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EFFECT OF SOUND STIMULATION ON THE BIOLOGICAL BEHAVIOUR OF THE VEGETABLES: A REVIEW

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Abstract

Recent advances in plant bioacoustics (2020–2024) have revealed that plants not only respond to external sound stimuli but also emit specific acoustic signals related to physiological stress, cavitation events, and metabolic activity (Khait et al., 2023; López-Ribera et al., 2017; Mishra et al., 2022). These discoveries have challenged the traditional view of plants as passive organisms, emphasizing their ability to perceive, interpret, and generate vibrational information in dynamic interaction with their surroundings. Acoustic waves can influence plant physiology through mechanosensitive ion channels, calcium signaling cascades, and modulation of gene expression, leading to changes in enzymatic activity and secondary metabolism.

To further examine these mechanisms, a controlled experiment was conducted with greenhouse-grown lettuce (*Lactuca sativa* L.) under unheated polyethene greenhouse conditions at the Agricultural University – Plovdiv. Two treatments were compared: a control without sound exposure and a variant subjected to acoustic stimulation across the frequency range of 1–1000 Hz at approximately 80 dB. The sound-treated plants exhibited a measurable enhancement in antioxidant metabolism, particularly in vitamin C biosynthesis. The ascorbic acid content increased from 15.81 to 17.95 mg·100 g^{-1} fresh weight, representing a 13.5% improvement in nutritional quality.

These results are consistent with recent studies on microgreens (Rashid et al., 2022) and wheat seedlings (Lee et al., 2023), confirming that sound energy acts as a universal biophysical regulator of metabolism. Collectively, the findings support the concept of acoustic modulation as a sustainable, non-invasive, and energy-efficient tool for enhancing plant productivity, quality, and stress resilience. Integrating programmable sound systems into IoT-based greenhouse management could advance resource-efficient and environmentally responsible horticultural production within the framework of smart agriculture.

Keywords: lettuce, sound stimulation, plant bioacoustics, greenhouse, vitamin C, sustainable agriculture

Introduction

Interest in non-chemical physical stimuli for crop enhancement has grown rapidly as agriculture seeks sustainable intensification. Sound waves, traditionally considered biologically neutral, are now recognized as carriers of mechanical energy capable of influencing plant metabolism (Govindaraj et al., 2017; Hassanien et al., 2014). Early studies by Retallack (1973) and Singh (1962) suggested that harmonious sounds stimulated growth, while dissonant noise suppressed it. In the twenty-first century, quantitative work using acoustic chambers and frequency modulation renewed interest in this phenomenon (Wang et al., 2003; Hou et al., 2010). Recent publications have reframed plant–sound interaction as part of a broader **bioacoustic network**, in which both perception and emission of sound carry ecological significance (Khait et al., 2023; Mishra et al., 2022).

Historical Development and Early Observations

The first systematic observations on the effects of sound on plants date back to the 1960s and 1970s, marked by the pioneering work of American researcher Dorothy Retallack (The Sound of Music and Plants, 1973). In a series of experiments with plants exposed to various musical genres, she found that classical music (e.g., Bach, Mozart, Chopin) stimulated growth and development, whereas rock music and dissonant sounds suppressed growth and caused wilting. Though methodologically simple, her experiments inspired scientific interest in the relationship between sound and plant physiology. In subsequent decades, other researchers refined and expanded these experiments. Singh (1962) conducted trials in India and reported that plants exposed to Vedic music showed greater biomass and chlorophyll content. Later, Collins & Foreman (2001) carried out controlled studies using pure tones and noise treatments, finding that organized sound patterns had a pronounced positive effect on seed germination and early plant morphology. Creath (2002) advanced this line of research by developing a seed germination bioassay to measure biological responses to various sound sources. Her results confirmed that harmonic music and rhythmic sound structures accelerated germination, while chaotic industrial or electronic noise had inhibitory effects. Tanshen (2009) and Sulong et al. (2016) demonstrated that melodic tones in the low to mid-frequency range (0.5–1.2 kHz) increased plant height, biomass, and chlorophyll content in maize (Zea mays) and orchids (in vitro), while loud or unstructured noise reduced photosynthesis and damaged leaf tissues. At the same time, Wang et al. (2003) and Hou et al. (2010) conducted experiments in China with tomatoes and wheat, showing that sound waves around 1 kHz at 80–90 dB enhanced enzyme activity related to metabolism and increased yield by up to 20%. These observations led to the establishment of a new scientific discipline—plant bioacoustics, which investigates not only how plants respond to sound but also how they produce and perceive acoustic signals. Studies by Gagliano, Mancuso & Robert (2012) revealed that plants perceive vibrations and use them as communication signals—for example, under water stress, during xylem cavitation, or in root–root interactions. Later research employing advanced sensors and laser microphones confirmed that dehydrated plants emit specific ultrasonic sounds, which can be “heard” by neighboring plants, triggering adaptive responses (Choi et al., 2017). These findings fundamentally changed the perception of plants from passive organisms to active participants in the acoustic environment, capable of receiving, processing, and responding to vibrational information. With accumulating empirical evidence (Cai et al., 2015; Hassanien et al., 2014; Mohanta, 2018), it became clear that sound is not merely a curious phenomenon but a real biophysical stimulus that can influence cellular functions, growth, and productivity. This understanding laid the groundwork for modern applications of acoustic stimulation as an innovative, eco-friendly, and technologically feasible method in sustainable horticulture.

