REVISTA DELOS DESARROLLO LOCAL SOSTENIBLE

Development and biochemical profile of *Zingiber officinale* under different population densities of *Meloidogyne javanica*

Desenvolvimento e alterações bioquímicas do gengibre sob diferentes densidades populacionais de *Meloidogyne javanica*

Desarrollo y perfil bioquímico de Zingiber officinale bajo diferentes densidades de población de Meloidogyne javanica

DOI: 10.55905/rdelosv17.n53-027

Originals received: 02/01/2024
Acceptance for publication: 03/07/2024

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ABSTRACT
Ginger is a medicinal plant known for its aromatic, antioxidant, and pharmacological properties. This study aimed to examine the vegetative growth and biochemical profile of ginger exposed to *Meloidogyne javanica* at different initial inoculum levels. The experiment was conducted in a greenhouse using a completely randomized design. Treatments comprised 0, 2000, 4000, 6000, 8000, and 10,000 eggs of *M. javanica* and eight replications per treatment. At 70 days after inoculation, plants were harvested and evaluated for nematode parameters, vegetative growth, total phenolic compounds, gingerol content, antioxidant activity, and soluble sugars content. Total nematode number increased linearly as a function of initial inoculum level. The reproduction factor was greater than one (RF>1) in all treatments. Vegetative development, however, was not affected. The highest concentrations of total phenolics and gingerol were estimated to occur with initial inoculum levels of 4500 and 4000 eggs, respectively. Higher population levels (>6000 eggs) stimulated the production of soluble sugars in ginger rhizomes. Although increasing levels of *M. javanica* did not affect ginger vegetative development, it significantly altered biochemical parameters, such as total phenolic compounds, gingerol content, antioxidant activity, and soluble sugars content, proving that *M. javanica* influences the quality of ginger.

Keywords: ginger, root-knot nematode, phenolic compounds, gingerol, antioxidant.

RESUMO
O gengibre é uma planta medicinal conhecida por suas propriedades aromáticas, antioxidantes e farmacológicas. O objetivo deste trabalho foi analisar o crescimento vegetativo e as alterações bioquímicas do gengibre sob diferentes níveis de inóculo inicial de Meloidogyne javanica. O experimento foi conduzido em casa de vegetação em delineamento inteiramente casualizado, com níveis de população inicial (IP) crescentes: 0, 2000, 4000, 6000, 8000 e 10000 ovos e eventuais juvenis de segundo estádio (J2) de M. javanica. Aos 70 dias após a inoculação, as plantas foram colhidas e avaliadas quanto às variáveis nematológicas, crescimento vegetativo, compostos fenólicos totais, teor de gingerol, atividade antioxidante e açúcares solúveis. Houve aumento linear do número total de nematoides em função dos níveis crescentes de inóculo inicial, sendo o fator de reprodução maior que um em todos os níveis avaliados. Todavia, o desenvolvimento vegetativo não foi afetado. O pico de compostos fenólicos totais e gingerol ocorreu sob IP de aproximadamente 4500 e 4000 ovos + J2 de M. javanica, respectivamente. Por outro lado, a inoculação com maiores níveis de nematoides (>6000 ovos + J2) estimulou a produção de açúcares solúveis em rizomas de gengibre. Apesar do crescimento linear da população de M. javanica não terem afetado o desenvolvimento vegetativo do gengibre, afetou significativamente os parâmetros bioquímicos como compostos fenólicos totais, teor de gingerol, potencial antioxidante e açúcares solúveis, comprovando que M. javanica pode comprometer a qualidade do gengibre.

Palavras-chave: gengibre, nemátodo das galhas, compostos fenólicos, gingerol, antioxidante.

