TU Delft

Delft University of Technology

Document Version
Final published version

Licence
CC BY

Citation (APA)
SharathKumar, M., Bieling, T. J., de Klerk, B. B., Dutta, S., & Verbiest, G. J. (2026). Tuning into plant ultrasonics: Can acoustics enable smart agriculture? *Computers and Electronics in Agriculture*, *254*, Article 112274. https://doi.org/10.1016/j.compag.2026.112274

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

Computers and Electronics in Agriculture 254 (2026) 112274



Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag



Review article

Tuning into plant ultrasonics: Can acoustics enable smart agriculture?

Malleshaiah SharathKumar [a,b,*], T.J. Bieling [c], B.B. de Klerk [c], S. Dutta [c], G.J. Verbiest [c,*]

[a] Horticulture and Product Physiology, Wageningen University and Research, Droevendaalsesteeg 1, 6708 PB, Wageningen, The Netherlands
[b] Department of Breeding and Research, Deliflor Chrysanten B.V., Korte Kruisweg 163 -2676 BS, Maasdijk, The Netherlands
[c] Department of Precision and Microsystems Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands

ARTICLE INFO

Keywords:
Plant acoustics
Ultrasound
Sensors
Artificial intelligence
Data analysis

ABSTRACT

Plant ultrasonic acoustic emissions (UAEs) are low-intensity sound signals that arise primarily from physiological processes associated with transpiration-driven water transport. By monitoring these emissions, researchers and farmers can detect physiological changes related to water/drought stress, heat stress, or disease, allowing timely interventions and optimized resource management. However, substantial variability in UAEs across plant species and environmental conditions, together with limited detection sensitivity and a lack of standardized measurement protocols, present significant challenges for robust interpretation and large scale deployment. Recent advancements in portable sensor technologies and network integration, supported by collaborations between crop physiologists, engineers, and data scientists, aim to address some of these challenges. Standardization efforts and more robust methodologies for data collection and analysis are emerging, alongside innovative applications in precision agriculture. These developments promise to boost crop yields, enhance sustainability, and increase resilience to environmental stressors. In this perspective article, we review the current state of plant acoustics research,critically assess available sensing and analytical approaches, and discuss both their opportunities and limitations. We further argue that targeted research into the biological interpretation of UAEs' including their potential roles in plant-to-plant and plant–animal interactions, in natural ecosystems as well as in controlled environments like greenhouses and vertical farms, is crucial. Within a smart farming toolkit, plant acoustics may become a complementary tool for applications in agriculture, forestry, plant breeding, and conservation, provided that integration across sensing, data analytics, and agronomic decision-making is achieved.

Contents

1. Introduction 2
2. Technological advances in plant acoustics 2
3. Xylem vessel and its role in ultrasound emission 3
4. Production and perception of sounds by plants 5
5. Opportunities for plant acoustics in plant breeding and cultivation 5
6. Discussion: Strengths, limitations, and future applications 7
7. Future directions and conclusion 8
CRediT authorship contribution statement 9
Declaration of competing interest 9
Acknowledgment 9
Data availability 9
References 9

* Corresponding authors.
E-mail addresses: sharath.malleshaiah@wur.nl (M. SharathKumar), G.J.Verbiest@tudelft.nl (G.J. Verbiest).

https://doi.org/10.1016/j.compag.2026.112274
Received 9 September 2025; Received in revised form 10 July 2026; Accepted 30 July 2026
Available online 10 August 2026
0168-1699/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Plant ultrasonic acoustic emissions (UAEs) typically refer to low-intensity sound bursts emitted by plants at frequencies ranging from 20 kHz to several hundred kHz, which are beyond human audible range (Milburn and Johnson, 1966; Nardini et al., 2024). These emissions largely originate from the dynamics of water transport within plants' xylem vessels (Venturas et al., 2017; Tyree et al., 1984; van Ieperen et al., 2002), although other mechanisms like granular movements in the vascular tissue are also reported to play a role (Moebius et al., 2012; Brancheriau and Baillères, 2002). According to the classical cohesion–tension theory of transpiration (Zimmermann, 2013; Tyree and Sperry, 1988), a negative pressure is generated that facilitates the upwards transport of water against gravity from roots to leaves. Factors such as soil moisture, ambient temperature, drought conditions, and plant structural characteristics of influence this tension and its dynamics. When the pressure differential exceeds a critical threshold, tiny air bubbles are formed in the xylem (Zimmermann et al., 1993; Caupin and Herbert, 2006; Schenk et al., 2015), triggering vibrations in the surrounding vascular tissue and leading to UAEs (Ponomarenko et al., 2014; Rosner et al., 2006; Vergeynst et al., 2015; Nijsse et al., 2001; Hölttä et al., 2005; S. Dutta et al., 2022) (Fig. 1a). The intensity, frequency and duration of these brief emissions (Fig. 1b) have therefore been associated with changes in plant physiological state and structural (vascular) integrity of plants.

