Sonic Stimuli and Plant Growth: A Comprehensive Review with Emphasis on Yogic Sound Frequencies

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Abstract: ***Plants, while lacking a central nervous system, exhibit remarkable responsiveness to external stimuli, including light, gravity, touch, and increasingly, sound. This review consolidates current knowledge on the effects of sound waves-particularly audible frequencies and Yogic mantras-on plant growth, physiology, and biochemistry. Recent evidence suggests that sound waves can modulate gene expression, hormone signaling, secondary metabolite synthesis, and cellular activities, leading to enhanced germination, growth, flowering, and stress resilience. Ancient traditions, notably Vedic mantra practices, align with emerging findings in acoustic biology. We explore historical contributions, mechanistic hypotheses, and modern technological applications such as Plant Acoustic Frequency Technology (PAFT). Limitations in instrumentation and methodological standardization are discussed, alongside a proposed framework for future research. The integration of traditional sound practices with modern plant science could unlock novel strategies for sustainable agriculture and horticulture.***

Keywords: plant acoustics, Yogic mantra, sound wave therapy, gene expression in plants, sustainable agriculture

1. Introduction

1. Plants, though immobile and without a nervous system, exhibit remarkable ways of sensing and responding to a different type of environmental signals (1). Generally, plant growth and development is studied in regard to light (phototropism), gravity (gravitropism), touch (thigmotropism), or chemicals (chemotropism). In recent decades, scientists began to investigate a more unusual, but intriguing field of study, which is plant responses to mechanical vibrations, particularly sound waves (2). Plant studies with sound, often referred to as acoustic biology, or Phyto musicology examines how different kinds of sound stimuli, including music, mantras and ultrasonic waves, impact physiological and molecular responses in plants. We have a complete understand of the physical basis of sound, as being mechanical vibrations that propagate through a medium (air, water, or solid) as pressure waves. The audible sound spectrum typically ranges from 20 Hz to 20,000 Hz, while infrasound (below 20 Hz) and ultrasound (above 20kHz) are of some utility in experimental plant biology (3). What is really remarkable is that, although plants have no ears or central auditory system, several studies show that they are not deaf to sound. They respond through mechanoreceptors, cytoskeletal responses, hormonal signaling, and epigenetic modulation. Sound waves represent an ecologically relevant signal. In natural habitats, plants are exposed to a wide range of acoustic vibrations: wind rustling through leaves, the buzzing of pollinators, raindrops, and even seismic activity (4). These vibrations may convey meaningful environmental information. For example, recent studies have demonstrated that plants can distinguish between vibrations caused by insect herbivory and those caused by mere wind or touch. In response to such cues, they may activate defensive biochemical pathways. Furthermore, in agricultural and laboratory contexts, artificially generated sound frequencies have been tested for their ability to influence plant behavior (5). These studies have reported positive effects on seed germination, shoot and root growth, flowering time, fruit ripening, photosynthetic efficiency, and secondary metabolite production (6). This opens up potential for the use of sound as an inexpensive, non-invasive tool for crop enhancement, especially relevant in resource-limited settings Using sound in plant cultivation is not entirely novel. Traditional approaches to agriculture have long recognized the belief that certain sounds, especially religious chants, mantras, and musical rhythms, could offer benefits for plant development. For example, ancient Vedic writings in India stressed that nāda (meaning "primordial sound") was a basis for life (7). Likewise, ancient Chinese and Greek traditions pursued an understanding of life's harmonic qualities and inherent vibrations. Sir Jagadish Chandra Bose, a forward-thinking Indian scientist and one of the first to experimentally demonstrate plant responses to various stimuli, including sound, suggested some sort of 'plant sensitivity' (8).

2. In India, Vedic mantras such as Gayatri mantra, Mahamrityunjaya mantra, or the syllable Om have been mentioned with planting and harvesting rituals, in which these prayers/mantras are chanted. These mantras not only have spiritual resonance for humans but occur in an environment that can slightly affect the environment/ecosystem too (9). Modern experiments have started to support these ritual practises (i.e. chanting mantras) led to measurable changes in plants' physiological aspects. For example, it has helped contribute to the modern understanding of how sound/chanting can affect plant physiology. Advances in plant physiology and molecular biology have also helped shed light on how sound measures could lead to some changes in plant biology (10". Mechanoreceptors in the plant plasma membrane are able to detect the physical stimuli that initiate calcium influx, reactive oxygen species (ROS) signaling, and activation of transcription factors. These activities can lead to increased expression of genes involved in growth, defense, and metabolism (11). Various studies suggest that sound waves at 1000 Hz can delay ethylene production and tomato fruit ripening; and sound waves (200–1500 Hz) can enhance flavonoid production in sprouted crops. A lot of these effects are frequency- and species-specific, suggesting that

biological responses to acoustical signals are highly specific (12).

