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Impacts of plant acoustic frequency technology (PAFT) on crop performance in agriculture: Harmonizing acoustics and indigenous knowledge systems

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Abstract

Plant acoustics frequency technology (PAFT) is a budding area reconceptualizing customary principles of senses in plants. On contrary to being seen as docile beings, plants are now being recognized as vital and vibrant organisms with capability to receive, transmit and propagate sound frequencies up to huge extent and how it benefits the growth. Using the effects of sound frequencies on plant, the practical application is possible in agriculture to enhance yield and quality of crops. This review attempts to provide a holistic framework of plant acoustics, with clear emphasis on sound production and reception, evaluation techniques, applications in agriculture, and finally mentioning the role of Indian knowledge system in plant acoustics.

The aim of this review is to evaluate the mechanisms of sound reception in plants at external morphological, tissue, cellular, and genetic level. It also in detail discusses the method of sound production in plants by various mechanisms like xylem cavitation events, stress-induced clicks or bursts and cellular movements. It critically assesses various acoustic frequency techniques used to evaluate plant health and growth and reinforces empirical evidence for the application of PAFT across multiple agricultural sectors. The recent synergy of modern research on plant acoustics to indigenous wisdom highlights India's potential to contribute significantly in the field of plant acoustics.

Keywords: Agriculture, plant acoustics, plant acoustic frequency technology, plant music, agriculture, music therapy

Introduction

Spaces around plants are filled with variety of sounds, whether it comes from a creature like a cow mowing or a bird twittering, or is from abiotic sources like gushing water, or blowing winds. It is hence obvious that plants developed a specific form of sensitivity towards sound vibrations (SVs) in the surroundings which are ecologically relevant frequencies. (Ghosh *et al*., 2016) [18]. Sound waves are expressed in intensity/volume (dB) and frequency/pitch (Hz). The human range to hear sounds is from 20 Hz to 20kHz and can be used as positive growth regulators and evidence of using sound waves ultrasounds (>20kHz) in priming seed germination has also been found (Yeoh *et al*., 2024) [56].

Meditative music like classical music has a pleasant beat which supports the growth in plants. Music created from violin generally increases plant growth significantly (Chivukula & Ramaswamy, 2014) [9]. Based on the principle of positive impact of music, the Plant Acoustic Frequency Technology (PAFT) is being utilized to administer plants with a specific sound frequency and intensity. Under this treatment positive biological benefits have been noted in vegetables and fruits. (Meng *et al*., 2012) [34]. In greenhouses it also enhanced disease resistance and higher yields in vegetables. Defiance to abiotic stress such as drought and pest attacks in rice shown by lowered levels of Hydrogen peroxide (H_2O_2) synthesis in sound stimulated plants is also evident, as compared to control group (Jeong *et al*., 2014) [24]. Religious chanting and plant growth have centuries long relationship studied in various Asian countries like Nepal, India and China. The mantras mentioned in Hindu Vedas like Agnihotri Mantra or Gayatri Mantra have been used to test the plant growth performance and medicinal properties of certain plants (Chandrakala & Trivedi, 2019) [7]. Several sound frequencies or hard-core vibrations can also have counterproductive influence on plant development. When it comes to a sensitive plant, heavy metal music can deteriorate growth of plant even at lower intensity or volume (Chivukula & Ramaswamy, 2014) [9].

This manuscript systematically explores plant sound perception through multifaceted lenses -morphological adaptations, physiological responses, cellular signalling, and genetic pathways later while cataloguing endogenous sound emissions from plants, such as cavitation-induced pops, xylem emboli, intracellular vibrations, and stress-triggered acoustic bursts. It also summarises plant monitoring methods for crop vital development using the PAF technique, expressing the practical use in field of agriculture. Lastly, it discusses the critical role of Vedic chants, mantras, and ragas stimulate plant growth through melodious vibrations.

Methodology of review

An exhaustive literature search was concluded using research databases consisting of Semantic Scholar, Web of Sciences, Scopus and Google Scholar. Studies were founded using keywords like plant music, plant acoustics, mantras and plants, plants and Indian knowledge system, sound and plants, music in agriculture and articles relevant to plant acoustic from 2000 to 2025 were only considered. The selection of studies was on the basis of whether they discussed effect (either positive or negative) of sound frequencies on plant, plant perception of sound, various physical and physiological response to sound by plants and studies related to metabolic pathways activation leading to gene expression changes or other physiological changes. Research papers lacking in genuine experimental data and non-relevant articles were excluded from literature review.

Data driven from the studies consist of details like plant species, frequency, pressure or intensity of sound used, metabolic pathway involved and stimulation response noted in plants.

The data was further inspected qualitatively in detail to find similar trend in responses in various plant species and it is synthesised to develop a scientific framework by linking sound frequencies with physical and physiological alterations in plant body.

Sound Reception Structures in Plants

Plants hold unique morphological features which allows them to respond and perceive to acoustic stimuli in their surroundings. The response and perception to sound involves various plant tissues and structures at distinct levels, i.e. cellular and tissue-level adaptations.

1. Morphological Scale

1.1 Epidermis

Plant cell walls and plasma membranes act as the first reception sites. Vibrations cause disfigurement in cell membranes and cell walls, which leads to successive mechanosensory responses and finally the activation of ion channels (Dalal, 2021) [14].

Some studies observe the presence wider openings of stomatal aperture under sound influence, acting as supporting evidence for hypothesis that epidermal cell, including guard cells, plays significant role in mechano-perception by plants (Hendrawan *et al*., 2025) [22].

1.2 Roots

Sound induced changes have been identified in sound sensitive regions such as underground root tips and vascular tissues in form of increased root length, altered xylem activity, and enhanced cell number in apical meristem region (Dalal, 2021) [14]. Directional root growth response with respect to sound is recorded. (Frongia *et al*., 2020; Ghosh *et al*., 2016) [17, 18]. Among the tested frequencies upto 900 Hz, *Zea mays* roots bend towards the acoustic signals of frequency 100-300 Hz in hydroponic setup, showing structural responses in roots due to sound (Gagliano *et al*., 2012) [34].

1.3 Stem and leaves

Some studies show that various plants organs like leaves, stems, flowers show resonant frequencies and distinct sensitivities (Frongia *et al*., 2020; Pagano & Del Prete, 2024) [17, 37]. Under appropriate sound frequencies, leaves exhibit better physiological activities and protoplasmic changes.

