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Effect of Sonic Bloom Treatment on the Growth of Green Mustard and Pak Choi

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Abstract. Productivity of green mustard (*Brassica juncea* L.) and pak choi (*Brassica rapa* L.) is often constrained by suboptimal cultivation practices. Sound-based stimulation, such as Sonic Bloom, offers a novel approach to enhance plant growth, yet comparative evidence across sound types remains limited. This study evaluated the effects of Qur'anic recitation and classical music on the growth and yield of both crops. A Randomized Block Design with a non-factorial time-series approach was implemented from July to September 2022. Two plant species (J1: green mustard; J2: pak choi) and three treatments were tested: S0 (control), S1 (Qur'anic recitation), and S2 (classical music). Sound exposure (90 dB, 20–14,500 Hz) was applied daily for 2 hours, beginning 7 days after planting and continuing until harvest (24 DAP). Growth parameters and biomass were analyzed using ANOVA and Tukey's HSD (5%). Classical music (S2) significantly enhanced early growth, with plant height increases reaching 102.08% in green mustard and 91.16% in pak choi (6–12 DAP). Green mustard consistently outperformed pak choi across stages (77.88% vs 60.92% at 12–18 DAP; 42.07% vs 27.72% at 18–24 DAP). Leaf number increased up to 44.12%, and leaf area reached 208.74% under S2. Qur'anic recitation (S1) showed stronger effects at later stages, including higher dry root weight (0.34 g). Chlorophyll content was higher in green mustard but was not significantly affected by treatments. Classical music promotes early vegetative growth, while Qur'anic recitation supports sustained development. Sound-based stimulation represents a promising, sustainable strategy to enhance leafy vegetable productivity.

Keywords: block design time series; brassica; sonic bloom

1. Introduction

Green mustard (*Brassica juncea* L.) and pak choi (*Brassica rapa* L.) are economically important leafy vegetables widely cultivated across Asia, particularly in Indonesia, where consumer demand continues to increase (Chapara et al., 2024). Their short growth cycle, high nutritional value, and market acceptability make them strategic horticultural commodities. Recent statistical data from Indonesia indicate an 8.2% increase in vegetable production in 2021 compared to 2020 (BPS Indonesia, 2022). Despite this encouraging growth, domestic production remains insufficient to meet the steadily rising demand (Ngantung et al., 2018). This imbalance underscores the need for innovative, sustainable strategies to enhance crop productivity.

One of the major constraints limiting optimal production is suboptimal cultivation management, particularly inefficient fertilization practices (Bangun et al., 2024). Improper nutrient management can reduce vegetative growth, leaf expansion, and overall biomass accumulation (Qaswar et al., 2020). To address these challenges, various improvements in agricultural practices have been investigated, including the application of organic fertilizers derived from plant waste (Idris et al., 2023; Munar et al., 2018) and the implementation of integrated pest management systems (Divekar et al., 2024; Yadav, 2019). While these approaches have shown promising results, they often require additional inputs or management complexity, encouraging the exploration of complementary, low-input, and non-invasive technologies.

One emerging innovation in sustainable agriculture is Sonic Bloom technology, which utilizes sound waves to stimulate plant growth (Mawarni et al., 2022). This

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technology is based on the premise that sound vibrations, particularly at certain frequencies, can influence plant physiological processes (Patel et al., 2019). Previous research has demonstrated that high-frequency sound exposure may enhance stomatal opening, improve nutrient absorption, stimulate enzyme activity, and increase photosynthetic efficiency (Hassanien et al., 2014; Romero-Munar & Aroca, 2023). Enhanced stomatal opening allows plants to absorb more carbon dioxide, thereby potentially improving photosynthetic performance and biomass production.

Several studies have reported positive effects of sound stimulation on plant development. For instance, sound exposure has been associated with accelerated seed germination and improved vegetative growth in green mustard (Bangun et al., 2022). Additionally, sound waves have been shown to influence soil microbial activity (Munar, Sembiring, et al., 2023) and phosphorus uptake (Munar et al., 2020), both of which are essential for plant nutrition. These findings suggest that sound-based treatments may contribute not only to plant physiology but also to soil health and nutrient dynamics (Robinson et al., 2024).

Beyond pure frequency exposure, specific types of music have also been investigated for their potential effects on plant growth. Classical music, in particular, has been reported to enhance seed germination and vegetative development more effectively than random noise (Creath & Schwartz, 2004; Nio et al., 2021). Furthermore, Arlius et al., (2021) reported that exposure to 5000 Hz for 1 hour daily resulted in optimal growth in mustard plants. However, not all sound sources yield positive effects. Supit et al., (2024) found that bamboo music reduced carotenoid and chlorophyll b levels, while K-pop music decreased carotenoid content. These contrasting results indicate that plant responses may vary depending on the type, frequency, and duration of sound exposure (De Melo, 2023).

In recent years, attention has also been directed toward the potential influence of Qur'anic recitation on plant growth. Qur'anic recitation generates rhythmic and harmonic sound vibrations that may act as structured acoustic stimuli (Wu et al., 2023). Research by Prasetyo & Lazuardi (2019) showed that exposure to classical violin music for three hours significantly improved lettuce morphology and productivity compared to noise and mixed music treatments. Kadarisman et al., (2010) suggested that sound waves can widen leaf stomatal openings, further supporting the physiological basis of acoustic stimulation. Meanwhile, studies on Qur'anic recitation have demonstrated therapeutic effects on humans, even among listeners who do not understand the linguistic meaning (Hasyim et al., 2017). This suggests that structured auditory patterns alone may induce measurable biological responses, raising interesting possibilities for plant research.

