The Effect of Music and Sound on Plant Growth: A Comprehensive Review

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Abstract. The influence of music on living things is extensive, as it has been shown to enhance mood, improve cognitive abilities, and promote physical health. At the same time, people are also paying attention to the potential impact of music on plants. Studies have shown that plants can sense and respond to sound and vibration, and respond to the rhythm, frequency, and sound intensity of music, such as changing growth rate, morphology, leaf size, and shape etc. These findings suggest that music can have an impact on plant growth and development. This article mainly reviews the effects of music on plant growth.

Keywords: music; plants; growth; sound waves; effect.

1. Introduction

Sound waves are mechanical vibrations produced by oscillating objects and propagate through various media, including air, water, and solids. These waves have frequencies typically ranging from 20 Hz to 20 kHz and travel at different speeds depending on the medium (e.g., 343 m/s in air and 1500 m/s in water)[1]. Within the audible window of 20 Hz – 20 kHz, its propagation is further modulated by temperature, humidity, and density, while its intensity and direction can be tuned by the position and power of the source. These characteristics have long been exploited in medicine (stethoscopes), industry (ultrasonic rangefinders), and communication (radio and telephony). More recently, sound has emerged as a subtle yet powerful environmental cue for plants, challenging the traditional view that vegetation is oblivious to acoustic stimuli.

In the mid-19th century, Italian agronomists expounded the effects of sound waves on the promotion and inhibition of radish growth, and in the following 100 years, the research on the relationship between sound waves and plant growth has been deepened, especially in the past 20 years, some scientists have determined that the two core factors of sound waves on plant growth are calcium ions and water, and revealed the relationship between sound waves and the production of plant self-derived ethylene, and explored a set of methods and supporting processes for the use of sound waves to promote plant growth. Plant acoustic frequency control technology has been used in many applications at home and abroad. DanCarlson Company of the United States has achieved good results by applying high-frequency music sound frequencies to crops[2]. The electronic sound frequency researched and developed by Hou Tianzhen and others has been popularized and applied in many provinces and cities in China[3]. Jiang et al. [4]conducted a large number of experiments on 10 kinds of plants, such as watermelon and peanuts, and a variety of edible mushrooms using the sound frequency mixed with music and insect sounds, and confirmed that this sound frequency has a significant effect on the growth and yield of these plants and edible mushrooms.

Conversely, indiscriminate noise—whether from highways, machinery, or industrial activity—constitutes a pervasive pollutant that disrupts these delicate acoustic relationships. Chronic noise reduces photosynthetic rates, alters hormone balance, and represses genes involved in growth and reproduction, leading to biomass losses of up to 40 % [5-6]. Indirectly, noise masks the acoustic cues used by pollinators and seed dispersers; for example, scrub-jays avoid noisy pinelands, causing a 75 % decline in pine-seling recruitment [7]. Even after the noise source is removed, plant communities and their attendant fauna may fail to recover fully, underscoring the long-term ecological cost of acoustic disturbance [8].

Taken together, these findings reveal a continuum of plant responses to sound, from the beneficial effects of precisely tuned frequencies to the deleterious impacts of unstructured noise. Elucidating the mechanistic basis of these phenomena—how vibrations are perceived at the cellular level, transduced into biochemical signals, and integrated with other environmental inputs—will be essential for translating laboratory insights into sustainable agricultural practices. Future research must therefore map species-specific frequency sensitivities, optimize acoustic delivery systems for field crops, and mitigate anthropogenic noise to safeguard both plant productivity and the broader ecosystems that depend on them. This article mainly reviews the effects of sound waves on plant growth.

2. The Positive Effects of Music on Plant Growth

As research on plant growth regulation progresses, music and sound, as unique environmental factors, have garnered significant attention. Music and other forms of sound stimulation have the potential to optimize plant growth conditions, enhance agricultural productivity, and contribute to the development of plant physiology and ecology[9]. Different genres of music and sound frequencies can influence plant growth, revealing fascinating patterns in how plants respond to various sound waves and rhythms. Early 20th-century studies primarily focused on the effects of single-frequency sounds on seed or whole plant germination, with limited exploration of audible sound (20-20,000 Hz) [10]. The mechanisms by which sound affects plant growth remain unclear, necessitating further investigation to identify the optimal sound frequencies and intensities for different plant species.

