Current asparagus (*Asparagus officinalis* L.) production and vermicompost usage in Atenco, State of México, and potential of leachates for rhizome rot control

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ABSTRACT
Objective: To describe the current, agronomic, and socioeconomic situation of the production of asparagus (*Asparagus officinalis* L.) and the use of vermicompost, and to determine if vermicompost leachates can suppress asparagus rhizome rot caused by *Fusarium proliferatum*, in the municipality of Atenco, State of Mexico.
Design/Methodology/Approach: Asparagus producers from the municipality of Atenco were surveyed. Additionally, two greenhouse experiments were carried out using soil from the same area. A completely randomized design was used to evaluate 14 treatments. Non-parametric statistical tests were used to analyze the results.
Findings/Conclusions: Although it faces organizational and technical limitations, asparagus is currently a profitable crop for the producers of Atenco. The intensive use of agrochemical inputs characterizes the production system. However, an increasing number of producers have begun to explore and implement the use of biological amendments as a strategy to transition toward a more sustainable production model. Vermicompost leachates made from sheep and cow manure had the potential to promote asparagus growth in the absence of pathogens; however, they did not reduce the rhizome damage caused by *F. proliferatum*.

Keywords: Vermicompost leachates, *Fusarium proliferatum*, asparagus, rhizome rot.

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INTRODUCTION

Asparagus (*Asparagus officinalis* L.) is a valuable crop grown worldwide. It is valued for its nutritional properties and economic profitability. Mexico ranks third in global asparagus production and holds a significant share of the world export market, with the United States as the primary destination (SIAP, 2024). Asparagus production faces various agronomic challenges, including the rhizome rot caused by fungi of the genus *Fusarium*. Rhizome rot

impacts crop development and yield. Water stress and nutritional deficiencies increase the susceptibility of asparagus crops to this phytopathogen, posing a significant challenge for producers due to its detrimental effects on crop development and yield (Elmer, 2001; González-Cruces *et al.*, 2024).

Sustainable crop management strategies are required to tackle these challenges. Donohoe (2018) proposed the use of organic amendments, such as vermicompost and its by-products. Vermicompost leachates —by-products of the vermicomposting process— contain a high concentration of nutrients, humic and fulvic acids (Ávila, 2015), growth-promoting bacteria (Gudeta *et al.*, 2021), and bioactive compounds that promote plant growth. Vermicompost leachates are known to enhance soil health and suppress diseases caused by soilborne pathogens (Nadana *et al.*, 2020). While these leachates have demonstrated beneficial effects in various crops, including tomato and eggplant (Ollen, 2016; Sundararasu and Alagarmalai, 2014), their efficacy against asparagus rhizome rot has not yet been investigated.

The municipality of Atenco, State of Mexico, has adopted asparagus production as a strategy to diversify its agricultural sector, particularly on the reclaimed soils of the former Lake Texcoco. In this context, the integration of agroecological practices —such as the application of vermicompost leachates— offers a sustainable approach to enhance crop productivity and mitigate the impact of rhizome rot. This study describes the current situation of asparagus production in the municipality of Atenco. It includes the results of two experiments focused on whether or not vermicompost leachates from different organic matter sources can suppress the infection caused by *Fusarium proliferatum*, one of the causal agents of asparagus rhizome rot (Elmer, 2001; Baayen *et al.*, 2000; Hamel *et al.*, 2005).

MATERIALS AND METHODS

Questionnaire

A 63-item questionnaire was administered to a randomized sample of eight asparagus producers in the municipality of Atenco. This sample represented 50% of the total producers in the area. The questionnaire was divided into the following thematic sections: personal and demographic information, plot characteristics, general asparagus cultivation practices, management of asparagus rhizome rot and the use of vermicompost leachates, production and harvesting costs, and commercialization.

Experimental evaluation of vermicompost leachates

Two experiments were conducted to evaluate the potential of vermicompost leachates from sheep, horse, and cow manure to control *Fusarium proliferatum*, the causal agent of asparagus rhizome rot.

Vermicompost leachates production

Vermicomposting beds with a 3% slope for drainage and collection were used to produce the leachate (Domínguez and Pérez, 2011). Redworms (*Eisenia foetida*) were fed with pre-composted sheep, cow, and horse manure in separate beds. The beds were stirred

and irrigated during the six-week pre-composting process to eliminate potentially toxic components for the worms and ensure the quality of the leachate (Acosta *et al.*, 2013).