Studying UAEs offers valuable opportunities for improving our understanding of plant physiology and environmental stress responses (Hussain et al., 2023; Venturas et al., 2017). However, most reported emissions are best understood as biophysical by-products of xylem hydraulics rather than intentional biological signals, and their quantitative interpretation remains challenging. Although research in this field is still emerging (S. Dutta et al., 2022; Del Stabile et al., 2022; Khait et al., 2023), evidence indicates that plants predominantly emit these sounds under stress conditions like drought, physical damage, or pathogen attack (Daneshmand et al., 2024; Waqas et al., 2023). The potential role of these emissions in the plant signaling and ecological interactions remains largely unresolved and requires careful experimental validation at the plant and crop levels (Gagliano et al., 2012; Beikircher et al., 2025). Given their intrinsic connection to xylem function, investigating UAEs yields critical insights into plant–water relations and other physiological processes relevant for advancing agricultural practices (Venturas et al., 2017; Tyree et al., 1984; Olson et al., 2014). By monitoring acoustic emissions, researchers can detect early indicators of plant stress, including heat stress, drought, pest infestations, or diseases, enabling timely interventions that can mitigate potential damage. At present, however, most demonstrations are limited to laboratory or controlled-environment conditions, and translation to open-field agriculture remains constrained by environmental noise, biological variability, and a lack of standardized measurement protocols.

In the context of climate change, which imposes multiple and interacting stresses on agriculture, understanding plant acoustics is therefore of growing interest (Hussain et al., 2023; Del Stabile et al., 2022). As a non-invasive, real-time monitoring approach, acoustic measurements represent a promising and yet still developing tool for assessing plant health and responses to environmental shifts (Khait et al., 2023; Waqas et al., 2023). Such a technology has the potential to empower farmers to optimize crop management practices, enhance yields, and promote sustainable resource-use (Beikircher et al., 2025; Daneshmand et al., 2024). Beyond agriculture, investigating UAEs may shed light on plant signaling and ecosystem dynamics, paving the way for new strategies in ecological conservation and biomimicry (Gagliano et al., 2012; Goldstein and van de Meent, 2015). Realizing these opportunities will require integration across sensing technologies, data analytics, and biological interpretation, as well as critical assessment of methodological limitations. Further advancements in this research area could lead to the development of bio-inspired technologies, such as sophisticated sensors and diagnostic tools, that enhance environmental monitoring and conservation efforts (Nakade and Dhadse, 2024; Woodhouse and Goldstein, 2013).

This perspective article is structured around three themes. We first review recent advances in plant acoustic sensing technologies. We then discuss the biophysical origins of UAEs, including xylem cavitation and sound production in plants, and their relation to the environmental drivers. Finally, we critically evaluate the opportunities and limitations of plant acoustics in plant breeding and cultivation, before outlining future directions for plant acoustic research toward smart agriculture.

2. Technological advances in plant acoustics

Recent developments in plant acoustic studies have shifted the field towards non-invasive methodologies for measurements on both woody and non-woody plants (Del Stabile et al., 2022). Historically, the detection of ultrasonic acoustic emissions relied on invasive techniques such as removing bark and underlying tissues to expose xylem conduits in woody plants, allowing direct sensor attachment to capture emissions (Tyree and Sperry, 1988; Zweifel and Zeugin, 2008; Vergeynst et al., 2015). While these approaches provided high signal sensitivity, they also introduced significant limitations, including physical damage to plant tissues, potential interference from ultrasound generated by measurement equipment (Steppe et al., 2009), and restricted applicability to non-woody species (Rosner et al., 2006; Nijsse et al., 2001).

Advancements in sensor technology have been pivotal in addressing several of these limitations associated with invasive measurements (Khait et al., 2023; Daneshmand et al., 2024). In particular, the development of contactless and highly sensitive ultrasound microphones has enabled passive, non-invasive detection of plant acoustic emissions without physical disturbance of plant tissues (Waqas et al., 2023). These innovations have broadened the applicability of the technology to a wide variety of species, including both woody plants and herbaceous crops like tomato (Hussain et al., 2023; Nardini et al., 2024). However, while contactless microphones, facilitate continuous monitoring in laboratory and controlled environments, their performance under field conditions remains constrained by environmental factor interference, signal attenuation with distance, and challenges in attributing detected signals to specific physiological processes (Del Stabile et al., 2022; Beikircher et al., 2025).