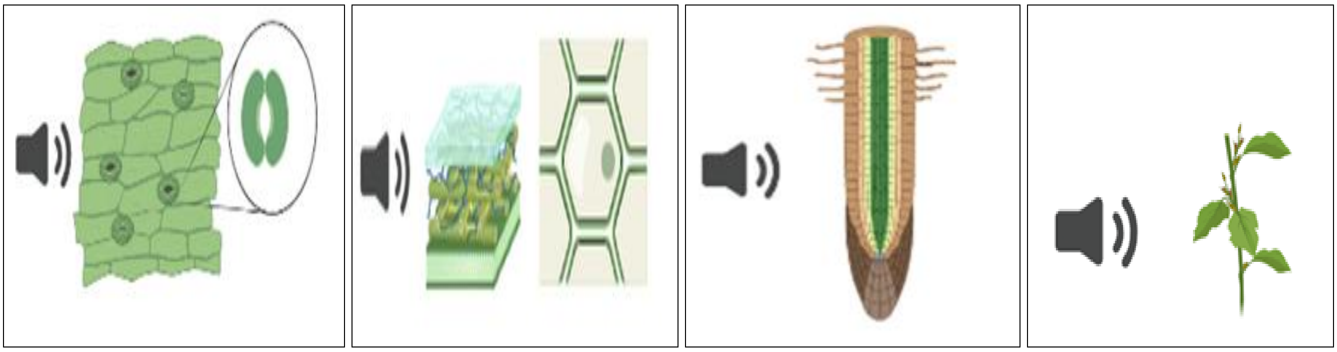

Fig 1: Various mechanosensitive receptors for acoustics stimulation in plants (a) wider openings of stomatal aperture (b) epidermal cell walls and membranes act significant role in mechanoreception of sound. (c) underground root tips and vascular tissues (d) stem and leaves

2. Tissue Scale

2.1 Xylem

During drought or other stress conditions, the water column in xylem vessels experiences increased tension due to transpiration pull. This tension leads to the formation and burst of vapour or air bubbles within the vessels, which is a process referred to cavitation resulting in ultrasonic acoustic emissions (UAEs) from the xylem vessels. These pulses typically die out within about 0.5 milliseconds, corresponding to resonant vibrations in the xylem vessels acting as acoustic resonators. The emitted ultrasound frequency and pulse characteristics depend on the xylem vessel's geometry and the tissue's viscoelastic properties, which can be studied using ultrasound emission spectroscopy. Hence, xylem acts as structural and functional sound sensor in plants (Frongia *et al*., 2020) [17].

2.2 Phloem

Mechanical stimuli such as sound vibrations induce localized responses in plants that are then communicated systemically via phloem-mobile signalling molecules. The phloem plays a crucial role in transporting these chemical signals from the point of sound perception to distant tissues, coordinating defense responses, growth regulation, and physiological changes. Sound-induced vibrations lead to molecular and hormonal changes that the phloem helps distribute, enabling whole-plant adaptation.

Feeding by localized predators activate signalling molecules that move through pathways dependent of electrical signals, which leads to secretion of chemical defence factors in non-damaged cells (Allievi *et al*., 2021) [1].

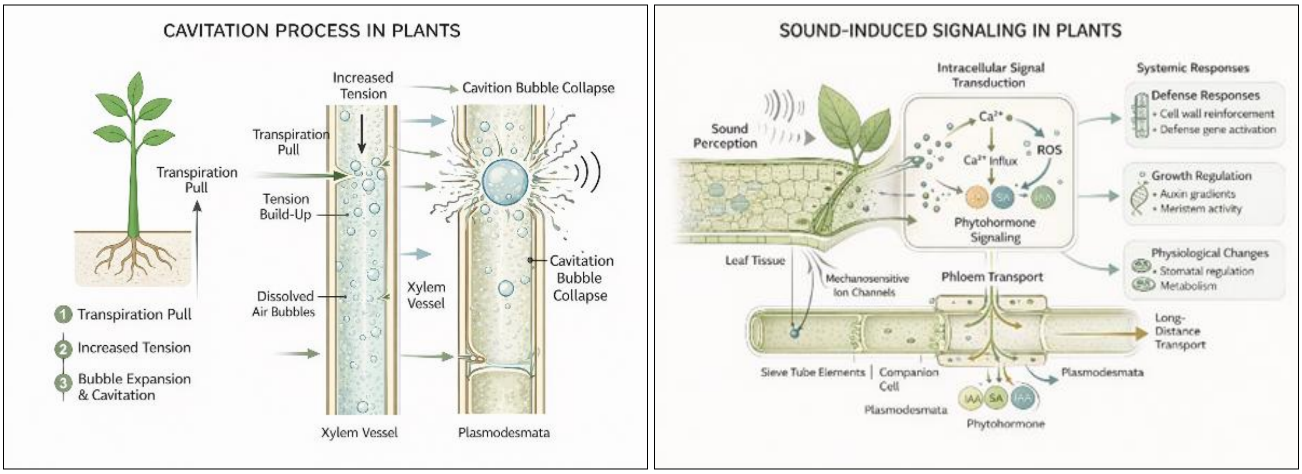

Fig 2: (A) Under stressful condition, the process of cavitation within xylem vessels is caused by transpirational pull leading to Ultrasonic emissions corresponding to resonant vibrations in the xylem vessels acting as acoustic resonators, hence xylem vessels acting as sound sensor in plants. (B) Role of phloem in transporting chemical signals from the point of sound perception to distant tissue (Created using Biorender)

3. Cellular Scale

Plants lack specialized auditory organs but are capable of detecting sound through ion channels or mechanosensitive proteins present on the surfaces of leaves, stem, roots or xylem tissues). Sound affects the calcium ion influx, plasma membrane H+-ATPase activity, microfilament rearrangement and cytoskeletal dynamics. As dedicated sensory receptors for sound remain unidentified, mechanosensory channel functions as substitute to sound receptor. (Frongia *et al*., 2020; Ghosh *et al*., 2016) [17, 18].

Membrane proteins in cell walls and membranes have the ability to alter their shape and configuration under sound treatment, they convert the mechanical acoustic signals into electrical or chemical signals, hence act as molecular sensors. In response to sound vibrations, mechanosensitive channels present in membranes open, converts sound signals into biochemical and electrical signals leading to cellular responses like changes in gene expression involved in stress responses and hormone biosynthesis (Dalal, 2021) [14].