Maghfiroh et al., (2024) compared classical music and Qur'anic recitation in hydroponically grown spinach and reported that classical music produced more pronounced growth enhancement, although Qur'anic recitation still performed better than the control without sound exposure. These findings indicate that different auditory stimuli may generate distinct physiological responses. However, comparative studies that evaluate multiple sound types across different vegetable species under controlled experimental conditions remain limited (D'Alessandro et al., 2015).

Despite the growing body of literature on sound stimulation in plants, several research gaps persist. Most previous studies have focused on a single plant species or a single type of sound treatment (Demey et al., 2023). In addition, limited research has directly compared religious recitation and classical music within the same experimental framework (Hassan et al., 2025). Furthermore, species-specific responses to sound stimulation have not been thoroughly investigated, particularly in economically

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important leafy vegetables such as green mustard and pak choi. Understanding these differences is essential for determining whether sound application can be practically implemented in horticulture. Therefore, this study aims to evaluate the differences in growth responses and yield of green mustard (*Brassica juncea* L.) and pak choi (*Brassica rapa* L.) under the influence of sound applications, specifically Qur'anic recitation and classical music.

2. Materials and Methods

This study was carried out at the experimental field of the Faculty of Agriculture, UMSU, situated in Sampali Village, Percut Sei Tuan District, Deli Serdang, at an elevation of about 25 meters above sea level. The study period spanned from July to September 2022.

Materials

The materials used in this study included pak choi seeds, green mustard seeds, compost, organic insecticide, and fungicide. The equipment comprised a speaker, sound level meter, MP3 player, amplifier, megaphone, ruler, AccuWeather device, spectrophotometer, plastic string, measuring tape, insect net, plywood, hoe, thermometer, and various laboratory tools for analysis.

Methods

In this study, sound exposure treatments were not conducted in the same or adjacent locations to prevent cross-contamination between the control and the different sound treatments. Therefore, the experiment was arranged using a Randomized Block Design (RBD) combined with a non-factorial time series approach, following the methodology of Fretheim et al. (2013). The experimental factor investigated was plant type (J), with two levels and three replications: J1 = green mustard (*Brassica juncea* L.) and J2 = pak choi (*Brassica rapa* L.). Data were initially analyzed using analysis of variance (ANOVA) to evaluate differences in green mustard growth percentage. Subsequently, data from the three different sound exposure locations were combined and analyzed according to the approach described by Fretheim et al. (2013). The sound treatments (S) consisted of three levels: S0 = no sound (control), S1 = murottal recitation of Surah Ar-Rahman from the Al-Qur'an, and S2 = Mozart classical music.

When significant differences were found, they were further analyzed using Tukey's Honestly Significant Difference (HSD) test at the 5% confidence level (Abdi & Williams, 2010; Hassanien et al., 2014). This test helped identify specific group differences by comparing the mean values of the treatments to determine which pairs of means were significantly different from each other. This step was crucial for gaining a deeper understanding of the treatment effects and for ensuring that the observed differences were statistically robust and reliable.

Sound Treatment Application

Sound treatments were applied under controlled field conditions with careful consideration of acoustic parameters. Each treatment plot was located at least 100 meters apart to prevent sound interference between treatments. Within each plot, speakers were positioned at approximately 50–100 cm from the plant canopy to ensure uniform sound distribution across all plants. The sound intensity was maintained at 90 dB Sound Pressure Level (SPL), measured at plant height with a sound level meter and continuously monitored via a Sound Analyser application on a Vivo Y-20 device. The frequency range of the sound treatments differed according to the sound source: S1 (Qur'anic recitation): 20–14,000 Hz, S2 (classical music): 20–14,500 Hz. Sound exposure was initiated at 7 days after planting (DAP) and applied daily from 09:00 to 11:00 WIB for 2 hours per day until harvest (24 DAP). This consistent exposure regime was designed to evaluate the cumulative effects of acoustic stimulation on plant growth.

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Study Implementation

In the experimental setup, conditions were carefully controlled to ensure uniform plant growth and minimize environmental variability. Each plot was arranged with a spacing of 50 cm between individual plants and 100 cm between replications to reduce potential interference. Plants were cultivated in containers measuring 30 cm × 35 cm, providing a controlled growth environment. The planting media consisted of a mixture of 1300 kg of topsoil and 40 kg of composted cow manure, containing approximately 1.5–2.5% nitrogen, 1.0–1.5% phosphorus, 1.0–2.5% potassium, and 10–25% organic carbon. Prior to planting, the substrate was thoroughly homogenized and irrigated to field capacity to ensure adequate moisture availability for optimal plant growth.

Data Collection Procedures

The study parameters included the percentage increase in plant height (from the stem base to the highest leaf), the number of fully opened leaves, stem height from the stem base to the leaf base, and leaf area. Plant growth and physiological parameters were measured using standardized procedures to ensure accuracy and reproducibility. Plant height was measured using a ruler from the base of the stem at the soil surface to the highest fully expanded leaf (Poehlman & Sleper, 1995). These growth parameters were assessed at 3 stages: 6–12, 12–18, and 18–24 days after planting (DAP). Leaf number was determined by counting all fully opened leaves per plant at each observation stage (Poehlman & Sleper, 1995). Stem height was measured from the base of the stem to the point of leaf attachment using a ruler (Poehlman & Sleper, 1995). Leaf area was estimated non-destructively by measuring the length and maximum width of the largest leaf, followed by calculation using a correction factor of 0.6825, according to Munar et al. (2018).