Current research in plant acoustics incorporates both active and passive measurement techniques (Del Stabile et al., 2022) (Fig. 1c). Active approaches involve stimulating plants with external forces, such as mechanical vibrations or ultrasound waves, to elicit specific acoustic responses (Gagliano et al., 2012; Berardi et al., 2017; Agrawal et al., 2016), depending on plant geometry and elastic properties (Shah et al., 2017; Vogler et al., 2015). These methods are valuable for isolating and studying targeted biophysical responses under well-defined conditions (Beikircher et al., 2025), but they often require close coupling, precise alignment, and controlled environments, which limits their applicability outside laboratory settings. Passive approaches in contrast, capture spontaneously occurring emissions without external intervention, providing a more holistic and undisturbed perspective of plant responses under natural conditions (Khait et al., 2023; Waqas et al., 2023). However, passive approaches face challenges related to signal attribution, background noise, and variability across plants and environments. Together, active and passive approaches offer complementary insights into plant stress responses and internal physiological processes, yet neither approach alone currently provides a comprehensive or field-robust solution (Daneshmand et al., 2024; Hussain et al., 2023).

A range of sophisticated sensors, including high-frequency microphones, laser vibrometers, and piezoelectric devices, are now used to capture ultrasonic acoustic emissions with high sensitivity and temporal resolution, drawing on technologies originally developed for engineering and biomedical applications (Kolkman et al., 2004; Hoskins,

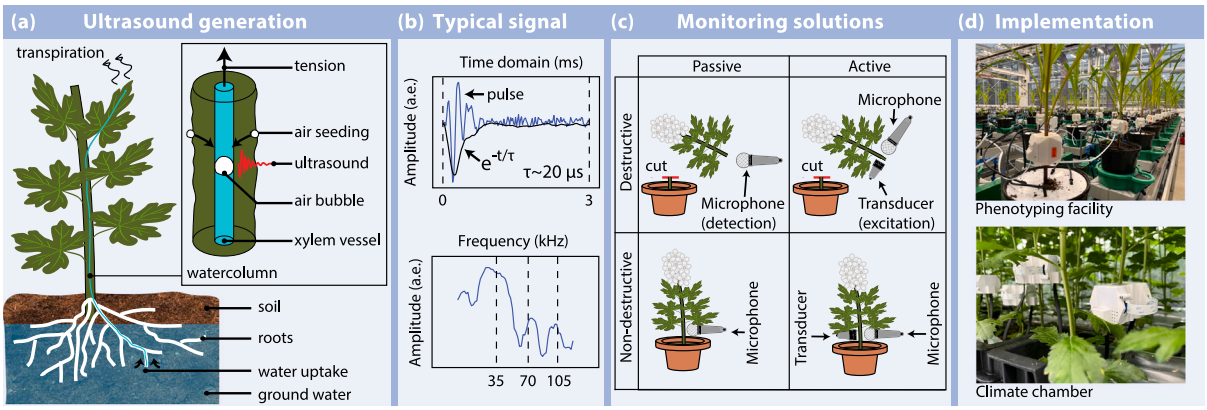


Fig. 1. UAE in plants: mechanism, methods and implementation. **(a)** Ultrasound generation by plant is the result of the tension in the water-column originating from an imbalance between transpiration and water uptake by the roots in the soil of (ground) water. The tension can lead to air-seeding into the xylem vessel or break the water-column altogether leading to an air bubble formation and the emission of an ultrasound pulse. **(b)** Typical signal of the ultrasound pulses (S. Dutta et al., 2022) both the time domain (top) and frequency domain (bottom). **(c)** Monitoring solutions, which encompass both passive, i.e. listening to the spontaneous emitted sound wave from a plant, and active, i.e. listening to the reflection and/or transmission of an excitation sound wave. These solutions can be either employed destructively, i.e. on cut plants, or non-destructively. **(d)** Implementation examples of ultrasound sensors in a phenotyping facility (top) and climate chamber (bottom).