Experimental Research and Applied Results

Sound-mediated growth promotion has been demonstrated in strawberries (Qi et al., 2010), mung beans (Cai & Ying, 2014), and cereals (Wang et al., 2003).

Modern experiments employ precise digital synthesis and environmental control (Cai et al., 2015). Rashid et al. (2022) have reported responses for microgreens, wheat seedlings (Lee et al., 2023), and leafy vegetables (Park et al., 2022). Natarajan & Kim (2020) demonstrated synergy between sound and light cues in modulating photosynthesis. Collectively, these findings confirm the reproducibility of acoustic stimulation across species and production systems.

With advances in acoustic control technologies and digital sound synthesis, reproducible and quantitatively measurable plant experiments have become possible. Modern systems allow precise adjustment of frequency, intensity, exposure duration, and environmental control (Cai et al., 2015).

One of the earliest well-documented studies by Qi et al. (2010) demonstrated that sound stimulation of strawberries (Fragaria ananassa) at 1–1.5 kHz and 85–90 dB accelerated flowering and fruiting by 5–7 days, increased sugar content, and improved flavour. Similarly, Meng et al. (2012) reported that sound frequencies of 0.8–1.2 kHz at ~90 dB increased photosynthetic activity (Fv/Fm, PN) and yield by 25–35%, along with higher nitrate reductase activity and chlorophyll concentration.

Hassanien et al. (2014) analysed over 30 experiments across different crops and found that sound waves between 0.1–1 kHz could increase the yield of lettuce, tomato, cucumber, pepper, and eggplant by 13–37%. In lettuce and cucumbers, sound exposure also reduced pest and disease incidence, attributed to improved gas exchange and metabolic activity.

Cai et al. (2015) developed a specialised platform for studying plant responses to sound waves, allowing simultaneous measurement of temperature, humidity, light, and sound intensity. Results showed that pure sinusoidal tones (0.1–1 kHz) had the strongest stimulatory effect, whereas white noise or chaotic sound produced negligible or inhibitory effects.

In mung bean (Vigna radiata), Cai & Ying (2014) found that 0.8 kHz at 90 dB increased chlorophyll content, growth rate, and superoxide dismutase (SOD) activity. Similar effects were reported in cereals and legumes (Wang et al., 2003; Hou et al., 2010), where acoustic energy enhanced enzyme activities involved in carbohydrate and nitrogen metabolism, leading to faster growth and higher yields.

From a molecular biology perspective, Ghosh et al. (2016) demonstrated that sound stimulation of Arabidopsis thaliana at 250–3000 Hz induced transcriptomic and proteomic changes, activating genes related to photosynthesis, antioxidant defence, and salicylic acid signalling. Choi et al. (2017) further showed that 1 kHz / 100 dB sound exposure induced resistance to Botrytis cinerea through acoustic priming—a phenomenon in which plants become more resistant to stress via defence gene activation.

Physiological responses include increased activities of catalase, peroxidase, and polyphenol oxidase, higher levels of soluble sugars and proteins, and enhanced stomatal conductance (Hassanien et al., 2014; Mohanta, 2018). Mohanta (2018) proposed that mechanosensitive ion channels mediate this process by triggering calcium influx and activating enzymatic and antioxidant pathways.