3.

Transcriptomic approaches (i.e., RNA-Seq and qRT-PCR) have demonstrated that exposure to sound can modify gene expression that controls (and/or is controlled by) ethylene biosynthesis, the phenylpropanoid pathway, and antioxidant enzymes. Where ultrasound (20–100 kHz) forms cavitation effects and induces cell permeability for seed priming and secondary metabolites extraction is also used for seed priming and extraction of secondary metabolites. Given the growing challenges of food security and climate instability, sound, and acoustical approaches have the potential to complement or replace fertilizers and pesticides in an environmentally friendly manner (13). Technologies using Plant Acoustic Frequency Technology (PAFT) surround improved crop yield, pest and disease resistance, and reduced reliance on agrochemicals (14). There have been studies showing that acoustic treatments also increase levels of chlorophyll content, found increase efficiency of photosystem II, increase nutrient incorporation, improve root systems. In addition to this sound may reduce post-harvest losses by modulation of ripening and senescence, particularly in climacteric fruit. An interesting area of sound-plant interaction concerns the Yogic sounds and spiritual sounds. Yogic sounds are specific frequencies that are structural, harmonic, and rhythmic (13). In contrast to random noise or industrial vibrations, mantras are based on specific phonetic patterns believed to represent universal frequencies. Research examining the chanting of Om or reciting of Gayatri mantra showed improvement in plant parameters such as radicle length, fresh and dry biomass, and even enzyme activity (15).

2. Basics of Sound and Plant Perception Mechanisms

While plants lack auditory organs, they respond dramatically to mechanical signals in their environment. Among these is sound, defined as mechanical pressure waves transmitted through a medium. Specifically, sound is becoming more accepted as an environmental signal that alters plants' physiology (16). In this section, we provide an overview of the physics of sound, the forms of sound and their physical interaction with plant tissues, and the biological structures and processes governing sound perception, signal transduction, and development of physiological responses. Sound can be recognized as the mechanical wave that has the following characteristics: frequency (in Hertz, Hz), wavelength (in meters, m), amplitude (the intensity of sound, measured in decibels, dB), velocity (the speed of sound transmission in meters per second, m/s), and timbre (the quality of sound waveforms, (17). Sound transmits faster through solid than air, making the soil-plant interface a relevant zone for sound transmission.

- **Infrasonic (<20 Hz):** These sound waves are produced by natural phenomena, such as earthquakes, and probably far below the range of human hearing. Some studies have implied that low frequency (LFV) vibrations can modify root orientation, but to my knowledge, no studies have assessed the effect of infrasonic sound on plant seedling vigor (18).
- **Audible (20 Hz > 20 kHz):** This is the most studied range of soundwaves on biological systems, and has been assessed in relation to the amount of quantifiable biological effects on plants. Sounds created by musical instruments, natural sounds in the environment, and human speech all fall within the audible range (19).
- **Ultrasonic (>20 kHz):** Measurement of ultrasonics have been used in seed priming of plant seeds, but also used in sterilization as well as extraction of juices containing metabolites from food sources. Ultrasound creates cavitation, can increase nutrient permeability and the breakdown of plant tissue into cellular suspendible-chunks (20).

When sound travels through air, water, and the tissues of plants, it is subject to mechanical impedance, absorption coefficients, and resonance characteristics. not all frequencies are the same; plant tissues resonate at resonance frequencies, so certain will frequencies will be amplified or attenuated according to the structure of the tissue (21). Distinct structures and systems exist in plants to detect physical forces-structures that are mechanosensitive. These structures when disturbed mechanically, activate signalling cascades that involve a signal backbone of Ca^{2+}, ROS, MAP kinases, and phytohormones (auxin, ethylene, and jasmonic acid) okes). One of the earliest reported responses to mechanical disturbances involved the uptake of Ca^{2+}. When subjected to sound waves, plant cells show a marked increase in cytosolic calcium which is a secondary messenger, that promotes myriad downstream responses (23). Sound induced Ca^{2+}Iinflux was demonstrated in Arabidopsis thaliana via MCA1 (Mechanosensitive Channel of Small conductance) (24). Some sound frequencies induce the oscillation of Ca^{2+} wave when incubated in 1000 Hz sound waves, demonstrating frequency encoding/reception of physical forces. The signalling pathways downstream of Ca^{2+}I uptake, include, calmodulin (CaM), calcium-dependent protein kinases (CDPKs), and CAMTA transcription factors. Calcium imaging experiments have shown plants can produce spatially synchronized Ca^{2+} waves in response to sound, suggesting there is an intracellular communication network similar to neural signaling in animals (25). Production of ROS generated by sound waves is another documentation of mechanotransduction. In proper amounts ROS can function as a signalling cue for plant growth, defence and differentiation. Too much ROS will lead to oxidative stress (26).