Establishment of the experiments

Fourteen treatments (Table 1) were established in two independent experiments to evaluate the effect of the application of vermicompost leachates (VCL) before and after the transplant of asparagus plants, with and without inoculation of *Fusarium proliferatum*. The experiment also included two control treatments: one inoculated but without VCL application, and a non-inoculated control that received neither inoculation nor VCL.

The treatments were applied based on a completely randomized experimental design with ten repetitions. The experiment was conducted under growing chamber conditions, with semi-controlled temperature, inside a greenhouse located at the Colegio de Postgraduados - Campus Montecillo, Texcoco, State of Mexico.

Sowing and leachate application

Seeds of the Sulken genotype of *Asparagus officinalis* L. were used in the experiment. Seeds were disinfested with 5% sodium hypochlorite and rinsed with sterile distilled water (Gómez, 2020). Subsequently, they were hydrated for 24 hours. Sowing was carried out in 200-cavity trays with peat and vermiculite substrates (2:1) and sterilized three times at 15 lb/in^2 for one hour (Nongthombam *et al.*, 2022). Three months after germination, the seedlings were transplanted into 2-L plastic bags.

Two phases of leachates were applied as follows: pre-transplant (20 mL per cavity) and post-transplant (200 mL per plant per month, for six months). Control treatments only received distilled water.

Table 1. Treatments applied to asparagus plants (*Asparagus officinalis* L.) in two independent experiments.

Treatment	Source of vermicompost leachate	Inoculation with Fusarium proliferatum	Pre-transplant application (in germination trays)	Post-transplant application
PHI	Horse	YES	YES	YES
HI	Horse	YES	NO	YES
PHNI	Horse	NO	YES	YES
HNI	Horse	NO	NO	YES
PSI	Sheep	YES	YES	YES
SI	Sheep	YES	NO	YES
PSNI	Sheep	NO	YES	YES
SNI	Sheep	NO	NO	YES
PCI	Cow	YES	YES	YES
CI	Cow	YES	NO	YES
PCNI	Cow	NO	YES	YES
CNI	Cow	NO	NO	YES
IC	INOCULATED CONTROL			
NIC	NON-INOCULATED CONTROL			

* Six applications were made per treatment, one each month.

Inoculation

The treatments were inoculated with *Fusarium proliferatum* strain P3RD, reactivated in PDA medium with oxytetracycline. After 10 days of growth in Petri dishes, a suspension was prepared with Tween 80 (0.01%) and adjusted to 1×10^6 conidia/mL. A sterile syringe was used to apply 8 mL of this suspension to the rhizome of each plant, immediately after the foliage was pruned (Miguel *et al*., 2018; González-Cruces *et al*., 2024). Foliage dry weight (FDW), root and crown dry weight (RCDW), and total spear number (TSN) were evaluated 60 days after the inoculation. Measurements were taken in the field and the laboratory using a measuring tape and an OHAUS® precision electronic scale. A forced air oven was used to dry the samples at 70 °C for 72 h (Quevedo *et al*., 2017).

Re-isolation of *Fusarium proliferatum*

To re-isolate and identify *Fusarium proliferatum* from the inoculated plants, rhizome fragments were collected, surface-disinfected, and sown in a PDA medium. The mycelium was purified after several days of incubation under continuous light (Figure 1). Fungal structures were observed under the microscope to identify the pathogen, following the recommendations of the handbook published by Leslie F. and Summerell (2006).

Statistical analysis

Statistical analysis was performed using R (v.4.3.2) (R Core Team, 2020). The Shapiro-Wilk test was used to evaluate data normality (Shapiro and Wilk, 1965). The nonparametric Kruskal-Wallis (Kruskal and Wallis, 2012) and Mann-Whitney U (Mann and Whitney, 1947) tests were applied to evaluate the planned comparisons between treatments (Table 2).

RESULTS AND DISCUSSION

Situation of the asparagus production in Atenco

In the municipality of Atenco, asparagus is cultivated by *ejidatarios* (*ejido* landowners), in plots of 1 to 6 ha. All producers started with one hectare and have gradually expanded

Figure 1. Mycelium growth from a root infected with *Fusarium proliferatum* (A). Mycelium sown using the carnation leaf method (B).

Table 2. Planned comparisons to analyze the effects of different treatments applied to asparagus plants (*Asparagus officinalis*) in two experiments involving plants with and without inoculation with *Fusarium proliferatum*, treated or not with vermicompost leachates, derived from three sources of pre-composted manure (horse, cow, and sheep).