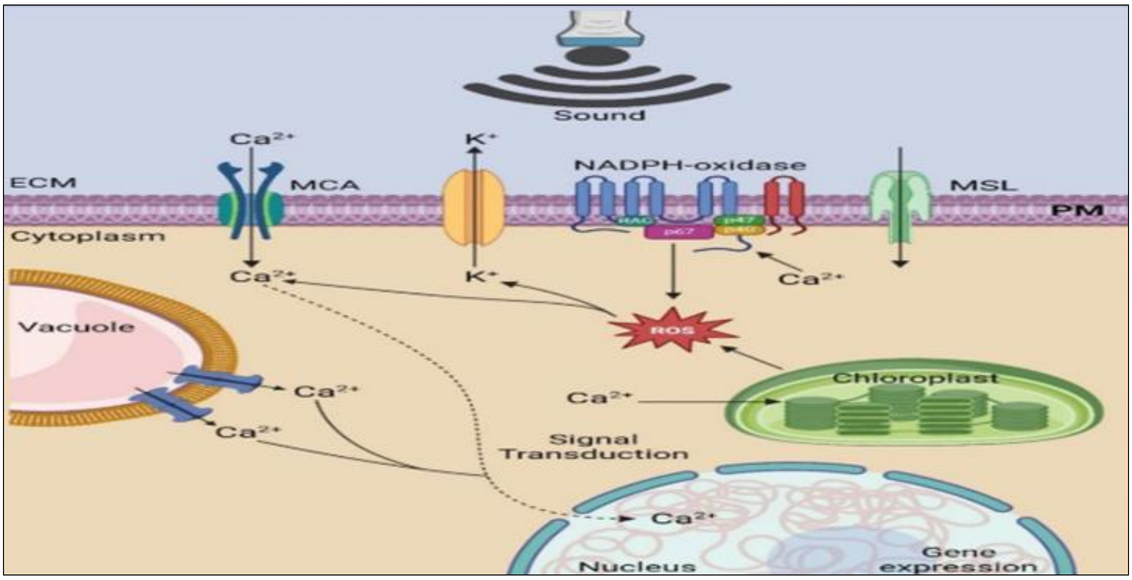

Fig 3: A model outlining the molecular phenomenon in a plant cell triggered by acoustic stimulation. MCA and MSL serve as unique key plasma membrane channels enabling sound-induced Ca^{2+} influx and efflux. Increased Ca^{2+} concentrations and K^+ levels in cytosol (boosting potassium efflux) is connected with external stimulus of sound. Specific sounds activate Ca^{2+} signalling by opening Ca^{2+} channels, activating Respiratory Burst Oxidase Homologs (RBOHs), releasing ROS, further up regulating gene expression and signalling pathways (Kumar, 2025) [31].

4. Genetic Scale - Signalling Within Cell

Sound-induced vibrations can enhance protoplasmic movement within a plant cell, helping in better efficiency of signalling cascade and metabolic pathways.

4.1 Growth hormones

Acoustic vibrations enhance auxin biosynthesis genes (e.g., *TAA1*, *YUCCA*) and modulate polar auxin transport via PIN-FORMED (PIN) proteins. This leads to directional elongation of cells and improved phototropic and gra*vitro*pic responses (Pagano & Del Prete, 2024) [37]. Upregulation of isopentyl transferases responsible for cytokinin biosynthesis is stimulated by sound, altering auxin cytokinin balance for cell division and spiked mitotic activity in meristematic tissues, (Dalal, 2021) [14]. Under influence of low-frequency sounds (200–500 Hz) activation of expansin genes and enzymes like xyloglucan endotransglucosylase/hydrolase (XTH) takes place to promote cell wall loosening. (Kim *et al*., 2018) [25]. Epigenetic remodelling in promoter region of auxin and cytokinin genes are recorded in methylation analysis and differential expression of hormone-regulated genes and transcription factors such as *ARFs*, MYB, and *ARRs*, and is observed under sound stimulus. (Chen *et al*., 2008) [8]. Controlled acoustic frequencies can enhance root biomass, seed germination rates, and synchronization of flowering by optimization of hormones (Wang *et al*., 2024) [50].

4.2 Cell division and cell cycle

Cell cycle processes and protoplasmic mobility in cell are also affected by acoustic vibrations, regulating physiological changes that underpin changes in gene expression of phytohormones. Growth changes in plants are enabled by Phytohormones, resulting in cell division and elongation, hence changes in their level under sound treatment is essential. (Frongia *et al*., 2020) [17]. When studied via cell flowcytometry, sound vibrations are shown to speed up cell division by modulating the cell cycle in Chrysanthemum plant. Decreased count of cell in G0 or G1 phase were observed as compared to those in S- phase, indicating that Sound Vibrations can fasten cell growth (Jung *et al*., 2018) [25].

4.3 Photosynthesis-related genes

Systemic integration via hormone signalling coordinates whole-plant responses, improving photosynthesis and biomass accumulation under sound exposure (Frongia *et al*., 2020) [17]. Genes such as Rubisco small subunit (rbcS) and Fructose 1,6-bisphosphate aldolase showed increase in expression under sound treatments especially at frequencies like 125-500 Hz in rice, enhancing photosynthetic activity and growth (Jung *et al*., 2018) [25]. In Arabidopsis, sound vibration up-regulated light-harvesting chlorophyll a/b binding protein genes (e.g., *LHCB2*, At3g27690), which are part of the PSII antenna complex and enhance light absorption efficiency (Ghosh *et al*., 2016) [18]. Proteomic analyses in Arabidopsis revealed to sound of frequency 250–500 Hz showed increased abundance of multiple photosynthesis-related proteins, including components of photosystems and carbon-fixation enzymes, consistent with enhanced photosynthetic capacity. (Jung *et al*., 2018) [25]. Genes encoding photosynthesis-antenna proteins (LHCII components such as Lhcb2 and Lhcb6) were up-regulated, corresponding with increased Fv/Fm and higher photosynthetic efficiency in duckweed treated with music (Ye *et al*., 2023) [4].

4.4 Defense

Stress responses genes are upregulated, including those related to pathogen defense (chitin-responsive ubiquitin-ligase-like enzyme) and drought tolerance. Calcium binding messengers like calmodulin- like CML38 found in *Arabidopsis* are activated under sound treatment leading to crucial signalling for stress management in plants (Jung *et al*., 2018) [25]**.** MSL and MCA genes linked mechanosensitive ion channels are also regulated by sound effect showcasing transfer of sound signals into biochemical signals for plant defense and adaptation. Sound vibrations also affect signal pathways involving ROS (Reactive Oxygen Species), Phytohormones like gibberellin, auxin, jasmonic acid, and calcium transients to enhance plant growth. Changed plasma membrane construct, enhanced activity of H^+-ATPases in membrane, increased protein, sugar synthesis and amylase activity has also been reported. (Ghosh *et al*., 2016) [18].

Mechanism of Sound Production in Plants

Plants are now widely accepted as the producers of acoustic emission of ultrasonic range (20-200 KHz). Sound emissions by plants arises from biophysical processes of plants rather than being result of signal cascades or biochemical pathways, neither plant hold any specialized auditory or vocal organ. Such biophysical processes are ruled by fluid dynamics, biomechanical characteristics of plant tissues and water tension. In recent findings, modern use of Laser Doppler vibrometry and ultrasonic microphones led to demonstration of plants under stress emitting unique sharp sound pulses, without any metabolic loss or biochemical pathway (Khait *et al*., 2023) [27].