RESUMEN
El jengibre es una planta medicinal conocida por sus propiedades aromáticas, antioxidantes y farmacológicas. El objetivo de este estudio era examinar el crecimiento vegetativo y el perfil bioquímico del jengibre expuesto a Meloidogyne javanica a diferentes niveles de inóculo inicial. El experimento se realizó en un invernadero utilizando un diseño completamente aleatorizado. Los tratamientos comprendían 0, 2000, 4000, 6000, 8000 y 10.000 huevos de M. javanica y ocho repeticiones por tratamiento. A los 70 días de la inoculación, se cosecharon las plantas y se evaluaron los parámetros de nematodos, el crecimiento vegetativo, los compuestos fenólicos totales, el contenido de gingerol, la actividad antioxidante y el contenido de azúcares solubles. El número total de nematodos aumentó linealmente en función del nivel inicial de inóculo. El factor de reproducción fue superior a uno (RF>1) en todos los tratamientos. El desarrollo vegetativo, sin embargo, no se vio afectado. Las concentraciones más elevadas de fenoles totales y gingerol se estimaron con niveles iniciales de inóculo de 4500 y 4000 huevos, respectivamente. Los niveles de población más elevados (>6000 huevos) estimularon la producción de azúcares solubles en los rizomas de jengibre. Aunque el aumento de los niveles de M. javanica no afectó al desarrollo vegetativo del jengibre, alteró significativamente parámetros bioquímicos, como los compuestos fenólicos totales, el contenido en gingerol, la actividad antioxidante y el contenido en azúcares solubles, lo que demuestra que M. javanica influye en la calidad del jengibre.

Palabras clave: jengibre, nematodo del nudo de la raíz, compuestos fenólicos, gingerol, antioxidante.

1 INTRODUCTION

Ginger (*Zingiber officinale*) is a perennial herbaceous plant whose underground rhizomes are commonly used as seasoning, food, nutritional supplement, medicinal remedy, and flavoring agent owing to their aromatic, nutritional, antioxidant, and pharmacological properties (EL SAYED; MOUSTAFA, 2016; NOUR et al., 2017). The rhizome contains volatile compounds, essential oil constituents, and non-volatile compounds, as well as polysaccharides, lipids, organic acids, and dietary fibers (PRASAD; TYAGI, 2015). The major phenolic compounds of ginger rhizomes include gingerols, shogaols, and paradols. Gingerols are the major polyphenols found in fresh ginger, particularly 6-gingerol, 8-gingerol, and 10-gingerol (MAO et al., 2019). 6-Gingerol, the primary pharmacologically active component of ginger, exhibits a multitude of biological activities, including anticancer, anti-inflammatory, and antioxidant (SCHADICH et al., 2016; JI et al., 2017). These valuable characteristics have stimulated ginger production, as well as research on secondary metabolites for the development of alternative therapies.

The relative proportions of gingerols, shogaols, and paradols in ginger extract are influenced by several factors, including geographical origin, drying conditions, and extraction

method (GRZANNA et al., 2005; VERNIN; PARKANYI, 2005; ALI et al., 2008). Abiotic factors may also influence secondary metabolite production in ginger rhizomes, as evidenced by a study analyzing the composition of the same cultivar grown in different localities (GAUR et al., 2016). As for biotic factors, ginger can be affected by nematodes (TURAGANIVALU et al., 2013; MYERS et al., 2017; ALMURSYIDI et al., 2023). Damage is severe when nematodes and other pathogens are present together (DOHROO et al., 1987; MEENU; JEBASINGH, 2019).

Root-knot nematodes (*Meloidogyne* spp.) are common pests of medicinal plants, reducing the quantity and quality of active compounds (GUPTA et al., 2015; GUPTA et al., 2017; TIWARI et al., 2017). Two species, *Meloidogyne incognita* and *M. javanica*, are reported to cause damage to ginger plants (SANTOS; LOZANO 1993; SINGH; GUPTA, 2011; MYERS et al., 2017; ALMURSYIDI et al., 2023). Infection by *M. incognita* can lead to reductions of up to 80% in ginger rhizome weight (MYERS et al., 2017). These nematodes feed on rhizome, root, and pseudostem cells (MEENU; JEBASINGH, 2019). The aerial part of infected plants develops leaf atrophy, chlorosis, and marginal necrosis. Furthermore, the roots of infected ginger plants are commonly stunted and deformed, and both roots and rhizomes exhibit galls and rot symptoms (MEENU; JEBASINGH, 2019).

Despite the wealth of information on the pathogenicity of root-knot nematodes (SUKUMURAN; SUNDARARAJU, 1986; MEENU; JEBASINGH, 2019), little is known about the impact of nematode infestation on the production of active compounds in ginger. This study aimed to assess the effects of increasing levels of *M. javanica* on the vegetative development, phenolic profile, gingerol content, antioxidant activity, and soluble sugars content of ginger rhizomes.

