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Efficiency of Vinasse Application on Root-Knot Nematodes in Soybean

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Abstract: Vinasse is not only effectively used in pest control but also creates a conducive environment for the growth of antagonistic microorganisms. Thus, this study aimed to evaluate the potential of vinasse applied via soil for the management of root-knot nematodes in soybean culture. The experimental design was entirely random, in a factorial scheme (2 × 6), consisting of two species of nematodes, *Meloidogyne incognita* and *M. javanica*, under vinasse application at five concentrations (20, 40, 60, 80, and 100%) and one control (water), with five repetitions. Soybean plants Intacta cv. M-Soy 8644 IPRO were inoculated with 4000 eggs/juveniles of each species separately. At 60 days after the first application of vinasse, evaluations of parasitism and agronomic characteristics in soybean were performed. Stillage resulted in the highest average values for root volume and root fresh mass in plants inoculated with *M. incognita*, showing respective increases of 24.33% and 14.92% compared to plants inoculated with *M. javanica*. However, concentrations exceeding 60% had a detrimental effect on all agronomic variables of soybean. For parasitism, an interaction among the factors was observed, with a significant effect ($p < 0.01$) for most of the evaluated variables, except for the number of eggs in the soil. The concentration equivalent to 60% vinasse promoted a sharp reduction in parasitism for the two nematode species, making reproduction on plant roots unfeasible.

Keywords: Glycine max; Meloidogyne incognita; Meloidogyne javanica; wastewater; sugar-alcohol residue

1. Introduction

Soybean (*Glycine max* (L.) Merrill) has been the most prominent crop across all sectors of agricultural activity in Brazil. In the 2022/2023 harvest, Brazil achieved a new production

record with 154,603.4 million tons, marking a 0.9% increase compared to the previous record set during the 2020/2021 harvest [1]. Increasing agricultural productivity is a challenging task, mainly due to the presence of biotic factors, such as phytonematodes, which induce significant limitations in crop production and development [2,3].

In Brazil, among the most common species in soybean cultivation are *Meloidogyne javanica* (Chitwood, 1949) [4] and *M. incognita* (Chitwood, 1949) [5], which are considered key nematode species for cultivation [6]. As sedentary endoparasites, with a polyphagic habit and wide geographical distribution, they present survival mechanisms such as anhydrobiosis, which makes it impossible to eradicate them. In this way, several integrated control methods are used, mainly chemical nematicides, due to their efficiency and speed of control [7,8]. However, they have faced stringent regulations worldwide due to their high toxicity, risk of environmental contamination when used inappropriately, and high cost of their production [9,10].

In this way, alternative products capable of controlling phytonematodes and maintaining agricultural production have been sought, in addition to contributing to sustainable agriculture [11,12]. In this context, vinasse also has high value as a biofertilizer. It is a byproduct from sugarcane processing, distillation, and fermentation for ethanol production. It is also considered a nutritional source due to the presence of nitrogen, carbon, potassium, calcium, boron, phosphorus, magnesium, and sulfate, among others, in addition to organic matter [13–15]. Several studies indicate that vinasse increases the biological activity of the soil, which favors potential antagonistic microorganisms and promotes the formation of organic substances such as volatile fatty acids, which can have antimicrobial action [16,17].

Some studies have demonstrated that the efficiency of vinasse in pest control is attributed to the presence of organic matter and total sugars, which are favorable to the development of antagonistic microorganisms [18,19]. Despite these advantages, there is still a limited amount of research on the use of vinasse to control nematodes. Therefore, the goal of the current study was to assess the impact of vinasse applied to the soil in the management of *M. incognita* and *M. javanica* in soybean cultivation.

2. Materials and Methods

2.1. Collection and Preparation of Nematode Inocula and Acquiring Vinasse

The inoculum was collected from commercial soybean crops in the municipality of Bom Jesus, Piauí, which exhibited visible symptoms due to nematode activity. The extraction process involved liquefaction (immersing in 300 mL of water with 5 mL of sodium hypochlorite), followed by sieving and centrifugation in a sucrose solution, following the method described in reference [20]. The nematodes were quantified using a metallized Peters slide under an optical microscope.

Once collected, the nematodes were euthanized in a water bath (55 °C for 4 min) (Solidsteel, Araras, Brazil) and preserved in a fixed solution of triethanolamine and formalin. Subsequently, they were identified through examination of their perineal configuration, as outlined in reference [21], and their identity was confirmed using isoenzyme electrophoresis (esterase), following the procedure detailed in reference [22].

After identification, the gall nematodes (*M. incognita* and *M. javanica*) were introduced to tomato plants (*Solanum lycopersicum*) of the Santa Cruz variety. These plants were cultivated in pots with a substrate capacity of 5 dm^{-3} and were maintained in a greenhouse for a period of fifty-five days to allow for multiplication.

Vinasse was obtained from small distilleries in the municipality of Palmeira-PI, Brazil. The physicochemical composition of the pure vinasse used in the assay presented the following characteristics: N (0.36 kg m^{-3}); P_2O_5 (0.13 kg m^{-3}); K_2O (1.43 kg m^{-3}); Ca (0.41 kg m^{-3}); Mg (0.21 kg m^{-3}); S (1.28 kg m^{-3}); organic matter (18.49 kg m^{-3}); Fe (53.15 ppm); Cu (5.84 ppm); Zn (1.07 ppm); Mn (3.21 ppm); pH in water (3.8); DBO (25,285.00 mg L^{-1}); DQO 38,785.00 mg L^{-1}); and CE (8.12 ds m). To ensure optimal preservation, the product was stored in glass jars and placed in a refrigerator at 4 °C until the time of application.

2.2. Location and Experimental Setup

The experiment was conducted in a greenhouse and in the Laboratory of Plant Pathology at the Campus Professora Cinobelina Elvas of the Federal University of Piauí, located in the municipality of Bom Jesus.