2.1 The effect of music on plant photosynthesis

Photosynthesis is the process by which plants convert carbon dioxide and water into organic matter through light energy. Studies have shown that music has a promoting effect on photosynthesis in plants. First, the sonic vibration of music can cause small vibrations in plant leaves, which in turn increase the stomatal openness of leaves. Stomata are the key structures in plants that regulate water transpiration and gas exchange, and the vibration of music can open the stomata, increasing the absorption of CO_2 and water, and providing more raw materials for plants to photosynthesize. Secondly, music can also affect the physiological activity of plant leaves[11]. It has been found that specific music rhythms and frequencies can regulate the biopotential of plant leaves, activate photosynthesis-related enzyme systems, accelerate the synthesis and renewal of photosynthetic pigments, and improve chlorophyll content and photosynthetic efficiency. In addition, music can also modulate light and dark responses in plant photosynthesis. The light reaction is the first step in plant photosynthesis, absorbing light energy through photosynthetic pigments to produce the high-energy compounds ATP and NADPH. Studies have shown that the rhythm and melody of music can affect the light absorption efficiency and electron transfer rate of plant photosynthetic pigments, thereby regulating the progress of light reactions. The dark reaction is the second step of photosynthesis and produces carbohydrates by utilizing ATP and NADPH[12]. The sound wave vibration of music can affect the carbohydrate allocation and metabolic rate of plants, thereby regulating the progress of dark reactions.

2.2 Effects of Music on Root Growth in Plants

As a form of acoustic art, music not only evokes pleasure in humans but has also been shown to modulate plant growth and development. Emerging evidence indicates that music can exert a positive influence on root architecture and function. Music promotes root elongation and biomass accumulation. Controlled experiments reveal that plants exposed to defined musical stimuli exhibit markedly accelerated root elongation and a higher number of lateral branches. This response is likely attributable to music-induced modulation of endogenous biochemical pathways, including the stimulation of root apical cell division and elongation. Ye et al. [13]found that the total root length and root surface area of 7 angel duckweed treated with light music (100-3 000 Hz) increased by 24% and 32%, respectively, and the soluble protein content in the roots increased by 60%, accompanied by the upregulation of glutamate-calcium signaling pathway, indicating that music can promote root growth and nitrogen assimilation through signal cascade.

Music significantly reshapes root morphology and systemic architecture. Exposure to specific acoustic stimuli increases lateral-root density while concurrently shortening the primary root, thereby expanding the total absorptive surface area. Concurrently, music modulates branching angles and reinforces the structural integrity of the root system, collectively enhancing plant acclimation to heterogeneous edaphic environments and augmenting tolerance to abiotic stresses. Furthermore, music optimizes nutrient acquisition and water-use efficiency in roots. Specific acoustic frequencies enhance the uptake of nitrogen, phosphorus, and potassium, thereby promoting vegetative growth. Simultaneously, music improves root hydraulic conductivity and water absorption capacity, ultimately strengthening plant drought tolerance. This paper summarizes that specific frequency (125-500 Hz) of sound waves can significantly increase lateral root density and root dry weight of crops such as tomatoes and cucumbers, and improve the absorption efficiency and water use efficiency of roots of nitrogen, phosphorus, and potassium, with an average increase of 15-40%[14].

2.3 The promoting effect of music on plant disease resistance

Music, as a special external stimulus, can have a positive effect on the disease resistance of plants by influencing their physiological and biochemical processes. In past studies, many scientists have found that music promotes the ability of plants to resist diseases, and some theoretical explanations have been proposed.

First, music regulates the plant's immune system. Studies have shown that music stimulation can increase the synthesis of some key disease-fighting proteins in plants, such as antioxidant enzymes, thereby improving the plant's ability to resist pathogenic bacterial invasion, and can also increase the expression of immune-related genes in plants, activating the plant's defense system and making it more resistant to diseases. 100 Hz sound waves induced an increase in antioxidant enzyme (SOD, CAT) activity and inhibition of pathogen-associated ROS accumulation, thereby enhancing the overall disease resistance of plants[5].

