Influence of pyroligneous acid on cucumber cultivation under organoponic conditions

Influencia del ácido piroleñoso sobre el cultivo de pepino en condiciones de organopónico

Influência do ácido pirolenhoso no cultivo de pepino em condições organopônicas

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Rev. Fac. Agron. (LUZ). 2024, 41(3): e244126
ISSN 2477-9407
DOI: https://doi.org/10.47280/RevFacAgron(LUZ).v41.n3.06

Crop production
Associate editor: Dr. Jorge Vilchez-Perozo
University of Zulia, Faculty of Agronomy
Bolivarian Republic of Venezuela

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Received: 27-05-2024
Accepted: 15-07-2024
Published: 08-08-2024

Keywords:
Cucumis sativus L.
Vegetable
Wood vinegar
Biostimulant

Abstract

Pyroligneous acid is recognised as an effective biostimulant in a wide range of crops, improving processes such as germination, growth and yield, as well as inducing stress tolerance and increasing plant resistance to adverse conditions. To evaluate the effect of applying pyroligneous acid (PA) foliarly and on the substrate on the growth, development and yield of cucumber crops, an experiment was set up under organoponic conditions in Bayamo, Granma, Cuba. Seven treatments were used, consisting of PA doses of 5 $mL.L^{-1}$ foliar (FD1), 10 $mL.L^{-1}$ foliar (FD2), 15 $mL.L^{-1}$ foliar (FD3), 5 $mL.L^{-1}$ substrate (SD1), 10 $mL.L^{-1}$ (SD2), 15 $mL.L^{-1}$ (SD3) and an absolute control. The treatments were established using a completely randomised design. Each treatment was replicated three times, with a sample size of 15 plants per replicate. The product was applied at 7, 14 and 21 days after germination. At 21 days after germination, stem length (cm), stem base diameter (cm), number of leaves, leaf diameter and length (cm), number of branches formed per plant and yield ($t.ha^{-1}$) were evaluated. The application of PA, both on the leaves and on the substrate, promoted plant growth and development at doses of 5 and 10 $mL.L^{-1}$. Similarly, the yield-related variables also showed improvements with the application of the product, highlighting that the greatest stimulation was observed when the dose of 5 $mL.L^{-1}$ was applied foliarly.

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Resumen

El ácido piroleñoso es reconocido como un bioestimulante efectivo en una gran variedad de cultivos, ya que mejora procesos como la germinación, el crecimiento y el rendimiento, además de inducir tolerancia al estrés y aumentar la resistencia de las plantas a condiciones adversas. Para evaluar el efecto de la aplicación de ácido piroleñoso (AP) aplicado foliarmente y al sustrato sobre el crecimiento, desarrollo y rendimiento del cultivo de pepino, se estableció un experimento en condiciones de organopónico en Bayamo, Granma, Cuba. Se utilizaron siete tratamientos consistentes en dosis de AP a razón de 5 $mL.L^{-1}$ foliar (FD1), 10 $mL.L^{-1}$ foliar (FD2), 15 $mL.L^{-1}$ foliar (FD3), 5 $mL.L^{-1}$ sustrato (SD1), 10 $mL.L^{-1}$ (SD2), 15 $mL.L^{-1}$ (SD3) y un control absoluto. Los tratamientos se establecieron sobre un diseño completamente aleatorizado. Cada tratamiento se repitió tres veces, con un tamaño de muestra de 15 plantas por repetición. El producto se aplicó a los 7, 14 y 21 días después de la germinación. A los 21 días después de la germinación, se evaluó la longitud del tallo (cm), diámetro de la base del tallo (cm), número de hojas, diámetro y longitud de las hojas (cm), cantidad de ramas formadas por planta y rendimiento del cultivo ($t.ha^{-1}$). La aplicación de AP, tanto de forma foliar como al sustrato, promovió el crecimiento y desarrollo del cultivo con dosis de 5 y 10 $mL.L^{-1}$. Asimismo, las variables relacionadas con el rendimiento también mostraron mejoras con la aplicación del producto, destacando que la mayor estimulación se observó al aplicar la dosis de 5 $mL.L^{-1}$ de manera foliar.