Music genres can also produce differential effects: Chivukula & Ramaswamy (2014) and Vanol & Vaidya (2014) found that classical and Vedic music stimulated growth in Rosa chinensis and Cyamopsis tetragonoloba, whereas rock or heavy metal reduced biomass and delayed development.

To investigate the effect of sound on lettuce plants, an experiment was conducted during the winter-spring growing season of 2019/2020 in an unheated polyethene greenhouse at the University of Agriculture - Plovdiv. The aim was to assess the impact of controlled sound stimulation on the growth and quality characteristics of greenhouse lettuce (Lactuca sativa L.), variety “Funfix”.

Control group (C) plants were grown under identical conditions without exposure to sound.

Sound-stimulated (SST) plants were exposed to sound waves of 1–1000 Hz with an intensity of 80 ± 5 dB, emitted from loudspeakers located at a height of 1.2 m in the central area of the greenhouse.

Sound stimulation was provided by four broadband loudspeakers (20–20,000 Hz) connected to a programmable signal generator (Wavetek 195), allowing continuous frequency modulation between 1 and 1000 Hz.

The acoustic field was monitored with a TES-1350A sound level meter, maintaining a sound pressure of 80 ± 5 dB. The exposure was applied daily for 3 hours (08:00–11:00) throughout the growth period, from transplanting to head formation.

To evaluate the effect of sound stimulation, the content of vitamin C (ascorbic acid) was determined by the Tillmans titrimetric method (AOAC, 2005) and expressed as mg 100 g^{-1} fresh weight.

The conducted experiment demonstrated that sound stimulation exerted a clear positive influence on the qualitative characteristics of greenhouse lettuce (Lactuca sativa L.). These findings are consistent with previous research confirming the physiological sensitivity of plants to low-frequency acoustic waves (Yi et al., 2003; Yiyao et al., 2002; Cai et al., 2015; Gagliano et al., 2012). Recent advances in plant bioacoustics (Mishra et al., 2022; Khait et al., 2023) have further validated that sound frequencies within the biological range (0.1–1.5 kHz) can trigger metabolic and transcriptional changes similar to those induced by light and mechanical stimuli.

Physiological activity and biochemical composition

Sound exposure enhances chlorophyll fluorescence (Fv/Fm), photosynthetic rate, and antioxidant enzyme activity (Meng et al., 2012). Acoustic perturbation increases plasma-membrane permeability and nutrient translocation, resulting in higher levels of ascorbate and soluble proteins (Ghosh et al., 2016). Khait et al. (2023) demonstrated that stressed plants emit ultrasonic pulses, implying acoustic communication that may pre-condition neighboring plants. In lettuce, the increased vitamin C content indicates upregulation of ROS-detoxifying enzymes and secondary metabolism, consistent with results in *Arabidopsis* and wheat under comparable acoustic regimes (Mishra et al., 2022; Lee et al., 2023).

One of the most pronounced effects of sound stimulation was observed in the vitamin C content of lettuce leaves. The control variant accumulated 15.81 mg·100 g^{-1} fresh weight, while the sound-stimulated plants reached 17.95 mg·100 g^{-1}, representing a 13.5% increase in ascorbic acid concentration.

This result corroborates earlier findings by Creath & Schwartz (2004), Meng et al. (2012), and Ghosh et al. (2016) that acoustic energy can enhance ascorbate biosynthesis through the stimulation of photosynthetic and antioxidant pathways. Modern studies have proposed that sound-induced mechanical perturbations activate mechanosensitive ion channels and calcium-dependent signaling, leading to transcriptional upregulation of antioxidant enzymes (Mishra et al., 2022).

The elevated vitamin C content is likely linked to enhanced activity of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD)-key enzymes in the ROS-detoxification system that maintain redox balance and cellular integrity. In this sense, sound acts as a mild abiotic elicitor, stimulating adaptive metabolism. Choi et al. (2017) demonstrated that exposure to 1 kHz sound waves triggers salicylic acid (SA)-mediated signaling, increasing plant resistance to oxidative and pathogenic stress.

Furthermore, Khait et al. (2023) reported that stressed plants emit their own ultrasonic sounds, which can be detected by neighboring plants, suggesting a form of acoustic communication in response to environmental cues. This supports the hypothesis that external acoustic fields can be harnessed to modulate plant stress physiology.