1. Physical Basis of Sound Production

Xylem, the complex tissue of plants responsible for water transport performs supplementary role of emission of acoustic waves sourcing from cavitation events. Cavitation occurs when water is pulled up in the vessels and as the tension exceeds the threshold the water column breaks leading to formation of air bubbles, this sudden creation and collapse of bubbles lead to mechanical sound emissions. These emissions are further sensed by the mechanosensitive channels present in membranes of parenchyma cells leading to influx of Ca^{2+} ions in the cytoplasm. Calcium ions act as secondary messengers, activating signal pathways such as stress response gene regulation. Concurrently, the production of ROS like hydrogen peroxide is initiated due to oxidative and mechanical stress in xylem parenchyma cells. Such reactive oxygen species not only helps in local signalling but also plays crucial role in systemic signalling in plants by strengthening the calcium signalling, hence enhancing the mechanical signals. These signals are responsible for antioxidant dependent defence system, opening and closing of stomata, hormone biosynthesis and regulation. Rapid changes like change in cell turgor pressure can also create vibrations in tissues in stem or leaves, however it is affected by elasticity of cell walls and arrangement of vessels. Thigmonastic responses in form of leaf movements are also triggered in plants like *Mimosa* pudica by mechanical stimuli such as vibrations or touch.

Pulvinus is specialised for detection of such mechanical stimuli, which is present at the petioles or leaf base. When mechanical stimuli are detected, the pulvinus generates electrical signals that rapidly propagate through motor cells to induce movement by changing cell turgor pressure via ion fluxes, primarily potassium (K^+) and chloride (Cl^-) ions. Mechanoreceptor cells, believed to be derived from stomatal subsidiary cells, respond to mechanical stimuli by generating receptor potentials and connecting through plasmodesmata to excitable motor cells, initiating the cascade leading to leaf closure (Michael & Cocroft, 2025) [35].

Plants under biotic stress such as herbivory or pathogen attack have been documented to increase the emission of sound waves, likely emanating from damage-induced cavitations or cellular disruptions that act as acoustic alarms

(Wu *et al*., 2023) [27]. These acoustic signals could act as cues within plant communities for defense priming or stress signalling sound emissions from herbivore-induced damage may attract predators or parasitoids of herbivores, constituting an indirect plant defense mechanism (Wu *et al*., 2023) [4].

Table 1: Summary of Key Mechanisms to Sound production in Plants

Species of Plant	Stress Condition / Sound Type	Frequency Range	What the it Supports	Reference
Solanum lycopersicum (Tomate/Tomato)	Drought & cutting → airborne ultrasonic clicks	20–100 kHz	Strong evidence that drought or cutting sharply increases ultrasonic emissions. Cutting causes sudden, high-energy events; drought gives progressive increases.	(Khait *et al*., 2023) [27]
Nicotiana tabacum (Tobacco)	Drought & mechanical damage → airborne clicks	15–80 kHz	Drought triggers ultrasonic pulses, machine-learning analysis shows emissions carry stress-specific patterns, supporting that the temporal/spectral structure reflects cavitation dynamics.	(Khait *et al*., 2023) [27]
Zea mays (Maize/Corn)	Natural & laser-induced cavitation → internal ultrasonic emissions	80–200 kHz (tissue-conducted)	Laser-triggered cavitation experiments proved cavitation produces ultrasonic signals. By inducing cavitation at known locations and recording the waveform, gives mechanistic evidence that bubble expansion/collapse produces the acoustic signature.	(Sancho-Knapik *et al*., 2012) [51]
Vitis vinifera (Grapevine)	Drought→ acoustic emissions correlated with xylem embolism	~100–200 kHz	Micro-CT imaging recorded embolism formation at the same moments AE bursts occurred, providing direct visual confirmation that AE = cavitation/embolism events. AE rate tracks percentage loss of conductivity, validating AE as a hydraulic stress indicator in woody plants.	(Vergeynst *et al*., 2016) [48]
Pinus contorta (Conifers)	Freeze–thaw cycles → cavitation & thaw-induced bursts	~100–200 kHz	Freeze–thaw cycles form gas bubbles during freezing, which expand during thawing → generating ultrasonic emissions. Strong evidence linking bubble expansion during phase change to AE.	(Vergeynst *et al*., 2016) [48]