Secondly, music can improve the growth environment of plants, thereby reducing the occurrence of diseases. Studies have found that music can increase the stomatal movement of plants, improve gas exchange efficiency, and increase oxygen supply, thereby enhancing plant resistance to pathogens. Music can also regulate photosynthesis and respiration in plants, promote the smooth transport of photosynthetic products to the diseased site, and speed up wound healing, thereby shortening the course of the disease and reducing the incidence of the disease. 10 kHz sound waves activate the glucosinoside synthesis pathway through H3K27me3 epigenetic modification, enhancing the immune response to bacterial wilt[15].

Thirdly, music can also affect the hormone levels of plants, which in turn have an impact on the plant's ability to resist diseases. Studies have found that music can promote the synthesis and secretion of plant growth hormones, such as gibberellin and ethylene. These plant hormones can enhance the resistance of plants to pathogenic bacteria and improve the immunity and disease resistance of plants. 500 Hz sound waves significantly increased the content of defense-related hormones (SA and JA) in Arabidopsis thaliana, and up-regulated the expression of immune genes such as PR-1 and PDF1.2, enhancing the resistance to Botrytis gray mold[16].

Additionally, the vibration and frequency of music may also have an impact on the plant's ability to resist disease. Studies have shown that the vibration of music can accelerate cell division and cell wall synthesis in plants, increasing the vitality and stability of plant cells. At the same time, the frequency of music can also affect biochemical reactions in plants, such as enzyme activity and metabolite synthesis. 1000 Hz sound waves significantly up-regulated Arabidopsis salicylic acid synthesis and signal transduction genes, induced cell wall enhancement of related enzyme activities, and enhanced resistance to Botrytis gray mold[12]. These changes can improve the identification and defense of plants against pathogens and enhance plant disease resistance.

2.4 The effect of music on plant height and stem thickness

Emerging evidence indicates that music, as a unique acoustic stimulus, can modulate both plant height and stem diameter. Controlled experiments reveal that exposure to gentle classical music significantly increases plant height and produces thicker, more robust stems. This response is largely attributed to music-induced enhancement of photosynthetic efficiency and the re-regulation of endogenous phytohormones, which collectively accelerate vegetative growth. When duckweed was placed in light music (≈60 dB) for 7 days, the average plant height in the treatment group was 2.7 cm higher than that in the control group, and the average stem diameter was thickened by 0.15 mm, and the actual photochemical efficiency of photosynthetic system II was significantly improved[13].

Conversely, musical genre and tempo introduce distinct morphological signatures. Fast-paced pop music, characterized by higher rhythmic frequencies, generally elicits greater stem thickening, whereas the slower, softer cadence of classical music exerts a milder effect on stem diameter. These findings underscore the importance of acoustic tempo and amplitude in determining plant architectural outcomes. In the controlled greenhouse, the plant height of roses increased by 18% and the stem diameter by 22% after 30 days of classical music treatment. However, fast-paced rock music only brought about an 8% increase in plant height and a 12% increase in stem diameter, suggesting that the music type and rhythm frequency had obvious differences in plant morphology[17].

Moreover, the magnitude of these effects is species- and environment-dependent. Herbaceous species often exhibit heightened sensitivity to acoustic cues, whereas woody species display a comparatively attenuated response. Concurrent environmental variables—temperature, humidity, and light intensity—further modulate how music influences plant stature and stem girth, highlighting the necessity of integrating acoustic stimuli with optimized cultivation conditions for maximal agronomic benefit. Experiments showed that herbaceous plants (e.g., Arabidopsis thaliana and chrysanthemum) were highly sensitive to sound waves at 250 - 1000 Hz, which was manifested by significant increases in plant height and stem thickness. However, the response amplitude of woody plants (such as kiwifruit seedlings) was significantly lower, suggesting differences in sensitivity between species[18]. Wang et al. found that herbaceous plants respond quickly to short-term fluctuations in microenvironmental variables such as temperature, humidity, and light, while woody plants show a lagging and weakened response to the same stimulus due to their slow migration and adaptation rates, providing direct evidence for "species-environment dependence"[19].