To conduct the experiment, soil was collected from the 0–20 cm layer in a soybean production area, and it was classified as dystrophic red latosol with a clayey–sandy texture. The substrate was a mixture of soil, sand, and manure in a 3:2:1 ratio. This mixture was presterilized in a vertical autoclave (Prismatec, Piracicaba, Brazil) at a temperature of 120 °C and a pressure of 1.05 kg cm^2 for two hours. After sterilization, the substrate was placed in plastic containers with a capacity of 5.0 dm^3 on a workbench. Following analysis, the substrate exhibited the following characteristics: dystrophic red latosol with a medium-sand texture; pH = 6.2 (H_2O); organic matter = 15.8 (g kg^{-1}); sand = 710 (g kg^{-1}); silt = 50 (g kg^{-1}); clay = 240 (g kg^{-1}); Ca^{+2} = 2.6 (cmolc dm^{-3}); Mg^{+2} = 1.3 (mg dm^{-3}); P exchangeable = 108 (mg dm^{-3}); K^+ = 88.0 (mg dm^{-3}); and Zn = 6.7 (mg dm^{-3}).

The experimental design consisted of 60 plots, organized in a completely random manner with five repetitions, following a factorial scheme (2 × 6). The first factor involved two nematode species (*M. incognita* and *M. javanica*), and the second factor encompassed five concentrations of vinasse, measured at 100 mL per pot (20, 40, 60, 80, and 100%), as detailed by Ranzani [23], along with a control group that used 100 mL of water. The 100% concentration corresponds to 100 mL of pure vinasse, and the other concentrations were formulated based on it.

The sowing was performed with five seeds of the Intacta M-Soy 8644 IPRO cultivar in each pot. After the seventh day of germination, thinning was carried out, leaving only two plants per pot, which constituted the experimental unit of the experiment. Seventy-two hours after thinning, a suspension containing 4000 eggs/juveniles of the *M. incognita* and *M. javanica* species was inoculated into the soybean plants. The 10 mL suspension of the inoculum was evenly distributed, using a pipette, into three holes, each with a depth of 3.0 cm and spaced 2.0 cm apart around the hypocotyl of the plants.

After inoculation, the plants were maintained for 72 h with a single watering event, supplying 100 mL daily. After this initial period, irrigation was adjusted to 200 mL and split into two intervals per day (9 a.m. and 4 p.m.), except on the days when treatments were applied.

Ten days after inoculating the plants with nematodes, treatments were administered by spiking soils with various concentrations of vinasse (20, 40, 60, 80, and 100%), alongside a control using water. The concentrations were prepared in a 100 mL beaker, homogenized, and subsequently transferred to disposable cups, with each cup receiving the full 100 mL of the respective concentration. These concentrations were achieved by diluting the vinasse in distilled water and were prepared only 2 h prior to applying the treatments to the soil.

Throughout the experiments, environmental conditions were closely observed, with ambient temperature and relative humidity data monitored using a digital thermohygrometer, while soil temperature was gauged using a digital soil thermometer (AMTAST, Belo Horizonte, Brazil). The average ambient temperature inside the greenhouse ranged between 25 and 35 °C, with the soil temperature in the pots ranging from 23 to 32.5 °C. Relative air humidity levels between 23 and 45% were recorded.

2.3. Evaluation of Agronomic and Parasitism Characteristics

The evaluations were carried out after 60 days of vinasse application. For the agronomic variables, root fresh mass (g), root length (cm), and root volume (cm^3) were measured. Root volume was calculated by the difference in the volume of water displaced in the specimen (1000 mL) after root immersion and considering 400 mL as the standard volume. Before the above measurements, the roots were washed in running water to remove aggregates from the soil and dried on paper towels.

For the parasitism variables, the number of galls (NG) was counted using a magnifying glass. Additionally, the population of nematodes in the plant roots was determined,

considering both the number of eggs in the roots (ER) and the number of juveniles in the roots (JR). This quantification was achieved through a process of liquefaction (immersed in 300 mL of water with a solution of sodium hypochlorite (NaOCl) at 1% for 30 s, in low rotation), sieving, and centrifuging in sucrose solution according to the method proposed by Hussey and Barker [24], modified by Bonetti and Ferraz [25]. The nematodes were quantified on a metallized Peters slide under an optical microscope (40× magnification) (Zeiss, Oberkochen, Germany).

For the nematode population in the soil, the number of soil eggs (ES) and the number of soil juveniles (JS) were quantified from soil samples of 300 cm^3 using the sieving technique combining centrifuge fluctuation (Novatecnica, Piracicaba, Brazil) with sucrose solution, as described by Jenkins [26]. Furthermore, the reproduction factor (RF) of the parasite was calculated using the method proposed by Oostenbrink [27], where RF = 0: immune (I); $0 < RF \leq 1$: resistant (R); and RF > 1: susceptible (S). Additionally, the number of nematodes per gram of root (NGR) was determined, as defined by the ratio of the total number of nematodes in the roots to the fresh mass of the roots in grams.

2.4. Statistical Analysis

Data on agronomic characteristics and parasitism were submitted to the analysis of normality by the Shapiro–Wilk test and analysis of variance by the F test ($p < 0.05$). The means of the variables for qualitative treatments (nematode species) were compared by the Tukey test ($p < 0.05$) using the statistical program "R" version 4.3.1 [28]. The averages of the quantitative treatment variables (vinasse concentrations) were fitted in regression equations using Sigmaplot 11.0 software. For analysis of variance in the parasitism data, the values were transformed into Log (x + 1). The values presented in the tables and graphs are the original means.

To discriminate the treatments as a function of the variables, canonical discriminant analysis was performed, represented by a biplot graph constructed for the first two canonical variables. Furthermore, ellipses with 95% confidence were constructed to detect significant differences ($p < 0.05$) between treatment groups. All analyses were performed with R software, version 4.3.1 [28]. Canonical discriminant analysis was performed using the candisc package [29].