2 MATERIAL AND METHODS

2.1 GENERAL EXPERIMENTAL INFORMATION

The experiment was conducted in a greenhouse at the State University of Maringá, Umuarama, Paraná, Brazil, using a completely randomized design with six treatments. *Meloidogyne javanica* was isolated from the roots of tomato (*Solanum lycopersicum* L.) (State University of Maringá, Umuarama, Paraná, Brazil) and multiplied on tomato "Santa Clara" under greenhouse conditions. Treatments consisted of increasing levels of initial population (IP) of *M. javanica*, as follows: 0, 2000, 4000, 6000, 8000, and 10,000 eggs and eight replications per

treatment. Nematode variables and vegetative development were evaluated in six replications per treatment. Chemical parameters were analyzed in three replications per treatment.

Ginger rhizome were kindly provided by EMBRAPA Hortaliças, Brasília, Federal District, Brazil. The rhizomes were washed, trimmed, and transferred individually to 3 L plastic pots. Each pot contained 1 L of a 2:1 mixture of soil and sand, and a top layer (3 cm) of sand, onto which the rhizome was placed. Then, rhizomes were covered with a layer of commercial substrate (Bioplant, Nova Ponte, MG, Brazil). Prior to their use in the experiment, soil, sand, and substrate were separately autoclaved at 120 °C for 2 h. This configuration of substrate layers was adopted to prevent water accumulation and subsequent rotting of ginger rhizomes.

Two months after planting, plants were inoculated with 2 mL of a suspension containing nematodes at the respective levels of each treatment. Inoculation was performed using a pipette by depositing the nematode suspension into two holes about 2 cm deep made in the soil around the base of the plant. At 70 days after inoculation, plants were harvested and evaluated for nematode, vegetative, and biochemical variables.

2.2 NEMATODE ANALYSIS

For nematode analysis, plants were removed from the pots and separated into shoots and roots. The root system was washed under running water to remove excess soil. Subsequently, the rhizomes were peeled by removing a layer of approximately 3 mm in thickness. Peels and secondary roots were weighed and subjected to nematode extraction according to the method proposed by Hussey and Barker (1973) and adapted by Boneti and Ferraz (1981). The roots were ground in a blender with a solution of water and 0.5% sodium hypochlorite. The material obtained from crushing was passed through 100 mesh sieves coupled with another 500 mesh. The solution containing nematode eggs was retained in the 500 mesh sieve and transferred to Falcon tubes using a wash bottle. The number of nematodes was counted in a Peters chamber under a light microscope (Motic B1-252). The total number of nematodes was calculated as the sum of nematodes in peel and root samples. The reproduction factor (RF) of the nematode was calculated by the equation RF = Final population/IP (OOSTENBRINK, 1966).

2.3 VEGETATIVE GROWTH ANALYSIS

Plant height was measured with a ruler and expressed in centimeters. Shoot and root fresh weights were determined using a semi-analytical balance and expressed in grams. Shoot dry weight was estimated by drying samples in paper bags in a forced air oven at 65 °C until constant weight was achieved (72 h).

2.4 CHEMICAL ANALYSIS

Ginger rhizomes were analyzed for total phenolics, gingerol, antioxidant activity, and soluble sugars. For this, samples were dried at 60 °C to a moisture content of 10% (w/w) and ground in a blender (Cadence) at maximum speed. Subsequently, 1 g of sample was mixed with 20 mL of 80% (v/v) ethanol. The mixture was sonicated for 30 min at room temperature and centrifuged at 3000 rpm for 10 min. The supernatant was collected and reserved. The residual fraction was washed with 10 mL of 80% ethanol, sonicated for a further 15 min, and centrifuged at 3000 rpm for 10 min. The supernatants were combined and used as crude extract for analysis of phenolic compounds and antioxidant activity (DANADONE et al., 2020).

2.5 DETERMINATION OF PHENOLIC COMPOUNDS

Total phenolic compounds (TPC) were quantified by the Folin–Ciocalteu method, as described by Shahidi and Zhong (2015). An analytical curve (R^2 = 0.99) was constructed using gallic acid solutions at concentrations ranging from 0.1 to 0.7 mM. The results are expressed in mg gallic acid equivalents (GAE) 100 g^{-1} sample on a dry weight basis.