	Comparisons	Description	Statistical test
1	IC *vs*.. NIC	Inoculation effect	Mann-Whitney U
2	IC *vs*.. PHI, PSI, PCI	Pre-transplant control effect of VCLs	Kruskal-Wallis.
3	IC *vs*. HI, SI, CI	Post-transplant control effect of VCLs	Kruskal-Wallis.
4	PHI, PSI, PCI *vs*. PHNI, PSNI, PCNI	Effect of inoculation with pre-transplant application of VCLs	Mann-Whitney U
5	HI, SI, CI *vs*. HNI, SNI, CNI	Effect of inoculation with post-transplant application of VCLs	Mann-Whitney U
6	PHI, PSI, PCI *vs*. HI, SI, CI	Effect of VCLs between pre- and post-transplant application in the presence of the pathogen	Mann-Whitney U
7	PHNI, PSNI, PCNI *vs*. HNI, SNI, CNI	Effect of VCLs between pre- and post-transplant application in the absence of the pathogen	Mann-Whitney U
8	PSI, SI *vs*. IC	Effect of sheep-derived VCL in the presence of the pathogen	Mann-Whitney U
9	PSNI, SNI *vs*. NIC	Effect of sheep-derived VCL in the absence of the pathogen	Mann-Whitney U
10	PHI, HI *vs*. IC	Effect of horse-derived VCL in the presence of the pathogen	Mann-Whitney U
11	PHNI, HNI *vs*. NIC	Effect of horse-derived VCL in the absence of the pathogen	Mann-Whitney U
12	PCI, CI *vs*. IC	Effect of cow-derived VCL in the presence of the pathogen	Mann-Whitney U
13	PCNI, CNI *vs*. NIC	Effect of cow-derived VCL in the absence of the pathogen	Mann-Whitney U
14	PSI, SI, *vs*. PHI, HI	Effect of sheep- *vs*. horse-derived VCL in inoculated plants	Mann-Whitney U
15	PSNI, SNI, *vs*. PHNI, HNI	Effect of sheep- *vs*. horse-derived VCL in non-inoculated plants	Mann-Whitney U
16	PSI, SI, *vs*. PCI, CI	Effect of sheep- *vs*. cow-derived VCL in inoculated plants	Mann-Whitney U
17	PSNI, SNI, *vs*. PCNI, CNI	Effect of sheep- *vs*. cow-derived VCL in non-inoculated plants	Mann-Whitney U
18	PHI, HI, *vs*. PCI, CI	Effect of horse- *vs*. cow-derived VCL in inoculated plants	Mann-Whitney U
19	PHNI, HNI, *vs*. PCNI, CNI	Effect of horse- *vs*. cow-derived VCL in non-inoculated plants	Mann-Whitney U

VCL=Vermicompost leachate.

their growing areas. Given the lack of formal producer associations in the area, individual producers undertake their own crop management and commercialization.

Sulken and Early California are the most commonly used seed varieties because they have adapted to the local soil. Producers mainly use chemical fertilization, although some of them combine chemical fertilizers with agroecological inputs (vermicompost), beneficial microorganisms, and commercial organic products. Arancon *et al.* (2003) and Lazcano

and Domínguez (2010) have reported significant improvements in horticultural crops by using vermicompost. However, no experimental demonstration about the benefits or improvements of such a combination for asparagus cultivation has been reported for Atenco yet. Brandenberger *et al.* (2015) emphasized that proper irrigation and fertilization management are key to maximizing asparagus yield. Practices such as the use of organic amendments can also improve soil quality and extend the productive life of crops.

The main diseases identified by producers in Atenco are rhizome rot, Cercospora leaf spot, and rust. Grasshoppers are the most common pest in the area. Chemical fungicides are used for disease management; however, some producers are initiating preventive processes with vermicompost leachates and microorganisms, and they have reported that this method is quite effective. According to Altieri and Nichols (2012), agroecology seeks to optimize agricultural systems not only in terms of production, but also in terms of their social and ecological impact. The adoption of agroecological practices (*e.g.*, the use of leachates and beneficial microorganisms) aligns with the strategies followed by some Atenco producers to improve soil fertility and crop health.

