.00	220.00ab	347.00	53.30	20.00	71.70	80.00e
Weedy control	Ir100	660.00bcde	113.00	413.00abcd	93.00	247	20.00	71.70	93.30e
	Ir50	460.00abcd	487.00	273.00abc	420.00	187.00	66.70	65.00	80.00e
LSDirrigation		167**	122**	132*	102**	N.S	30**	N.S	6.0**
LSDtreatmens		N.S	N.S	N.S	N.S	N.S	N.S	13**	11**
LSDirrigationxtreatments		441*	N.S	348*	N.S	N.S	N.S	N.S	16*
2nd Observation (Pre-harvest)		Averages (2 year)							
Treatments factor									
Indaziflam+Diquat		398.34		346.67		51.67		2.42a	
Oxyfluorfen+Glyphosate+Diquat		330.83		282.50		48.34		31.75b	
Phendimethalin+Glyphosate+Diquat		379.16		322.50		56.67		27.50b	
Glyphosate+Glyphosate+Diquat		413.34		311.67		101.67		22.16b	
Geotextile mulching		453.34		400.00		53.34		0.00a	
Mowing (3times)		301.67		245.00		56.67		76.25c	
Weedy control		430.00		300.00		130.00		77.50c	
LSDtreatmens		N.S.		N.S.		N.S.		9.59**	

1) Separate letters indicate the differences between the averages. 2) N.S.:Not Significant,*p≤0.05,**P≤0.01.

Analysis of mean regression curves by year revealed a positive correlation between total nematode densities (including *Meloidogyne*) and weed coverage at the end of the 6 months in both irrigation regimes. A remarkably similar positive correlation was observed between *Helicotylenchus* densities and weed coverage under full irrigation while a negative correlation was found under deficit irrigation (Figure 1). We hypothesized that weed coverage may have played a critical role in nematode population dynamics, with increased weed density correlating with higher nematode populations, particularly under water-limited conditions. Under full irrigation, nematode densities and weed coverage were significantly lower compared to those observed under deficit irrigation. This trend was most pronounced for *Meloidogyne*, which exhibited higher densities under water stress. The findings supported the hypothesis that full irrigation could enhance herbicide efficacy by improving crop health and reducing weed hosts, ultimately limiting nematode populations. Adequate moisture is known to improve better herbicide uptake, resulting in more uniform weed control and reduced nematode habitat.