2.5 The regulatory effect of music on plant flowering and fruit development

Flowering and fruiting represent two of the most critical phase transitions in the angiosperm life cycle. Accumulating evidence indicates that music, defined as organized acoustic vibrations, can serve as an exogenous cue that modulates both processes across temporal and qualitative dimensions. Controlled-environment studies have shown that plants exposed to low-amplitude classical music (≈60–70 dB, 500-1000 Hz) exhibit enhanced photosynthetic carbon assimilation, resulting in a 15–25 % increase in soluble carbohydrate pools within the shoot apex[13]. Elevated assimilate availability accelerates floral evocation by up-regulating FLOWERING LOCUS T (FT) and LEAFY (LFY) expression, leading to earlier bud break and an extended flowering window [17]. Moreover, acoustic stimulation modulates the balance of endogenous phytohormones: indole-3-acetic acid (IAA) and gibberellin A3 (GA_3) concentrations rise transiently, while abscisic acid (ABA) declines, collectively shortening the plastochron and increasing floret number per inflorescence.

Vibrational frequencies that overlap with the natural wing-beat spectra of pollinators (200-400 Hz) enhance pollen release in buzz-pollinated species[20]. In greenhouse trials, tomato plants subjected to 250 Hz sine waves displayed a 30 % higher pollen dehiscence rate and a 12 % increase in fruit set compared with silent controls, indicating that acoustic cues can partially substitute for insect-mediated buzz pollination.

Post-fertilization, music sustains elevated cytokinin (CK) and gibberellin levels, stimulating cell division in the ovary wall and leading to larger fruit with improved dry-matter accumulation. Strawberry plants treated with 1 kHz acoustic stimulation exhibited a 20 % increase in mean berry mass and a 0.8 °Brix rise in soluble solids relative to untreated plants[21]. Colourimetric analyses further revealed accelerated anthocyanin accumulation, enhancing external pigmentation and marketability.

Effective acoustic regimes can be delivered either via continuous playback of classical compositions (tempo 60-80 beats min^{-1}) or through programmable transducers generating pure-tone frequencies. Differential responsiveness has been documented: herbaceous crops such as lettuce and strawberry respond robustly, whereas woody perennials like citrus display a muted reaction, underscoring the need for species-specific calibration[18]. Integrating acoustic treatments with optimized temperature (22-25℃) and relative humidity (60-70 %) regimes maximizes efficacy by minimizing environmental noise.

Future research should disentangle the molecular circuitry linking mechanosensitive Ca^{2+} channels, calmodulin-like proteins, and downstream transcriptional regulators (e.g., MYB and bZIP TFs) to refine acoustic protocols for precision agriculture.

3. The Negative Effects of Noise on Plant Growth

Sound is a longitudinal mechanical wave that propagates through elastic media—air, water, or solids-by inducing oscillatory particle motion parallel to the direction of energy transport. During propagation, each vibrating particle periodically compresses and rarefies the surrounding medium, giving rise to alternating regions of elevated (compression) and reduced (rarefaction) pressure[22]. The spatial-temporal succession of these pressure fluctuations constitutes the acoustic waveform. Because particle vibration relies on intermolecular interactions, sound transmission is contingent upon the presence of a material medium; consequently, sound cannot traverse a vacuum. Under standard atmospheric conditions (20℃, 1 atm), the phase velocity of sound in dry air is approximately 340 m s^{-1}. The perceived loudness of an acoustic signal is directly proportional to the wave's amplitude; an increase in amplitude corresponds to a greater pressure differential between compressions and rarefactions, thereby enhancing acoustic energy and subjective loudness[23].

Noise is conventionally defined as a stochastic acoustic waveform whose instantaneous amplitude and frequency are governed by random processes rather than deterministic periodicity [24]. Its spectral composition is therefore characterized by broadband energy that lacks coherent phase relationships, resulting in an aperiodic temporal envelope[25]. Sources may be geophysical—e.g., thunder, wind turbulence—or anthropogenic, encompassing road traffic, aircraft overflights, and industrial machinery. Traffic noise, for instance, constitutes a complex superposition of engine harmonics, tyre–road interactions, and sporadic impulsive events (horns, braking) that together generate a spectrum extending from <20 Hz to >8 kHz[26].

Perceptually, the classification of a sound as "noise" is inherently subjective, contingent upon the listener's cognitive state, cultural context, and motivational salience[27]. Thus, identical acoustic stimuli may be judged as either innocuous background or highly aversive, illustrating the psychosocial dimension of noise evaluation.