Sound waves increase the expression of NADPH oxidase, an important enzyme for ROS production. Increased ROS accumulation leads to changes in the action of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) (27). Ultrasound (≥20 kHz) can lead to disrupt membranes causing a local ROS burst that may affect gene expression connected to stress and development. Plant cell walls are dynamic and do not remain static but constantly remodelling from internal and external cues and forces (28). Sound waves induce mechanical perturbations. The actin cytoskeleton behaves differently when it experiences sound vibrations including reorganizing filaments, allowing vesicle trafficking and controlling cell expansion (29). Increased high frequency acoustic signals have been shown to induce genes associated with the expression of expansion proteins, proteins that loosen the matrix of the cell wall during growth. Although no distinct "sound receptor" analogous to the animal cochlea has yet been established in plants, their responses indicate sound-responsive areas in mechanosensory proteins. There is now speculation that mechanosensitive channels function as acoustical sensors. Certain transmembrane kinases or recept-like proteins may respond to vibrational conformational changes. Additionally, epigenetic modulators such as histone deacetylases may respond to nuclear remodelling due to pressure-wave induction. There is also preliminary transcriptomic evidence that indicates large scale vectors of change in gene expression after exposure to sound. Different plant tissues vary in their sensitivity to frequency (30). Some examples of manifestations include: fruit ripening in tomatoes delayed by 1 kHz; larger quantities of flavonoid content in sprouts from 0.25 to 1.5 kHz sound; an increase in chlorophyll synthesis in wheat seedlings with 5 kHz sound. This suggest that each plant species (possibly each developmental stage) has its own "resonant frequency" at which each is eliciting maximum response. Therefore, future acoustic applications in agriculture must be specified based on the frequency sound exposure of the plant type (31).

3. Historical Background and Traditional Insights

The notion that sounds affects living systems is not a new idea. Many cultures have records and traditions that document the vibrational aspect of existence, defining sound as the essence, core, or music of existence, and that existence and life are based on harmony (32). In ancient agrarian societies, particularly in India, China, Egypt, and Greece, sound was more than a channel of hearing, ritual, or communication; sound was believed to determine growth, health, balance, and harmony. This section outlines the evolution of human understanding of sound and plants, from ancient philosophies and spirituality to the first scientific reflections that led to today's field of acoustic biology (33).

3.1 The Concept of Nāda and the Primordial Sound

Sound (Nāda) is seen as one of the basic creative forces in Indian philosophy, as demonstrated in Vedanta, Samkhya, and Yoga. According to the Vedas, the bhoomi was created from a primordial vibration - Om (also spelled Aum) (34). This syllable is seen to contain authenticity that encapsulates the totality of the universe - all manifestations of physical and non-physical reality. Proponents of Nāda Yoga assert that all forms of matter, including human beings, are composed of vibration, and consequently sensitive to sound. Ancient sages believed they could influence not only human consciousness but also the surrounding environment and all living beings by chanting specific mantras (33). This worldview serves as the philosophical basis for the claim that Yogic sounds can enhance plants' health and vigor.

3.2 Vedic Agriculture and Mantra Farming

Farming in traditional India was incredibly spiritual and ritualistic in practice. The Agnihotra, a fire ritual discussed in the Atharva Veda, involved chanting particular mantras at prescribed times at the dawning of sunrise and sunset while offering ghee (clarified butter) and grains to a fire altar. Farmers believed this would purify the atmosphere, enhance soil fertility, and attract beneficial insects to the farm while repelling pests (35).

Mantra farming refers to farming practices that employ chanting of sacred texts at selected times with the most frequent use of the chanting during water application, sowing and harvest. The three most frequently used mantras include: Gayatri Mantra: Associated with mental clarity, light, and growth. Mahamrityunjaya Mantra: Associated with healing and rejuvenation. Om Chanting: Universally used for calming and harmonizing effects.

3.3 Ancient Chinese and Greek Perspectives

Taoism conveyed philosophical perspectives in ancient Chinese history similar to those mentioned above. In China's ancient past, vital force, or Qi, was described in vibrational terms and association with sound. The I Ching, one of the earliest texts of Chinese philosophy, even describes the world as the swirling of all vibrations and energies (36). In the context of traditional Chinese music therapy, the Five Tones Theory explicitly handled the association of tones with natural elements (wood, fire, earth, metal, and water), plus their balance with respect to human health and nutrition and the environment (37). Similarly, the ancient Greeks contemplated the act of music, harmony, and living organisms. Pythagoras, the famous mathematician and philosopher, believed that the "music of the spheres" describes the movements of celestial bodies, producing a cosmic symphony and impacting all life forms (38). Additionally, Greek medical physicians Hippocrates and Galen incorporated music into their healing practices. They believed that physical vibrational harmonics could replace the balance of the four humors, affect us in a positive way to create health and wellness—a notion similar to the idea of vibrational medicine we called measure in contemporary science (39).