For identification and quantification of phenolic compounds, the extracts were filtered through a hydrophobic PVDF membrane (25 mm diameter, 0.22 µm pore size, Filtrilo) and analyzed on a Shimadzu Prominence 20A high-performance liquid chromatograph (HPLC) coupled to a UV detector (Shimadzu, SPD-20A, Tokyo, Japan) operating at 280 and 320 nm. A column oven (CTO-20A) was used to maintain a C-18 column (Shim-Pack CLC-ODS/(H)™, 25 cm × 4.6 mm × 5 mm) at 25 °C during chromatographic runs. Extracts (20 µL) were injected by manual injection (SIL-10A). Elution was maintained by a quaternary pump (LC-20AT) operated at 0.8 mL min^{-1}. The mobile phase consisted of 0.05% (v/v) formic acid (A) and 0.1% (v/v) methanol (B) in ultrapure water, used in gradient mode according to the following program: 0.01 to 5.00 min, 20% B; 5.00 to 25.00 min, 50% B; 25.00 to 30.00 min, 80% B; and 35.01 to 40.00

min, 100% B. Quantification was achieved by comparing the results against an analytical curve of gingerol, gallic acid, and *trans*-cinnamic acid (1 to 10 mg mL^{-1}). Results are expressed in mg 100 g^{-1} (DANADONE et al., 2020).

2.6 ANALYSIS OF ANTIOXIDANT ACTIVITY

Antioxidant activity was determined by the ferric reducing antioxidant power (FRAP) assay and by the 2,2'-azino-bis(3-ethylbenzthiazoline-6-sulfonic acid) (ABTS) free radical method. The FRAP assay was performed according to Benzie and Strain (1966). Briefly, 90 µL of crude extract was homogenized with 270 µL of distilled water and 2.7 mL of FRAP reagent. Samples were incubated at 37 °C for 30 min, and the absorbance was read at 595 nm (Shimadzu, UV 1800, Tokyo, Japan). The ABTS assay was performed as described by Thaipong et al., (2006). Briefly, 30 µL of extract was added to 3 mL of ABTS solution. After 6 min of reaction, samples were read at 734 nm. Ethanol was used as blank. Analytical curves were constructed using Trolox solutions at concentrations ranging from 0.20 to 0.75 mM for the FRAP method and from 0.10 to 0.20 mM for the ABTS method. Results are expressed in mol Trolox equivalents (TE) g^{-1} sample on a dry weight basis.

2.7 DETERMINATION OF SOLUBLE SUGARS

Soluble sugars were extracted by mixing rhizome samples with 80% (v/v) ethanol at a ratio of 1:40 (w/v), followed by ultrasonication (Schuster, L100, Shenzhen, China) at 42,000 Hz and 40 °C for 10 min. After extraction, samples were centrifuged (Metroterm, MTD III PULS, Porto Alegre, Brazil) at 1000 × *g* for 10 min, and the supernatants were filtered through a 0.45 µm hydrophobic PDVF membrane (Filtrilo, Colombo, Brazil) (CASTANHEIRA et al., 2020). Filtered samples (10 µL) were injected into an HPLC system (Shimadzu, Prominence 20AD, Tokyo, Japan) equipped with a refractive index detector (RID-20A), a column oven (CTO-20A), and an automatic injector (SIL-10A). Elution was achieved on a Shim-pack GIST NH_2 column (250 × 4.6 mm × 5 µm, Shimadzu) maintained at 40 °C. The mobile phase consisted of acetonitrile and ultrapure water (Milli-Q) (70:30 v/v) pumped in isocratic mode at a flow rate of 1 mL min^{-1}. Analytical curves ($R^2 \geq 0.99$) were constructed with glucose, fructose, and sucrose solutions (0.5 to 15 mg mL^{-1}). Results are expressed as g 100 g^{-1} on a dry weight basis (GIOMBELLI et al., 2020).