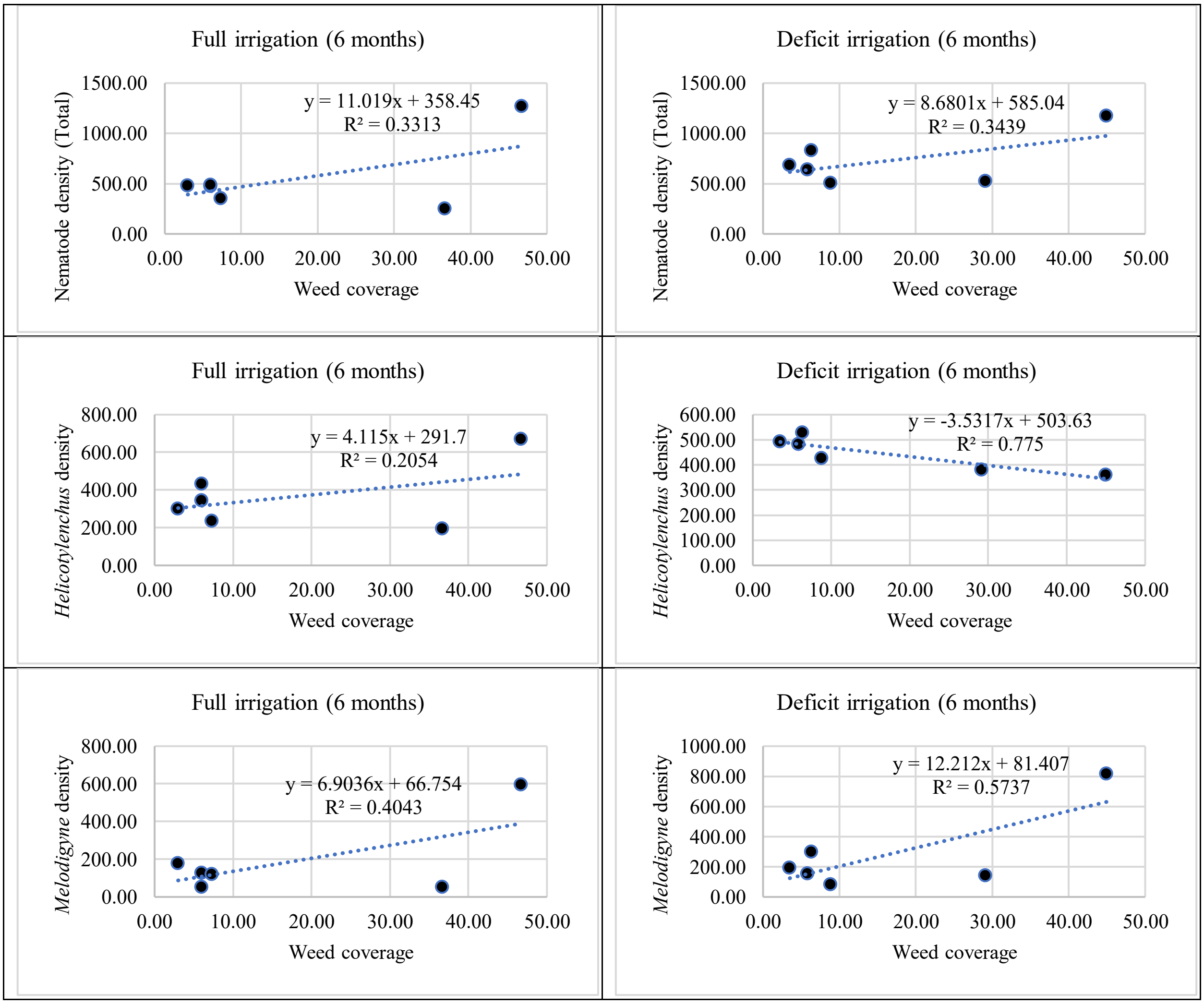

Figure 1. Weed treatment effects of full and deficit irrigation on weed coverage (%) - nematode density (number 100 g soil^{-1}) after 6-months observation (average 2022-2024).

The regression curve analysis of nematode densities and weed coverage during the pre-harvest period, based on the two-year average, revealed distinct patterns depending on the irrigation levels. A negative correlation was observed between total nematode and *Helicotylenchus* densities and weed coverage, as lower densities of both were associated with higher weed coverage. Conversely, a positive correlation was found between *Meloidogyne* densities and weed coverage, with nematode populations increasing as weed coverage increased (Figure 2). These trends may be related to the interaction between soil moisture, weed control, and nematode dynamics. Under full irrigation, the relationship between total nematode density and weed coverage was relatively balanced, suggesting that optimum moisture levels could stabilize both weed control and nematode management. This indicates that full irrigation provides a balanced environment, where both weed, and nematode populations are effectively controlled. In contrast, a slight negative correlation between weed coverage and nematode density was observed under deficit irrigation, particularly for *Helicotylenchus*. This implies that water scarcity limits the effectiveness of both weed and nematode management, as water-stressed plants and weeds become more resilient hosts for nematodes.