Asparagus is harvested manually. First, spears with closed, flawless bracts are selected. Then, the product is classified by size (pencil thin, small, standard, and jumbo), hydrated, and transported for its commercialization to the Central de Abastos in Mexico City. Production is higher in summer (up to 7 t/ha) than in winter (1.5-2 t/ha). However, winter is a more profitable season, because asparagus is sold at higher prices. Although some producers harvest asparagus twice a year, they agree that three harvests in two years are the best choice. Drost (2023) reported that asparagus productivity depends on the development of plant structures during the previous harvest cycle. In this sense, less frequent harvests give plants more time to replenish their reserves and strengthen their root system.

Producers are doing their sales. No middlemen are involved in this process. Despite challenges such as water access, high input costs, and labor shortages, producers believe that asparagus is a resilient and profitable crop because it has adapted to saline soils and adverse climatic conditions; due to its high quality, it has good marketing potential. Although producers are not organized, the construction of agroecological cooperation networks, to improve market access and strengthen the resilience of production systems, is still possible (Rosset and Altieri, 2017).

Establishment costs of asparagus crops

Currently, 16 producers grow asparagus at approximately 22 ha in Atenco. It takes two years to obtain the first harvest. Land preparation includes mechanized leveling, subsoiling, harrowing, plus furrowing or bed preparation. Costs of these tasks are shown in Table 3.

In addition to the mechanized work, essential activities for crop establishment and management are manually performed, including transplanting, irrigation, weed control, pest and disease management, amendment or nutrient incorporation, harvesting, and packaging. The shortage of agricultural workers is a common problem among producers. In 2024, the National Agricultural Council (CNA) reported a considerable shortage of agricultural workers. Table 4 shows the cost and number of days required to establish and maintain the crops.

Table 3. Mechanized labor costs for the establishment of the asparagus crop in the municipality of Atenco, State of Mexico.

Activity	Quantity	Unit cost ($)	Subtotal ($)
Land leveling*	1	7,000.00	7,000.00
Subsoiling	1	2,500.00	2,500.00
Manure incorporation	1	800.00	800.00
Harrowing**	3	1,100.00	3,300.00
Furrowing or bed shaping	1	1,200.00	1,200.00
Cutting of old shoots***	1	1,300.00	1,300.00
Total cost of the mechanized work process			16,100.00

*Leveling is carried out in an average of 10 hours, depending on the condition of the land.
**One harrowing is performed before and two after the leveling.
***Cutting of old shoots is performed prior to harvest.
Source: M. Méndez, Personal communication, March 20, 2025.

Table 4. Costs and number of workdays for transplanting, maintenance, and first harvest of the asparagus crop.

Activity	Workdays ha^{-1}	Workers	Unit cost ($)	Subtotal ($)
Transplanting and maintenance				
Transplanting	1	5	350	1,750
Nutrition	3	1	350	1,050
Pest and disease control	3	1	350	1,050
Irrigation	18	2	350	12,600
First harvest (20 to 30 days)				
Weeding	1	3	350	1,050
Harvest	25	2	350	17,500
Trimming and packing	25	2	350	17,500
General crop management				
Packing facility worker*	313	1	350	109,550
Total workdays and cost	389			162,050

*Required for daily crop management.
Source: A. Gonzalez, Personal communication, March 20, 2025.

The estimated total cost of crop establishment is MXN 248,150.00 per hectare. This cost includes daily wages, mechanized work, and the purchase of seedlings (MXN 50,000.00), plus agricultural inputs such as fertilizers, fungicides, pesticides, and herbicides (MXN 20,000.00). The first harvest yields approximately 7 t ha^{-1}, generating an estimated gross income of MXN 490,000.00. These data indicate that, during the first production cycle, recovering the initial investment and obtaining a significant net profit is possible (M. Méndez, personal communication, March 20, 2025).

Experimental results

The Shapiro-Wilks test for normality was used to evaluate the RCDW, TSN, and FDW data (Shapiro and Wilk, 1965). The results indicated that all variables had a nonparametric

distribution (P=0.0001 to 0.0431). Table 5 shows the results of the statistical comparisons between treatments for the two experiments.

The effect of the *Fusarium proliferatum* inoculation without VCL (IC *vs.* NIC) in both experiments significantly reduced RCDW, indicating a lower accumulation of underground biomass in infected plants (Figure 2). A significant FDW decrease in inoculated plants was recorded in Experiment 1 (E1). A similar trend was observed in Experiment 2 (E2). However, TSN did not have significant differences in either experiment, suggesting that the infection had a lower impact on the spear production capacity.