2.8 STATISTICAL ANALYSIS

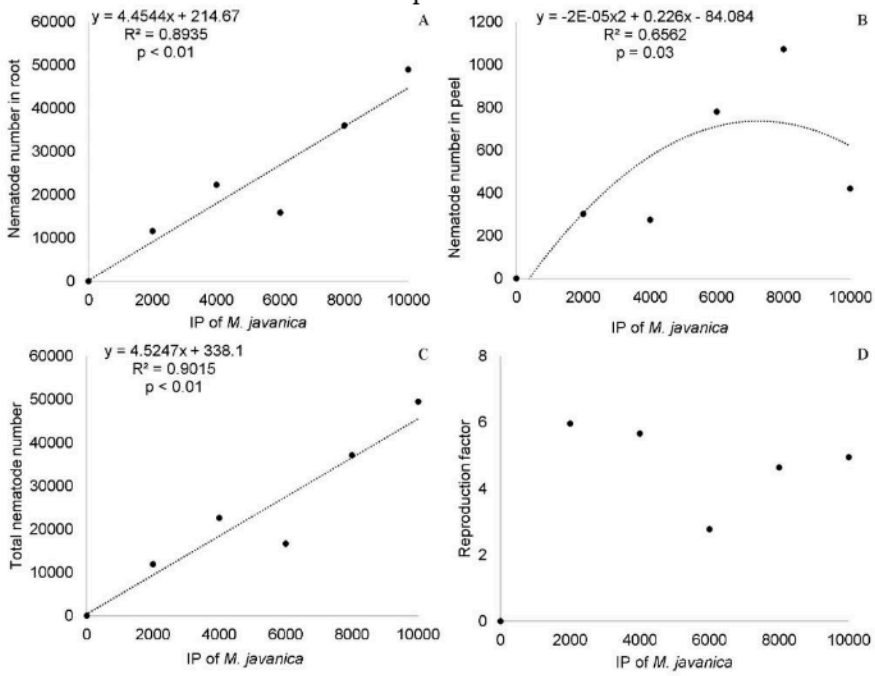
Experimental data were subjected to analysis of variance (ANOVA) with the *F*-test. Shapiro–Wilk and Levene's tests were previously performed to assess normality and homoscedasticity, respectively. Linear and quadratic regression models were used to examine the effects of inoculum levels and dependent variables on final nematode population, plant growth, phenolic compounds, and soluble sugars. The effects of inoculum levels on gingerol content and antioxidant activity were compared by the Scott–Knott test. The level of significance was set at $p < 0.05$ for all comparisons. Analyses were performed using SISVAR software (FERREIRA, 2011).

3 RESULTS

3.1 NEMATODE ANALYSIS

There was a linear increase in the number of nematodes in roots and roots + peel as a function of increasing IP level (Figure 1A and C, respectively). While, the nematode number in ginger peels had a quadratic relationship with the different initial population levels (Figure 1B). The maximum number was estimated to be achieved with an IP of 8000 eggs (Figure 1B). There was no significant difference in RF (Figure 1D), with means ranging from 5.97 (IP = 2000) to 2.77 (IP = 6000).

Figure 1. Number of Meloidogyne javanica in ginger (A) root, (B) peel, and (C) root + peel and (D) nematode reproduction factor as a function of increasing initial population (IP) level. Points in figure are the mean of six replicates



Source: Own authorship, 2024.

3.2 VEGETATIVE GROWTH ANALYSIS

Meloidogyne javanica IP levels did not affect the vegetative development of ginger, either aboveground or underground (Table 1).

Table 1. Plant height, shoot fresh weight (SFW), shoot dry weight (SDW), root weight, and rhizome weight of ginger inoculated with different initial populations (IP) of *Meloidogyne javanica*

IP (eggs)	Plant height (cm)	SFW (g)	SDW (g)	Root weight (g)	Rhizome weight (g)
0	39.55^{ns}	18.90^{ns}	2.72^{ns}	41.60^{ns}	70.92^{ns}
2000	39.27	17.61	2.28	28.54	43.11
4000	41.88	17.66	2.48	33.89	48.07
6000	34.82	16.78	2.19	27.35	44.69
8000	44.75	22.64	2.96	30.58	73.97
10,000	43.73	20.15	2.70	29.19	58.75
MSD	19.92	14.54	1.92	28.37	49.70