Growth rate was expressed as a percentage increase using Equation (1).

$$\% = \frac{a-b}{b}\ 100\% \ \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(Eq 1.)}$$

where:

% = Percentage of test parameters.

a = Initial observation measurements.

b = Observation measurements after a time interval.

At 24 DAP, plants were harvested to determine biomass. Fresh weight of roots and shoots was measured immediately after harvesting using an analytical balance, following careful removal of adhering soil. For dry weight determination, plant samples were oven-dried at 105°C for 24 hours, then at 65°C for 12 hours, until a constant weight was achieved. Chlorophyll content was analyzed using a spectrophotometric method (Pérez-Patricio et al., 2018). Leaf samples (10 g) were homogenized, extracted with 10 mL of 96% ethanol, and incubated overnight. The extract was filtered, and absorbance was measured using a spectrophotometer to determine chlorophyll concentration. All measurements were conducted on three replicate plants per treatment, and mean values were used for statistical analysis.

3. Results and Discussion

The application of sound treatments, including classical music (S2) and Qur'anic recitation (S1), resulted in varied responses in the growth and yield of green mustard (*Brassica juncea* L.) and pak choi (*Brassica rapa* L.). The magnitude and direction of these responses differed across growth parameters, observation periods, and plant types, indicating that plant sensitivity to acoustic stimulation is closely related to developmental stage and species characteristics.

Plant height and leaf number under sound treatments

Plant height and leaf number are closely related indicators of vegetative growth, reflecting how plants allocate assimilates toward structural development and canopy expansion. These parameters provide a

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sensitive measure of plant responses to external stimuli during different growth phases. In this study, sound treatments, including classical music (S2) and Qur'anic recitation (S1), did not produce statistically significant differences in plant height or leaf number (Figure 1A-C) (ANOVA, $p > 0.05$).