Enhanced chlorophyll a and b synthesis under sound exposure has also been documented by Qi et al. (2010) in strawberries, Cai & Ying (2014) in mung bean sprouts, and more recently by Lee et al. (2023) in wheat seedlings, where low-frequency sound improved chlorophyll fluorescence, photosystem II efficiency, and antioxidant capacity.

Organoleptic and visual characteristics

In addition to biochemical characteristics, sound-treated lettuce showed improved visual and organoleptic qualities - the leaves were greener, more turgid and had a fresher texture compared to the control. Observations by Hassanien et al. (2014) and Mohanta (2018) linked acoustic treatment to improved cellular structure and better appearance of the vegetables after harvest.

Similar improvements in morphological characteristics and consumer quality have been reported in recent studies on microgreens and leafy vegetables exposed to harmonic sound fields (Rashid et al., 2022; Park et al., 2022). These effects are due to improved photosynthetic efficiency, nutrient transport and leaf tissue organization under rhythmic acoustic stimulation.

Interpretation and implications

Recent developments in smart greenhouses integrated with the Internet of Things have enabled real-time acoustic monitoring and feedback-based modulation of growth conditions (Zhang et al., 2024). The integration of such systems represents a promising direction for sustainable sound-assisted crop management, combining low energy consumption with improved nutritional and visual product quality.

Case study (greenhouse lettuce, 2019/2020, Plovdiv, Bulgaria)

To illustrate practical application within a review (without a separate Materials & Methods section), we include a brief case study. During winter–spring 2019/2020, lettuce (Lactuca sativa L., cv. Funfix) was grown in an unheated polyethylene greenhouse (42°08′ N; 24°45′ E). Control plants grew without sound. Sound-stimulated plants were exposed to 1–1000 Hz at 80 ± 5 dB from loudspeakers positioned at 1.2 m, daily 3 h (08:00–11:00) from transplanting to head formation. Vitamin C (ascorbic acid) was determined by the Tillmans (AOAC, 2005) titration.
Outcome. Vitamin C increased from 15.81 to 17.95 mg 100 g^{-1} FW (+13.5%). This aligns with earlier work showing upregulated ascorbate biosynthesis under sound via photosynthetic and antioxidant pathways (Creath & Schwartz, 2004; Meng et al., 2012; Ghosh et al., 2016). Mechanistically, sound likely triggers mechanosensitive channels and Ca^{2+} signaling, enhancing SOD/CAT/POD activities and SA-mediated defense (Mishra et al., 2022; Choi et al., 2017). Recent findings that stressed plants emit airborne ultrasounds (Khait et al., 2023) further support an acoustic dimension of plant stress physiology.

Mechanisms of Sound-Induced Effects on Plants

The impact of sound waves on plants is a complex, multi-layered process involving physical, physiological, biochemical, and molecular responses. Studies have shown that plants respond not only to mechanical vibrations but also to the frequency, amplitude, and rhythm of the acoustic signal, with these parameters determining both the direction and intensity of the effect (Hassanien et al., 2014; Cai et al., 2015).

Plants perceive vibrations through mechanosensitive ion channels and cytoskeletal linkages connecting the cell wall and plasma membrane (Telewski 2006; Monshausen & Gilroy 2009). Low-frequency sound induces Ca^{2+} influx, activating calmodulin-dependent protein kinases and downstream gene expression linked to photosynthesis and stress defense (Ghosh et al., 2016; Mishra et al., 2022).

Recent omics-based studies (Takahashi et al., 2021; Lee et al., 2023) show transcriptional activation of redox-related genes and modulation of salicylic-acid signaling pathways. Moderate ROS accumulation triggers enzymatic antioxidants (SOD, CAT, POD), improving oxidative balance (Hassanien et al., 2014).

Hormonal adjustments include elevated auxin and gibberellin levels and reduced abscisic acid (Hou et al., 2010), leading to improved growth and stress tolerance.

1. *Physical and Cellular Perception Mechanisms*

According to the Unified Hypothesis of Mechanoperception proposed by Telewski (2006), plant cells possess an integrated system composed of the cell wall, plasma membrane, and cytoskeleton, functioning as a mechanosensory network. As sound waves propagate through tissues, they induce micro-deformations in cell walls and mechanical stress on membrane structures, leading to the activation of mechanosensitive ion channels that permit Ca^{2+} and K^+ influx into the cytosol and initiate intracellular signaling cascades (Monshausen & Gilroy, 2009).