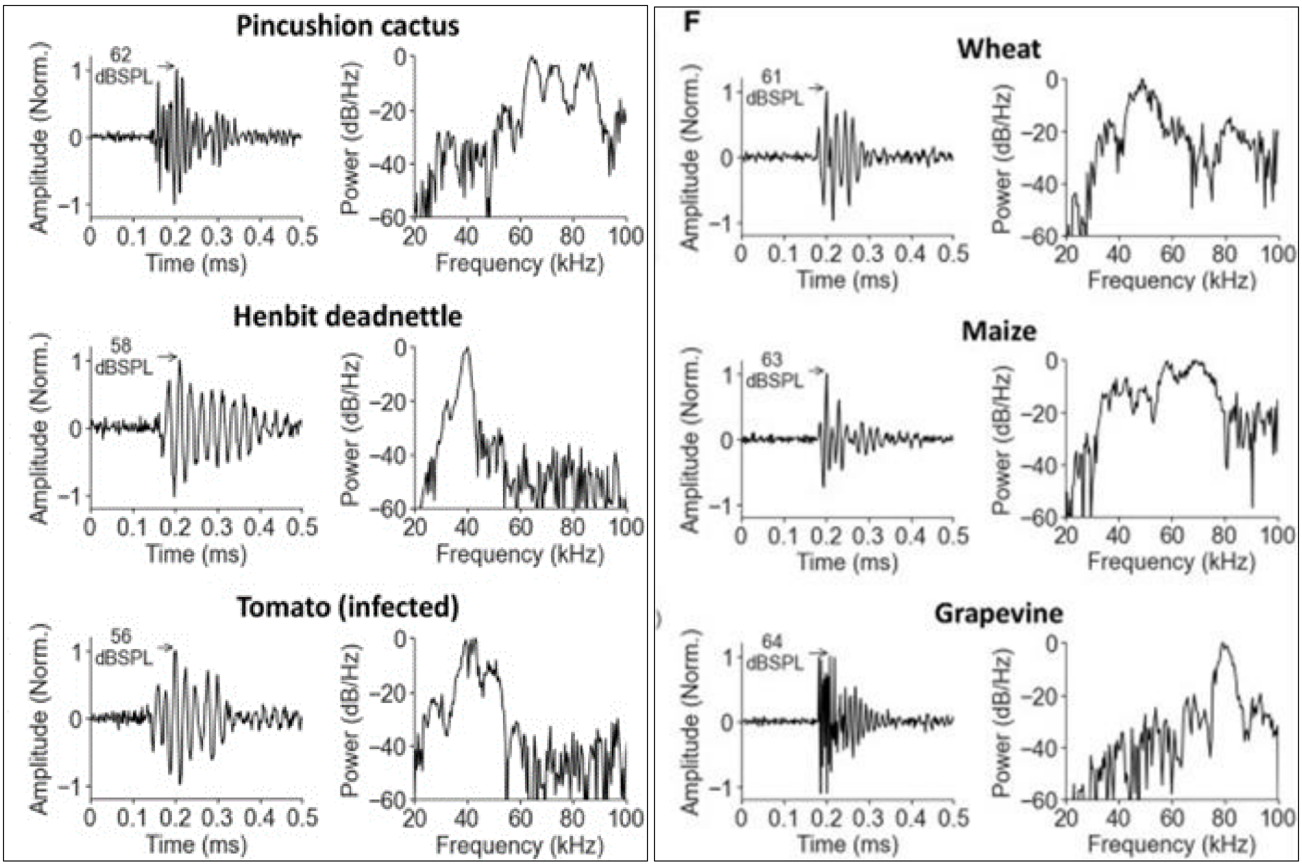

Fig 5: Documented acoustic signal in various plants. On Left - Samples of time signals of 6 plants (top to bottom): Triticum aestivum (Wheat, dry), Zea mays (Corn, dry), Vitis vinifera (Grapevine, Cabernet Sauvignon variety, cut), Mammilaria spinosissima (Pincushion Cactus, with cut), Lamium amplexicaule (Henbit deadnettle, with cut), and Solanum lycopersicum (Tomato, infested by TMV). On the right side are normalised spectra of spectra on right side. Under stress, each plant emits a decent amount of acoustic signal, reflecting that sound emission is a common trait of plant during stress. (Khait *et al*., 2023) [27]

Role of Plant Acoustics in Agriculture

Agricultural productivity is enhanced on a large scale by ingenious application of Plant Acoustic Frequency Technology derived from acoustic stimulation and sensing using vibration sensors, sensitive microphones and logical algorithms. This technology aims to detect stress keenly and upgrade usefulness of resources in the environment. Signals involving in xylem cavitation can be used in real time analysis of water stress and managing irrigation duration. Upon integration to platforms like IoT, such systems can classify types and severity of stress, locus specific management techniques. PAFT can play crucial role in pest and disease management too, as pathogen or herbivore attack release unique vibrations and sound pattern. Early detection of plant diseases by PAFT systems can prevent symptoms. It can further strengthen pest management methods and reduced dependence on chemical pesticides leading to mitigation of harmful effects on environment.

Other than diagnostic abilities, the technique consists of sound stimulation using plant response behaviour to promote plant growth in terms of seed germination, nutrient uptake, plant length, production of secondary metabolites or root formation. These properties of plants can be used to produce higher yields and quality in field of agriculture, especially in controlled environment like poly greenhouses. In conclusion, PAFT can be a way forward to smart and sustainable way of agriculture to curb the problem of food scarcity. It provides practical, environment friendly method with minimal investment to enhance the products of cultivation.

1. Evaluation Techniques for Plant Health and Growth

Treatment studies of Plant Acoustic Frequency Technology show enhanced productivity, stress resilience and growth across various species. It uses specific frequency ranges of 3-5 Hz or more to stimulate physical or physiological changes like metabolite production, photosynthetic efficiency, chlorophyll production, and defence against biotic or abiotic stress (Hendrawan *et al*., 2020) [23].

Some of findings also show upregulation in photosynthetic factors like electron transportation rate, non-photochemical quenching, or chlorophyll flouroscense (Fv/Fm) (Ghosh *et al*., 2016) [18].

a. PAFT Engineered crops in Floriculture

Plant Acoustic Field Technology (PAFT) enables non-invasive monitoring of plant health and optimizing growth conditions. Flowers are particularly sensitive to water stress, nutrient fluctuations, and mechanical damage, all of which can generate characteristic acoustic emissions detectable through PAFT systems (D. C. C. da Silva Medeiros *et al*., 2020) [13]. Beyond monitoring, PAFT has been explored for growth stimulation in floriculture through controlled acoustic exposure. Studies have reported that specific sound frequencies can influence flower bud initiation, stem elongation, and overall biomass accumulation, indicating that flowers actively respond to acoustic cues in their environment (Orhan *et al*., 2022) [36].

Table 2: Effects of sound frequencies on key plant species used in floriculture crops, detailing administered frequencies, sound types/sources, and primary physiological or growth responses observed

	Plant Species	Frequency (Hz/kHz)	Sound Type/Source	Main Effects Observed	Citations
1.	*Arabidopsis thaliana*	100 Hz, 1 kHz, 9 kHz	Pure tone	↑ Root growth, defense genes, stress tolerance	(Kim *et al*., 2021; Wu *et al*., 2023) [10]
2.	*Rosa chinesis*	Not mentioned	Violin music of Raaga Sindhu Bhairavi, RigVeda chants	Increase in stem length, soft bending of branches towards the source of music	(Chivukula & Ramaswamy, 2014) [9]
3.	*Chrysanthemum*	800 Hz,1,000 Hz, 100 dB	Pure tone	Increase in amylase activity from 9.35 U to 11.64 as compared with control group, enhanced quantity of soluble sugar (by 30 percent),	(Yiyao *et al*., 2002) [57]
4.	*Impatiens (Impatiens sp.)*	12,000 Hz-13,500 Hz ,91–94 dB	Pure tone	Enhanced leaf dimension (1.0 in. × 1.7 in.)	(Teixeira da Silva & Dobránszki, 2014) [47]
5.	*Dendrobium officinale (Dendrobium orchid)*	>20,000 Hz	Pure tone	Rise in the ratio of total cytokinin to indole-3-acetic acid, Protocorms- like structures develop into shoots rapidly, and rise in ratio of phytohormones (cytokinin to Auxin IAA).	(Wei *et al*., 2012) [51]
6.	*Aloe (Aloe arborescens Mill.)*	28 kHz	Pure tone	Enhancement of V-ATPase transport and ATP hydrolysis activities	(Liu *et al*., 2003) [32]

b. PAFT Engineered crops in Agriculture

Plant Acoustic Frequency Technology (PAFT) uses chosen acoustic waves to enhance crop growth and resilience in agriculture. Emerging from plant acoustics research, it stimulates physiological responses like better germination, nutrient uptake, and pest resistance in various crops. This sustainable approach integrates easily into modern farming for higher yields.

1. Effect on cereals

Cereals like wheat, mustard, corn, mung bean, rice are important crops involved in tackling global food scarcity and providing essential nutrients to human beings. Plant acoustics can help in enrichment of nutrient quality and biomass enhancement in cereal plants.