Palabras clave: *Cucumis sativus* L., vegetales, vinagre de madera, bioestimulante

Resumo

O ácido pirolenhoso é reconhecido como um bioestimulante eficaz em uma ampla variedade de culturas, pois melhora processos como germinação, crescimento e rendimento, além de induzir a tolerância ao estresse e aumentar a resistência das plantas a condições adversas. Para avaliar o efeito da aplicação do ácido pirolenhoso (AP) aplicado foliarmente e no substrato sobre o crescimento, o desenvolvimento e o rendimento das culturas de pepino, foi realizado um experimento em condições organopônicas em Bayamo, Granma, Cuba. Foram usados sete tratamentos, consistindo em doses de AP de 5 $mL.L^{-1}$ foliar (FD1), 10 $mL.L^{-1}$ foliar (FD2), 15 $mL.L^{-1}$ foliar (FD3), 5 $mL.L^{-1}$ de substrato (SD1), 10 $mL.L^{-1}$ (SD2), 15 $mL.L^{-1}$ (SD3) e um controle absoluto. Os tratamentos foram estabelecidos em um projeto completamente aleatório. Cada tratamento foi repetido três vezes, com um tamanho de amostra de 15 plantas por replicação. O produto foi aplicado aos 7, 14 e 21 dias após a germinação. Aos 21 dias após a germinação, foram avaliados o comprimento do caule (cm), o diâmetro da base do caule (cm), o número de folhas, o diâmetro e o comprimento das folhas (cm), o número de ramos formados por planta e a produtividade da cultura ($t.ha^{-1}$). A aplicação de AP, tanto foliar quanto no substrato, promoveu o crescimento e o desenvolvimento da cultura nas doses de 5 e 10 $mL.L^{-1}$. Da mesma forma, as variáveis relacionadas à produtividade também apresentaram melhorias com a aplicação do produto, destacando-se que o maior estímulo foi observado quando se aplicou a dose de 5 $mL.L^{-1}$ por via foliar.

Palavras-chave: *Cucumis sativus* L., vegetais, vinagre de madeira, bioestimulante

Introduction

Cucumber (*Cucumis sativus* L.) is a globally consumed vegetable, with an annual production exceeding 93.5 million tons and yields of up to 40.5 $t.ha^{-1}$. It is not only consumed as food but also has applications in the pharmaceutical and cosmetic industries (FAOSTAT, 2022; Jia & Wang, 2021). The Caribbean region's production is relatively low, with approximately 9,000 hectares yielding 122,724.85 tons at an average of 13.74 $t.ha^{-1}$ (FAOSTAT, 2022).

According to the National Office of Statistics and Information (Oficina Nacional de Estadística e Información de la República de Cuba (ONEI), 2023), in Cuba, over 19,900 hectares are planted annually, yielding around 79,185 tons with an average yield of 12.76 $t.ha^{-1}$. Compared to other countries in the region, the yields are relatively low. However, with the use of appropriate cultivation technology, yields can increase to over 50 $t.ha^{-1}$ (FAOSTAT, 2022).

One common method of cucumber cultivation nationwide is through organoponic. Organoponics in Cuba represents an intensive system of urban agriculture, based on sustainable agroecological principles. These principles incorporate integrated pest and disease management, plant nutrition with organic amendments, biostimulants and biofertilizers, and cultivation practices that minimize environmental impact. These systems permit the continuous cultivation of vegetables and other short-cycle crops, thereby supporting local production in urban and peri-urban areas throughout the year (Mendivil *et al*., 2020; Orberá *et al*., 2021; Rodríguez *et al*., 2020).

Several biostimulants are used in organoponic systems, including humic and fulvic acids, amino acids, algae and plant extracts, chitosan, inorganic compounds, beneficial fungi, and bacteria (Galbán *et al*., 2021). In recent years, a substance called wood vinegar or pyroligneous acid has been incorporated into this group of substances, a product resulting from the combustion process of wood (Singh *et al*., 2020).