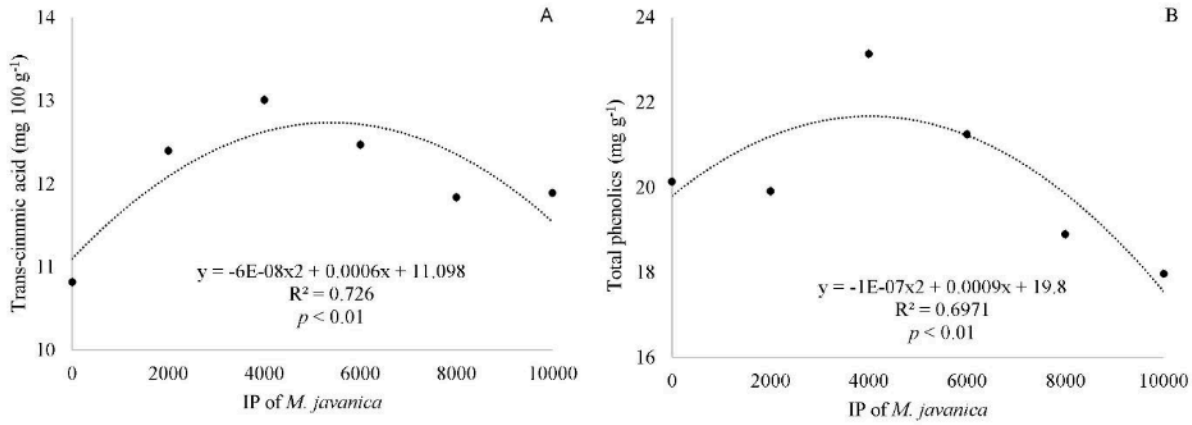
Note: ns, not significant at $p < 0.05$; MSD, minimum significant difference
Source: Own authorship, 2024.

3.3 CHEMICAL ANALYSIS

The TPC of ginger ranged from 17.97 to 23.14 mg g^{-1}, depending on nematode IP. The compounds gallic acid, *trans*-cinnamic acid, and gingerol were detected. Gallic acid contents did not differ between treatments, with values of 3.24 (IP = 0) to 3.49 mg 100 g^{-1} (IP = 10,000) (data

not shown). *trans*-Cinnamic acid and TPC had a quadratic relationship with nematode IP (Figure 2). The maximum *trans*-cinnamic acid content was estimated to be achieved with an IP of 3750 eggs; the mean content of treatments was 12.22 mg 100 g^{-1} and that of the control was 10.82 mg 100 g^{-1}. Peak TPC (21.83 mg g^{-1}) was estimated to be achieved with an IP of 4500. This value is 18% higher than the lowest experimental mean (17.97 mg g^{-1}), obtained with an IP of 10,000 eggs.

Figure 2. Levels of (A) trans-cinnamic acid and (B) total phenolic compounds in ginger rhizomes inoculated with increasing initial populations (IP) of Meloidogyne javanica. Points in figure are the mean ± standard error of three replicates



Source: Own authorship, 2024.

Nematode IP significantly influenced gingerol levels and antioxidant activity, as assessed by ABTS and FRAP methods (Table 2). However, regression equations did not provide a good fit to the data; therefore, the data were subjected to mean tests. The variables increased significantly at nematode IP levels from 2000 to 4000 eggs, compared to the highest levels and the control. At higher IP levels (6000, 8000, and 10,000 eggs), gingerol and ABTS antioxidant activity remained constant, not differing from the control ($p > 0.05$). The values of gingerol content and ABTS activity obtained with higher IP were about 43% and 38% lower, respectively, than those obtained with an IP of 4000 eggs. Similarly, FRAP activity decreased in ginger exposed to an IP greater than 4000 eggs, being nevertheless significantly higher than that of the control.

