Enhancing Spinach Productivity with Plant Acoustic Frequency Technology in Wick Hydroponics

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Abstract. Acoustic frequency has emerged as a promising non-invasive tool to enhance plant growth in controlled environments. This study investigates the effects of varying sound frequencies (3000 Hz, 8000 Hz, and 13,000 Hz) on the growth of spinach (*Spinacia oleracea*) in a wick hydroponic system. Spinach plants were exposed to Folk Pop music with specific frequency profiles for 3 hours daily over a 14-day period. Results indicated that exposure to 3000 Hz increased plant height by 18.5% and leaf area by 22.3% compared to the control, while higher frequencies (8000 Hz and 13,000 Hz) showed negligible effects. Greenness index values were also highest in the 3000 Hz group, demonstrating a significant correlation with enhanced chlorophyll content. These findings highlight the potential of specific acoustic frequencies to improve hydroponic spinach productivity. Practical implications include the integration of sound-based interventions for optimizing plant growth in resource-efficient agricultural systems.

1 Introduction

Spinach (*Amaranthus sp.*) is a highly nutritious leafy green vegetable integral to human diets worldwide due to its rich content of vitamins, minerals, and antioxidants [1]. Spinach is recognized as a significant source of essential vitamins and minerals, including iron, calcium, and vitamins A and C, making it a staple in many diets worldwide [2][3]. Its ability to accumulate beneficial elements such as manganese and cobalt further enhances its nutritional profile, particularly for populations with high vegetable consumption. Moreover, spinach exhibits a unique response to environmental stressors, such as heavy metal accumulation, which can be critical for studies focused on food safety and environmental health [4][5]. Its rapid growth cycle and adaptability to various growing conditions make it an ideal candidate for experimental studies in hydroponics and other innovative agricultural practices [6]. The rising global demand for spinach necessitates innovative agricultural techniques to enhance its productivity and quality [7]. Among these techniques, plant

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acoustic frequency technology is emerging as a novel approach, using specific sound frequencies to stimulate plant growth and development [8].

Sound waves influence various plant growth parameters, including cell division, enzyme activity, and hormonal responses, leading to improved yields, enhanced resilience, and reduced disease incidence under both open-field and controlled environments. Research indicates that specific sound frequencies can enhance photosynthetic activity by regulating the expression of genes related to photosynthesis, leading to improved growth rates in plants such as *Chamaecostus cuspidatus* and *Arabidopsis thaliana* [9][10].

Additionally, sound waves can stimulate stomatal opening, which optimizes water and nutrient absorption, thereby increasing overall plant health and yield [11]. Moreover, exposure to sound has been linked to increased production of secondary metabolites, which play crucial roles in plant defense and growth [12][13]. Studies have also demonstrated that sound waves can affect root development and phytohormone levels, further contributing to enhanced growth [14]. However, the effects of sound on plants can vary based on frequency, intensity, and duration of exposure, necessitating further research to optimize these parameters for agricultural applications [15][16].

The concept of plant acoustic frequency technology is based on the hypothesis that sound waves can affect physiological processes in plants. Prior research has shown that exposure to specific frequencies enhances seed germination, nutrient uptake, and overall plant health. For instance, Hendrawan et al. [17] demonstrated that exposing Kailaan plants to Javanese gamelan music at 3–5 kHz for three hours improved plant length, wet weight, stomatal openings, and chlorophyll content. Similarly, red lettuce exhibited optimal vegetative growth metrics such as height, wet and dry weight, leaf area, and stomatal opening under 3–5 kHz sound frequencies [18]. Mustard greens also benefited from these frequencies, with increased plant height, leaf count, and chlorophyll content when combined with organic planting media [19]. However, despite these promising results, research on the application of acoustic frequency technology in hydroponic systems, particularly the wick hydroponic method, remains sparse.