In both experiments, the effect of pre-transplant VCL application did not improve the development of the plants inoculated with *F. proliferatum*, compared with the inoculated control (IC *vs.* PHI, PSI, PCI). RCDW and TSN did not have significant differences. In addition, biomass values were within the range of the inoculated control (Figure 3). RCDW and TSN did not record significant differences: the values found in the leachate treatments were within the control range, indicating the absence of protective effects on the root system or the shoot. Furthermore, a significant reduction in FDW was recorded in the plants treated with VCL in both experiments, suggesting that the treatment may have accentuated the negative effects of the pathogen on aerial biomass.

Table 5. Significance of the differences between Experiments 1 and 2, resulting from the application of the Kruskal-Wallis and Mann-WhitneyU statistical tests to the TSN, FDW, and RCDW variables, in different comparisons between treatments.

Comparisons		Experiment 1			Experiment 2		
		TSN	**FDW**	**RCDW**	**TSN**	**FDW**	**RCDW**
1	IC *vs*.. NIC	0.2676	0.0258	0.0058	0.101	0.0887	0.0101
2	IC *vs*.. PHI, PSI, PCI	0.0051	0.0003	0.0099	0.2098	0.0087	0.0603
3	IC *vs*. HI, SI, CI	0.1459	0.1008	0.4495	0.9251	0.1008	0.4495
4	PHI, PSI, PCI *vs*. PHNI, PSNI, PCNI	0.0001	0.0001	0.0001	0.0008	0.0001	0.0001
5	HI, SI, CI *vs*. HNI, SNI, CNI	0.0022	0.0019	0.0054	0.0498	0.0001	0.0001
6	PHI, PSI, PCI *vs*. HI, SI, CI	0.0664	0.0004	0.0398	0.1157	0.0003	0.0102
7	PHNI, PSNI, PCNI *vs*. HNI, SNI, CNI	0.6718	0.6788	0.9293	0.4692	0.1332	0.4125
8	PSI, SI *vs*. IC	0.0619	0.0193	0.3125	0.7572	0.3438	0.6121
9	PSNI, SNI *vs*. NIC	0.6559	0.4154	0.7248	0.4229	0.1589	0.1589
10	PHI, HI *vs*. IC	0.0335	0.031	0.0642	0.6116	0.1081	0.3903
11	PHNI, HNI *vs*. NIC	0.8593	0.0114	0.0005	0.6223	0.5971	0.3008
12	PCI, CI *vs*. IC	0.0556	0.0038	0.0808	0.309	0.2095	0.2339
13	PCNI, CNI *vs*. NIC	0.025	0.0476	0.1655	0.7455	0.9817	1
14	PSI, SI, *vs*. PHI, HI	0.2527	0.7043	0.3387	0.9675	0.2672	0.8708
15	PSNI, SNI, *vs*. PHNI, HNI	0.9783	0.1676	0.0883	0.6997	0.2182	0.7555
16	PSI, SI, *vs*. PCI, CI	0.692	0.5591	0.492	0.353	0.0501	0.9675
17	PSNI, SNI, *vs*. PCNI, CNI	0.0661	0.3103	0.5427	0.6281	0.0742	0.2107
18	PHI, HI, *vs*. PCI, CI	0.5715	0.9328	0.8108	0.7138	0.5158	0.6255
19	PHNI, HNI, *vs*. PCNI, CNI	0.1494	0.6455	0.2554	0.875	0.489	0.3317

FDW=Foliage dry weight. RCDW=Root and crown dry weight. TSN=total spear number.

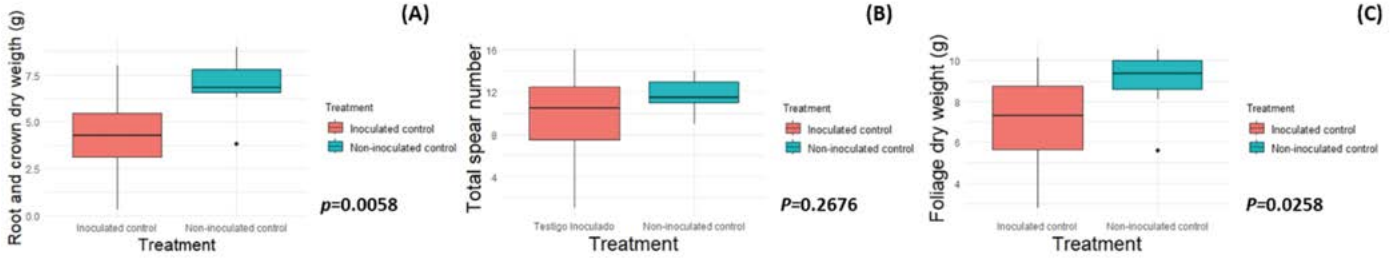

Figure 2. Effect of *Fusarium proliferatum* inoculation on asparagus (*Asparagus officinalis*) plants. RCDW (A), TSN (B), and FDW (C) comparison between IC and NIC. The treatments were compared with the Mann-Whitney U test. Experiment 1. Similar results in Experiment 2.