3. Results

3.1. Agronomic Characteristics

By summarizing the analysis of variance, there was no significant interaction ($p < 0.05$) between the nematode species and vinasse concentrations for the variables of the soybean root system (Table 1). However, for the individual effect of the nematode species factor, there was a significant difference in volume and root fresh mass. The averages of all the variables of the root system were significantly different as a function of vinasse concentration.

Table 1. Summary of ANOVA (mean squares and F test) for agronomic variables in soybean plants inoculated with *M. incognita* and *M. javanica* under varying vinasse concentrations (CCv).

Source of Variation	Agronomic Variables		
	Root Length	Root Volume	Root Fresh Mass
(NS)	0.03 ^{ns}	315.10 **	140.11 *
(CCv)	406.04 **	129.81 **	274.71 *
NS x CCv	73.42 ^{ns}	15.81 ^{ns}	9.73 ^{ns}
C.V. (%)	16.06	26.27	20.74

** significant to 1%; * significant to 5%; ^{ns} nonsignificant; C.V. (%)—coefficient of variation.

The development of the root system was influenced by the presence of *M. incognita* and *M. javanica*, with distinct responses between species for the variables root volume (RV) and root fresh mass (RFM). The best protection performance of vinasse was observed for RV and FRM in plants inoculated with *M. incognita*, with respective percentages of 24.33% and 14.92%, in comparison to plants inoculated with *M. javanica* (Figure 1).

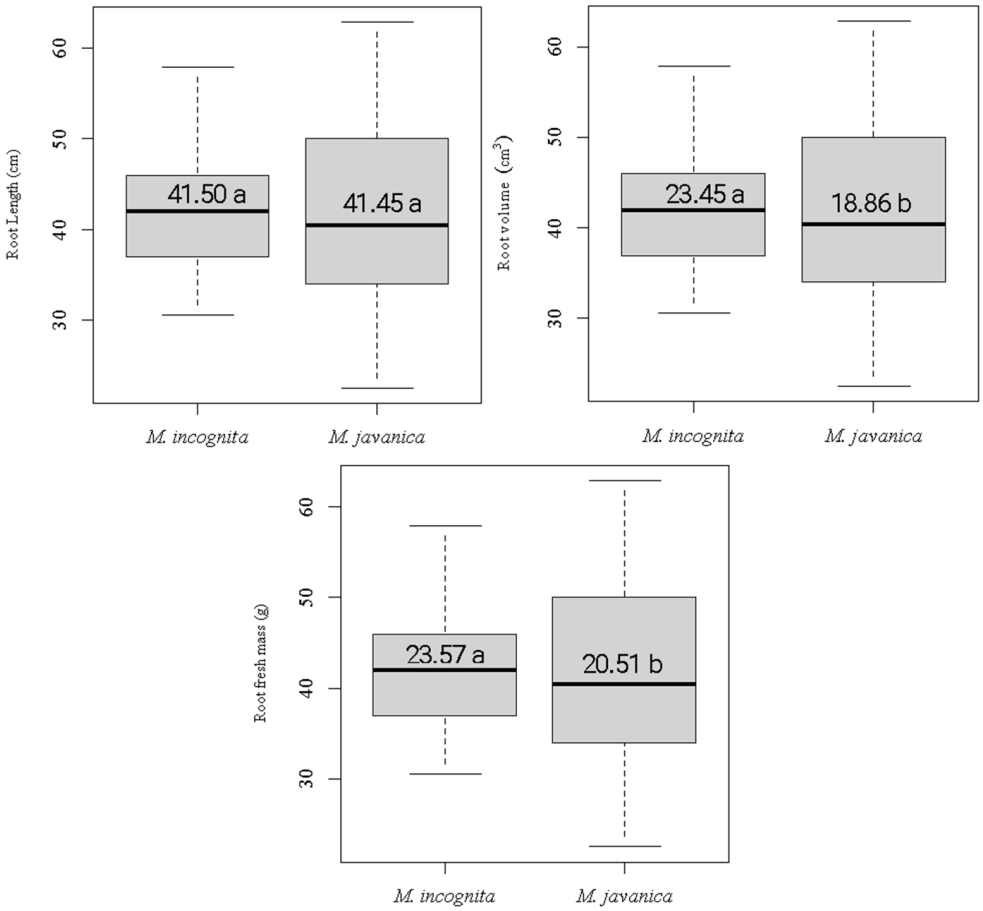

Figure 1. Average values for the agronomic variables of soybean plants inoculated with *M. incognita* and *M. javanica* in relation to the concentrations of vinasse. Averages followed by the same letter among *Meloidogyne* species do not exhibit statistically significant differences as determined by Tukey's test at 5% probability.

For the effect of vinasse concentration on the variables of the root system, a quadratic polynomial regression model was fitted (Figure 2). Regarding the root length (Figure 2A), the best stillage concentration (69.11%) was estimated, which resulted in an increase of 56.68% in the mean of this variable. For the root volume (Figure 2B), the maximum response was obtained with 76.63% vinasse, reaching a maximum increase of 108.67%. The greatest increases in root fresh mass (Figure 2C) were observed at a concentration of 100%, resulting in a 99.34% increase in RFM.