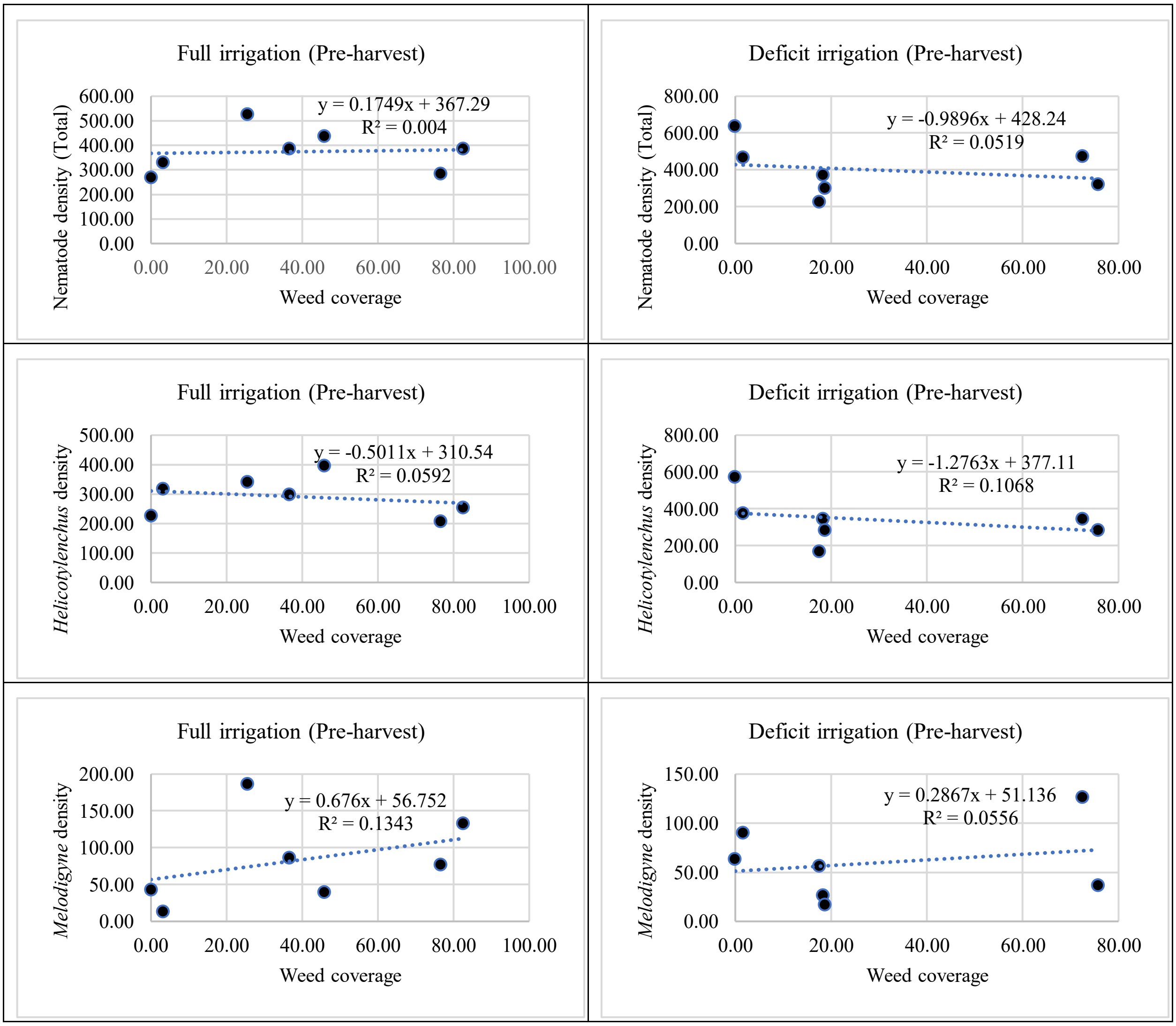

Figure 2. Weed treatment effects of full and deficit irrigation on weed coverage (%) - nematode density (number 100 g soil^{-1}) pre-harvest observation (average 2022-2024).

Discussion

Weed species in banana production areas of Colombia and Brazil pose significant challenges to control efforts (Moura Filho et al., 2015; Quintero-Pertúz et al., 2020). Weeds inhibit seedling growth and serve as hosts for nematodes (Isaac et al., 2007; Fongod et al., 2010). Our results showed that weed control significantly affected nematode densities and weed coverage, particularly in the first six months. Higher nematode densities were observed in irrigated areas, likely due to favorable conditions for nematode development, including irrigation and dense weeds. Nematode densities were highest in the weedy and mowing plots, suggesting early weed density supported nematode populations. Reduced densities later were due to increased weed control, reduced irrigation, and insufficient time for nematodes to recover (Tables 2, 3 & 4). Full irrigation reduced nematode activity, as Wallace (1964) noted, while drought stress increased plant vulnerability to nematodes (Barker & Olthof, 1976). Herbicides reduced nematode populations by controlling weed hosts (Stirling et al., 1992). Geotextile mulching reduced nematode populations by altering soil temperature and moisture, making conditions less favorable for nematodes, particularly under deficit irrigation. These findings align with Govaerts et al. (2007b) and Klose et al. (2008), who emphasized that consistent soil moisture improves herbicide penetration and reduces nematode survival. In contrast, deficit irrigation increased nematode densities, as water stress heightened plant susceptibility to nematodes, reducing herbicide effectiveness and promoting weed survival, which in turn provided more habitat for nematodes. These results highlight the importance of optimal irrigation and weed control strategies in integrated pest management for banana cultivation. Weed control during the first six months, particularly under full irrigation, resulted in higher nematode densities than in the pre-harvest period. The use of herbicide combinations combined with irrigation contributed to a gradual reduction in nematode populations over time. These results are consistent with the findings of Özarslan & Dinçer (2015), who suggested that weeds can increase nematode populations, leading to reduced yield and quality in bananas. Although the interaction between irrigation and treatment did not significantly affect total nematode, *Helicotylenchus*, or *Meloidogyne* densities, differences in nematode densities were observed in the first year. In the second year, a significant reduction in total nematode and *Helicotylenchus* densities was observed, probably due to the increased effectiveness of the weed management strategies. Weed coverage was a significant factor influencing nematode densities in our study, with higher weed coverage in weedy plots correlating with higher nematode populations. This observation correlates with findings reported in previous studies, which suggest that dense weed populations create favorable habitats for nematodes, particularly around banana roots (Araya et al., 1998; Araya & Blanco, 2001). Additionally, nematodes continue to thrive on host plants from common families such as Euphorbiaceae, Poaceae, and Solanaceae (Araya & De Waele, 2005; Quénéhervé et al., 2006; Duyck et al., 2009; Dinçer et al., 2024).