Pyroligneous acid (PA) is derived from pyrolysis, a process involving organic matter's chemical breakdown through heat without oxygen for a specified duration (Catacora *et al*., 2019). This vinegar comprises aromatic and aliphatic compounds, hydrocarbons, and various oxygenated compounds like phenols, furans, alcohols, acids, ethers, aldehydes, and ketones, along with macro and microelements, phytohormones, and vitamins C and K (Catacora *et al*., 2019; Viltres & Alarcón, 2022). Due to these properties, PA is increasingly employed in agriculture, notably as a soil conditioner, rooting agent, and foliar fertilizer (Lescay *et al*., 2023).

In cucumber cultivation, studies have focused on seed treatment to enhance germination, exploring doses that stimulate physiological processes or may affect them. Additionally, research has targeted pest control strategies (Catacora *et al*., 2019).

In horticultural crops such as lettuce and peppers, wood vinegar has demonstrated efficacy in stimulating growth, development, and yield. However, there is a paucity of documentation on its application in Cuban cucumber cultivation (Galbán *et al*., 2021). The use of pyroligneous acid in cucumber cultivation is an opportunity for two important reasons. Firstly, it improves the yield of the crop. Secondly, it allows the agricultural use of Marabú, one of the main weeds in Cuban fields, by using it as a raw material for extraction. The objective of this study was to determine the influence of pyroligneous acid, obtained from Marabú (*Dichrostachys cinerea* L.) biomass, on the growth, development, and yield variables of cucumber under organoponic conditions.

Materials and methods

The experiment was conducted under production conditions at the “Las Caobas I” Organoponic in the city of Bayamo, Granma province, Cuba (20°21’35.6”N-76°37’54.9”W). The variety used was INIVIT P-2007, obtained from the Research Institute of Tropical Root and Tuber Crops (INIVIT, Instituto Nacional de Investigaciones de Viandas Tropicales). Planting was carried out at the end of May, with plants spaced 30 cm apart in double rows on the bed with guards. The final evaluation harvest took place in mid-July. Decomposed bovine manure organic matter with a C/N ratio of 15:1 was used as substrate, homogeneously distributed over the surface of each bed and in the same quantity, in order to control variations in its fertility gradient. The agrotechnical management was carried out in a homogeneous way throughout the experiment, following the recommendations of the technical manual for organoponics, intensive orchards, and semi-protected organoponics (as per its Spanish title, ‘Manual Técnico para Organopónicos, Huertos Intensivos y Organoponía Semiprotegida’) (Rodríguez *et al*., 2020).

A total of seven treatments were employed, derived from the combination of two application methods and three different concentrations. The first application method consisted of foliar spraying, whereby the entire leaf surface of each plant was uniformly sprayed. To prevent the product from contacting the substrate, a plastic cover was placed over the substrate during each application, and it was removed 30 min after the product was applied. The second method involved spraying directly onto the substrate in an approximately 15 cm radius, starting at the base of the stem and continuing until the substrate was visibly wet. Furthermore, three application concentrations of 5, 10, and 15 mL.L^{-1} were utilized (table 1).

Table 1. Description of treatments evaluating the effects of pyroligneous acid (PA) applied to foliage and substrate on cucumber plants grown under organoponic conditions.

No.	Treatments	Denomination
1	FD1	5 mL.L^{-1} of PA Foliar
2	FD2	10 mL.L^{-1} of PA Foliar
3	FD3	15 mL.L^{-1} of PA Foliar
4	SD1	5 mL.L^{-1} of PA substrate
5	SD2	10 mL.L^{-1} of PA substrate
6	SD3	15 mL.L^{-1} of PA substrate
7	C	Control

PA: Pyroligneous acid

The treatments were established in raised beds with borders, each covering an area of 24 m². They were distributed according to a completely randomized design, made feasible by ensuring substrate homogeneity. Each treatment was replicated three times, with 15 plants per replicate. To avoid edge effects, two plants were removed from each end of the plot.

Pyroligneous acid was obtained using the rapid pyrolysis process described by Viltres and Alarcón (Viltres & Alarcón, 2022). The pyroligneous acid used in this study was derived from Marabou plant biomass (*Dichrostachys cinerea* L.). Specific data on the chemical and biochemical composition of Marabu-derived pyroligneous acid are not currently available. However, it has been shown that this compound contains common components regardless of the biomass used as the raw material. These components include phenols, acids (such as acetic and formic acids), and alcohols (such as methanol and ethanol). Other compounds present include furans, aldehydes, ketones, ethers, and certain hydrocarbons (Viltres & Alarcón, 2022).