Wick hydroponics is a cost-effective and simple hydroponic system that uses passive wicking to deliver nutrient solutions to plant roots [20]. This method is well-suited for small-scale and urban farming due to its low maintenance and minimal reliance on electricity. Integrating acoustic frequency technology with wick hydroponics may create synergistic effects, boosting spinach productivity while preserving the system's inherent simplicity. Wick hydroponics relies on capillary action to transport nutrients, eliminating the need for pumps or energy inputs. Kim et al. [21] identified that using eight horizontal wicks optimized the growth of ‘Dejima’ seed potatoes, increasing tuber weight and yield. Similarly, Kang and Han [22] showed that nutrient solutions and Multicote fertilizers maximized tuber size and count. Kang [23] highlighted the effectiveness of perlite-peat moss and Jeju scoria-peat moss mixtures as growing media in wick hydroponic systems. The combination of wick hydroponics and sound wave technology presents a promising approach to enhance plant productivity. Wick hydroponics allows for efficient nutrient delivery to plants while maintaining moisture levels, which is crucial for optimal growth [24][25]. This method is particularly beneficial for leafy greens, as it minimizes water usage and provides a stable environment for root development [26][27]. Integrating sound wave technology can further amplify these benefits. Research indicates that specific sound frequencies can stimulate stomatal opening, enhancing gas exchange and nutrient absorption [28]. This stimulation can lead to improved photosynthetic rates and increased plant resilience against diseases, thereby boosting overall productivity. Furthermore, sound waves have been shown to influence root growth and enhance nutrient uptake efficiency, making them a valuable addition to hydroponic systems [29].

This study aims to bridge the gap in understanding by investigating the effect of plant acoustic frequency technology on spinach productivity in wick hydroponics. By examining critical growth parameters such as germination rate, biomass accumulation, and nutrient content, the research seeks to elucidate the potential of acoustic frequencies to optimize spinach cultivation. These findings could offer sustainable and efficient agricultural solutions, addressing global food security challenges and conserving resources in an increasingly dynamic environment.

2 Methods

This research is based on the plant acoustic frequency technology method by utilizing music exposed to plants using active speakers as loudspeakers. A randomized block design was used as the experimental design method. There are two treatment factors: the sound wave frequency, which consists of F1 = 3000 Hz, F2 = 8000 Hz, and F3 = 13000 Hz. The second factor is the duration of music exposure, which consists of J1 = 1 hour, J2 = 2 hours, and J3 = 3 hours. The control treatment with the code F0J0 represents plant samples without sound exposure. Each treatment was replicated three times, resulting in a total of 30 plants. Music exposure was conducted twice a day, from 07:00 – 10:00 am and 02:00 – 05:00 pm. The design of plant acoustic frequency technology is shown in Fig. 1.

The parameters to be observed include plant height, number of leaves, leaf area, plant fresh weight, greenness index, and root length. The music was created using DAW software and a MIDI Controller as the instrument. The genre of the music used is Folk Pop. The music creation focused on adjusting the frequencies produced by the music to meet the research requirements at frequencies of 3000 Hz, 8000 Hz, and 13000 Hz. After that, the samples were mixed and mastered to maximize the sound quality. The music samples can be accessed through the following links : https://youtu.be/0hcGkP0olFg for 3000 Hz music sample, https://youtu.be/K3ET9fVSc54 for 8000 Hz music sample, and https://youtu.be/Mc8w7RwzIzs for 13000 Hz music sample. The frequency graph of each music sample can be seen in Fig. 2. The sound intensity produced by the loudspeakers was set at the same level, ranging from 57 to 71 dBa.

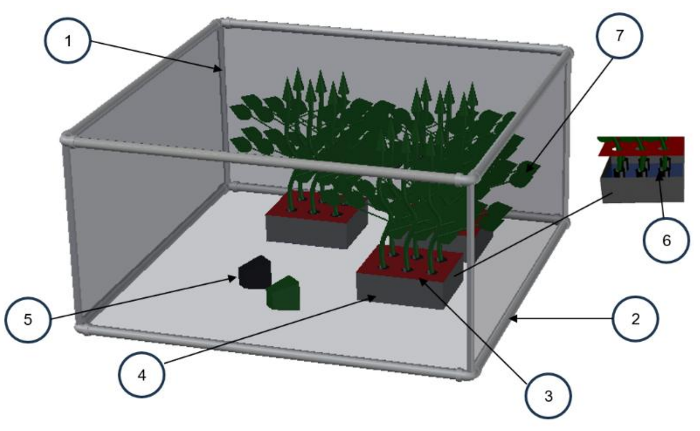

Fig. 1. Design of PAFT: 1. cover; 2. frame; 3. growth medium; 4. chamber; 5. loudspeaker; 6. water source; 7. plants.

(a)

(b)

(c)

Fig. 2. The frequency of the music: a) 3000 Hz; b) 8000 Hz; c) 13000 Hz.