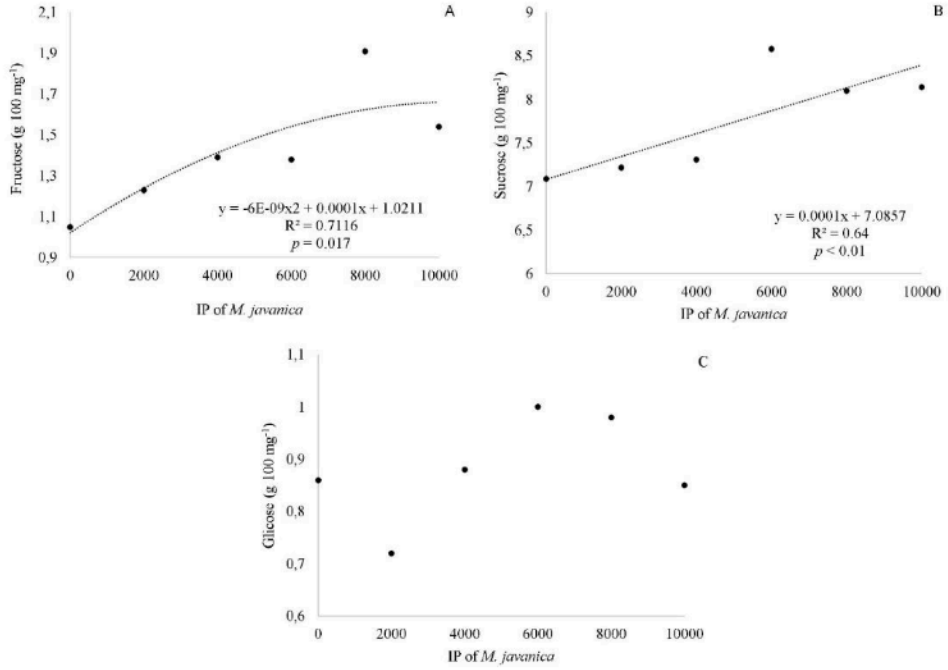
Table 2. Gingerol content and antioxidant potential, as assessed by ABTS and FRAP methods, in ginger rhizomes inoculated with increasing initial populations (IP) of *Meloidogyne javanica*

IP (eggs)	Gingerol (mg 100 g^{-1})	ABTS (µmol TE g^{-1})	FRAP (mmol TE g^{-1})
0	229.62 c	0.094 c	1.89 e
2000	301.88 b	0.138 b	3.26 b
4000	402.01 a	0.153 a	3.59 a
6000	240.02 c	0.088 c	2.38 d
8000	249.22 c	0.098 c	2.86 c
10,000	227.33 c	0.107 c	2.58 d
CV (%)	4.89	5.80	5.07

Note: Means in a column followed by the same letter do not differ significantly at $p < 0.05$ by the Scott–Knott test. TE - Trolox equivalents, CV, coefficient of variation
Source: Own authorship, 2024.

Fructose content had a quadratic relationship with IP ($p = 0.02$) (Figure 3A). As shown by the derivative of the equation, the maximum content (1.63 g 100 g^{-1}) was estimated to be achieved with an IP of 10,083 eggs. A linear increase in sucrose levels was observed with increasing IP ($p < 0.01$) (Figure 3A). Regression equations did not fit well to glucose content data, but the variable differed significantly according to treatment. The highest means (1.00 and 0.98 g 100g^{-1}) were observed in ginger exposed to an IP of 6000 and 8000 eggs, respectively. Glucose levels ranged from 0.88 to 0.72 g 100 g^{-1} for IP levels of 4000 and 2000 eggs, respectively.

Figure 3. Levels of (A) fructose, (B) sucrose, and (C) glucose in ginger rhizomes inoculated with increasing initial populations (IP) of *Meloidogyne javanica*. Points in figure are the mean of three replicates.



Source: Own authorship, 2024.

4 DISCUSSION

Was constated an increase in total *M. javanica* number in ginger as a function of increasing IP. In a previous study, *M. incognita* populations increased significantly in ginger roots with increasing inoculum levels (SUNILKUMAR, 2014). Seinhorst (1965), showed that final number of root-knot nematode had a significant linear relationship with the common logarithm of initial inoculation density. Under the conditions of the current experiment, initial inoculation density had a significant effect on final *M. javanica* density in ginger. However, in ginger peel, nematode number increased as a function of IP up to 8000 eggs, decreasing at higher IP levels (10,000 eggs). This finding can be attributed to the fact that pathogen infection causes rhizome deterioration (SUNILKUMAR, 2014), thereby affecting nematode reproduction.