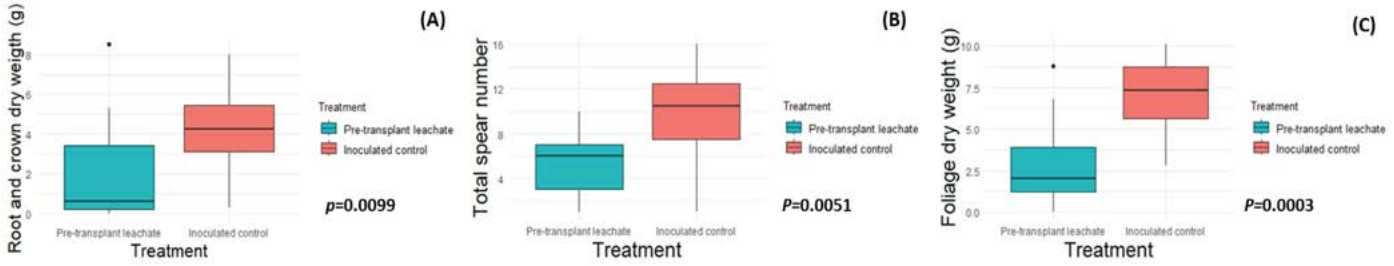

Figure 3. Effect of the pre-transplant VCL (sheep, horse, and cow) application on the RCDW (A), TNS (B) and FDW (C) of asparagus (*Asparagus officinalis*) plants inoculated with *Fusarium proliferatum* and compared with inoculated treatments without VCL application (PSI, PHI, and PCI *vs.* IC). Experiment 1. Similar results in Experiment 2.

In both experiments, the pre-transplant VCL application in non-inoculated plants, the accumulation of root and crown biomass, foliage dry weight, and shoot production were significantly higher than in plants treated with the same leachates but inoculated with the pathogen (PHI, PSI, PCI *vs.* PHNI, PSNI, PCNI) (Figure 4). These results indicated that the pathogen infection had a negative impact on the overall development of the plants, despite the application of pre-transplant leachate.

Plants that were inoculated and treated with leachates post-transplant also recorded a higher RCDW, FDW, and TSN reduction in both experiments than non-inoculated plants treated with VCL (HI, SI, CI *vs.* HNI, SNI, CNI) (Figure 5). These results indicated that inoculation affected plant growth and productivity, and that the inoculation harmed the overall development and productivity of the plants. The post-transplant leachate

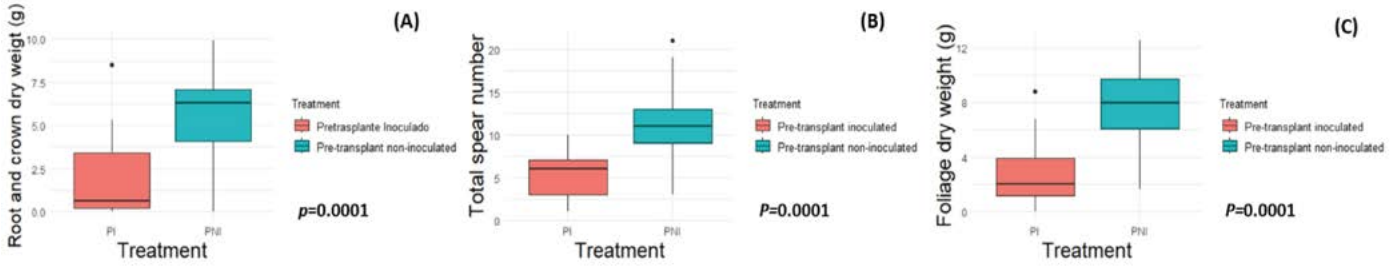

Figure 4. Effect of *Fusarium proliferatum* inoculation on asparagus (*Asparagus officinalis*) plants treated with a VCL pre-transplant application. Comparison of inoculated and non-inoculated plants (PHI, PSI and PCI *vs.* PHNI, PSNI, and PCNI) in RCDW (A), TNS (B) and FDW (C). Experiment 1. Similar results in Experiment 2.