Table 3: Effects of sound frequencies on key plant species used in agriculture crops, detailing administered frequencies, sound types/sources, and primary physiological or growth responses observed

	Plant Species	Frequency (Hz/kHz)	Sound Type/Source	Main Effects Observed	Citations
1.	*Triticum aestivum* (Wheat)	0.1–1 kHz	classical music Havasi - 73 Rise of instruments and Led Zeppelin's tracks	Increased yield, protein, fat, starch content, increased plant height	(Rachieru *et al*., 2017) [38]
2.	*Brassica juncea* (mustard)	4 -5 kHz	Pure tone	↑ Height, leaves, harvest weight	(Arlius *et al*., 2021) [3]

3.	*Gossypium herbaceum* (Cotton)	0.06–2 kHz	pure tone	↑ Height, leaf area, boll number, yield, drought tolerance	(Hassanien *et al*., 2014); (Das, 2023) [15, 21]
4.	*Vigna radiata* (Mung Bean)	(a)70-100 dB, (b) 85 dB 60 watt	Devotional music	Radical development and seed vigour index upregulated by 37.5% and 42.56%, (b)↑ root length, plant shoot height, fresh weight and dry weight leaf count,	(Hendrawan *et al*., 2025) [22]
5.	*Zea mays* (Corn)	20kHz	Pure tone	↑ Germination rate and thicker stem	(Hendrawan *et al*., 2025) [22]
6.	*Oryza sativa* (Rice)	400 Hz,106 dB	Pure tone	↑ plant Growth, however excess of 4 kHz at 111 decibels is damaging for paddy seeds.	(Bochu *et al*., 2003) [5]

2. Effects on nuts

Corylus avellana exposed to 40 kHz ultrasound showed increased phenolic content in cells, though flavonoids significantly decreased, Taxol biosynthesis was notably enhanced (Rezaei *et al*., 2011) [41]. *Arachis hypogaea* treated with PAFT and violin music exposure exhibited increased plant height (Hendrawan *et al*., 2020) [23]. These effects continue the pattern of acoustic stimulation influencing growth, phytochemistry, and stress responses across diverse species.

Table 4: Effects of sound frequencies on key plant species used in nuts, detailing administered frequencies, sound types/sources, and primary physiological or growth responses observed

	Plant Species	Frequency (Hz/kHz)	Sound Type/Source	Main Effects Observed	Citations
1.	*Corylus avellana*	40 kHz	Ultrasound	Phenolic content of the cells increased flavonoids content decreased. Taxol biosynthesis enhances.	(Rezaei *et al*., 2011) [41]
2.	*Arachis hypogaea* (Peanut)	Not mentioned	violin music	Increased Plant height	(Hendrawan *et al*., 2025) [22]

3. Effect on medicinal plants

Acoustic treatment activates plant growth and production of bioactive components in plants with healing properties. *Swertia chirata,* extensively used for hepatoprotection and hypoglycemia showed enhanced phenolic, flavonoid content and increased shoot length under pure tones of 1 Hz, 1.5 Hz, 500 Hz (Singh *et al*., 2025) [46]. Similarly, *Chamaecostus cuspidatus* and *Stevia rebaudiana* treated with Indian classical music ragas exhibited elevated phytohormones like GA3 and IAA (Rout *et al*., 2022) [42]. *Dendrobium officinale* treated with ultrasound at 300 W for 5 minutes experienced an increased ratio of total cytokinins and indole-3-acetic acid (IAA), promoting balanced growth and development (Wei *et al*., 2012) [51].

Table 5: ffects of sound frequencies on key plant species used in medicinal crops, detailing administered frequencies, sound types/sources, and primary physiological or growth responses observed

	Plant Species	Frequency (Hz/kHz)	Sound Type/Source	Main Effects Observed	Citations
1.	*Swertia chirayita*	500 Hz, 1 kHz, 1.5 kHz	Pure tone	↑ Shoot growth, phenolics, flavonoids, antioxidant activity	(Singh *et al*., 2025) [46]
2.	*Chamaecostus cuspidatus,*	Indian classical music	Ragaas	↑ Phytohormones (GA3, IAA)	(Rout *et al*., 2022) [42]
3.	*Stevia rebaudiana*	Indian classical music	Ragaas	↑ Phytohormones (GA3, IAA)	(Rout *et al*., 2022) [42]
4.	*Dendrobium officinale*	Ultrasound treatment at 300 W for 5 min	Pure tone	increase in the ratio of total cytokinin (CTKs) to indole-3-acetic acid (IAA),	(Wei *et al*., 2012) [51]

4. Effects on crops in spices farming

Plant acoustics offers promising applications in spice farming by enhancing growth, yield, bioactive compounds, and stress resistance in high-value crops like saffron (*Crocus sativus*), black pepper (*Piper nigrum*). Saffron (*Crocus sativus*) exposed to 0.5–16 kHz pure tones showed peak crocin and picrocrocin increases at 8–12 kHz (Razavizadeh & Delooei, 2021) [39]. *Satureja hortensis* seeds treated with 800–7000 Hz music/noise exhibited enhanced germination, growth, phenolics, and flavonoids (Azgomi *et al*., 2023) [4].

Table 6: Ffects of sound frequencies on key plant species used in spices crops, detailing administered frequencies, sound types/sources, and primary physiological or growth responses observed

	Plant Species	Frequency (Hz/kHz)	Sound Type/Source	Main Effects Observed	Citations
1.	*Crocus sativus* (Saffron)	0.5–16 kHz	Pure tone	↑ Crocin, picrocrocin at 8–12 kHz	(Razavizadeh & Delooei, 2021) [39]
2.	*Satureja hortensis*	800–7000 Hz	Music, noise	↑ Germination, growth, phenolics, flavonoids	(Azgomi *et al*., 2023) [4]

5. Effect on Bioindicators/Bioremediatory plants

Festuca arundinacea exposed to pure tones between 200–1000 Hz showed increased biomass and improved cadmium (Cd) phytoextraction efficiency, aiding in phytoremediation efforts (Gu *et al*., 2021). Porphyridium cruentum, a red microalga, treated with pure tones above 20 kHz exhibited up to 58% higher biomass productivity along with enhanced antioxidation ability in algal cells (Chen *et al*., 2008) [8].