3.4 Sound and Ritual in Indigenous Farming Systems

Across the globe, indigenous farming communities have long believed that singing, whistling, and drumming near crops can improve growth and keep pests away. For example, Maori communities in New Zealand use chants (karakia) during planting. Native American tribes perform rain dances and seed songs, which are thought to sync plant rhythms with natural cycles (40). African tribal farming rituals often include rhythmic drumming and chanting to boost soil and seed fertility (41). While many of these practices were dismissed as superstition during the colonial era, ethnobotanists and agroecologists today are reevaluating their ecological knowledge. These communities understood the bioacoustic sensitivity of plants, a wisdom passed down through generations.

3.5 Sir Jagadish Chandra Bose: Pioneer in Plant Neurobiology

A significant milestone in the study of how plants respond to sound came from Sir Jagadish Chandra Bose (1858–1937), an Indian thinker. Bose challenged the common belief that plants were passive organisms. He created highly sensitive instruments, like the Crescograph, to detect tiny movements in plants. His experiments showed that plants reacted to external factors such as light, temperature, touch, and sound. Bose demonstrated that plants could produce electrical signals similar to nerve impulses in response to injury or stimulation. He suggested that plant cells communicate through electrical and hydraulic signals, much like animal nervous systems, though at a slower speed. While Western scientists initially doubted his theories, they laid the groundwork for what we now call plant electrophysiology, anticipating the current renewed interest in plant neurobiology and bioacoustics.

The notion that sound can affect plant health has deep roots in human history, mythology, and spirituality. From Vedic hymns and Taoist tones to tribal chants and Pythagorean harmonics, sound has been seen as a link between the material and spiritual realms. Today, science is starting to catch up, providing tools to explore the molecular, cellular, and systemic aspects of these ancient beliefs. Understanding the cultural background of acoustic plant stimulation enriches the scientific story and opens paths for holistic, sustainable, and respectful advancements in agriculture. As we tackle global issues like food security and ecological decline, looking back may help us rethink the future, where sound becomes a means of regeneration, not just communication.

4. Experimental Studies on Sound Frequencies and Plant Growth

In the past two decades, there has been a growing number of studies exploring how acoustic stimuli affect plant physiology, growth, development, and metabolite production. These studies cover a wide variety of plant species and experimental settings, focusing on different types of sound, including audible, ultrasonic, and sometimes infrasound. The collective evidence strongly indicates that sound waves can influence a variety of biological responses in plants, from seed germination to flowering and the production of secondary metabolites. This section reviews key experiments and research findings that show how various sound frequencies, intensities, and exposure durations affect plant behavior and performance.

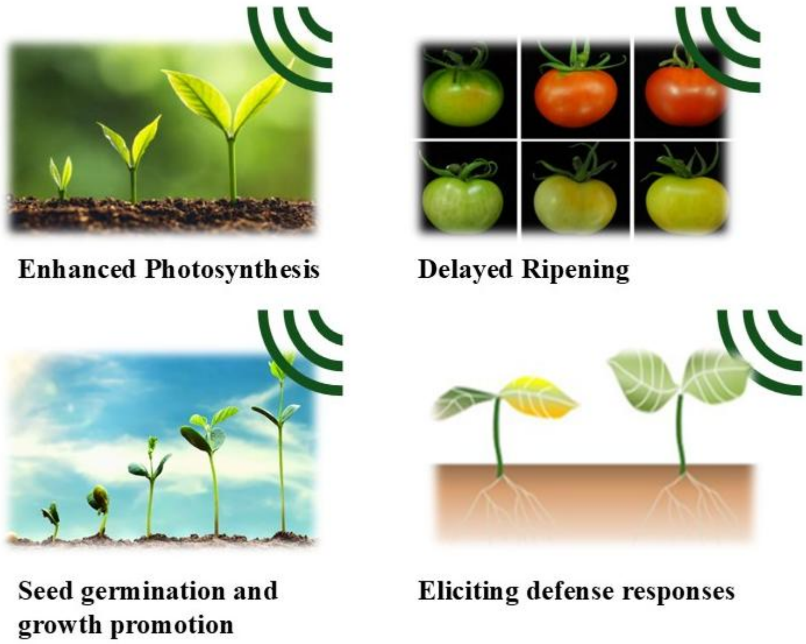

Figure 1: Illustration of key physiological and developmental responses of plants to acoustic stimulation

4.1 Experimental Designs: General Framework

Experimental studies typically involve exposing plants or plant parts, such as seeds, seedlings, callus, or whole plants, to controlled sound treatments in laboratory or greenhouse settings. The basic variables in these experiments include:

- Frequency (measured in Hz): 100 Hz, 1000 Hz, etc. (49)
- Intensity (measured in decibels, dB): 70 dB, 90 dB, etc.
- Duration of exposure: 2 hours per day, continuous exposure, etc.
- Distance from the sound source
- Type of sound: pure tone, white noise, music, mantra, ultrasonic, etc.
- Control groups: untreated or exposed to non-harmonic noise.