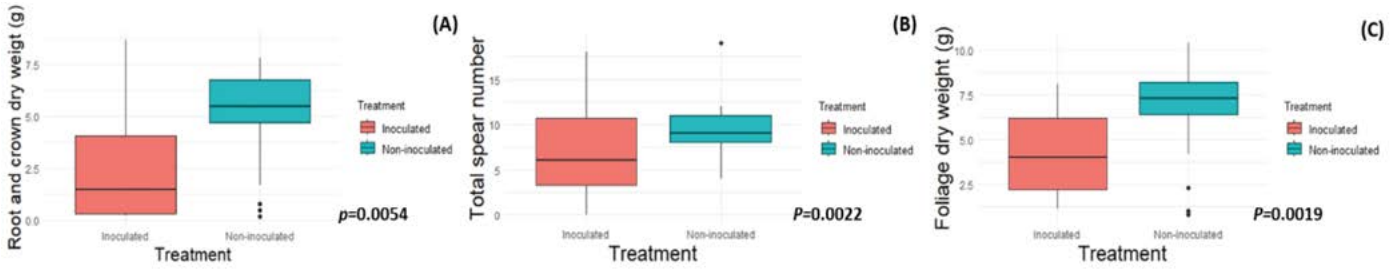

Figure 5. Effect of *Fusarium proliferatum* inoculation on asparagus (*Asparagus officinalis*) plants treated with post-transplant VCL applications. Comparison between inoculated and non-inoculated plants, treated with VCL (HI, SI, CI *vs.* HNI, SNI, CNI) on RCDW (A), TSN (B) and FDW (C). Experiment 2. Similar results to Experiment 1.

application did not counteract the negative effects of *F. proliferatum* under experimental conditions either.

In both experiments, plants inoculated and treated post-transplant with leachate (HI, SI, CI) showed a significantly higher accumulation of RCDW and FDW than those treated with pre-transplant VCL applications (PHI, PSI, PCI). Statistically significant differences were recorded (Figure 6). No significant TSN differences were recorded in both experiments. This indicated that the period of VCL application produced differences in biomass accumulation, but not in spear production under conditions of pathogen infection.

Compared with the inoculated control (PSI, SI *vs.* IC), the application of sheep VCL to the inoculated plants of E1 did not improve RCDW or TSN (Figure 7). However, a significant reduction in FDW was recorded. This indicated that this treatment did not

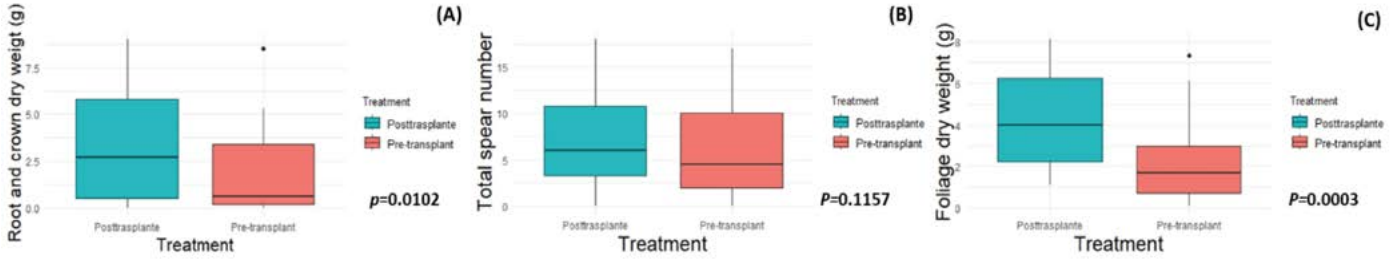

Figure 6. Effect of pre-transplant and post-transplant VCL application on the growth of asparagus (*Asparagus officinalis*) plants inoculated with *Fusarium proliferatum* (PHI, PSI, PCI *vs.* HI, SI, CI) in RCDW (A), TSN (B), and FDW (C). Experiment 2. Similar results to Experiment 1.