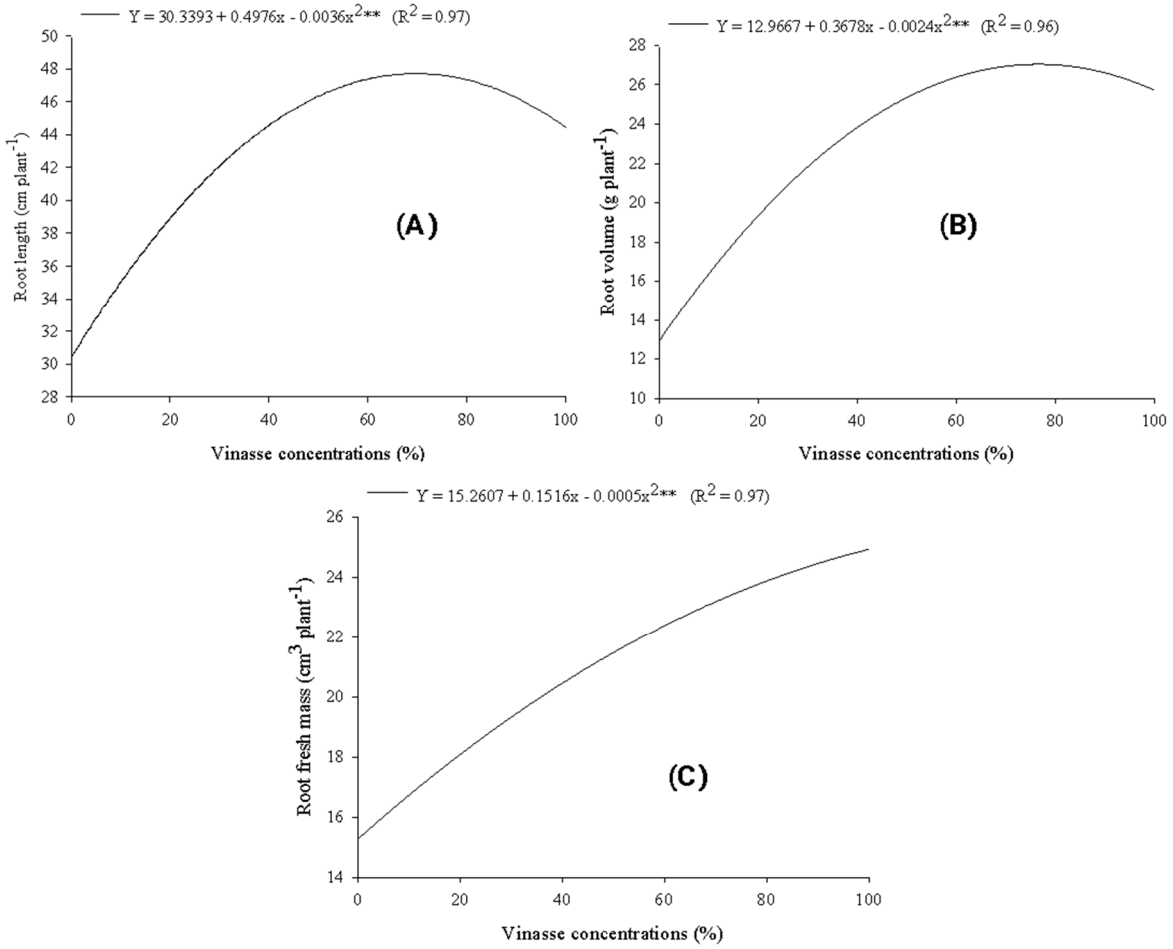

Figure 2. Root length (**A**), root volume (**B**), and root fresh mass (**C**) of soybean plants, according to the concentrations of vinasse in the management of *M. incognita* and *M. javanica*. ** Significant at 1%.

3.2. Characteristics of Parasitism

According to the results of the analysis of variance for the parasitism variables, there was an interaction between the nematode species and vinasse concentrations. This interactive effect was significant ($p < 0.01$) for most of the analyzed variables, except for the number of eggs in the soil. There was a significant effect of the isolated factors for all variables, except the species factor for the number of nematodes per gram of root (Table 2).

Table 2. Summary of the analysis of variance (mean squares and F test) for the parasitism variables of *M. incognita* and *M. javanica* in soybean plants, according to nematode species (NS) and vinasse concentrations (CCv).

Variation Source	Parasitism Variables						
	JR	NGR	JS	NG	ER	ES	RF
(NS)	17,957.40 **	0.57 ^{ns}	25,833.75 **	728.01 **	7216.06 **	58.01 **	0.0026 **
(CCv)	5296.22 **	246.13 **	11,773.78 **	1711.27 **	7242.70 **	28.49 **	0.0043 **
NS x CCV	833.56 **	19.61 **	3135.91 **	385.61 **	4775.78 **	3.37 ^{ns}	0.0004 **
C.V. (%)	25.5	29.01	11.58	13.51	17.06	23.71	18.4

** Significant to 1%; ^{ns} nonsignificant; C.V. (%)—coefficient of variation. JR—juveniles in root; NGR—nematodes per gram of root; JS—juveniles in soil; NG—number of galls; ER—eggs in root; ES—eggs in soil; RF—reproduction factor.

There were significant reductions in juvenile variables in the roots, juveniles in the soil, number of galls, and reproduction factor, i.e., 49.34, 59.26, 26.67, and 32.91%, respectively,

in the parasitism of the species *M. javanica* compared to *M. incognita*. For the variables, eggs in the root and eggs in the soil, a significant difference was also observed, with reductions of 56.19 and 67.39%, respectively, for the species of *M. incognita* with respect to *M. javanica* (Figure 3).