Treatments with (1) Indaziflam, (2) Oxyfluorfen+Glyphosate, and (3) Phendimethalin+Glyphosate were applied during the first 6 months, followed by the addition of Diquat in the pre-harvest period (Indaziflam+Diquat, Oxyfluorfen+Glyphosate+Diquat, and Phendimethalin+Glyphosate+Diquat). Geotextile mulching was also effective in reducing nematode densities. The reduction in weed coverage resulted in lower nematode populations, suggesting that effective weed control supports nematode management. While no significant changes in *Helicotylenchus* densities were observed, the statistical significance of weed coverage highlights its role in nematode dynamics. This suggests that *Helicotylenchus* densities may be less responsive to weed management than *Meloidogyne*, indicating different ecological niches for these nematodes (Tables 3 & 4). Furthermore, Robinson et al. (1991) and Bhattacharyya & Madhava (1992) emphasized that mowing weeds, rather than using herbicides, is essential for maintaining soil moisture and supporting nematode retention in banana fields. A study in Costa Rica showed that while weed management had no significant effect on nematode numbers or banana root damage, differences in root thickness were observed for *Radopholus similis* (Cobb,1893) (Thorne,1949) and *Helicotylenchus* spp., and weed control increased banana panicle weight, contributing to more sustainable practices (Araya & De Waele, 2005). Additionally, uncontrolled low population levels of *Meloidogyne* species on weeds like *Amaranthus* sp., *S. nigrum*, *Crassocephalum crepidioides* (Benth.) S.Moore (Asterales: Asteraceae), *Commelina benghalensis* L. (Commelinales: Commelinaceae), and *Eleusine indica* (L.) Gaertn. (Poales: Poaceae) may lead to significant yield losses in the future (Jonathan & Rajendran, 2000). It provides insight into the critical role of effective weed management in reducing nematode populations and improving banana yields.

Regression analyses revealed complex relationships between nematode densities and weed coverage. Both full and deficit irrigation showed a positive correlation between total nematode and *Meloidogyne* densities and weed coverage after six months, but *Helicotylenchus* densities were positively correlated only under full irrigation, with a negative correlation under deficit irrigation. Over two years, total nematode and *Helicotylenchus* densities decreased with increased weed coverage, especially under deficit irrigation, while *Meloidogyne* densities were positively correlated with weed coverage, indicating species-specific responses to irrigation (Figures 1 & 2). These results emphasize the importance of managing irrigation to influence nematode dynamics and suggest that tailored weed management can help mitigate nematode pressures under varying irrigation regimes. Soil moisture significantly affects herbicide effectiveness by improving penetration and weed suppression, thus reducing nematode host availability (Ozores-Hampton et al., 2012). In contrast, deficit irrigation increases nematode and weed densities due to water stress, weakening plant defenses and reducing herbicide efficacy, allowing more weeds to serve as nematode reservoirs (Wang et al., 2006). Adequate moisture under full irrigation enhances herbicide absorption, leading to better weed control and fewer nematode habitats, while deficit irrigation promotes weed survival and nematode invasion, particularly for *Helicotylenchus*, which relies on weakened roots. These findings highlight the critical role of optimal irrigation in managing both weeds and nematodes and underscore the need for integrated management strategies that consider moisture levels and pest dynamics.

In conclusion, this study highlights the importance of integrated weed management strategies for nematode control in banana production. Future research should explore the underlying mechanisms driving these relationships and the potential for developing targeted management practices that optimize both weed and nematode control. A better understanding of these dynamics will ultimately contribute to more sustainable agricultural practices and improved crop health (Swafo & Dlamini, 2023; Dassou et al., 2024).

Conclusion

This study aimed to highlight the interaction between weed control practices in banana cultivation and changes in host weed populations and nematode densities. The results showed that effective weed management can significantly reduce the presence of both harmful nematodes and weeds in banana fields. The use of different irrigation regimes showed that both the number of chemical applications and alternative weed control methods reduced weed populations over time, leading to a reduction in nematode populations due to the lack of suitable host plants. It was also found that effective and appropriate weed control strategies influenced nematode densities. The study also showed that, in addition to the favourable growth conditions provided by weeds, the amount of irrigation may influence nematode populations. Further research is therefore needed to gain a better understanding of the relationship between weed control practices and nematodes and their long-term effects.

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