3 Results and Discussions

Plant height is an important parameter to observe as it serves as a growth indicator used to determine the effect of the treatments applied. Based on the graph in Fig.3, it can be seen that the best average plant height 26 days after planting was achieved with the treatment of 3000 Hz frequency and 3 hours of music exposure, with a height of 63.33 cm. In contrast, the lowest average spinach plant height was observed in the control treatment, with a height of 49 cm. Spinach plants exposed to the 3000 Hz frequency for 3 hours exhibited the highest average height, increasing by 25.6% compared to the control. Conversely, the 13000 Hz frequency consistently resulted in the lowest growth performance across all durations, with only a marginal improvement of 5.2% over the control.

According to the ANOVA test results, the frequency variable had a significance value (sig.) of 0.001, meaning P < 0.01, indicating that the frequency variable had a very significant effect on spinach plant height. The duration of music exposure variable had a significance value of 0.012, meaning P < 0.05, indicating that the duration of music exposure had a significant effect on spinach plant height. Meanwhile, the interaction between frequency and duration of music exposure had a significance value of 0.175, meaning P > 0.05, indicating that the interaction between frequency and duration of music exposure did not have a significant effect on spinach plant height.

From the further LSD test at the 1% level, it was found that the 3000 Hz frequency had the highest effect on spinach plant height, with an average of 58.33 cm. The 13000 Hz frequency resulted in an average plant height of 53.11 cm, while the 8000 Hz frequency had the lowest effect, with a value of 52.67 cm. From the further LSD test at the 5% level, it was found that 3 hours of music exposure had the highest effect on spinach plant height, with an average of 57.22 cm. The 2-hour music exposure resulted in an average plant height of 54.22 cm, while the 1-hour music exposure had the lowest effect, with a value of 52.67 cm.

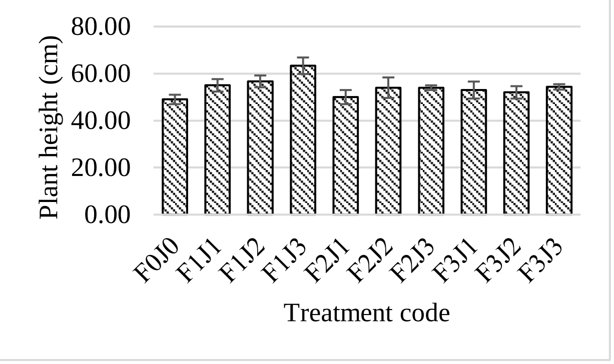

Fig. 3. The result of plant height.

Based on the graph in Fig. 4, the highest average number of leaves was achieved with the 13000 Hz frequency treatment and 3 hours of music exposure, resulting in 43 leaves. In contrast, the control treatment had the fewest leaves, with a total of 33. A significant interaction was observed between sound frequency and exposure duration. Plants treated with 3000 Hz for 2 hours produced the highest average number of leaves, 30% more than the control group. In contrast, plants exposed to 13000 Hz for 1 hour showed no significant difference from the control. The ANOVA test results showed that the frequency variable had a significance value of 0.362 (P > 0.05), indicating that frequency did not significantly affect the number of spinach leaves. Similarly, the duration of music exposure had a significance value of 0.134 (P > 0.05), suggesting that it did not impact the number of leaves. Additionally, the interaction between frequency and duration of music exposure had a significance value of 0.379 (P > 0.05), indicating no significant effect on the number of leaves. Given the ANOVA test results, both the frequency and duration of music exposure variables did not significantly influence the number of spinach leaves, making further LSD tests at the 1% and 5% levels unnecessary. The graph ranges from approximately 35 to 45 leaves, with some variation among the treatments. The graph has a similar pattern, and the differences in the number of leaves across the treatments are not very pronounced. The chart shows that different treatment combinations result in a similar number of leaves, with all treatments producing between 35 and 45 leaves on average. The control group (F0J0) shows the baseline number of leaves without any treatment, and the other groups do not deviate significantly from this baseline. The relatively small error bars suggest that the results are consistent within each treatment group.