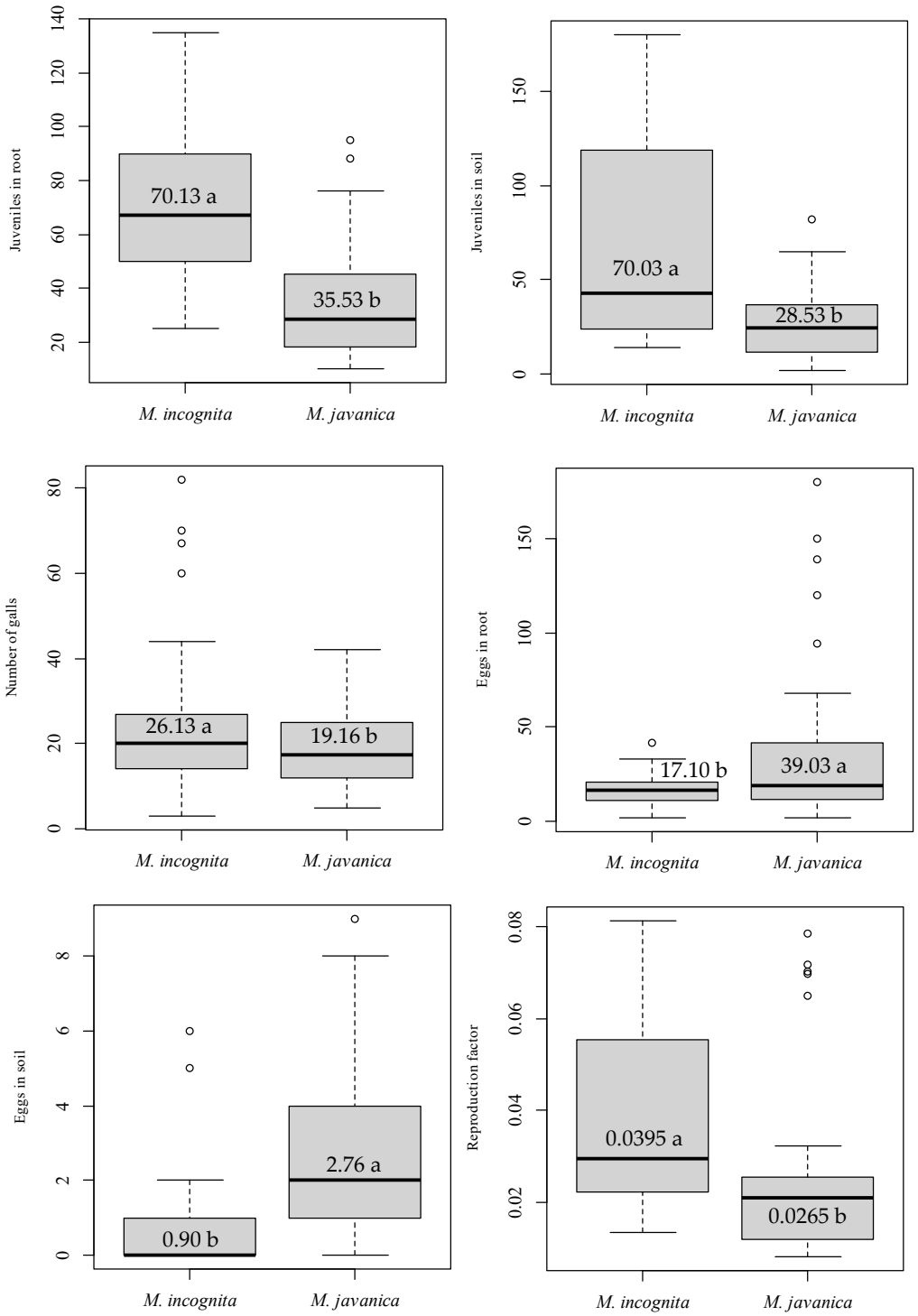

Figure 3. Average values for the parasitism variables of *M. incognita* and *M. javanica* in soybean plants in relation to the concentrations of vinasse. Averages followed by the same letter among *Meloidogyne* species do not exhibit statistically significant differences as determined by Tukey's test at 5% probability.

The number of juveniles in the roots (Figure 4A) and nematodes per gram of roots (Figure 4B) of *M. incognita* and *M. javanica* were adjusted to the decreasing exponential model. In the number of juveniles in the roots and nematodes per gram of roots of *M. javanica*, the lethal concentration (LC50), which corresponds to the concentration necessary to cause 50% mortality of nematodes, was 9.16 and 5.27%, respectively. However, maximum reductions in these variables, with values of 60.27 and 84%, respectively, were observed for the effect of 20% vinasse.