Outcomes are measured by assessing growth parameters, biochemical assays, gene expression levels, and yield traits (50).

4.2 Seed Germination and Early Growth

Several studies have shown that sound waves can improve seed germination. Wu et al. (2023) (47) found that sound frequencies of 250 to 1500 Hz significantly improved the germination rate of alfalfa, broccoli, carrot, and cauliflower sprouts. Paddy rice seeds exposed to 400 Hz and 106 dB for 4 hours daily showed a higher germination index, greater fresh weight, and more active root systems compared to controls. Echinacea angustifolia seeds exposed to 1000 Hz and 100 dB also germinated more quickly and had reduced dormancy (51). Ultrasound treatment is especially effective for seed priming. It induces cavitation effects, breaking the seed coat and improving water absorption. In Orthosiphon

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aristatus, ultrasound enhanced the antioxidant activity of in vitro cultures. These findings suggest that sound plays a positive role in breaking dormancy, stimulating enzyme activity, and improving metabolic readiness for germination (52).

4.3 Shoot and Root Development

Sound affects not only germination but also post-germination growth. Alyssum seedlings exposed to soft classical music grew taller and healthier than controls (53). In Arabidopsis thaliana, 1 kHz sound changed auxin-responsive gene expression, which increased root length and lateral root formation. These studies suggest that sound may affect hormonal signaling, particularly auxin and gibberellins, which regulate cell elongation and division (54).

4.4 Flowering and Reproductive Traits

Sound treatments can influence the timing of flowering, the density of flowers, and fruit ripening. Kim et al. (2018) exposed tomato plants to 1 kHz vibrations, resulting in the downregulation of genes involved in ethylene production (ACS2, ACO1) and ripening regulation (RIN, TAGL1) (55). This delayed ripening and extended shelf life. Using Plant Acoustic Frequency Technology (PAFT) on strawberries and tomatoes led to earlier flowering, larger fruits, and better photosynthetic efficiency. The effects on flowering appear to depend on the species and frequency, possibly involving modulation of the FT (FLOWERING LOCUS T) and CONSTANS (CO) genes (56).

4.5 Secondary Metabolite Production

The enhancement of secondary metabolites, such as flavonoids, alkaloids, and terpenoids, through sound has become an important area of research. One study showed that 1 kHz sound significantly increased flavonoid content in carrot sprouts (47). In Dendrobium candidum, sound treatment boosted levels of superoxide dismutase (SOD) and soluble proteins, enhancing its antioxidant profile. These observations link sound exposure to the activation of phenylpropanoid pathway genes, suggesting that sound acts as a mild stressor, triggering adaptive biosynthesis (57).

5. Molecular and Physiological Mechanisms

Understanding how sound waves affect plant growth and metabolism requires a closer look at the cellular, molecular, and physiological pathways involved. This section examines the known and suggested mechanisms through which plants perceive, process, and respond to sound signals, resulting in measurable biological changes (58).

Even though plants do not have ears or a nervous system, they have various mechanosensitive systems that can react to forces like wind, gravity, and touch. Sound is a mechanical wave that interacts with plant tissues through pressure changes, which can alter membrane tension, ion movement, and biochemical signaling (59). The plasma membrane serves as the main interface, where mechanical deformation from sound activates mechanosensitive ion channels (MSCs). This leads to intracellular signaling through calcium waves, reactive oxygen species (ROS), phytohormones, and changes in gene expression. These responses are interconnected with growth, photosynthesis, secondary metabolism, and adaptations to stress (60).

One of the first reactions to sound is a quick rise in calcium ion (Ca^{2+}) levels within the cell. Research using calcium-imaging techniques has shown that sound waves as low as 250 Hz can trigger calcium oscillations in root and leaf cells. Mechanosensitive Ca^{2+} channels open when membrane vibrations occur (61). Ca^{2+} then binds to calmodulin (CaM) and calcium-dependent protein kinases (CDPKs), initiating downstream phosphorylation processes. These processes control gene expression, especially for those linked to cell division, stress response, and hormone production. In Arabidopsis, sound treatments increase the levels of TCH genes (touch-induced genes), which are involved in cell wall remodeling, further supporting the importance of Ca^{2+} (62).