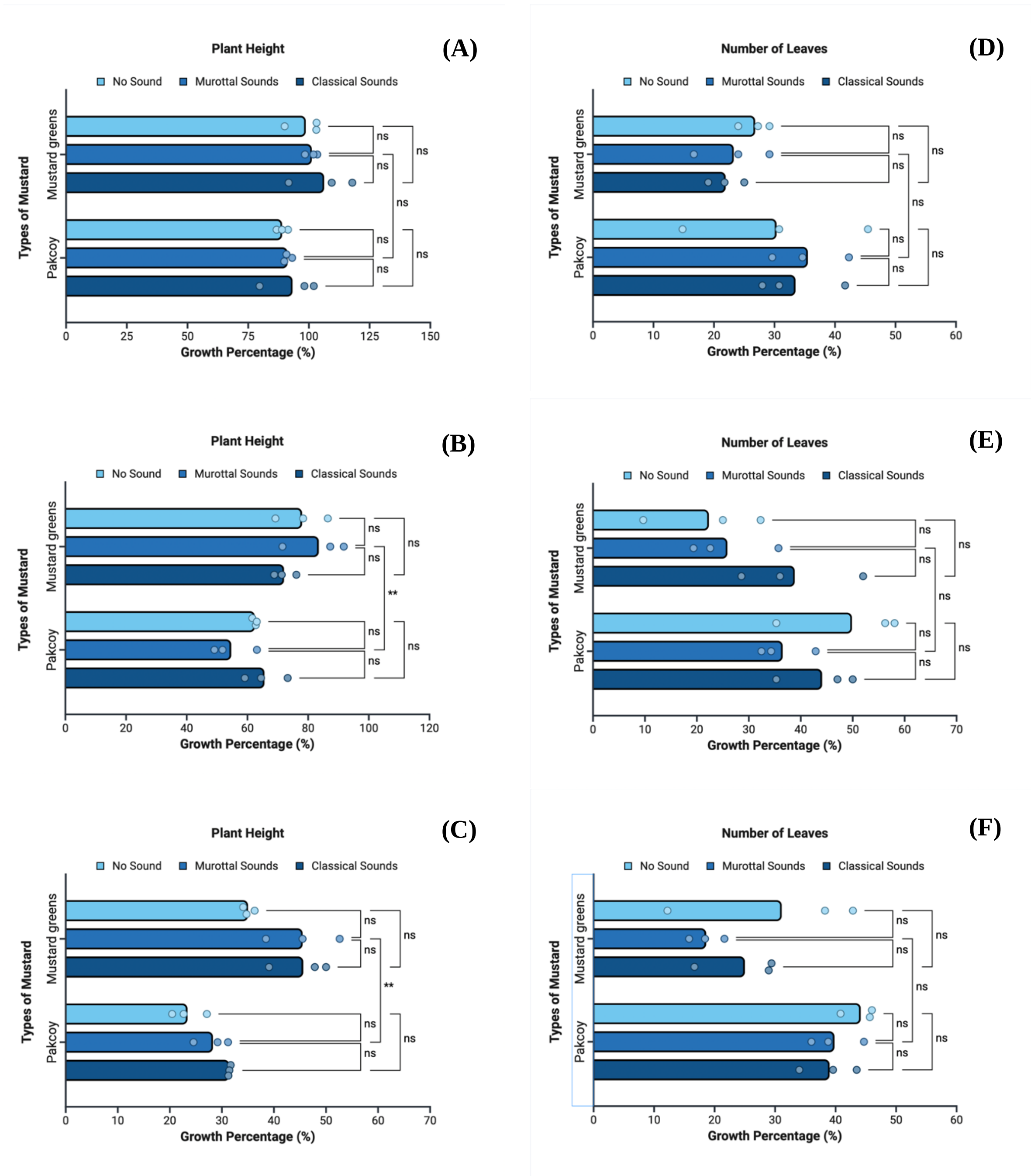

Figure 1. Percentage Increase in Height and Leaf Number of Green Mustard and Pak Choi Plants after Sonic Bloom Application. Legend, (A). Plant Height at 6-12 DAP. (B). Plant Height at 12-18 DAP. (C). Plant Height at 18-24 DAP. (D). Leaf Number at 6-12 DAP. (E). Leaf Number at 12-18 DAP. (F). Leaf Number at 18-24 DAP. ns = not significant based on ANOVA. * = Significant according to Tukey's test at 5%. ** = Significant according to Tukey's test at 1%.

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Despite this, clear biological trends were observed. During the early growth stage (6–12 DAP), classical music (S2) resulted in the highest increase in plant height, reaching 102.08% in green mustard and 91.16% in pak choi (Figure 1A). This trend persisted at 12–18 DAP, where green mustard under S2 showed a growth increase of 77.88% compared to 60.92% in pak choi (Figure 1B), and continued at 18–24 DAP with values of 42.07% and 27.72%, respectively (Figure 1C). A similar pattern was observed for leaf number, where pak choi showed greater increases across treatments, reaching up to 44.12% under classical music, compared with 32.01% in green mustard (Figure 1D–F).

These patterns suggest differences in growth strategy between the two species. Green mustard appears to prioritize stem elongation, while pak choi emphasizes leaf proliferation. Such variation is likely associated with species-specific physiological traits, including differences in meristem activity, hormonal regulation, and resource allocation. From a physiological perspective, the response to sound exposure may be linked to changes in stomatal behavior and metabolic activity. Hassanien et al (2014) demonstrated that sound waves can induce wider stomatal opening, enhancing CO_2 uptake and facilitating higher photosynthetic rates. Romero-Munar & Aroca (2023) further showed that acoustic stimulation improves gas exchange efficiency, which supports biomass accumulation and vegetative growth. Increased carbon assimilation provides the energy required for both stem elongation and leaf formation.

In addition to gas exchange, sound vibrations have been reported to influence enzymatic activity and cellular processes. Patel et al. (2019) found that sound exposure enhances enzyme activity in primary metabolism, thereby accelerating cell division and elongation. Yi et al. (2003) also reported increased soluble protein content and metabolic activity in plants exposed to sound, suggesting that acoustic stimulation may regulate internal biochemical processes. Evidence from previous studies supports the observed trends. Bangun et al. (2022) reported that classical music significantly improved plant height in green mustard, particularly during early growth stages. Munar et al. (2023) found that sound frequencies between 20–14,000 Hz enhanced both plant height and leaf area. Nio et al. (2021) highlighted that structured sound patterns are more effective than irregular noise in promoting vegetative growth, while Creath & Schwartz (2004) showed that harmonic sound produces stronger growth responses than non-structured sound.

The higher leaf number observed in pak choi suggests that this species may be more responsive to sound stimulation in terms of canopy development. Leaf formation is closely associated with nutrient availability and meristematic activity. Sound exposure has been linked to improved nutrient uptake and increased phosphorus availability in soil (Munar et al., 2020; Munar et al., 2023), which can support leaf initiation and expansion. Abdullah et al. (2019) also reported that acoustic treatments significantly increased leaf number in leafy vegetables. The absence of statistical significance indicates that variability among replicates remained relatively high, potentially masking treatment effects. Environmental factors, microclimatic variation, and individual plant responses may contribute to this variability. Even so, the consistent directional trends observed across growth stages suggest that sound treatments exert a measurable biological influence, particularly under classical music exposure.

Stem height and leaf area responses to acoustic stimulation

Stem height and leaf area describe structural growth and canopy development, both closely linked to photosynthetic capacity and biomass accumulation. In this study, responses varied across growth stages and

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sound treatments (Figure 2A–F), indicating that acoustic stimulation interacts dynamically with plant developmental phases.