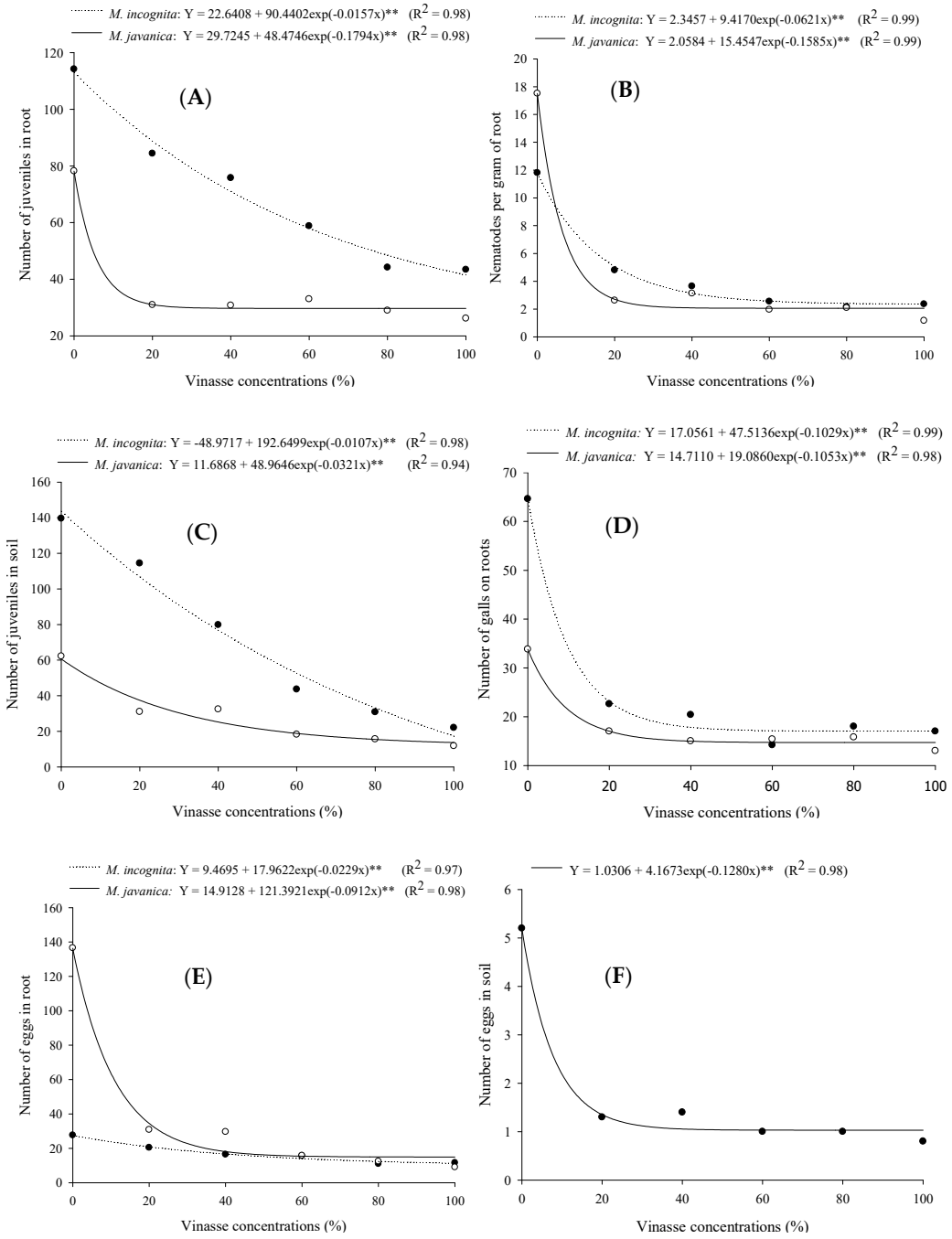

Figure 4. Number of juveniles in root (**A**), nematodes per gram of root (**B**), number of juveniles in soil (**C**), number of galls on roots (**D**), number of eggs in root (**E**), and number of eggs in soil (**F**) of *M. incognita* and *M. javanica* in soya plants, depending on the nematode species and concentrations of vinasse. ** Significant at 1%.

For *M. incognita*, the lethal concentrations (LC50) to reduce 50% of the number of juveniles in the roots (Figure 4A) and nematodes per gram of roots (Figure 4B) were estimated at 62.50 and 15.77% vinasse, respectively. Reductions of 63.34 and 73.38% in the number of juveniles in the roots and nematodes per gram of roots were obtained at concentrations of 100% and 40% vinasse, respectively.

The number of juvenile *M. incognita* and *M. javanica* in the soil was also exponentially reduced with vinasse concentration (Figure 2C). *M. incognita* had the number of juveniles in the soil reduced by 50% with the addition of vinasse at a concentration of 43.61%. Vinasse at a concentration of 100% was able to reduce 88.09% of *M. incognita* juveniles in the soil. Nevertheless, greater sensitivity of nematodes in the soil to vinasse was observed for the species of *M. javanica*, which suffered a 50% reduction in the control value (60.65 in 100 cm^{-3} of soil) by using vinasse at a concentration of 30.09%, reaching a maximum percentage of reduction (68.97%) with 60% vinasse.

The number of galls (Figure 4D) and eggs in the root (Figure 4E) for *M. incognita* and *M. javanica* were exponentially reduced in response to vinasse exposure. For *M. javanica*, a reduction in the mean of these variables by 50% was observed with stillage concentrations of 20.57 and 9.04%, respectively. The maximum reduction in these variables, which were the respective values of 55.64 and 86.74%, occurred with a 40% concentration of stillage for both variables. However, for *M. incognita*, the number of galls and eggs in the root was reduced by 50%, with stillage at concentrations of 11.06 and 62.98%, respectively. To achieve the maximum percentage reduction in these variables, which were 72.38% and 58.85%, applications of stillage at concentrations of 40% and 100%, respectively, were necessary.

The number of eggs in the soil of both *M. incognita* and *M. javanica* exhibited an exponential decrease with increasing vinasse concentrations, as depicted in Figure 4F. A 50% reduction in this variable was achieved with a vinasse concentration of 7.63%. However, the maximum reduction of 73.98% was observed only when 20% stillage was added. According to the analyses of the nematode reproduction factor (FR) of the galls in soybean plants, the application of vinasse induced a significant reduction in the reproduction of *M. incognita* and *M. javanica* (Figure 5). For *M. javanica*, vinasse application at 9.26% exponentially decreased the RF value of 0.071 of the control by 50%. It reached a maximum percentage of reduction (69.02%) with vinasse from 20%. For *M. incognita*, a higher concentration of vinasse (41.43%) was needed to reduce the RF of the control (0.073) by 50%. However, a more suppressive reduction (72.16%) in this variable was observed with vinasse at a concentration of 100%.

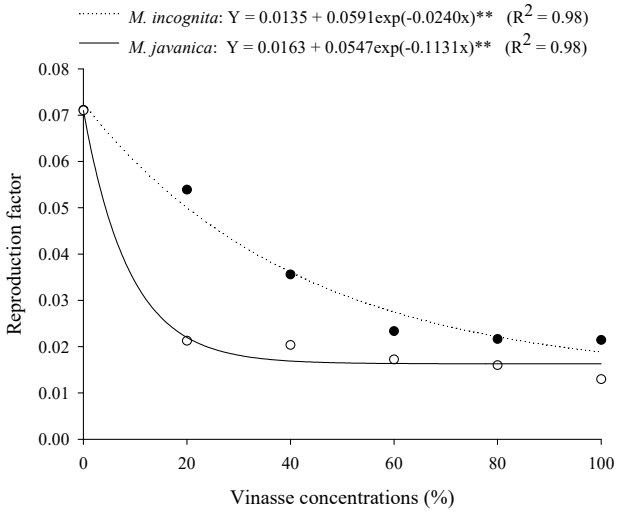

Figure 5. Reproduction factor of *M. incognita* and *M. javanica* in soybean plants, according to nematode species and vinasse concentrations ** significant at the 1% level.