Three applications of PA were carried out on days 7, 14, and 21 after germination. Three Matabí brand backpack sprayers of 16 liters each were used for these applications, one for each dose. Applications were performed between 7:30 and 8:30 am to avoid product exposure to intense sunlight and ensure optimal effectiveness. Furthermore, cultural practices were performed according to the Organic Garden and Intensive Gardening Manual (Rodríguez *et al*., 2020).

At 21 days after germination, evaluations were conducted on variables related to crop growth and development, including stem length (cm), stem base diameter (cm), leaf number, and number of branches formed per plant. Measurements were made using a caliper for stem base diameter and a flexometer for stem length. The number of leaves and branches formed per plant were also recorded. Leaf area was estimated from its length and width, according to the methodology described by Kemp (1960), using the equation; where , is the length of the leaf, is the width of the leaf and, is the correction factor equal to 0.66. Leaf width was determined at the widest part, while length was defined as the distance between the two most distant points: from the tip of the lamina to the point of intersection of the petiole with the midrib (Schrader *et al*., 2021).

Harvesting started 40 days after germination with an interval of 3 days between each harvest until the fifth harvest. At each harvest, all fruits from each plot were removed and weighed using an MKZ-BAS-ACS209 digital balance. To determine the yield per treatment, the total weight of all harvests from each replicate was summed and the yield was calculated in kg.m^{-2} and then estimated in t.ha^{-1}. The length of the stem and fruit was measured with a 3 m tape measure and the width of the stem and fruit was measured with a caliper. The data were processed using Statistica for Windows, version 10 (StatSoft, 2014). Cochran, Hartley-Bartlet tests were conducted to determine homogeneity of variance, and the Kolmogorov-Smirnov test was used to check for normal distribution. The results underwent a simple analysis of variance, and the Tukey test ($p \leq 0.05$) was used to determine differences between treatments.

Results and discussion

Effect of pyroligneous acid on length and diameter of cucumber stems

Pyroligneous acid exerted a positive influence on various variables related to the growth and development of the crop. This effect was observed at 21 days after germination, following two applications of the product. However, this behavior depended on the applied dose and the application method, as differences were observed among the treatments used. According to this, stem length was mainly benefited by foliar applications, showing significant differences compared to when the product was applied directly to the substrate and near the plant’s stem (figure 1a). In this case, the best results were obtained with the treatment where PA was applied via foliar application at doses of 5, 10, and 15 mL.L^{-1} (FD1, FD2, and FD3).

This behavior may be associated with various mechanisms involved in the uptake of pyroligneous acid compounds, which can occur through multiple pathways.