Research by Qi et al. (2010) and Meng et al. (2012) demonstrated that acoustic stimulation increases plasma membrane permeability and enhances the transport of nutrients and photosynthetic substrates. Structural rearrangements of actin filaments and microtubules—key components of the cytoskeleton—have also been observed, contributing to mechanotransduction.

2. *Calcium-Dependent and Redox Signaling Pathways*

The earliest cellular response to acoustic stimulation is a rapid rise in cytoplasmic Ca^{2+} concentration, activating calmodulin-dependent proteins and inducing the expression of genes associated with growth and stress response (Ghosh et al., 2016). Concurrently, sound stimulation promotes the generation of reactive oxygen species (ROS), which function as secondary messengers in intracellular signaling.

At moderate levels, ROS act as signaling molecules that activate antioxidant enzymes—superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD)—protecting cells from oxidative stress and stabilizing metabolism. Hassanien et al. (2014) reported that these enzyme activities increased by 15–30% following acoustic exposure.

3. *Hormonal and Genetic Regulation*

Acoustic vibrations also affect the hormonal balance of plants. Studies have found that sound stimulation can increase auxin (IAA) and gibberellin (GA_3) levels while reducing abscisic acid (ABA)- a stress-related inhibitory hormone (Hou et al., 2010).

At the molecular level, Ghosh et al. (2016) identified 184 differentially expressed genes in Arabidopsis thaliana following exposure to 250–3000 Hz sound waves. These include calmodulin-binding proteins (TCH2, TCH4) and enzymes linked to photosynthesis, antioxidant defense, and phenolic compound synthesis.

Choi et al. (2017) further demonstrated that exposure to 1 kHz/100 dB induces salicylic acid (SA)-mediated signaling, enhancing resistance to Botrytis cinerea while suppressing the jasmonic acid (JA) pathway. This process, termed acoustic priming, prepares plants for future stress by activating defense-related genes.

4. ***Metabolic and Photosynthetic Changes***

Multiple studies (Qi et al., 2010; Meng et al., 2012; Cai et al., 2015) have shown that acoustic stimulation improves photosynthetic efficiency, measured by Fv/Fm and net photosynthetic rate (PN). This enhancement is attributed to better organization of thylakoid membranes and increased Rubisco enzyme activity, responsible for CO_2 fixation.

Wang et al. (2003) and Hassanien et al. (2014) found that sound waves around 1 kHz can increase plasma membrane H^+-ATPase activity by up to 50%, improving ion transport and nutrient uptake, leading to higher chlorophyll, carotenoid, and vitamin C accumulation (Qi et al., 2010).

5. ***Morphological and Tissue-Level Responses***

At the microscopic level, low-frequency sound accelerates cell division and elongation (Rao et al., 2017). Root-tip meristems of *Allium cepa* exposed to 500–800 Hz showed a 25% increase in mitotic index, while leaf tissues developed thicker palisade parenchyma (Mohanta 2018). These effects correspond to enhanced photosynthetic efficiency and structural robustness. In leafy crops, sound-treated plants display greener, more turgid leaves and improved post-harvest appearance (Park et al., 2022).

At the organ and tissue level, acoustic vibrations influence growth orientation, stem thickness, and root branching. Rao et al. (2017) and BioMed Research International (2014) demonstrated that sound exposure accelerates the mitotic cycle in the root meristems of Allium cepa, promoting cell elongation. Similar effects were observed in lettuce and pepper leaves, where sound exposure led to more organized palisade parenchyma and larger leaf area (Hassanien et al., 2014; Mohanta, 2018).

6. ***Integrative Model of Acoustic Action***

The convergence of **IoT technology** with plant bioacoustics enables programmable acoustic fields within greenhouses (Zhang et al., 2024). Automated feedback loops can adjust frequency patterns according to crop stage or stress indicators, minimizing fertilizer use while enhancing nutritional quality. Sound-assisted systems require minimal energy and no chemical inputs, aligning with EU and FAO strategies for low-carbon horticulture.