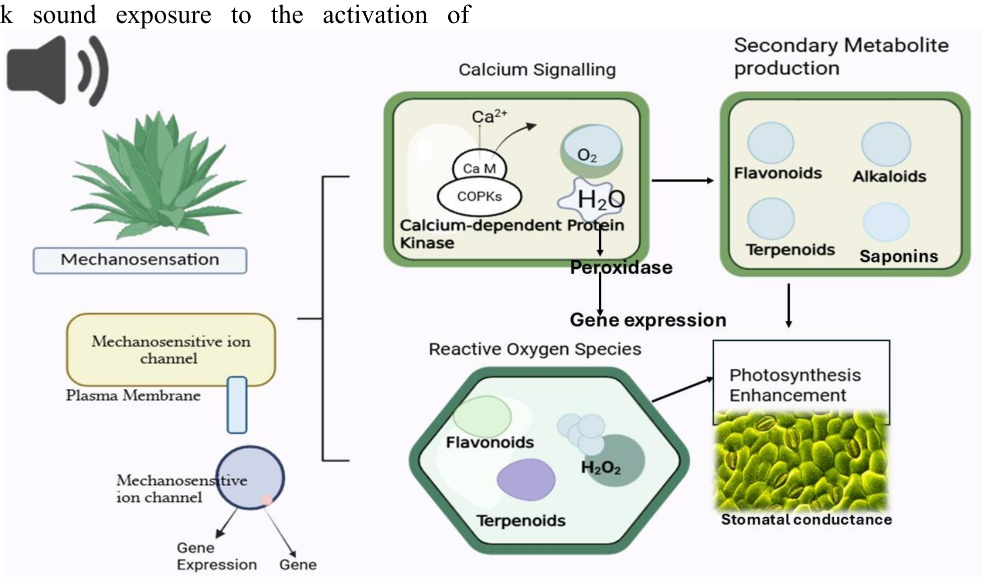

Figure: Proposed molecular and physiological mechanisms underlying plant responses to acoustic stimulation.

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Acoustic stimulation generates reactive oxygen species (ROS), which act as secondary messengers in stress signaling. Controlled ROS production starts antioxidant defenses and changes gene expression (63). Increased levels of superoxide (O_2^-) and hydrogen peroxide (H_2O_2) activate peroxidases, superoxide dismutase (SOD), and catalase (CAT). These enzymes protect against oxidative damage and regulate pathways linked to flowering, ripening, and secondary metabolite production. In Dendrobium candidum, for example, sound-induced ROS was associated with higher expression of genes in the phenylpropanoid pathway, which is essential for flavonoid biosynthesis (47).

Secondary metabolites like flavonoids, alkaloids, terpenoids, saponins, and phenolics are vital for plant defense and human nutrition. Sound stimulation influences their production by modulating key biosynthetic genes: PAL (phenylalanine ammonia lyase), CHS (chalcone synthase), and F3H (flavanone 3-hydroxylase) all show increased expression when exposed to sound. In carrots and alfalfa, sound waves at 250–800 Hz boosted total flavonoid yield by up to 200%. These compounds not only strengthen plant resilience but also enhance medicinal and nutritional quality, making sound a valuable tool in functional agriculture (64).

Sound waves can improve photosynthetic efficiency by increasing chlorophyll production and enhancing the efficiency of photosystem II. They raise stomatal conductance and improve CO_2 uptake while modulating the expression of genes related to photosynthesis, such as RbcL, LHC, and PsbA. Research on wheat, rice, and cucumber has shown significant gains in net photosynthetic rate and chlorophyll content after exposure to frequencies between 500 and 1000 Hz (65).

6. Effect of Yogic Sounds and Mantras

Among the different sound stimuli studied in plant biology, Yogic sounds and mantras form a unique group that combines ancient tradition with growing scientific interest. These sounds, with deep roots in Indian spiritual practices, have specific vibrational frequencies and harmonic structures that are believed to connect with natural and cosmic rhythms (66). This section looks at the historical origins, phonetic structures, experimental results, and suggested mechanisms behind the effects of Yogic mantras on plant growth and development.

Yogic sounds include a variety of sacred phonetic vibrations used in spiritual practices like meditation, chanting, and rituals. Some examples are:

- Seed sounds (bija mantras): e.g., Om, Aim, Hreem
- Vedic mantras: e.g., Gayatri mantra, Mahamrityunjaya mantra
- Tantric chants and Shlokas
- Aum (Om): Seen as the original vibration—the sound of creation.

Unlike random noise or Western music, Yogic sounds usually follow specific frequencies, syllabic rhythms, and intonation patterns. They are generally recited in Sanskrit, a vibrational language where pronunciation, rhythm, and tone are important to the sound's effects (67). Modern acoustics has shown that each mantra has a distinct sound frequency. For instance: Om resonates between 432 Hz and 528 Hz, depending on how it is intonated; when chanted rhythmically, the Gayatri Mantra produces harmonics within the 200–900 Hz range. These frequencies align with those that have shown biological effects in earlier studies on plants. Additionally, mantras often feature repetitive cycles and structured cadences, which may help synchronize or resonate with plant physiological rhythms (68).