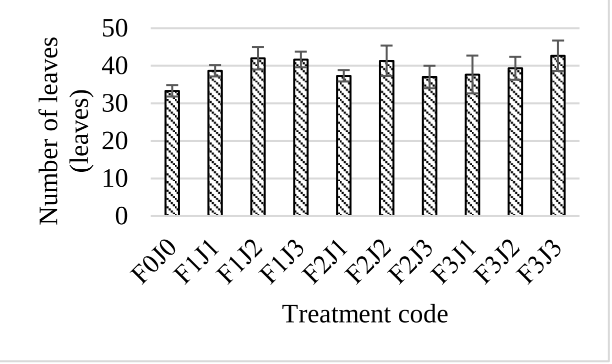

Fig. 4. The result of number of leaves.

Based on the graph in Fig. 5, the highest average leaf area 26 days after planting was achieved with the 3000 Hz frequency and 1 hour of music exposure, resulting in a leaf area of 2336.31 cm². Conversely, the treatment with 13000 Hz frequency and 1 hour of music exposure had the smallest leaf area, measuring 1795.8 cm². Leaf area was notably affected by sound frequency, with 3000 Hz treatments resulting in a 45.8% larger leaf area compared to control plants. Higher frequencies (8000 Hz and 13000 Hz) showed diminishing effects, suggesting reduced efficiency in promoting leaf expansion. The ANOVA test results showed that the frequency variable had a significance value of 0.000 ($P < 0.01$), indicating a very significant effect on the leaf area of spinach plants. In contrast, the duration of music exposure variable had a significance value of 0.455 ($P > 0.05$), indicating it did not significantly impact the leaf area. Furthermore, the interaction between frequency and duration of music exposure had a significance value of 0.326 ($P > 0.05$), suggesting that their interaction did not significantly affect the leaf area of spinach plants. Given the very significant impact of the frequency variable on leaf area, further testing was performed using the LSD test at the 1% level to identify differences in the effects of each treatment variable. The LSD test results at the 1% level revealed that the 3000 Hz frequency had the greatest effect on leaf area, with an average of 2291.72 cm². The 8000 Hz frequency resulted in an average leaf area of 1978.49 cm², while the 13000 Hz frequency had the least effect, with an average leaf area of 1937.31 cm². The graph ranges from approximately 1500 cm² to just under 2500 cm², showing some variability in leaf area depending on the treatment. However, all treatment results are still relatively close to each other, without any extreme deviations. The control group (F0J0), which has no treatment, shows a baseline leaf area that is slightly lower than some of the treated groups but within the same general range. The treatment F1J1 (3000 Hz, 1 hour) shows the highest leaf area, followed closely by F1J2 (3000 Hz, 2 hours) and F2J1 (8000 Hz, 1 hour). The treatments F2J3 (8000 Hz, 3 hours) and F3J3 (13000 Hz, 3 hours) exhibit slightly lower leaf areas compared to the other treatments, though still within a close range. The variability within some groups, as indicated by the error bars, is slightly larger, suggesting that some treatments may have more variable effects on leaf area. The chart indicates that different combinations of sound wave frequency and duration of music exposure lead to some variability in leaf area, but overall, the differences are not drastic. The highest leaf area is observed in the 3000 Hz frequency with shorter exposure durations (F1J1 and F1J2), while the longer durations and higher frequencies show slightly reduced leaf areas. Despite these variations, all treatments produce leaf areas within a relatively narrow range, indicating that the impact of these treatments on leaf area is moderate.

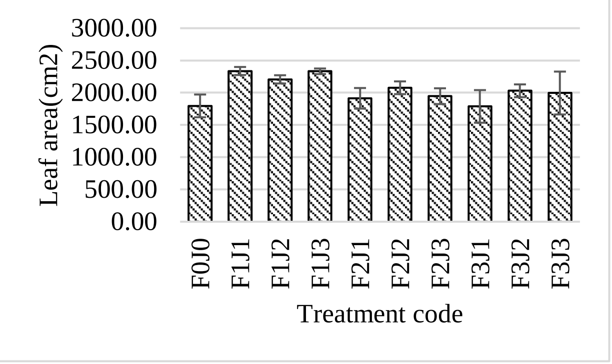

Fig. 5. The result of leaf area.