By canonical discriminant analysis for *M. incignita*, it was observed that the first two canonical variables explained 97.5% of the total variance contained in the original variables (Figure 6). Among the evaluated treatments, the highest averages for the variables (juveniles in roots, juveniles in soil, number of galls, eggs in roots, eggs in soil, and reproduction factor) of parasitism of *M. incognita* in soybean plants were observed in the control treatment. Concentrations of 60% vinasse were efficient in reducing parasitism of *M. incognita*, in addition to providing better root development of soybean plants with significant increases in the root length, root volume, and root fresh mass variables.

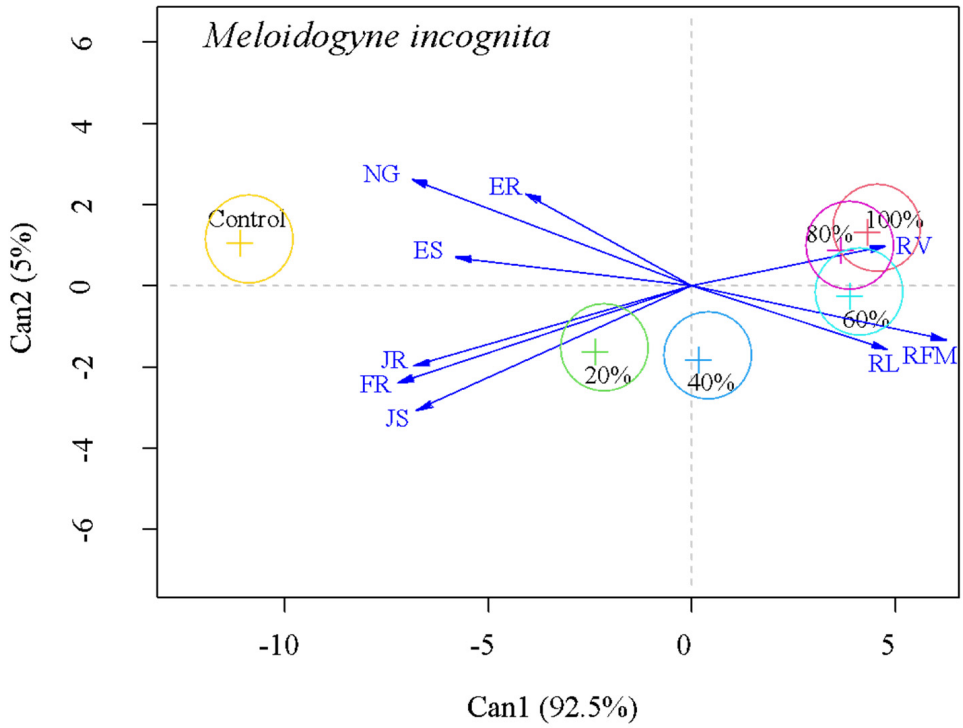

Figure 6. Graphical representation of the canonical discriminant analysis (canonical variables Can1 and Can2) of the soybean agronomic variables: root length (RL), root volume (RV), and root fresh mass (RFM) and of the parasitism variables of *M. incognita*: juveniles in root (JR), juveniles in soil (JS), number of galls (NG), eggs in root (ER), eggs in soil (ES), reproduction factor (RF), as a function of vinasse concentrations (%).

By graphical representation of the canonical discriminant analysis for *M. javanica*, it was observed that the first two canonical variables explained 96.8% of the total variance contained in the original variables (Figure 7). The control treatment showed the highest parasitism values of *M. javanica* parasitism in soybean plants, with the highest averages for nematodes per gram of root, juveniles in soil, number of galls, eggs in root, eggs in soil and reproduction factor. The parasitism of *M. javanica* in soybean plants was significantly reduced by vinasse applications, with an emphasis on concentrations from 60%, also providing an increase in root length, root volume, and root fresh mass of soybean plants.