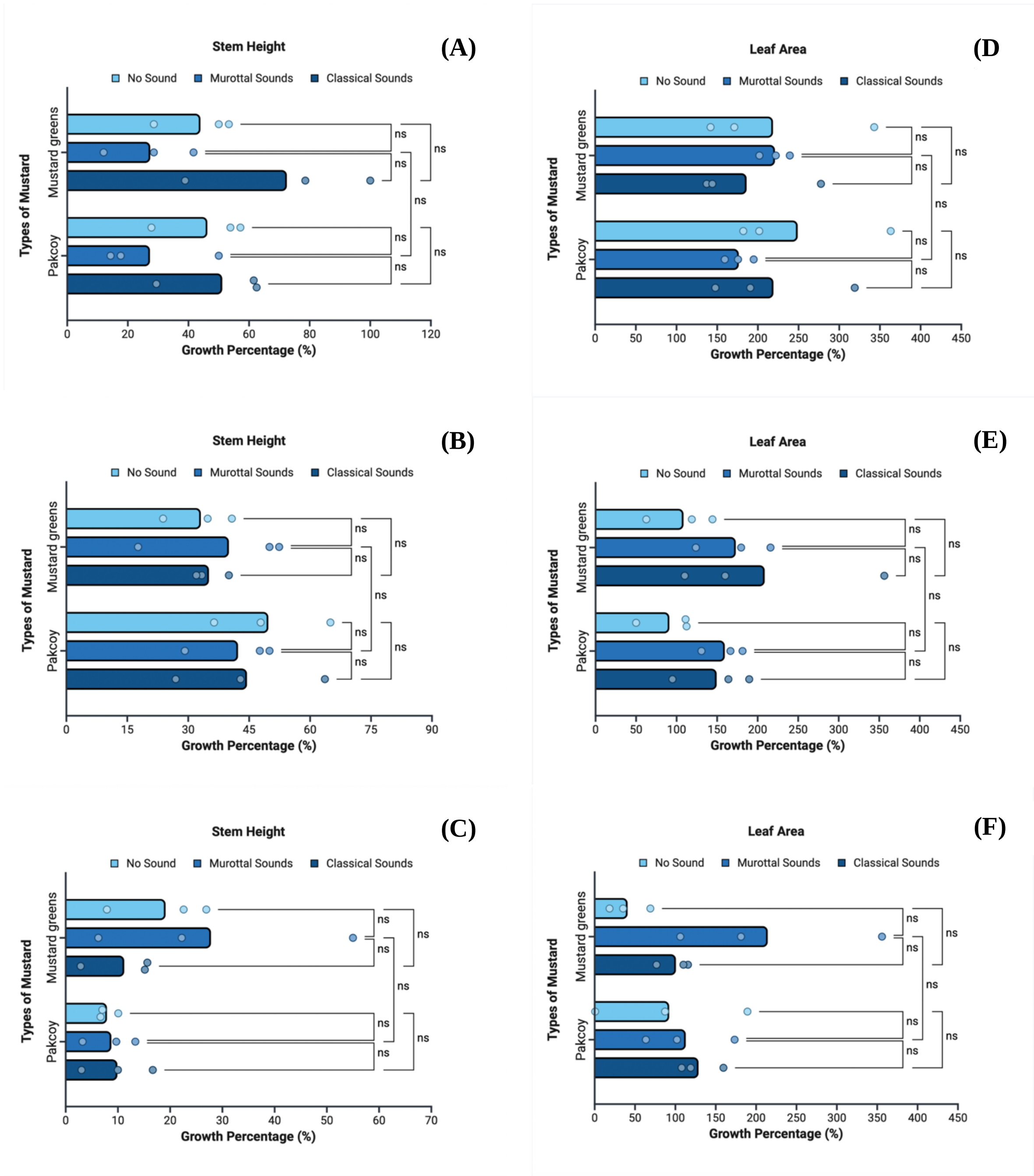

Figure 2. Percentage Increase in Stem Height and Leaf Area of Green Mustard and Pak Choi Plants after Sonic Bloom Application. Legend, (A). Stem Height at 6-12 DAP. (B). Stem Height at 12-18 DAP. (C). Stem Height at 18-24 DAP. (D). Leaf Area at 6-12 DAP. (E). Leaf Area at 12-18 DAP. (F). Leaf Area at 18-24 DAP. ns = not significant based on ANOVA. * = Significant according to Tukey's test at 5%. ** = Significant according to Tukey's test at 1%.

During the early growth stage (6–12 DAP), stem height increased under sound exposure, particularly in response to classical music (S2). Green mustard reached a growth increase of 72.49%, while pak choi reached 51.15% (Figure 2A). This pattern indicates that acoustic stimulation is more effective during the initial phase of vegetative growth,

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when cell division and elongation are highly active. At 12–18 DAP, pak choi showed relatively stronger stem growth across treatments, suggesting a shift in species response. At 18–24 DAP, stem elongation in green mustard declined under S2, while Qur'anic recitation (S1) maintained a more stable effect across stages (Figure 2C).

The leaf area showed a different response pattern. At 6–12 DAP, the highest expansion occurred in the control treatment (S0), particularly in pak choi (248.99%) and green mustard (218.62%) (Figure 2D). This suggests that early leaf expansion is largely regulated by internal physiological processes rather than external acoustic stimuli. At 12–18 DAP, classical music (S2) markedly increased leaf area in green mustard (208.74%), indicating that sound stimulation becomes more effective during the active vegetative phase when photosynthetic demand increases (Figure 2E). At 18–24 DAP, leaf area expansion declined under S2 but remained high under Qur'anic recitation (S1), particularly in green mustard (214.45%), suggesting a more sustained effect of rhythmic acoustic patterns (Figure 2F).

These responses can be linked to plant physiological mechanisms influenced by sound waves. Stem elongation depends on cell expansion regulated by hormonal activity, especially auxin. Sound vibrations have been shown to influence membrane permeability, ion transport, and cellular signaling, thereby enhancing elongation processes (Lestard et al., 2013). Kadarisman et al. (2010) reported that acoustic stimulation can widen stomatal openings, improving gas exchange and supporting growth. Increased stomatal conductance enables greater CO_2 uptake, which directly supports photosynthesis and structural development. Leaf expansion is strongly associated with photosynthetic activity and water regulation. Hassanien et al. (2014) demonstrated that sound waves stimulate stomatal opening, increasing transpiration and carbon assimilation. Romero-Munar & Aroca (2023) further showed that acoustic stimulation improves gas exchange efficiency, supporting leaf development and biomass accumulation. Enhanced photosynthetic performance provides the energy required for leaf enlargement, particularly during the mid-growth stage.