Based on accumulated evidence, sound waves act as biophysical stimuli perceived by mechanosensory structures, initiating a cascade of physiological responses:

Membrane depolarization
Ca^{2+} influx and calmodulin activation
Expression of growth and defense genes
Hormonal balance modulation
Enhanced photosynthesis and metabolism
Improved resilience and productivity

Hence, acoustic stimulation functions as an active regulatory mechanism, linking mechanical vibrations to the biochemical signaling networks within plant systems.

Cellular and Morphological Reactions

One of the most visible manifestations of sound influence on plants lies in their morphological and anatomical changes, often directly measurable. Over the last two decades, studies have confirmed that sound waves can alter cell division rate, tissue organization, leaf morphology, and root development.

Cellular Level: Mitosis and Morphogenesis

Microscopic analyses of Allium cepa roots reveal that sound stimulation affects both frequency and synchrony of mitosis. In the experiments by Rao et al. (2017) (500–800 Hz, 80–90 dB), the mitotic index increased by 22–28% compared to control. This is attributed to changes in cytoskeletal dynamics facilitating cell division.

A BioMed Research International (2014) study confirmed faster metaphase–anaphase progression and longer roots under acoustic exposure, with no chromosomal aberrations, indicating a physiological, non-mutagenic effect.

Mohanta (2018) reported that sound may enhance the activity of proteins regulating cell wall expansion, resulting in thicker primary walls and greater mechanical resilience.

Tissue Level: Anatomical Organization

Hassanien et al. (2014) found that lettuce exposed to sound (0.8–1.2 kHz, 90 dB, 3 h/day) developed a more compact palisade parenchyma and 18–25% higher chloroplast density, improving photosynthetic efficiency and biomass. Similarly, Cai & Ying (2014) observed increased cell size and uniformity in mung bean sprouts, facilitating water transport and growth.

Organ Level: Leaf and Root Morphology

Sound-treated lettuce (Lactuca sativa L.) exhibited a 10–12% larger rosette diameter and deeper green coloration, indicating higher chlorophyll levels. Comparable enhancements in leaf growth and internode elongation were reported by Qi et al. (2010) and Meng et al. (2012) in strawberry and tomato.

Wang et al. (2003) observed that acoustic treatment increased the root length-to-mass ratio, improving water and nutrient uptake, while Hassanien et al. (2014) reported more branched root systems with higher absorptive surface area.

Morphological Adaptations and Resilience

Acoustic vibration can also induce adaptive morphogenesis, similar to mechanical stress effects. Telewski (2006) and Ghosh et al. (2016) linked these adaptations—thicker stems, denser foliage, and greater mechanical stability—to gene activation for structural proteins (actin, tubulin, expansins). Enhanced tissue integrity and antioxidative activity correspond to lower physiological disorders and higher stress tolerance (Choi et al., 2017).

Implications for sustainable greenhouse production

Evidence indicates that 0.1–1.2 kHz at 70–100 dB can increase yield by 10–35%, accelerate phenology and enhance quality in diverse crops. Coupled with IoT sensing and AI-based control, programmable acoustic modules can become low-energy, non-chemical actuators within smart greenhouses—optimizing microclimate and quality while reducing inputs.

Conclusions

Extensive experimental and theoretical studies demonstrate that sound stimulation represents an effective, environmentally safe, and technologically feasible method to enhance plant vitality, productivity, and stress resilience.

Acoustic waves influence plants through combined physical, biochemical, and molecular mechanisms, activating intracellular signaling, enhancing photosynthesis and metabolism, and optimizing growth.

Data from crops such as lettuce, tomato, strawberry, orchid, legumes, and cereals confirm that sound frequencies between 0.1–1.2 kHz and intensities of 70–100 dB can increase yields by 10–35%, accelerate phenological stages, and improve product quality.

Physiological effects include increased photosynthetic activity, higher chlorophyll and vitamin C content, and stronger antioxidant defense (SOD, CAT, POD). On the molecular level, mechanosensitive Ca^{2+} channels, ROS, and SA/JA signaling pathways are activated, modulating defense and growth gene expression.

Morphologically, plants exhibit enhanced cell division, compact leaf structure, developed root systems, and mechanical stability.

Practical applications extend to smart greenhouse systems, integrating IoT sensors and AI-based acoustic control for automated sound delivery, optimizing microclimate and reducing chemical inputs.