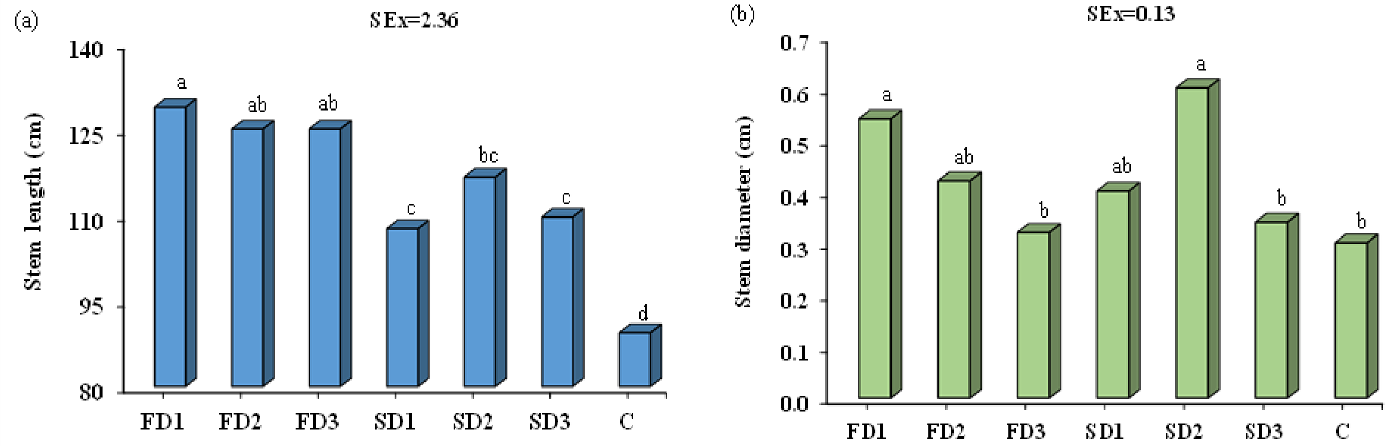

Figure 1. Influence of pyroligneous acid applied to foliage and substrate on the length (a) and diameter (b) of cucumber stems grown under organoponic conditions. FD1: 5 mL.L^{-1} of foliar PA; FD2: 10 mL.L^{-1} of foliar PA; FD3: 15 mL.L^{-1} of foliar PA; SD1: 5 mL.L^{-1} of substrate PA; SD2: 10 mL.L^{-1} of substrate PA; SD3: 15 mL.L^{-1} of substrate PA; C: control treatment. Bars with different letters differ significantly according to the Tukey test ($p<0.05$).

These include stomata, microcracks, and cuticular pores, as well as direct cuticular uptake through the lipid matrix of the cuticle (Halpern *et al*., 2015; Mellidou & Karamanoli, 2022).

The absorption of pyroligneous acid compounds is facilitated by several factors, including the lipid and water solubility of these compounds, the presence of natural surfactants, and environmental conditions such as high humidity and temperature (Parađiković *et al*., 2019; El Boukhari *et al*., 2020; Bell *et al*., 2022). Substances such as phenolic compounds, organic acids (acetic acid), and volatile compounds (acetone and methanol) have been demonstrated to be readily absorbed by leaves (Pratyusha, 2022; Eichert & Fernández, 2023).

However, the application of the product to the substrate at a dose of 15 mL.L^{-1} (SD2) demonstrated a tendency to increase stem length, while with SD2 and SD3, it exhibited a tendency to decrease. Nevertheless, in both cases, the values exceeded those of the control (figure 1a). The efficacy of the substrate application is likely attributable to the efficient uptake of water-soluble compounds by the roots, facilitated by the aqueous environment of the rhizosphere. These water-soluble compounds include organic acids, sugars, amino acids, and macro- and micronutrients (Kathpalia & Bhatla, 2018).

The impact of pyroligneous acid on stem diameter exhibited varied outcomes, with an increase in stem thickness observed in treatments where the product was directly applied to the substrate. In fact, the most favorable outcome was observed when the product was applied at a dose of 10 mL.L^{-1} (SD2), closely followed by the foliar application of 5 mL.L^{-1} (FD1), with statistically similar results. However, in treatments where higher doses of 15 mL.L^{-1} were applied, both foliar and to the substrate, stem diameter exhibited a tendency to align with the control (figure 1b).

It has been reported that some compounds, such as water-soluble phenols (e.g. ferulic acid), humic and fulvic acids, peptides and oligopeptides, can be taken up by roots due to their solubility in both lipids and water, as well as their appropriate molecular size (Chen *et al*., 2022). This result supports the potential benefits of substrate application of the product, although higher doses may be necessary compared to foliar application.

Influence pyroligneous acid on leaf and branch formation and leaf area

PA did not influence leaf formation in plants, as there were no significant differences between treatments, although a slight increase was observed in the FD1 treatment (figure 2a). However, the number of branches formed by plants was notable (figure 2b). Among the treatments used, the one that exerted the most influence on this variable was the foliar dose of 10 mL.L^{-1} (FD2), although foliar application of 5 mL.L^{-1} (FD1) and substrate application of 10 mL.L^{-1} (SD2) yielded similar results. Treatments with doses of 5 and 15 mL.L^{-1} applied to the substrate (SD1 and SD3) generated the lowest number of branches, with results like the control (figure 2b).

However, the number of branches formed by plants was notable (figure 2b). Among the treatments used, the one that exerted the most influence on this variable was the foliar dose of 10 mL.L^{-1} (FD2), although foliar application of 5 mL.L^{-1} (FD1) and substrate application of 10 mL.L^{-1} (SD2) yielded similar results. Treatments with doses of 5 and 15 mL.L^{-1} applied to the substrate (SD1 and SD3) generated the lowest number of branches, with results like the control (figure 2b).