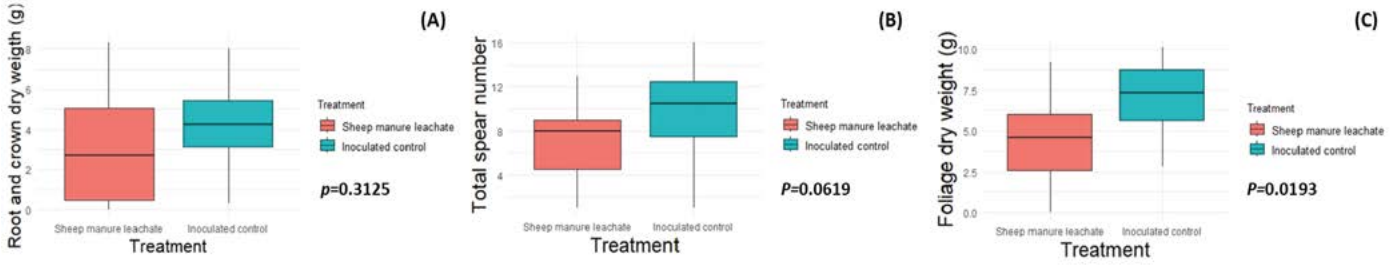

Figure 7. Comparison of the effect of pre-transplant and post-transplant sheep VCL application on asparagus (*Asparagus officinalis*) plants inoculated with *Fusarium proliferatum* and inoculated control (PSI and SI *vs.* IC). RCDW (A), TSN (B), and FDW (C) were evaluated. Experiment 1.

mitigate the impact of the infection. This situation suggests that the VCL source did not provide a protective effect against the pathogen.

The application of horse VCL to inoculated plants (PHI, HI *vs.* IC) did not significantly improve RCDW in E1. However, compared to the inoculated control (data not shown), a significant reduction in FDW and TSN was recorded. This result indicated that the horse VCL treatment did not protect against the pathogen; instead, it negatively impacted foliage accumulation and spear production. Applying horse VCL to non-inoculated plants (PHNI, HNI) significantly reduced RCDW and FDW, compared with the non-inoculated control (NIC). No significant TSN differences were recorded.

Compared with the inoculated control (PCI, CI *vs.* IC), the application of cow VCL to inoculated plants did not record significant RCDW or TSN differences in E1. However, FDW was significantly lower (data not shown). Compared with the non-inoculated control (PCNI, CNI *vs.* NIC), the application of cow VCL to non-inoculated plants did not record significant RCDW differences. However, TSN and FDW differences were recorded: plants treated with cow VCL recorded lower values than those of NIC. These results suggest that the application of cow VCL did not promote better aerial biomass development and better spear production. No significant differences were recorded in the evaluation of the remaining planned comparisons (3, 7, 9, and 14-19 in E1; 3 and 7-19 in E2) (Table 2) for any of the variables (Table 3).

Several studies have documented the positive effects of VCL on disease suppression and plant growth improvement. However, the results of this study indicated that, under our experimental conditions, VCL made from sheep, horse, and cow manure did not significantly protect the asparagus plants grown in Atenco soil against *Fusarium proliferatum*. In contrast, Mupambwa *et al.* (2024) reported an improved germination, root growth, and nutrient availability in crops treated with VCLs from small ruminants. The lack of protective effects in the asparagus plants recorded in this study could be related to the variability of the microbiological and chemical VCL composition, which could have been influenced by the type of manure used and the conditions under which the vermicompost was established (Sarker *et al.*, 2021). Zamora *et al.* (2017) documented that certain leachates can increase the severity of fungal infections, depending on their origin and microbiota. Another important factor could have been the interaction of the leachate with native soil microbiota, which may have limited the establishment of beneficial VCL microorganisms, resulting in a reduced suppressive potential (Birinchi *et al.*, 2010; Zhao *et al.*, 2019). Additionally, the availability of nutrients in the VCLs may not have been enough to cover the nutritional demand under biotic stress conditions (Ávila *et al.*, 2015). Therefore, the lack of protective effect could be the result of the combination of these factors. Consequently, optimizing VCL, from its preparation to its application in the plants, is fundamental.

CONCLUSIONS

Asparagus cultivation in Atenco is a profitable activity, despite the organizational and technical limitations for yield improvement and expansion of the growing area. According to the producers, agroecological practices (*e.g.*, VCL and beneficial microorganism application) improve soil health and crop resilience; nevertheless, the adoption of these

agricultural practices is limited. In this study, no protective effect was recorded with the application of the three different types of VCL in the soil of Atenco. However, sheep and cow leachates had some potential to promote asparagus growth in the absence of the pathogen. Further research is required under field conditions to validate the efficacy of VCL against diseases caused by *F. proliferatum* and other pathogens. This is particularly important when VCL is used in combination with other biological control strategies.

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