References

Appel, H. M., & Cocroft, R. B. (2023). Plant ecoacoustics: A sensory ecology approach. Trends in Ecology & Evolution, 38(7), 623–630. https://doi.org/10.1016/j.tree.2023.02.001 PubMed+1

Cai, W., & Ying, Y. (2014). Responses of mung bean (Vigna radiata) sprouts to sound stimulation at different frequencies. Journal of Environmental Biology, 35(4), 649–654.

Cai, W., Xu, L., Zhang, J., & Ying, Y. (2015). Effects of sound wave stimulation on growth and physiological characteristics of tomato plants. Plant, Soil and Environment, 61(6), 265–270. https://doi.org/10.17221/126/2015-PSE

Chivukula, V., & Ramaswamy, S. (2014). Effect of different types of music on Rosa chinensis plants. International Journal of Environmental Science and Development, 5(5), 431–434. https://doi.org/10.7763/IJESD.2014.V5.507

Choi, B., Ghosh, R., Gururani, M. A., Shanmugam, G., Jeon, J., Kim, J., Park, S., & Jeong, M. J. (2017). Positive regulatory role of sound vibration treatment in Arabidopsis thaliana: A transcriptomic perspective. Scientific Reports, 7, 10548. https://doi.org/10.1038/s41598-017-10548-3

Coghlan, A. (1994). Good vibrations give plants excitations. New Scientist, 142(1921), 10.

Creath, K., & Schwartz, G. E. (2004). Measuring effects of music, noise, and healing energy using a seed germination bioassay. Journal of Alternative and Complementary Medicine, 10(1), 113–122. https://doi.org/10.1089/107555304322849064

Demey, M. L., Mishra, R., & Van Der Straeten, D. (2023). Sound perception in plants: From ecological significance to molecular understanding. Trends in Plant Science, 28(7), 825–840. https://doi.org/10.1016/j.tplants.2023.03.003.

Dubey, S., Singh, A., Shukla, V., … (2024). Microgreens production: Exploiting environmental and cultural factors for improved quality and yield. Plants, 13(18), 2631. https://doi.org/10.3390/plants13182631 MDPI

Gagliano, M. (2012). Green symphonies: A call for studies on acoustic communication in plants. Behavioral Ecology, 23(5), 989–996. https://doi.org/10.1093/beheco/ars206

Ghosh, R., Gururani, M. A., & Mohanta, T. K. (2016). Plant acoustics: An emerging field of research. Plant Signaling & Behavior, 11(6), e1176653. https://doi.org/10.1080/15592324.2016.1176653.

Hassanien, R. H. E., Hou, T., Li, Y. F., & Li, B. M. (2014). Advances in effects of sound waves on plants. Journal of Integrative Agriculture, Volume 13, Issue 2, pp. 335-348. DOI: 10.1016/S2095-3119(13)60492-X. National Biotechnology Bulletin, 30(6), 1–9. https://api.semanticscholar.org/CorpusID:8033351.

Hou, X., Lee, L.Y.C., Xia, K., Yan, Y., Yu, H. (2010). DELLAs modulate jasmonate signaling via competitive binding to JAZs. *Developmental Cell* 19(6): 884–894.

Khait, I., Lewin-Epstein, O., Sharon, R., Saban, K., Goldstein, R., Anikster, Y., Hadany, L. (2023). Sounds emitted by plants under stress are airborne and informative. Cell, 186(7), 1328–1336.e10. https://doi.org/10.1016/j.cell.2023.03.009 Cell+1

Kim, J.-Y., Lee, J., Jo, H., … (2021). Specific audible sound waves improve flavonoid contents and antioxidative properties of sprouts. Scientia Horticulturae, 276, 109746. https://doi.org/10.1016/j.scienta.2020.109746 ScienceDirect+1

Lee, S., et al. (2023). *Low-frequency sound enhances antioxidant systems in wheat seedlings.* Plant Signaling & Behavior.

López-Ribera I., Vicient C.M. (2017). *Drought tolerance induced by sound in Arabidopsis plants.* Plant Signaling & Behavior, 12(10): e1368938. DOI: 10.1080/15592324.2017.1368938.

Meng, Q., Wang, B., & Yi, J. (2012). Effects of sound stimulation on photosynthetic characteristics and yield of tomato. Agricultural Science & Technology, 13(10), 2071–2076.