Ecologically, anthropogenic noise has emerged as a pervasive environmental stressor that impairs plant performance via direct and indirect pathways. Chronic exposure attenuates photosynthetic efficiency by disrupting stomatal conductance and chlorophyll fluorescence kinetics, ultimately reducing biomass accumulation and reproductive output. Indirectly, noise alters the foraging and dispersal behaviours of pollinators and seed vectors, leading to diminished gene flow and lowered plant diversity [24]. Such cascading effects compromise ecosystem stability and resilience, highlighting the urgent need for evidence-based mitigation strategies[25].

4. Mechanism of influence of musical sound waves on physiological processes in plants

Differential acoustic frequencies exert distinct quantitative and qualitative effects on plant growth and development. Across the audible spectrum, low- (<500 Hz), mid (500-2000 Hz), and high-frequency (>2000 Hz) musical vibrations are routinely employed to stimulate photosynthetic electron transport, lateral root proliferation, and mineral nutrient acquisition[18]. Hendrawan et al. [28] demonstrated that Javanese gamelan music centred at 3-5 kHz elevated chlorophyll-a fluorescence (Fv/Fm) by 18 % and increased stomatal conductance in mustard (Brassica juncea), resulting in a 22 % gain in plant height and a 15 % rise in seed yield compared with silent controls. These data exemplify the feasibility of frequency-specific acoustic regimes for precision modulation of discrete developmental processes.

Complementary research on tomato (Solanum lycopersicum) revealed that bespoke musical frequencies (500-1000 Hz, 70 dB) enhanced endogenous auxin (IAA) and cytokinin (CK) biosynthesis, while simultaneously up-regulating aquaporin gene expression, thereby improving stomatal aperture dynamics and drought tolerance [29-30]. Consequently, water-use efficiency increased by 12 % under controlled water-deficit conditions.

Comparative genre studies further indicate that musical style determines organ-specific growth responses. Electronic music (dominant frequencies 1-2 kHz, 80 dB) significantly augmented plant height and leaf chlorophyll content in lettuce (Lactuca sativa), enhancing net CO_2 assimilation rate by 19 %[31]. Mechanistically, acoustic stimulation promotes sustained stomatal opening, facilitating elevated uptake of both water and dissolved nutrients. This reduces irrigation frequency and supports resource-efficient agriculture aligned with sustainable intensification goals.

4.1 Regulation of Photosynthesis and Nutrient Uptake by Musical Sound Waves

Musical sound waves, acting as periodic mechanical stimuli, exert a multi-level regulatory effect on plant photosynthetic performance and nutrient acquisition. Controlled studies have demonstrated that specific acoustic frequencies enhance chloroplast activity and chlorophyll biosynthesis, thereby increasing the capacity of photosystems to harvest and convert light energy. Chen et al.[32] reported that exposure to 500-1000 Hz musical vibrations elevated chlorophyll-a fluorescence (Fv/Fm) and total chlorophyll content in lettuce leaves. Similarly, Wang[33]showed that a 1 kHz acoustic regime increased chlorophyll-a, chlorophyll-b and carotenoid concentrations by 23 %, 19 % and 15 %, respectively, which translated into a 17 % rise in net CO_2 assimilation rate.

Beyond chlorophyll modulation, sound waves fine-tune stomatal dynamics to optimise gas exchange and water-use efficiency. Mullineaux et al. [34]proposed that mechanical vibrations act on guard-cell ion channels, accelerating K^+ flux and thereby regulating stomatal aperture. Empirically, Kim et al.[11]demonstrated that 100 Hz plus 9 kHz dual-frequency stimulation shortened the stomatal opening/closing cycle of Arabidopsis by 28 %, elevating intercellular CO_2 concentration (Ci) and enhancing photosynthetic rate without additional water loss.

Acoustic stimulation further accelerates nutrient uptake and whole-plant metabolism. Transcriptomic profiling of duckweed exposed to soft classical music revealed up-regulation of nitrate transporter genes (NRT1.1, NRT2.1) and amino-acid biosynthetic pathways, increasing foliar N content by 21 % and soluble protein by 60 %. Enhanced nutrient flux, coupled with improved photo-assimilate partitioning, fortifies plant vigour and stress tolerance. Collectively, these findings establish musical sound waves as a non-chemical, environmentally benign tool to synchronise photosynthetic carbon gain with nutrient acquisition, thereby promoting sustainable crop production.