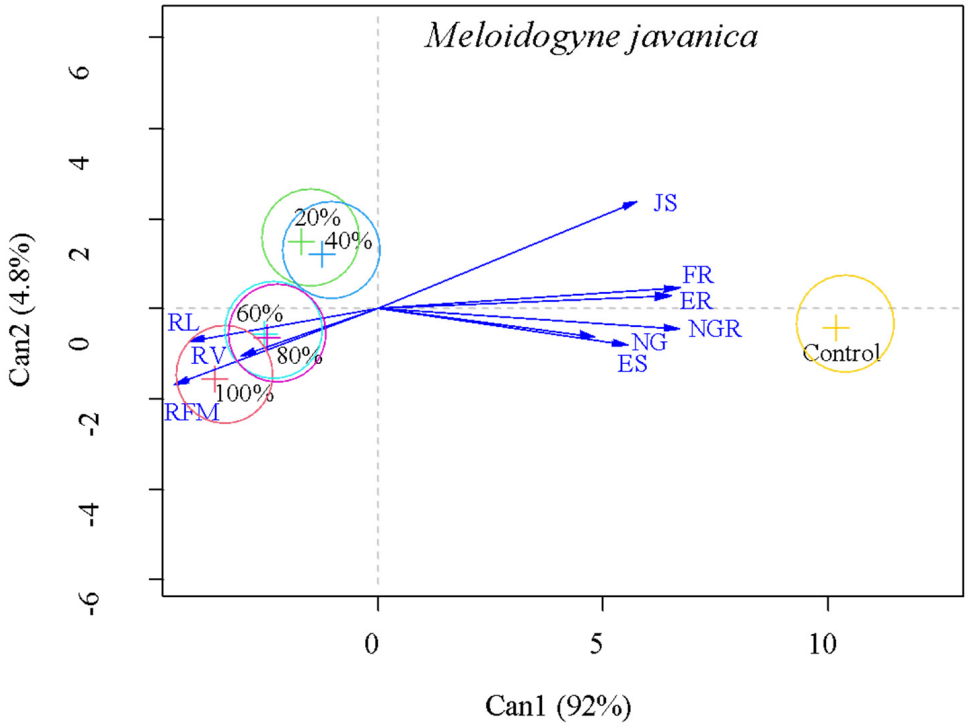

Figure 7. Graphical representation of the canonical discriminant analysis (canonical variables Can1 and Can2) of the soybean agronomic variables root length (RL), root volume (RV), and root fresh mass (RFM) and of the parasitism variables of *M. javanica* nematodes per gram of root (NGR), juveniles in soil (JS), number of galls (NG), eggs in root (ER), eggs in soil (ES), and reproduction factor (RF) as a function of vinasse concentration (%).

4. Discussion

The results from this study indicate that when vinasse was added to the soil, irrespective of the concentration, there was more pronounced root system development in plants inoculated with *M. incognita* than in those inoculated with *M. javanica*. This observation is in line with the findings of Asmus [30], who reported similar trends. The author noted that the most significant losses in soybean production in Brazil, estimated to be approximately 20 to 30%, are primarily attributed to *M. incognita*. The losses associated with *M. javanica* are approximately 18%.

Hence, there is a need to explore various management strategies to mitigate the impact of parasitism on crops. Some alternative products used in agriculture for disease management may not directly harm pathogens but can enhance plant protection through the induction of systemic resistance. This resistance can be acquired or induced by elicitors, leading to the production of chemical compounds such as phytoalexins through enzymatic activity. This fact has already been observed by Guimarães et al. [31], with foliar application of methyl jasmonate and potassium silicate in sugarcane, against the parasitism of *M. incognita* and *Pratylenchus zeae*.

Salicylic acid has also been found to have a similar impact, reducing the presence of *M. exigua* in coffee trees [32]. In a similar way, vinasse can enhance the plant's defense system by making essential nutrients more accessible, directly contributing to the enhancement of soil chemistry [33]. Furthermore, the decomposition of vinasse leads to the release of toxic compounds such as butyric acid and volatile fatty acids [34], which play a role in diminishing soil pathogens.

The addition of vinasse to the soil, regardless of the species of inoculated nematodes, positively affected root development, as indicated by increased length, volume, and fresh root mass. Given the results obtained for these parameters, we understand that the mineral and organic potential of stillage has provided improvements in the chemical properties

of the soil, influencing nutrition and greater plant resistance. Similarly, Bebé et al. [35] reported that adding stillage induced modifications in the chemical and physical properties of the soil, such as increased pH, increased nutritional availability, and cation exchange capacity. Martins et al. [36] also noted positive increases in corn crop production by stillage application because the potassium content increased proportionally with the dose of stillage, favoring physiological changes in the plant.

However, it was observed that the applications of vinasse at concentrations above 69.11 and 76.63%, root length and root fresh mass were negatively affected. This inhibitory effect of stillage on the vegetative development of crops, due to excessive doses, has already been highlighted [37]. In this context, Freire and Cortez [37] indicated that excessive doses stillage increased soil pH, which induced a release of high levels of soluble salts, which are harmful to the crop.

The parasitism variables of *M. incognita* and *M. javanica* significantly decreased as a function of vinasse concentration. Stillage has large amounts of elements that can become undesirable pollutants to the environment, especially due to the presence of phosphate and nitrate [38]. Nevertheless, when applied, taking into consideration the characteristics of each type of soil, it can positively interfere with the physical–chemical quality [39]. In addition to neutralizing pathogenic activities, such as nematodes, phenolic compounds such as tannic acid and humic acid have a direct impact on nematodes. They interfere with the central nervous system of nematodes, leading to disorientation and impaired movement. This interference ultimately reduces the nematodes' ability to parasitize the host plant [40].

Several studies have emphasized the efficiency of vinasse on pathogens by facilitating the decomposition of organic matter, thereby releasing volatile fatty acids that exhibit detrimental effects on both fungi and nematodes [19,41]. At the same time, vinasse serves as a nutritional source for the multiplication of antagonistic microorganisms, which indirectly enhances the control of plant pathogens [42,43]. However, there is little information that explains the direct action of vinasse on phytonematodes. It is believed that the efficiency of stillage is associated with the proliferation of natural enemies and the activity and biodiversity of nematodes, phytoparasites or not, in the ecosystem [44].

These findings suggest that vinasse has the potential to be effective against nematodes in the soil, particularly when dealing with new generations of these pests. Matos et al. [45], evaluating the effect of stillage on fertigation, nematode communities, and soil chemical attributes, found a reduction in the total number of nematodes in relation to the non-irrigated area. This study also stated that the population dynamics of nematodes are dependent on soil chemical characteristics. Similarly, Pedrosa et al. [46] found a decrease in the number of eggs and juveniles of gall nematodes with an increase in the rate of vinasse added to cane.

Consequently, the introduction of organic matter into the soil by vinasse enables the enhancement of plant nutrition. Nutrients in this organic matter play diverse roles in plant metabolism, contributing to plant growth and development and influencing plant resistance mechanisms against pathogens.

5. Conclusions

The use of vinasse in soil results in a notable reduction in the populations of both *M. incognita* and *M. javanica* in soybean cultivation. The nematicidal impact of vinasse correlates directly with the quantity applied, effectively targeting both species of gall-forming nematodes. Notably, the 60% concentration proved beneficial for fostering root system growth and development, as well as curbing parasitic infestation by gall-forming nematodes in soybean plants.

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