Table 7: Effects of sound frequencies on key plant species used in bioindicators/bioremediatory crops, detailing administered frequencies, sound types/sources, and primary physiological or growth responses observed

	Plant Species	Frequency (Hz/kHz)	Sound Type/Source	Main Effects Observed	Citations
1.	*Festuca arundinacea*	200–1000 Hz	Pure tone	↑ Biomass, Cd phytoextraction efficiency	(Gu *et al*., 2021)
2.	*Porphyridium cruentum* (Red microalga)	>20,00 Hz	Pure tone	↑ Biomass productivity up to 58% enhanced antioxidation ability of the algal cells	(Chen *et al*., 2008) [8]

c. PAFT Engineered crops in Horticulture

PAFT in horticulture stimulates plant growth, stomatal opening, photosynthesis, and gene expression through targeted sound frequencies. Optimal effects occur at 3-5 kHz for crops like red lettuce, cotton, strawberries, tomatoes, and peanuts, boosting height, leaf area, yield, and disease resistance.

Table 8: Effects of sound frequencies on key plant species used in vegetables/fruits crops, detailing administered frequencies, sound types/sources, and primary physiological or growth responses observed

	Plant Species	Frequency (Hz/kHz)	Sound Type/Source	Main Effects Observed	Citations
1.	Tomato	0.1–1 kHz, 1 kHz	Pure tone	↑ Yield, hormone levels, disease resistance	(Pagano & Del Prete, 2024) [37]
2.	Lettuce	0.1–1 kHz	Music	↑ Yield, leaf area, chlorophyll, productivity	(Hassanien *et al*., 2014) [21]
3.	Spinach	3 kHz	Music	Plant stem length and leaf area by 18.5 percent and 22.3 percent respectively relative to control group	(Hendrawan *et al*., 2025) [22]
4.	*Fragaria ananassa* (Strawberry)	1 kHz, 95–105 dB	Pure tone	↑ Growth, earlier fruiting, ↑ phenolics, vitamin C, early flowering with more fruits and darker green colour leaves.	(Meng *et al*., 2012) [51]
5.	Cucumber	Not mentioned	Pure tone	↑ Growth and yield	(Hassanien *et al*., 2014) [21]
6.	*Daucus carota*	24 kHz, amplitude 100 µm	At 20 °C, carrots were dipped in water, administered ultrasound for 300s	higher yields of ethylene, isocoumarin, 3-*O*-caffeoylquinic acid,	(Cuéllar-Villarreal *et al*., 2016) [12]
7.	*Cucurbita pepo* (L. Zucchini)	Not mentioned	healing energy for 15–20 mins twice per day	Seed germination rates ↑, using bioassay	(Creath & Schwartz, 2004) [11]
8..	*Phaseolus vulgaris* L	5,000 Hz, 91–94 dB	Pure tone	phenolic biosynthesis and antioxidative potential of common bean sprouts induced by ultrasound elicitation.	(Ampofo & Ngadi, 2020) [2]
9..	*Brassica rapa* (Bok choy)	>20kHz	Classical music	shoot with maximum total fresh weight, shoot fresh weight, and mean leaf numbers.	(Yeoh *et al*., 2024) [56]
10..	*Abelmoschus esculentus* L. (Okra)	Not mentioned	healing energy for 15–20 mins twice per day	Increased seed germination rates of okra, using bioassay	(Creath & Schwartz, 2004) [11]
11.	*Capsicum annuum L. (*Red bell pepper)	20–40 kHz	Ultrasonic	Controlled ultrasound, especially short-term direct sonication, enhances the release of bioactive compounds such as polyphenols, vitamin C, and antioxidants from bell pepper tissues, potentially increasing their measurable nutritional value.	(Rybak *et al*., 2025) [43]
12.	*Brassica alboglabra (*Kailaan*)*	3–5 kHz for three hours	Javanese gamelan music	Improved plant length, wet weight, stomatal openings, and chlorophyll content	(Hendrawan *et al*., 2020) [23]

2. Evaluation Techniques of Soil Quality

To monitor the soil quality in real time, Plant Acoustic Field Technology can be a fruitful non- invasive approach which uses sound signals to assess soil quality. The difference in moisture or particles properties affects the root hydraulics and water uptake, which in turn regulates sound emissions in plants (Deborah Cristina Crominski da Silva Medeiros *et al*., 2020) [13]. In soil water scarcity, different sound patterns related to cavitation helps in detection of water stress far before appearance of symptoms in crops. (Woo *et al*., 2022) [52]. It helps in regulated irrigation and soil management such as addition as manure, or quality check process. It acts an indicator to study physical parameters of soil affecting qualities like root growth. (Orhan *et al*., 2022) [36]. Overall PAFT helps in managing and monitoring soil by converting sound responses in plants into practical knowledge for precise and sustainable agriculture.

Table 9: Enlists various techniques used for soil quality evaluation in Plant Acoustics.

	Study	Technique used	How it works	Effectiveness
1.	(Deborah Cristina Crominski da Silva Medeiros *et al*., 2020) [13]	Ultrasound-supported extraction	Acoustic cavitation enhances the release of metals from soil matrices	Rapid, effective, and cost-efficient
2.	(Choi *et al*., 2021) [10]	Ultrasonic-assisted soil washing	Coupling ultrasound with agitation increases metal removal efficiency	Highly effective with reduced chemical consumption
3.	(Woo *et al*., 2022) [52]	Non-contact leaky Rayleigh wave technique	Surface acoustic waves are used to monitor soil moisture content	High accuracy ($R^2 = 0.98$) and non-invasive
4.	(Orhan *et al*., 2022) [36]	Ultrasonic texture analysis system	Signal intensity evaluation of soil–water mixtures	Fast, portable method for soil texture determination
5.	(Kewalramani *et al*., 2022) [26]	Dual-frequency ultrasonic PFAS treatment	Ultrasound promotes PFAS desorption from contaminated soil	Degradation constrained by cavitation energy losses
6.	(Xu *et al*., 2023)	Ultrasonic monitoring for MICP	Wave velocity correlates with $CaCO_3$ precipitation in soil	Strong correlation with unconfined compressive strength
7.	(Wang *et al*., 2024) [50]	Ultrasound wave propagation analysis	Examines acoustic behaviour at the transducer–soil boundary	Provides a basis for developing soil sensing devices
8.	(Bradley & Ghimire, 2024) [6]	Contact-free ultrasonic reflection	Porosity is estimated from reflected ultrasonic signals	High precision (±0.04 accuracy)
9.	(Kilinc & Orhan, 2025) [28]	Integrated ultrasound with EC/pH sensors	Multisensory data used for machine-learning-based texture prediction	Improved field performance

3. Evaluation Techniques for Seed Quality

(Guo *et al*., 2019) [20] developed two non-destructive acoustic methods for seed quality testing. Their impact-based approach analyzes sounds from dropping wheat kernels using Gaussian models and ELM classifiers in the time-frequency domain, achieving 95-96% accuracy in detecting damage. A second technique uses air-coupled ultrasound on cottonseeds, converting reflections to RGB images for MobileViT deep learning analysis, enabling rapid crack detection with 90.7% accuracy.