According to the diagram in Fig. 6, the highest average fresh weight of spinach plants was achieved with the 3000 Hz frequency and 2 hours of music exposure, reaching 102 g. The lowest fresh weight was observed in the control treatment, at 84 g. Fresh weight analysis revealed that spinach subjected to 3000 Hz for 3 hours yielded the highest biomass, 35.4% higher than control plants. Exposure to 8000 Hz and 13000 Hz frequencies resulted in significantly lower fresh weight gains, indicating limited effectiveness at these frequencies. ANOVA test results showed that the frequency variable had a significance value of 0.032 ($P < 0.05$), indicating a significant effect on the fresh weight of spinach plants. However, the duration of music exposure had a significance value of 0.765 ($P > 0.05$), suggesting it did not significantly impact fresh weight. Additionally, the interaction between frequency and duration of music exposure had a significance value of 0.931 ($P > 0.05$), indicating that this interaction did not have a significant effect on fresh weight. Since frequency had a significant effect on fresh weight, further analysis was carried out using the LSD test at the 5% level. The results revealed that the 3000 Hz frequency had the highest impact on fresh weight, averaging 100 g. The 8000 Hz frequency resulted in an average fresh weight of 91 g, while the 13000 Hz frequency had the lowest impact, with an average weight of 89.89 g.

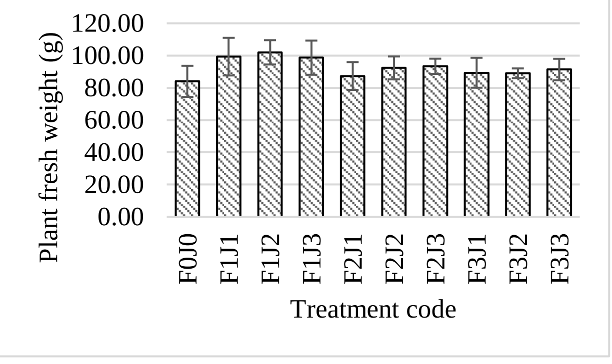

Fig. 6. The result of plant fresh weight.

The graph in Fig. 7 indicates that the spinach plants achieved their highest average greenness index with the treatment using a frequency of 3000 Hz and a music exposure duration of 2 hours, scoring 41.97. Conversely, the lowest index was seen in the control group, with a greenness index of 38.37. The music exposure treatments resulted in higher greenness indices compared to the control or plants with no music exposure. The greenness index, indicative of chlorophyll content, was highest in plants exposed to 3000 Hz for 3 hours, with a 22.5% increase compared to control plants. This result aligns with previous findings on chlorophyll enhancement under specific sound frequencies. ANOVA testing revealed that the frequency variable is significant, with a value of 0.012 ($P < 0.05$), showing a real effect on the spinach plants' greenness index. In contrast, the music exposure duration variable was not significant, with a value of 0.427 ($P > 0.05$), suggesting it does not impact the greenness index. Additionally, the interaction between frequency and exposure duration was also not significant, with a value of 0.794 ($P > 0.05$), meaning this interaction does not influence the greenness index. Given that frequency has a significant impact, further testing using the LSD method at a 5% significance level was conducted to discern differences between treatments. The LSD results indicate that a frequency of 3000 Hz has the greatest effect on the spinach plants' greenness index, with an average of 41.52. The 8000 Hz frequency results in an average index of 40.47, while the 13000 Hz frequency shows the lowest effect with an average of 40.16.

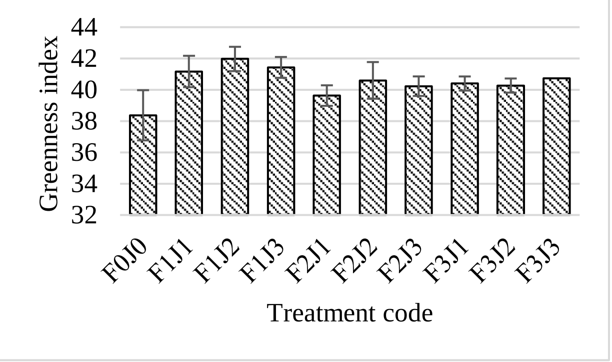

Fig. 7. The result of the greenness index.