4.2 Regulation of Hormonal Balance and Cell Division by Musical Sound Waves

Musical sound waves act as exogenous mechanical cues that modulate the biosynthesis and homeostasis of key phytohormones—particularly auxin (IAA) and cytokinins (CKs)—thereby orchestrating root architecture and meristematic activity. Ye et al.[13] demonstrated that exposure to 500 Hz acoustic stimulation increased endogenous IAA concentration in duckweed roots by 32 %, coinciding with a 28 % acceleration in primary-root elongation and a 1.4-fold rise in lateral-root density. Enhanced auxin signalling subsequently up-regulated genes encoding auxin influx carriers (AUX1, LAX3) and efflux regulators (PIN family), reinforcing the linkage between acoustic perception and root-system expansion[35]. A robust root system is indispensable for efficient nutrient acquisition and stress resilience, underscoring the agronomic relevance of acoustic modulation.

At the cellular level, musical vibrations shorten the mitotic cycle by elevating CK levels in the root apical meristem. Johnson[36] reported that 1 kHz sound pulses raised zeatin-type CKs by 25 % in Arabidopsis seedlings, shortening G1/S transition and increasing the mitotic index by 38 %. Elevated CKs activate cyclin-dependent kinases (CDKs) and cyclin genes (CYCD3;1, CYCA2;3), thereby accelerating cytokinesis and promoting both root and foliar growth. Collectively, these findings indicate that musical sound waves simultaneously regulate hormonal biosynthesis and cell-cycle kinetics, providing a non-chemical route to enhance plant vigour and productivity.

4.3 Specific application cases of musical sound waves on different plants

Musical sound waves produce different frequencies, types, and effects on different plants. Recent studies have found that specific frequency bands with certain musical sound waves can efficiently stimulate plant growth and development, such as increasing plant chlorophyll content, promoting root development, and increasing yield.

In Brassica juncea cultivation, exposure to Javanese gamelan music tuned to 3–5 kHz significantly boosts chlorophyll accumulation and fresh biomass [28]. Acoustic waves in this frequency window stimulate photosynthetic activity in the leaves, leading to enhanced CO_2 assimilation and greater accumulation of photosynthates. The same study also reports a marked increase in root vigor, indicating that the beneficial influence of gamelan sound extends below ground. Thus, integrating traditional gamelan music into agriculture offers a zero-pollution, low-cost means of improving crop quality and can serve as a practical acoustic protocol for related Brassicaceae species.

Electronic music outperforms conventional genres in accelerating the growth of lettuce (Lactuca sativa), chiefly by amplifying leaf expansion and photosynthetic efficiency[37]. Rich in high-frequency harmonics, electronic tracks stimulate cellular activity and raise chlorophyll biosynthesis, thereby enlarging the edible fraction of the plant and improving its economic value. The trial further showed that electronically treated lettuce reached market size faster while requiring less fertilizer, demonstrating that acoustic stimulation can serve as an eco-friendly, non-chemical substitute for a portion of agricultural inputs. Thanks to its precise controllability, electronic music is particularly promising for controlled-environment systems such as greenhouses and vertical farms.

Research on Arabidopsis thaliana has demonstrated that acoustic stimulation accelerates root elongation and cell-division rates. Kim et al.[11]showed that 100 Hz and 9 kHz sound waves lengthen primary roots by enhancing cytokinin activity and triggering auxin release, two hormones essential for root growth. Such molecular tuning improves both nutrient and water uptake, offering a non-chemical management tool, particularly valuable for crops grown in nutrient-poor or water-limited soils. Together with earlier findings—Javanese gamelan increasing chlorophyll and biomass in Brassica juncea, and electronic music boosting leaf expansion and photosynthetic efficiency in Lactuca sativa—these results sketch a coherent picture: tailored soundscapes can replace a portion of agrochemical inputs while simultaneously modulating key physiological pathways for higher, more sustainable yields.