6.1 Key Mantras Studied

6.1.1 Om Chanting

Om is known as the universal mantra, made up of A-U-M, which stands for creation, preservation, and dissolution. Experiments revealed that daily exposure to Om at moderate intensity (65–70 dB) improved radicle length, fresh biomass, and enzyme activity in crops like wheat, mung bean, and tomato. Studies also noted higher chlorophyll content and earlier flowering compared to controls (69).

6.1.2 Gayatri Mantra

The Gayatri Mantra consists of 24 syllables and is typically chanted in a synchronous rhythmic pattern. Ramekar et al. (2024) found that exposure to this mantra improved germination rates, shoot/root elongation, and dry matter accumulation in Ocimum sanctum and other medicinal plants. There was also a notable increase in flavonoid and alkaloid content, indicating a change in secondary metabolism (70).

6.1.3 Mahamrityunjaya Mantra

This healing mantra is dedicated to Lord Shiva and is linked to rejuvenation and vitality. Early studies reported improved recovery in drought-stressed plants exposed to this mantra. Additionally, plants showed reduced markers of oxidative stress, suggesting a potential effect in reducing stress (71).

6.2 Experimental Evidence

Numerous laboratory and semi-field studies have investigated mantra effects:

Study	Plant	Mantra	Duration	Key Findings
Ramekar et al. (2024)	Ocimum sanctum	Gayatri	30 mins/day for 15 days	↑ germination, ↑ biomass
Sharma et al. (2023)	Tomato	Om	1 hr/day	↑ flowering, ↑ chlorophyll
Prasad et al. (2022)	Wheat	Om + Gayatri	45 mins/day	↑ root length, ↑ enzyme activity
Patil et al. (2021)	Tulsi	Mahamrityunjaya	20 mins/day	↑ stress tolerance, ↑ antioxidant levels

These findings collectively support the positive influence of mantra chanting on plant development and stress physiology.

7. Plant Acoustic Frequency Technology (PAFT)

Plant Acoustic Frequency Technology (PAFT) is a new approach that combines agricultural biotechnology and acoustic engineering. It builds on years of research showing that plants respond to sound. PAFT uses specific sound frequencies to improve plant growth, resilience, yield, and quality (72). Unlike traditional methods, PAFT is non-invasive, energy-efficient, and may not require chemicals. This makes it a valuable tool for sustainable agriculture and climate-smart farming.PAFT became a formal term in the early 2000s, based on studies done in China, South Korea, Japan, and India. Initial experiments with audible sound frequencies (250–5000 Hz) found that crops like rice, tomato, and cucumber reacted positively to rhythmic sound exposure. Scientists saw this trend and started developing hardware systems to provide specific acoustic stimuli to crops (74). These systems evolved into the PAFT model, which includes:

- Speaker arrays designed for delivering frequencies,
- Digital frequency generators for controlling wave patterns,
- Timers and environmental sensors for adjusting in real-time,
- Data logging to track plant responses.

Commercial interest soon followed academic research. Several agri-tech startups are now incorporating PAFT modules into greenhouses, vertical farms, and automated irrigation systems (74).