In *Cucumis sativus*, the application of pyroligneous acid may have altered hormonal balance and nutrient distribution, favoring branch formation over leaf development. This preference for branch growth could be attributed to the meristematic activity induced by pyroligneous acid compounds, particularly in secondary branches where female flowers begin to form (Liu *et al*., 2021; Luo *et al*., 2023). Additionally, the photosynthetic capacity of green branches enhances total photosynthetic surface area, facilitating efficient energy production and compensating for reduced leaf formation (Aschan & Pfanz, 2003; Sun *et al*., 2021).

The application of pyroligneous acid significantly affected the leaf area compared to the control. Foliar application of 5 mL.L^{-1} (FD1) resulted in greater leaf development (figure 3) compared to other concentrations and regardless of the application method used. Intermediate concentrations of 10 mL.L^{-1}, both foliar (FD2) and to the substrate (SD2), also achieved an increase, although less than that obtained with FD1.

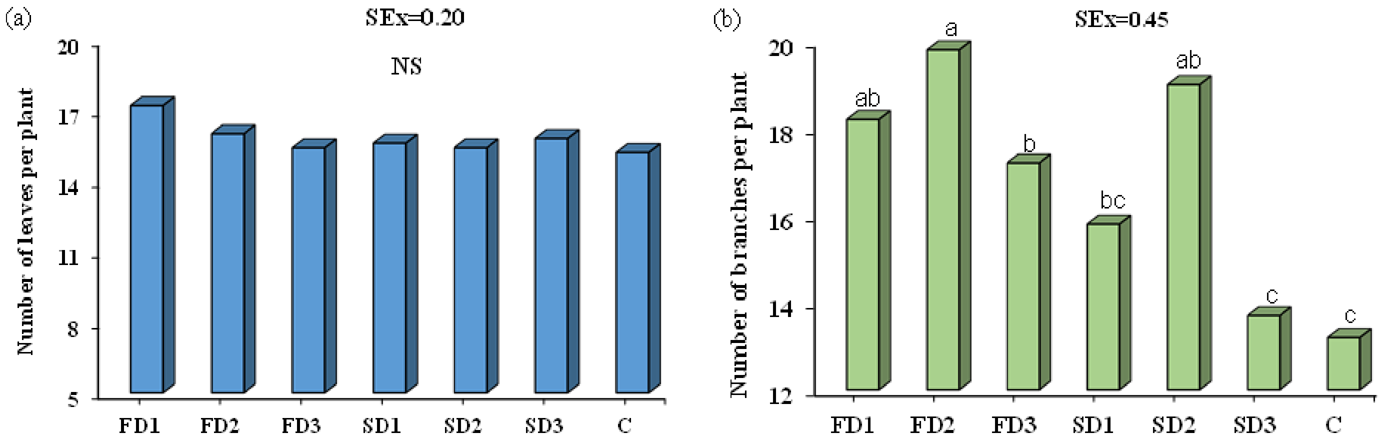

Figure 2. Influence of pyroligneous acid applied to foliage and substrate on the number of leaves (a) and branches (b) in cucumber plants grown under organoponic conditions. FD1: 5 $mL.L^{-1}$ of foliar PA; FD2: 10 $mL.L^{-1}$ of foliar PA; FD3: 15 $mL.L^{-1}$ of foliar PA; SD1: 5 $mL.L^{-1}$ of substrate PA; SD2: 10 $mL.L^{-1}$ of substrate PA; SD3: 15 $mL.L^{-1}$ of substrate PA; C: control treatment. Bars with different letters differ significantly according to Tukey's test (p<0.05).