Biochemical responses also contribute to these patterns. Wu et al. (2023) found that sound exposure increases enzymatic activity involved in plant metabolism, accelerating cell division and expansion. Xiujuan et al. (2003) reported increases in soluble protein content and metabolic activity under sound treatment, indicating that acoustic stimulation can regulate internal biochemical processes. These mechanisms are consistent with the increased stem height and leaf area observed under classical music at 12–18 DAP. Previous empirical studies support these findings. Prasetyo & Raju (2021) showed that Sonic Bloom technology, using classical music, significantly improved plant growth in green mustard. Pagano & Del Prete (2024) reported that sound frequencies ranging from 20–14,000 Hz enhanced plant height, leaf area, and chlorophyll content. Forde (2009) found that structured sound patterns produced stronger growth responses than irregular noise. Das (2023) also demonstrated that harmonic sound, such as classical music, promotes plant growth more effectively than random acoustic exposure.

Responses to Qur'anic recitation reflect a different pattern. Abdullah et al. (2019) reported that acoustic patterns, including Qur'anic recitation, significantly increased stem length and leaf number. Shah et al. (2023) observed improved growth parameters in mustard seedlings under Qur'anic recitation, including leaf expansion and biomass accumulation. Chaidir et al. (2019) found that specific recitation frequencies enhanced chrysanthemum growth, suggesting that rhythmic acoustic signals may provide stable stimulation over longer periods. This aligns with the sustained leaf area observed under S1 at later growth stages. Differences between green mustard

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and pak choi highlight species-specific responses. Green mustard showed stronger responses in stem elongation, while pak choi exhibited higher leaf expansion in early stages. These differences may be related to variation in growth strategy, morphological structure, and physiological sensitivity to external stimuli. Similar observations were reported by Alavijeh et al. (2016), who found that different plant species responded differently to sound treatments, indicating that acoustic sensitivity is not uniform across crops.

Biomass Accumulation and Root Development

Biomass accumulation reflects the integration of physiological processes, including photosynthesis, nutrient uptake, and assimilate allocation. In this study, sound treatments did not produce statistically significant differences in root and shoot biomass for either green mustard or pak choi (Figure 3A-D) (ANOVA, p > 0.05). Even so, consistent trends were observed across treatments, indicating that acoustic stimulation influenced biomass distribution patterns.