The results showed that *M. javanica* IP levels had no effect on ginger growth. By contrast, Okorocha et al. (2014) found that *M. javanica* population levels of up to 1000 eggs per plant can cause significant damage and yield reductions in ginger. Nevertheless, the authors observed that shoot growth remained vigorous, even with the occurrence of various root galls caused by *M. javanica.* In another study, yield parameters, rhizome fresh weight, and rhizome dry weight decreased with increasing *M. incognita* inoculum levels; the greatest reduction in yield was observed in plants inoculated with 10,000 J2 (SUNILKUMAR, 2014). Myers et al. (2017), observed that an *M. incognita* inoculum level of 2000 eggs per plant produced a mean yield loss of 50% in ginger grown in pots for six months. Differences in results can be attributed to the experimental period; here, ginger was grown in pots for 70 days after inoculation of *M. javanica*. In addition, it is possible that, under field conditions, the influence of nematode populations on growth parameters would be greater, given the presence of other soil organisms and the fact that pots partially limit ginger growth and root development (GUO et al., 2005).

Biochemical changes in rhizomes were caused by *M. javanica* inoculation. Changes were more pronounced at lower IP levels, up to 4000 eggs. Secondary metabolite production is an important adaptive mechanism adopted by stressed plants to prevent damage (MAHAJAN et al., 2020). Thus, nematode infection can stimulate the production of phenolic compounds and, consequently, enhance the antioxidant potential of ginger rhizomes, as there is a positive correlation between these parameters (PAWAR et al., 2010). On the other hand, under severe biotic stress caused by high IP, these compounds can be translocated to other organs, such as

leaves and stems, where antioxidants are needed to maintain plant development (TAIZ et al., 2017).

Higher gingerol contents were observed in ginger subjected to lower IP levels (up to 4000 eggs), being about 75% higher than that of the control. A similar behavior was observed for antioxidant activity. Nematode-induced stress is known to lead to an increase in reactive oxygen species in plants (SHARMA; SHARMA, 2017), triggering protective effects that induce the activity of antioxidant enzymes such as phenylalanine-ammonia lyase. This enzyme is responsible for the synthesis of polyphenols, which catalyze the deamination of L-phenylalanine to *trans*-cinnamic acid, an intermediate of phenolic biosynthesis (DIXON et al., 1992). Although phenylalanine-ammonia lyase does not only synthesize polyphenols from phenylalanine, an increase in its activity might be correlated with the higher gingerol content, as a form of protection against induced stress. However, at high IP levels, gingerol content was reduced, probably related to the lower carbon availability, as discussed previously.

Information on phenol content, particularly that of gingerol, in plants infected with *M. javanica* is important. These compounds provide antioxidant, antiviral, anti-inflammatory, antimicrobial, and anticancer properties (EL SAYED; MOUSTAFA 2016; NOUR et al., 2017; KAMARUDDIN et al., 2023). Thus, extracts of ginger affected by nematodes can be used in the food, beverage, pharmaceutical, and cosmetics industries (KAMARUDDIN et al., 2023). KAMARUDDIN et al., (2023), in optimizing the conditions of supercritical carbon dioxide extraction of ginger, found maximum levels of gingerol (171.26 mg g^{-1}) and TPC (17.84 mg GAE g^{-1}), being TPC slightly lower than those observed in the control of the current study.

It was possible to observe that high IP levels (>6000 eggs) stimulated the production of soluble sugars in ginger rhizomes. It is likely that secondary metabolites were translocated from other parts of the plant to the site of infection (KAVYA et al., 2019). Furthermore, more metabolites are produced by cells at the infection site, and, as such, more carbohydrates are needed for respiration and metabolism (NAYAK; PANDEY 2016). In a previous study, sugar production was 41.21% higher in okra infected with *M. incognita* than in uninfected plants (MOHANTA; MOHANTY 2012). The total sugar content of eggplant roots infected with *M. incognita* was 90.72% higher than that of the uninfected control (NAYAK; PANDEY 2016).

Information on ginger growth and biochemical changes according to nematode population density is essential for the implementation of pathogen management strategies. The

linear increase in final nematode population with increasing IP level led to significant changes in TPC, gingerol, and soluble sugar contents, as well as antioxidant potential. However, no major impact on vegetative development was observed.

ACKNOWLEDGMENTS

The authors thank the Brazilian National Council for Scientific and Technological Development (CNPq) for the research and productivity grant awarded to CRDA (grant No. 303269/2020-0) and the doctoral fellowship awarded to MTRS (grant No. 141287/2021-7).

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