According to the diagram in Fig. 8, spinach plants exhibited the longest average root length with a 3000 Hz frequency and 3 hours of music exposure, reaching 25.17 cm. The shortest root length was observed in the control group, measuring 22.67 cm. Generally, plants exposed to music had longer roots compared to the control. Root development followed a similar trend, with 3000 Hz treatments producing the longest roots, averaging 20.8% longer than the control. Higher frequencies (8000 Hz and 13000 Hz) resulted in significantly shorter root systems, with minimal differences across exposure durations. ANOVA results indicate that the frequency variable has a significance value of 0.2 ($P > 0.05$), suggesting that frequency does not significantly affect root length. Conversely, the duration of music exposure had a significance value of 0.003 ($P < 0.01$), indicating a strong effect on root length. Additionally, the interaction between frequency and exposure duration had a significance value of 0.029 ($P < 0.05$), showing that this interaction significantly affects root length. Given that the duration of music exposure has a strong effect, further analysis using the LSD test at a 1% significance level was performed to explore differences between treatments. The LSD results revealed that a 3-hour music exposure yields the highest average root length of 24.67 cm. A 2-hour exposure results in an average root length of 24.46 cm, while a 1-hour exposure has the lowest average of 24.04 cm. The LSD test at the 5% level showed that the combination of 3000 Hz frequency with 3 hours of music exposure achieved the highest root length, averaging 25.17 cm. Other combinations resulted in average root lengths of 24.67 cm for 3000 Hz with 2 hours, 24.57 cm for 3000 Hz with 1 hour, 24.53 cm for 8000 Hz with 2 hours, 24.27 cm for 8000 Hz with 3 hours, 24.17 cm for 13000 Hz with 2 hours, and 24.13 cm for 13000 Hz with 1 hour. The combination of 3000 Hz with 1 hour of exposure resulted in the shortest average root length of 23.83 cm.

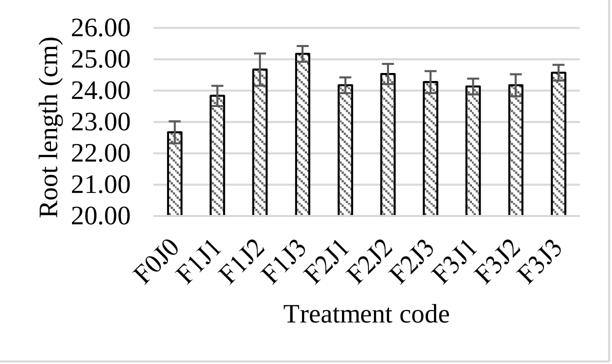

Fig. 8. The result of root length.

Table 1 presents the results for each treatment across the test parameters i.e. plant height (P1), number of leaves (P2), leaf area (P3), plant fresh weight (P4), greenness index (P5), and root length (P6). The data indicates that the treatment involving a 3000 Hz frequency with 3 hours of music exposure was the most effective in this study. ANOVA revealed statistically significant effects of sound frequency, exposure duration, and their interaction ($p < 0.05$) on all observed parameters. Tukey's post hoc test further confirmed the superior performance of the 3000 Hz frequency at longer exposure durations (2–3 hours). The results underscore the effectiveness of 3000 Hz sound frequency in promoting spinach growth, particularly at longer exposure durations. This aligns with previous studies, which found similar enhancements in plant physiological responses under low-frequency sound waves. In contrast, the limited performance of higher frequencies (8000 Hz and 13000 Hz) may be attributed to reduced resonance with cellular processes critical for growth.

Table 1. Best treatment analysis.

Code	Parameters (normalized value)						Total
	P1	P2	P3	P4	P5	P6	
F0J0	0	0	0.11	0	0	0	0.022
F1J1	0.77	0.44	1	0.88	0.77	0.11	0.706
F1J2	0.88	0.77	0.77	1	1	0.77	0.861
F1J3	1	0.77	0.88	0.77	0.88	1	**0.872**
F2J1	0.11	0.11	0.22	0.11	0.11	0.33	0.154
F2J2	0.44	0.66	0.66	0.55	0.55	0.66	0.583
F2J3	0.44	0.11	0.33	0.66	0.22	0.55	0.385
F3J1	0.33	0.33	0	0.33	0.44	0.22	0.264
F3J2	0.22	0.44	0.55	0.22	0.33	0.33	0.352
F3J3	0.66	1	0.44	0.44	0.66	0.77	0.651

4 Conclusions

This study highlights the potential of plant acoustic frequency technology (PAFT) to enhance spinach growth in wick hydroponic systems. The 3000 Hz frequency with 3 hours of exposure yielded the best results for plant height, leaf area, fresh weight, and greenness index. Root length was significantly influenced by exposure duration, demonstrating the importance of treatment customization. These findings suggest PAFT is an innovative and sustainable method to boost crop performance without chemical inputs, promoting eco-friendly agriculture. Further research on long-term impacts and scalability is recommended to advance its practical applications.

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