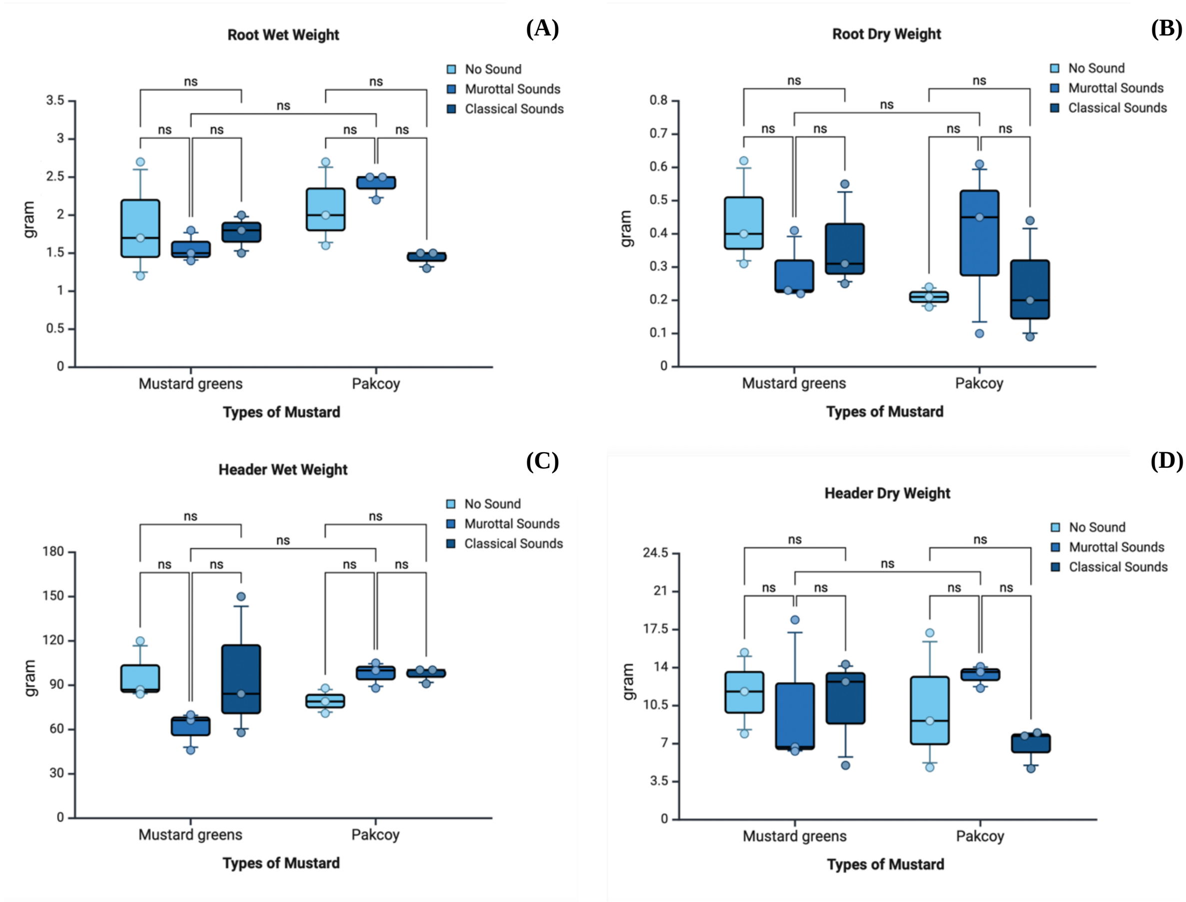

Figure 3. Observation of Plant Biomass of Green Mustard and Pak Choi after Sonic Bloom Application. Legend: (A). Root Wet Weight at 24 DAP. (B). Root Dry Weight at 24 DAP. (C). Header Wet Weight at 24 DAP. (D). Header Dry Weight at 24 DAP. ns = not significant based on ANOVA. * = Significant according to Tukey's test at 5%. ** = Significant according to Tukey's test at 1%.

Root biomass showed distinct responses depending on the type of sound applied. Classical music (S2) increased fresh root weight in both species, suggesting enhanced water uptake and root expansion. Qur'anic recitation (S1), on the other hand, resulted in slightly higher dry root weight, reaching 0.34 g compared to 0.33 g in the control (S0) and 0.31 g under classical music (Figure 3B). This pattern suggests that different sound types

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may affect root structure and water content differently, with S2 promoting hydration-related growth and S1 contributing to more compact or dense biomass formation.

Shoot biomass exhibited a similar trend. In green mustard, fresh shoot weight under classical music reached 97.28 g, compared to 88.17 g in the control and 79.22 g under Qur'anic recitation (Figure 3C). Pak choi showed a comparable pattern, although the differences were less pronounced. Dry weight measurements showed no clear separation among treatments for both species (Figure 3D), indicating that sound exposure did not significantly alter structural biomass accumulation.

These responses are closely related to root function and soil interactions. Root development determines the plant's capacity to absorb water and nutrients, which directly influences biomass production. Acoustic stimulation has been reported to affect soil-related processes, including microbial activity and nutrient availability. Munar et al. (2023) showed that sound exposure can stimulate phosphate-solubilizing microbes, while Sharpley et al. (1996) reported increased phosphorus availability under sound treatment. Improved nutrient availability can enhance root growth and indirectly support shoot biomass accumulation.

Physiological mechanisms may also explain these trends. Sound vibrations can influence membrane permeability and ion transport, facilitating nutrient uptake at the root level. Pagano & Del Prete (2024) reported increased biomass production in plants subjected to sound treatments, particularly in the root system. Enhanced metabolic activity under sound exposure, as reported by Wu et al. (2023), may further contribute to biomass accumulation through increased protein synthesis and energy availability. Variability in biomass data, particularly under classical music, indicates that plant responses to sound are not uniform. Environmental conditions, micro-scale variation in soil properties, and individual plant sensitivity may contribute to this variability. Although statistical significance was not achieved, the consistent tendency toward higher biomass under sound treatments, especially classical music, suggests that acoustic stimulation may influence plant growth, particularly through effects on root development and nutrient dynamics.

Chlorophyll Content and Physiological Implications

Chlorophyll concentration remained statistically unchanged across sound treatments (Figure 4) ($p > 0.05$), yet clear differences were evident between species. Green mustard consistently showed higher chlorophyll levels, with a median of 48.04 mg L^{-1}, while pak choi reached 40.11 mg L^{-1}. This pattern reflects inherent physiological differences rather than treatment effects, suggesting that chlorophyll accumulation is more strongly regulated by species-specific traits than by acoustic exposure under the given conditions.

Higher chlorophyll content is commonly associated with greater light-harvesting capacity and photosynthetic efficiency. The consistently elevated values in green mustard indicate a stronger ability to capture and utilize light energy, which aligns with its more pronounced performance in structural growth observed in earlier parameters. This relationship indicates a coordinated relationship between pigment concentration and biomass formation, in which chlorophyll availability supports sustained carbon assimilation during vegetative development.

Sound-related effects on chlorophyll are often described at the cellular and biochemical level. Wang et al. (2002) reported that acoustic stimulation can alter plasma membrane H^+-ATPase activity, which plays a role in ion transport and cellular homeostasis. Xiujuan et al. (2003) further showed that sound exposure may affect protein synthesis and enzymatic systems involved in chlorophyll metabolism. Under controlled conditions, these processes can

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translate into measurable changes in pigment concentration. The absence of significant differences in this study suggests that such responses may be highly dependent on exposure intensity, duration, or environmental stability.