5. Potential Applications and Challenges of Music Sound Wave Stimulation Technology

Music-sound-wave stimulation is emerging as a non-chemical, physical elicitor with vast potential in agriculture and forestry. Recent work demonstrates that carefully chosen acoustic frequencies can accelerate photosynthetic rate, modulate stomatal behavior and phytohormone balance, and ultimately raise growth and yield. In lettuce, for example, electronically generated sound elevated chlorophyll content, leaf-area index, and edible biomass to record levels, partially replacing synthetic fertilizer and reducing pesticide demand[31]. Such “ musical green ” technologies therefore, contribute simultaneously to crop quality and farm sustainability while enhancing disease resistance.

Looking ahead, the deployment of sonic stimulation will expand in lockstep with advances in smart farming. Because plant species differ markedly in their acoustic sensitivity, rigorous empirical optimisation of frequency, intensity, and exposure duration is still required to unlock the full agronomic benefit.

Greenhouses and vertical farms offer the most immediate arenas for scale-up. In these controlled environments, sound can be seamlessly integrated with automated irrigation and sensor networks to create intelligent farming systems that maximise water- and nutrient-use efficiency and boost stress tolerance [28], thereby delivering precision agriculture at its most productive.

Despite its promise, the large-scale adoption of sonic stimulation in agriculture still faces several hurdles. First, plant responsiveness is highly species-specific: whereas some crops thrive under acoustic treatment, others remain indifferent or even display negative growth responses[38]. For example, 3-5 kHz Javanese gamelan markedly boosts Brassica juncea performance, yet comparable results have not been replicated in a wider crop panel[28].

Identifying optimal frequency–duration combinations is equally challenging. Both excessively high frequencies and prolonged exposures can suppress growth or induce oxidative stress, obliging researchers to develop bespoke acoustic protocols for every genotype. Moreover, the installation and fine-tuning of sonic devices demand technical expertise that many small- or medium-scale farms currently lack [38].

A deeper bottleneck is our fragmentary understanding of the molecular circuitry underlying plant sound perception. It remains unclear how acoustic waves are sensed at the cellular level and how these signals are transduced into downstream physiological adjustments[39]. Bridging this knowledge gap will require interdisciplinary efforts—spanning bioacoustics, plant molecular biology, and precision engineering—to elucidate the complete signalling pathway and, ultimately, to enhance the reliability and efficacy of sonic agronomy.

6. Conclusion

Acoustic-wave technology has already demonstrated transformative potential at every step of the agrifood chain, from laboratory benches to commercial fields, by simultaneously boosting yield, improving quality, and strengthening resistance to biotic and abiotic stresses. A growing body of evidence shows that exposure to precisely tuned sound frequencies can upregulate photosynthetic efficiency, rebalance phytohormones, and prime plant immunity, translating into measurable gains in both productivity and marketable grade. Importantly, these acoustic interventions allow growers to cut back on synthetic fertilizers and crop-protection chemicals, accelerating the transition toward ecologically intensive agriculture. Looking ahead, the industrialization and large-scale deployment of sonic solutions within precision-ag systems promise to be substantial.

As a non-toxic, residue-free physical stimulus, agricultural acoustics leverages subtle shifts in membrane potential, stomatal aperture, and carbon-assimilation kinetics to enhance plant growth and resource-use efficiency, an inherently greener alternative to chemical regulators. Published experiments reveal that specific combinations of frequency and acoustic power can markedly influence net photosynthetic rate and ultimate biomass, opening fresh avenues for canopy management and microclimate control.

Field and greenhouse trials further illustrate that musical genre itself can matter: traditional Javanese gamelan (3-5 kHz) elevates chlorophyll density in mustard greens, while synthetic electronic music accelerates leaf expansion in lettuce. Because each species-and even cultivar-exhibits a unique acoustic sensitivity profile, future research must map crop-specific response surfaces to refine frequency, intensity, and exposure windows. High-throughput phenotyping and multi-omics sequencing will be instrumental in dissecting the molecular circuitry that underpins sound perception and signal transduction.

Once optimized, acoustic protocols can be embedded in IoT-enabled smart-farm architectures, synchronizing sonic dosing with real-time sensor feedback on light, temperature, and nutrient status.

In vertical farms and greenhouse modules, where environmental variables are already under tight digital control,music-wave technology is poised to become a plug-and-play tool for closing yield gaps and minimizing environmental footprints. Continued innovation will therefore make sound a cornerstone of next-generation, resource-efficient agriculture.

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