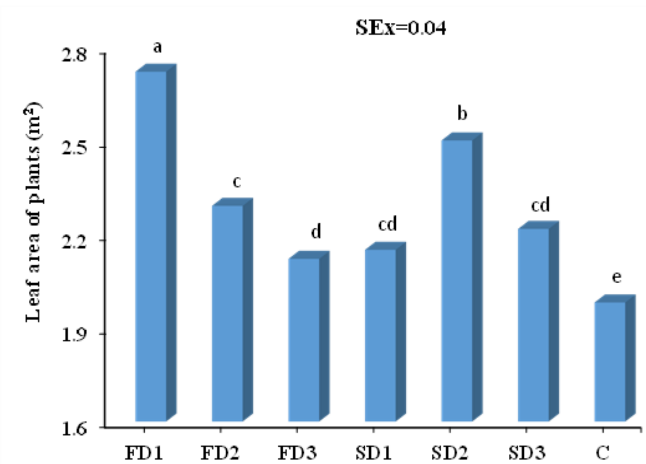

Figure 3. Influence of pyroligneous acid applied to foliage and substrate on the leaf area of cucumber plants grown under organoponic conditions. FD1: 5 $mL.L^{-1}$ of foliar PA; FD2: 10 $mL.L^{-1}$ of foliar PA; FD3: 15 $mL.L^{-1}$ of foliar PA; SD1: 5 $mL.L^{-1}$ of substrate PA; SD2: 10 $mL.L^{-1}$ of substrate PA; SD3: 15 $mL.L^{-1}$ of substrate PA; C: control treatment. Bars with different letters differ significantly according to Tukey's test (p<0.05).

Among the substrate applications, SD2 showed the best results. It is important to note that higher concentrations (15 $mL.L^{-1}$) did not show significant improvements, indicating that beyond this dose, pyroligneous acid does not exert a positive effect. On the contrary, it is possible that from this dose it acts by inhibiting cell growth. In fact, studies suggest that at high doses, pyroligneous acid can act as an herbicide (Korkalo *et al*., 2022; Rodrigues & Abbade, 2024).

Effect of pyroligneous acid on yield variables

The results demonstrate that yield-related variables, such as number of formed fruits, as well as length and width of fruits, were benefited by the application of pyroligneous acid (table 2). Treatment FD1 (5 $mL.L^{-1}$ of PA) yielded the highest number of fruits per plant, along with longer and wider fruits (table 2). Substrate application similarly influenced these variables, yielding comparable results.

Table 2. Effect of pyroligneous acid applied to foliage and substrate on the number, length, and width of fruits of cucumber plants grown under organoponic conditions.

Treatment	Number of fruits per plant	Fruit length (cm)	Fruit width (cm)
FD1	64.00a	21.34a	5.18a
FD2	59.00b	20.62ab	5.00ab
FD3	40.40d	21.09ab	4.36c
SD1	46.20c	20.74ab	4.60b
SD2	61.20ab	19.24ab	4.80ab
SD3	29.00e	19.07ab	4.44bc
C	20.20f	17.57b	4.00c
SD	**2.69**	**0.33**	**0.08**

FD1: 5 $mL.L^{-1}$ of foliar PA; FD2: 10 $mL.L^{-1}$ of foliar PA; FD3: 15 $mL.L^{-1}$ of foliar PA; SD1: 5 $mL.L^{-1}$ of substrate PA; SD2: 10 $mL.L^{-1}$ of substrate PA; SD3: 15 $mL.L^{-1}$ of substrate PA; C: control treatment; SD: standard error of the mean. Letters that are different in the columns differ significantly according to the Tukey test (p<0.05).

However, foliar application of 10 $mL.L^{-1}$ of PA (FD2) led to a decrease in fruit number, with the lowest count observed at 15 $mL.L^{-1}$ (FD3). Interestingly, substrate-applied treatment SD1 with 15 $mL.L^{-1}$ of PA surpassed this count.

Significant differences in fruit length were minimal, with most treatments yielding fruits between 19 and 21 cm, showing no notable distinctions. However, the 5 $mL.L^{-1}$ dose tended to produce longer fruits exceeding 21 cm, while the control treatment yielded the shortest fruits at 19.07 cm (table 2).

More pronounced differences were observed in fruit width between treatments, as the best results were found when using the foliar dose of 5 $mL.L^{-1}$ (FD1), followed by the dose of 10 $mL.L^{-1}$ (FD2). However, good results were also found with substrate application, especially with the 15 $mL.L^{-1}$ dose (SD2), which was statistically like the foliar applications (table 2). When evaluating yield, a similar trend to the rest of the variables analyzed previously can be observed because the highest values were achieved when using the 5 $mL.L^{-1}$ foliar application dose (FD1) (figure 4). Yield in the other treatments used decreased significantly, although in all cases, they exceeded the control.