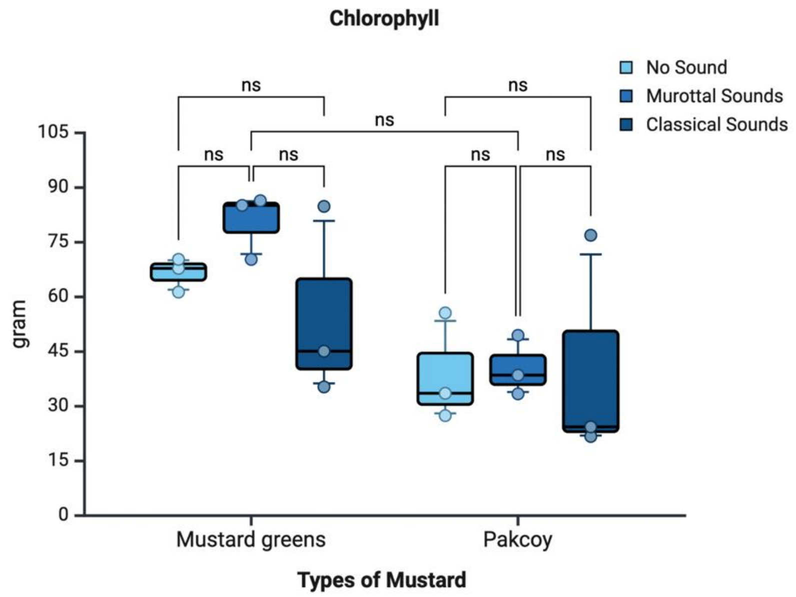

Figure 4. Chlorophyll Content of Green Mustard and Pak Choi Plants after Sonic Bloom Application. ns = not significant based on ANOVA. * = Significant according to Tukey's test at 5%. ** = Significant according to Tukey's test at 1%.

The distribution of chlorophyll values provides additional insight. Green mustard showed a relatively narrow interquartile range, suggesting a more uniform physiological response across replicates. Pak choi exhibited a wider spread, reflecting greater variability in pigment accumulation. Outliers were present in both species, including values exceeding 80 mg L^{-1} in green mustard, which may reflect localized differences in microenvironmental conditions such as light exposure, leaf position, or nutrient availability. This variability highlights the sensitivity of chlorophyll dynamics to external and internal factors. Field conditions introduce fluctuations in temperature, humidity, and radiation, all of which interact with plant metabolism. Acoustic stimulation may act as an additional modifier, but its effect can be masked when environmental variability is high. The results indicate that sound exposure did not disrupt chlorophyll stability, suggesting a neutral rather than a negative response. Taken together, chlorophyll content in this study appears to be governed primarily by species characteristics and environmental conditions, while sound treatments exert a limited influence under field-scale variability. The stability of chlorophyll levels across treatments suggests that acoustic stimulation may affect growth through pathways other than pigment synthesis, such as resource allocation or metabolic regulation.

4. Limitations and Future Directions

This study examined how sound treatments affect the growth and physiological responses of green mustard (*Brassica juncea* L.) and pak choi (*Brassica rapa* L.). Growth tended to be higher under acoustic exposure, especially with classical music, but the differences were not statistically significant, suggesting that the effect of sound depends on specific conditions.

Some limitations should be noted. Variation among plants was quite high, likely

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influenced by microenvironmental factors that were difficult to control in field conditions. The sound treatments were also limited in terms of frequency and exposure time, so they may not represent the most effective settings. Observations focused only on the vegetative stage, making it unclear how sound affects later growth or yield. In addition, physiological processes were not directly measured, so the mechanisms underlying the responses remain uncertain.

Future research should test a wider range of sound frequencies, intensities, and durations to determine optimal conditions. More controlled environments would help reduce variability. It is also important to extend observations to later growth stages and include direct measurements of physiological, biochemical, and soil-related parameters to better understand how sound influences plant growth.

5. Conclusion

This study demonstrated that sound exposure significantly influenced the growth performance and physiological characteristics of leafy vegetables, with green mustard exhibiting superior growth responses compared to pak choi under different sound treatments. Classical music exposure showed the most consistent positive effect by enhancing vegetative growth dynamics, promoting leaf area development, improving root biomass accumulation, and supporting higher chlorophyll content, indicating improved photosynthetic efficiency. Meanwhile, Qur'anic recitation contributed to sustained growth improvement during later developmental stages. These findings advance current knowledge by confirming the effectiveness of sound stimulation, particularly classical music within Sonic Bloom technology, as an environmentally friendly approach to optimize plant growth and productivity, thereby offering potential applications for sustainable agricultural management and controlled cultivation systems.

Despite these promising findings, the study was limited by the use of separate sound-exposure locations and a restricted number of plant species and environmental conditions, which may limit the generalizability of the results. Future research is recommended to investigate the long-term physiological and biochemical mechanisms underlying plant responses to sound stimulation, including molecular and microbial interactions in the rhizosphere. Further experiments involving additional crop species, varying sound frequencies and intensities, and controlled environmental conditions are necessary to validate and expand the applicability of sound-based agricultural technologies. Integrating advanced monitoring systems and multi-factor experimental designs may also provide deeper insights into optimizing Sonic Bloom applications for broader agricultural implementation.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the author(s) did not use any generative artificial intelligence (AI) or AI-assisted technologies in the writing, analysis, or preparation of the manuscript. All aspects of the work were conducted entirely by the author(s), who take full responsibility for the originality and content of this publication.

Authorship Contribution Statement

Asritanarni Munar: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft preparation; Mukhtar Yusuf: Methodology, Validation; Reza Azhari: Data curation, Visualization, Formal analysis; Dafni Mawar Tarigan: Investigation, Validation; Wan Arfiani Barus: Investigation, Validation, Formal analysis; Imam Hartono Bangun: Conceptualization, Supervision, Writing – review and editing, Final approval of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal

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