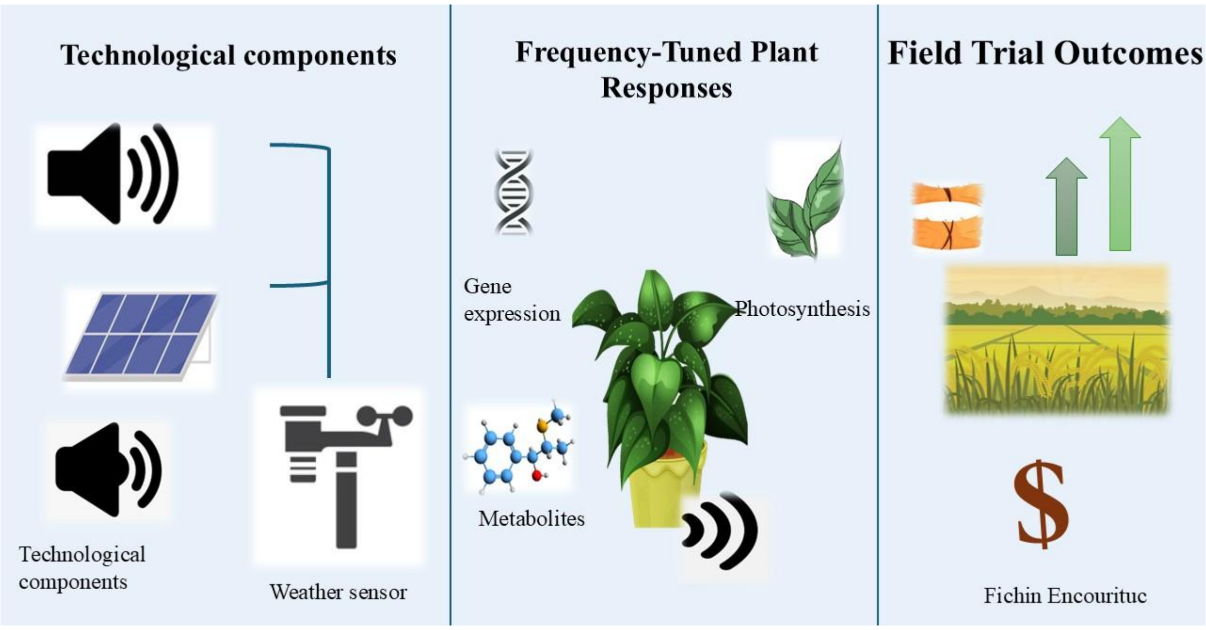

Figure: Schematic overview of Plant Acoustic Frequency Technology (PAFT), highlighting its core technological components, plant responses, and field-level outcomes.

7.1 Frequency Mapping for Plant Stimulation

Different plants and growth stages respond to different frequencies. PAFT allows **frequency tuning** for species-specific and purpose-specific effects:

Plant Response	Optimal Frequency Range (Hz)	Notes
Seed germination	300–800	Increases enzyme activation
Root development	500–1000	Enhances auxin distribution
Shoot elongation	1000–1500	Associated with GA pathways
Flowering initiation	1500–2500	May influence photoperiod genes
Fruit ripening delay	800–1000	Downregulates ethylene genes
Metabolite enhancement	250–1500	Stimulates flavonoid biosynthesis

Studies suggest that short daily exposures, lasting 30 to 60 minutes, are enough to trigger biological responses. Frequencies above 5000 Hz are usually avoided due to risks of cellular stress.

7.2 Field Trials and Case Studies

PAFT exposure to tomato (Solanum lycopersicum) at 1 kHz and 70 dB for 45 minutes a dayresulted in a 15% increase in plant height, a 20% delay in ripening, and a 12% improvement in fruit firmness. Trials conducted by the Nanjing Institute of Sound Agriculture showed that PAFT-treated rice plots produced 18% more grain, had fewer instances of leaf blight and stem borer attacks, and demonstrated improved root mass and water uptake efficiency. Medicinal plants such as Ocimum basilicum and Withania somnifera exhibited higher alkaloid and phenolic content. They also had increased biomass under mantra-based and frequency-based PAFT protocols.

8. Conclusion

The effect of sound on plant growth represents an exciting area of research in plant biology and sustainable agriculture. Extensive studies confirm that plants are not merely passive organisms; they can perceive and respond to mechanical sound vibrations with complex physiological, biochemical, and genetic changes. Specific sound frequencies, especially those from 250 Hz to 1500 Hz, have shown significant impacts on various aspects of plant development. These include seed germination, root and shoot elongation, leaf expansion, flowering initiation, fruit maturation, and the creation of valuable secondary metabolites such as flavonoids, alkaloids, and terpenoids. Notably, yogic sounds and mantras, like Om, Gayatri, and Mahamrityunjaya, provide a fascinating aspect of bioacoustic stimulation. These structured and harmonious sound sequences resonate at specific frequencies and have been shown to improve chlorophyll content, root development, antioxidant enzyme activity, and overall plant health. Unlike random noise or dissonant sounds, these mantras seem to align with the plant's natural vibrational patterns, enabling resonance that may improve biological efficiency. Integrating such sound practices, which are deeply rooted in traditional systems like Vedic agriculture, with modern plant science reveals a strong connection between ancient ecological knowledge and contemporary molecular insights. Supporting these findings, technological advancements, such as Plant Acoustic Frequency Technology (PAFT), now provide precise and scalable methods for delivering sound frequencies to plants in both controlled settings and open fields. PAFT systems use programmable frequency generators, environmental sensors, and speaker arrays to enhance plant responses in real-time, improving yield, quality, and stress resistance while lowering reliance on chemical inputs. Trials with crops including tomato, rice, basil, and wheat have consistently shown better growth, improved ripening control, and enhanced metabolites under targeted acoustic treatments. Moreover, adopting bioacoustic farming practices encourages a comprehensive understanding of how plants interact with their environment, respecting both scientific research and traditional knowledge. In the evolving field of precision agriculture and regenerative practices, sound-based methods offer a promising approach that links biophysical processes with ecological balance and sustainability with productivity. The fundamental truth is clear: plants listen—not with ears, but with their cells, membranes, and genomes. Using this sensitivity thoughtfully and respectfully could reshape the future of farming. We could progress toward an agricultural model where crops flourish not only with sunlight and water but also with the healing rhythm of sound.

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