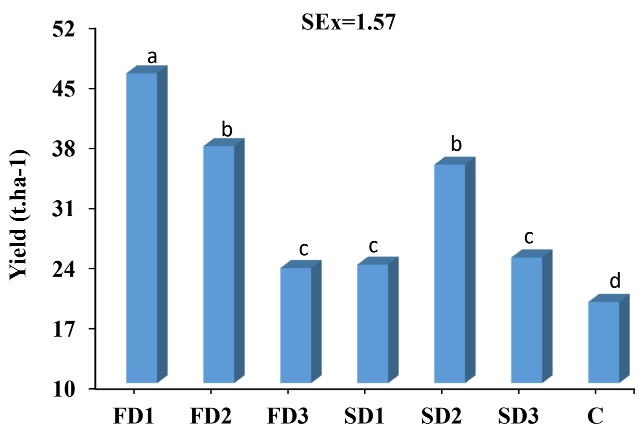

Figure 4. Influence of pyroligneous acid (PA) applied to foliage and substrate on cucumber crop yield grown under organoponic conditions. FD1: 5 mL.L^{-1} foliar PA; FD2: 10 mL.L^{-1} foliar PA; FD3: 15 mL.L^{-1} foliar PA; SD1: 5 mL.L^{-1} substrate PA; SD2: 10 mL.L^{-1} substrate PA; SD3: 15 mL.L^{-1} substrate PA; C: control treatment. Bars with different letters differ significantly according to Tukey's test ($p<0.05$).

However, applications of 10 mL.L^{-1} both foliarly and to the substrate (FD2 and SD2) showed the second-best performance with statistically similar results between them. Treatments with the lowest results were obtained with FD3, SD1, and SD3, which behaved similarly.

As observed, with foliar application, the best yield values were achieved with the lowest doses of 5 mL.L^{-1} (FD1), while in substrate application, the dose that yielded the best results was 10 mL.L^{-1} (SD2).

This indicates that foliarly, with a minimum dose, there is adequate absorption of biostimulant elements and nutrients, resulting in a positive conversion of these into yield. The increase in dose leading to a decrease in yield suggests that at higher concentrations, the product may have an opposite effect, acting as an inhibitor rather than a biostimulant. The research findings indicate that pyroligneous acid can positively impact cucumber growth, development, and yield when applied foliarly at a concentration of 5 mL.L^{-1} or to the substrate at 10 mL.L^{-1}.

Therefore, future research could consider additional variables related to yield, such as the proportion of male and female flowers, as well as others that occur at the biochemical, molecular, and ultrastructural levels, which can explain variations and alterations underlying the effects of pyroligneous acid on the growth and development of cucumber and related species, which remain incompletely understood.

Further research is required to elucidate processes such as the uptake and distribution of pyroligneous acid compounds in the plant, their hormonal influence on cell division and differentiation, and interactions with environmental factors like light, temperature, humidity, or substrate pH, as well as with nutritional variables such as macronutrient and micronutrient availability. This will represent a significant advancement in this field of study. Additionally, research could focus on identifying the detrimental effects at the cellular level that cause irreparable damage associated with specific doses and compounds involved. This could potentially facilitate the development of natural herbicides, offering a promising pathway for sustainable growth.

Conclusions

Pyroligneous acid, applied both foliarly and to the substrate at 5 mL.L^{-1} and 10 mL.L^{-1} respectively, is effective in stimulating growth, development and yield variables in cucumber crops. The most effective treatment is observed with a foliar application of 5 mL.L^{-1}.

Recomendations

Further studies under controlled conditions are needed to elucidate the biochemical and molecular mechanisms, as well as potential structural variations at the cellular level, that explain the action of the various compounds in pyroligneous acid.

Acknowledgments

We extend our gratitude to the University of Granma and the administration of the organoponic "Las Caobas I" for their invaluable support and contribution to this research. We also thank CONAHCYT for the scholarship granted to the first author, which allowed her to get enrolled in the MCPAT postgraduate program at UNACH.

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