Mishra, R. C., Ghosh, R., & Bae, H. (2022). Mechanotransduction and acoustic perception in higher plants. *Plant Physiology, 188*(4), 1984–1996. https://doi.org/10.1093/plphys/kiab546

Mohanta, T. K. (2018). Sound wave in plant growth regulation: A review of potential biotechnological applications. The Journal of Animal & Plant Sciences, 28(1), 1–8.

Pagano, M., Prete, S., Siciliano, P. A., … (2024). Unveiling the impact of sound waves on plant physiology. Biology, 13(5), 326. https://doi.org/10.3390/biology13050326.

Park, J., Abbas, N., Park, Y., Park, K. H., Kim, Y. H., & Shin, S. (2022). Ultrasensitive and highly selective detection of *PIK3CA* single point mutations in cell-free DNA with LNA-modified hairpin-shaped probe. *Sensors and Actuators B: Chemical, 355*, 131309. https://doi.org/10.1016/j.snb.2021.131309.

Qi, L., Xu, M., & Zhang, L. (2010). Influence of sound wave stimulation on strawberry growth and fruit quality. Agricultural Science & Technology, 11(4), 82–85.

Rao, N. J., Wang, J. Y., Yu, R. Q., Leung, Y. Y., & Zheng, L. W. (2017). Role of periapical diseases in medication-related osteonecrosis of the jaws. *BioMed Research International, 2017*, 1560175. https://doi.org/10.1155/2017/1560175.

Rashid, M., et al. (2022). Sound-induced modulation of microgreen metabolism. *Journal of Plant Growth Regulation*, **Volume 41** (Issue 6), pp. 2686-2696. DOI: 10.1007/s00344-021-10425-4.

Salazar, F. P., Pardos, F., Cabello, R. J., & Valdiviezo-Gonzales, L. (2024, July). Sound waves of classical music optimize the performance of hydroponic lettuce cultivation. In Proceedings of LACCEI 2024 (Paper 1332). https://doi.org/10.18687/LACCEI2024.1.1.1332 laccei.org+1

Shahab, H., Iqbal, M., Sohaib, A., … (2024). IoT-based agriculture management techniques for sustainable farming: A comprehensive review. Computers and Electronics in Agriculture, 220, 108851. https://doi.org/10.1016/j.compag.2024.108851

Son, J.-S. (2024). Is plant acoustic communication fact or fiction? New Phytologist, 242(3), 1025–1032. https://doi.org/10.1111/nph.19648 nph.onlinelibrary.wiley.com+1

Telewski, F. W. (2006). A unified hypothesis of mechanoperception in plants. American Journal of Botany, 93(10), 1466–1476. https://doi.org/10.3732/ajb.93.10.1466

Wang, B., Yi, J., & Bochu, W. (2003). Effects of sound wave stimulation on growth of chrysanthemum roots. Colloids and Surfaces B: Biointerfaces, 29(2–3), 115–118.

Wang, L., He, X., Ma, X., … (2023). Performance analysis of two typical greenhouse lettuce production systems: Commercial hydroponic production and traditional soil cultivation. Frontiers in Plant Science, 14, 1165856. https://doi.org/10.3389/fpls.2023.1165856.

Wang, S., & Xiao, Q. (2023). Effect of audio control technology on lettuce growth. Sustainability, 15(3), 2776. https://doi.org/10.3390/su15032776 MDPI

Ye, Z., et al. (2023). Evidence for the role of sound on the growth and signal transduction in plants. Plant Signaling & Behavior, 18(1), e2163346. https://doi.org/10.1080/15592324.2022.2163346.

Yi, J., Bochu, W., Xiujuan, W., & Daohong, W. (2003). Effect of sound wave on the metabolism of chrysanthemum roots. Colloids and Surfaces B: Biointerfaces, 29(2–3), 115–118.

Yiyao, L., Wang, B., Xuefeng, L., Chuanren, D., & Sakanishi, A. (2002). Effects of sound field on the growth of chrysanthemum callus. Colloids and Surfaces B: Biointerfaces, 24(4), 321–326. https://doi.org/10.1016/S0927-7765(01)00243-5

Zhang, X., Lu, X., Zhang, Z., Yang, G., He, Y., & Fang, H. (2024). Simultaneous detection of reference lines in paddy fields using a machine-vision-based framework. *Computers and Electronics in Agriculture, 221*, 108923. https://doi.org/10.1016/j.compag.2024.108923