Table 10: Summary of detailed techniques, mechanisms of action in soil quality evaluation methods in agricultural applications

	Study	Technique used	How it works	Effectiveness
1.	(Guo *et al*., 2019) [20]	Impact-based acoustic analysis with Gaussian modelling and ELM	Acoustic signals generated by kernel impact are analysed in the time–frequency domain, and damage is identified using a COAS-ELM classification framework.	Enables non-destructive detection with high reliability, achieving 95–96% accuracy for identifying damaged wheat kernels.
2.	(Guo *et al*., 2019) [20]	Air-coupled ultrasound combined with sound-to-image encoding	Ultrasonic reflections from cottonseeds are transformed into RGB image representations and analyzed using a MobileViT-based deep learning architecture.	Demonstrates rapid and non-invasive detection of minor cracks with an average accuracy of 90.7%.

4. Evaluation Techniques for Plant Disease and Pest Control

Sound waves to help control plant diseases and pests in agriculture by activating natural plant defences and beneficial microbes while disrupting insect behaviour. This eco-friendly method reduces chemical use and fits well in integrated pest management.

Table 11: Summary of detailed techniques, mechanisms of action in plant disease and pest control evaluation methods in agricultural applications

	Study	Technique used	How it works	Effectiveness
1.	(Wang *et al*., 2018) [49]	Ultrasonic xylem cavitation monitoring	Detected xylem cavitation through sound emissions to examine water transport failure due to drought.	Critical for drought stress physiology, early warning system for cavitation.
2.	(Fariñas *et al*., 2014) [16]	Ultrasonic sensing of leaf response	Used ultrasound to monitor leaf reactions to environmental stimuli like drought or cold.	Effective for studying stress-response pathways in real time.
3.	(Ghosh *et al*., 2016) [18]	Ultrasonic leaf sensing	Ultrasonic sensors monitored plant water needs by detecting changes in leaf acoustics.	Highly sensitive to water stress, useful for irrigation scheduling.
4.	(Singh *et al*., 2022) [45]	Non-contact ultrasound in ambient air	Used ultrasound to monitor plant health responses without direct contact, detecting physiological changes remotely.	Promising for real-time monitoring in open-field conditions, non-invasive.
5.	(Khait *et al*., 2023) [27]	Airborne stress-induced sound recording	Emission of ultrasonic sound by plants under stress were captured.	Recorded plants emit detectable sounds under stress, usable for remote stress sensing.
6.	(Maginga *et al*., 2024) [33]	Ultrasound IoT + CNN-LSTM	Combined weight transducers and deep learning with ultrasound & VOC data for early disease detection.	High accuracy in non-visual early disease identification.

Role of Indian Knowledge System in Plant Bioacoustics

Research on Indian classical music, ragas, and Vedic chants demonstrates consistent positive impacts on plant growth, biochemical profiles, and physiological responses, often outperforming controls, Western classical music, or discordant sounds like rock. In a controlled 60-day experiment with *Rosa chinensis* (rose), exposing groups to Indian classical ragas, Vedic chants, western classical melody, rock music, and silence.

Vedic chants lead to production of large size and number of flowers, whereas classical ragas support largest internode expansion almost up to 4 cm and enhanced rate of bud formation. Western classical music reflects moderate growth; however, rock music treatment has seen undersized development of plants as compared to control group, concluding that pleasant waves of sound and harsh ones degrade it (Chivukula & Ramaswamy, 2014) [9].

Plants of *Stevia rebaudiana* and *Chamaecostus cuspidatus* in seedling period treated with coordinated sounds of classical music in India played over contemporary instruments showed 25% taller plants, better phytochemical levels, higher biomass accumulation and enhanced phenolics and flavonoids, leaf area expansion as compared to control indicating that these responses affect plants photosynthetic ability and metabolic activity. (Rout *et al*., 2022) [42].

Study done by Dr. T.C. Singh, Annamalai University on balsam plants under influence of Indian ragas by violin or flute reported 72% biomass increase and 20% height increase in comparison with control group. Alike effects were noted in species of horse gram, wheat and spinach and also enhanced metabolic synthesis of chlorophyll by 30 % and starch by 40% (Reddy & Ragavan, 2013) [40]. A 2022 study on *Ocimum sanctum* (holy basil) using Bharata Natyam dance vibrations and violin-based ragas found 20-60% faster height growth, denser foliage, and higher essential oil yields, linking rhythmic harmonics to improved stomatal conductance and antioxidant enzyme activity.

According to JETIR (2022) higher protein content (by 35%), higher carbohydrate levels (by 28%) and taller plants (13.25 cm height), exceeding values of control group or rock music group. It was also noted that denser leaves were obtained with more root volume (90 cm^3 against 77 cm^3 in control group.

Hill Quest (2024) suggest that octave consonants of traditional music support growth in root and mitosis in onion, whereas rough sound reduces it. Harmonious raga music enhances photosynthetic activity, metabolism and defence compounds in *Stevia* (Rout *et al*., 2022) [42].

Future Scope

For real time, non-invasive monitoring for crop stress management and environment control using acoustic sensors and machine-based classifiers is in talk however for its practical use is still a far journey. Crucial knowledge gaps of exactly how plant senses sound and finding the pathways adapted is yet to be studied in detail. Use of standard protocols is also important for reproducibility of experiments. It is also needed to link species specific plant responses and specific frequencies using standard instruments. Moreover, agricultural practical application of PAFT from laboratory findings requires much detailed resources and research to bring it on field.

Conclusion

Sound is meaningful for plants as natural sounds like wind, water and bee buzzing affects how plants grow and function upon its perceiving and responding. Plants are capable of communicating in form of acoustic frequencies. It is not at all random rather it is a systematic response based on various morphological structure and its constituent tissues including signalling pathways. Plant hormonal levels, gene expression and calcium signalling are affected by sound indicating sound is a regulatory factor just like water, chemicals or sunlight.

Stress response, xylem cavitation and tissue deformation are true indicators of plant health. Combining these keen observations with high value technology such as sensing and signal analysers, monitoring of stress level, status of health, diseases and productivity without disturbing the natural environment is possible. The vision of plants as producers and receivers changes traditional ideology of plants as mute and inaudible plants. Controlled exposure of frequency and sensor – run diagnostic systems show better seed germination, flowering aspects, enhanced plant growth and stress resilience. PAFT provides a low cost, eco-friendly and energy saving way towards sustainable agriculture farming.

Credit authorship contribution statement

Harsharan Singh: Reviewing, proofreading and supervision.

Khushi Verma: Conceptualization, data collection, Review of literature, original draft formation.

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Data availability statement

Data are available in a publicly accessible repository. No new datasets were generated or analysed during the study.

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