2007; Lizzi et al., 2003; Migliori and Darling, 1996; Rae and Brown, 2016), and more recently applied to plant systems (Khait et al., 2023; Daneshmand et al., 2024). Each sensing modality offers distinct advantages, but also presents specific limitations: piezoelectric sensors provide high sensitivity yet depend strongly on sensor–plant coupling; laser vibrometers enable contactless measurements with exceptional resolution but are costly and sensitive to external vibrations; and airborne microphones offer scalability and non-invasive deployment but are vulnerable to signal attenuation and environmental noise. Consequently, no single sensor technology currently satisfies the combined requirements of sensitivity, robustness, scalability, and ease of deployment needed for routine agricultural use. Ongoing efforts toward portable and wireless sensor systems aim to extend plant acoustic measurements beyond laboratory and greenhouse environments (Del Stabile et al., 2022; Beikircher et al., 2025). While such developments are essential for enabling field studies, their success will depend on improvements in sensor robustness, power efficiency, and data reliability under variable environmental conditions (Waqas et al., 2023; Hussain et al., 2023).

Advances in data processing and analysis tools are central to translating raw acoustic data into biologically and agronomically meaningful information (Fig. 1d) (Khait et al., 2023; Daneshmand et al., 2024). Commonly applied techniques such as noise filtering, Fourier analysis, and machine learning algorithms to distinguish plant-derived signals from background noise and to identify patterns associated with physiological states and environmental conditions (Del Stabile et al., 2022; Waqas et al., 2023). These methods also facilitate the identification of patterns associated with different physiological states and environmental conditions (Nardini et al., 2024). However, the interpretation of such patterns remains challenging, as similar acoustic features may arise from different physiological processes or external disturbances, and machine learning models are often sensitive to training conditions and data bias. For understanding the physiological status and mechanistic insight can be strengthened by integrating concepts from engineering disciplines, such as fluid dynamics, wave propagation in pipes, and the mechanics of cellular solids, which provide useful analogies for interpreting xylem hydraulics and tissue-level responses (Satadal Dutta et al., 2022; Ashby, 2006, 1983; Boudon et al., 2015; Gibson and Ashby, 1982; Gibson, 2005, 2012; Gomez et al., 2007; Ongaro et al., 2016; Pintelon et al., 2004; Warner et al., 2000). The complexity of acoustic data analysis therefore necessitates a multidisciplinary approach that integrates expertise in plant physiology, acoustics, and data science (Gadalla et al., 2014; Gagliano et al., 2012; Goldstein and van de Meent, 2015). Therefore, collaboration between botanists, engineers, and data scientists has become increasingly important in the advancement of the plant acoustic research (Nakade and Dhadse, 2024; Woodhouse and Goldstein, 2013) as suggested in Fig. 2.

Further progress will depend on integrating acoustic monitoring systems with complementary environmental and physiological sensors such as those monitoring temperature, humidity, and soil/substrate moisture, or sap flow to enable a more comprehensive understanding of complex plant–environment interactions (Daneshmand et al., 2024; Dutta et al., 2025; Hussain et al., 2023; Waqas et al., 2023). While, multi-sensor networks offer a promising route toward improved interpretation and decision support, their practical value in agriculture will require standardized data pipelines, robust validation across environments, and careful assessment of uncertainty before claims of yield optimization or sustainability gains can be substantiated (Steeneken et al., 2023; Beikircher et al., 2025; Nardini et al., 2024; Del Stabile et al., 2022).

By embracing these approaches, plant acoustic studies can make significant contributions to our understanding of plant behavior and interactions with their environment, paving the way for innovative solutions in agriculture, ecology, and beyond.

3. Xylem vessel and its role in ultrasound emission

Xylem vessels are central to plant water transport. When the water column within xylem vessels is subjected to high tension due to transpiration (Tyree et al., 1984; Zimmermann, 2013), this tension can cause air seeding or the formation of air bubbles, which can generate characteristic acoustic signals (Milburn and Johnson, 1966; Vergeynst et al., 2015). Under severe stress, the tension can exceed cavitation thresholds, leading to the formation of vapor-filled cavities, known as embolisms. Such embolisms can disrupt the continuous flow of water and significantly impair the plant's ability to transport water and nutrients (Rosner et al., 2006; Venturas et al., 2017). The physical mechanism behind cavitation involves the stretching and breaking of the hydrogen bond between water molecules. Yet, the tension required for this mechanism is high, indicating that clustering of micro- and nanobubbles (Nijsse et al., 2001; Ponomarenko et al., 2014), naturally present on the inner surface of xylem vessels, may also play a role in acoustic signal generation (Nijsse et al., 2001; Moebius et al., 2012; Schenk et al., 2015). External factors such as soil moisture, atmospheric conditions, and plant species-specific xylem structure can directly influence the tension and thereby the occurrence of cavitation (Hölttä et al.,

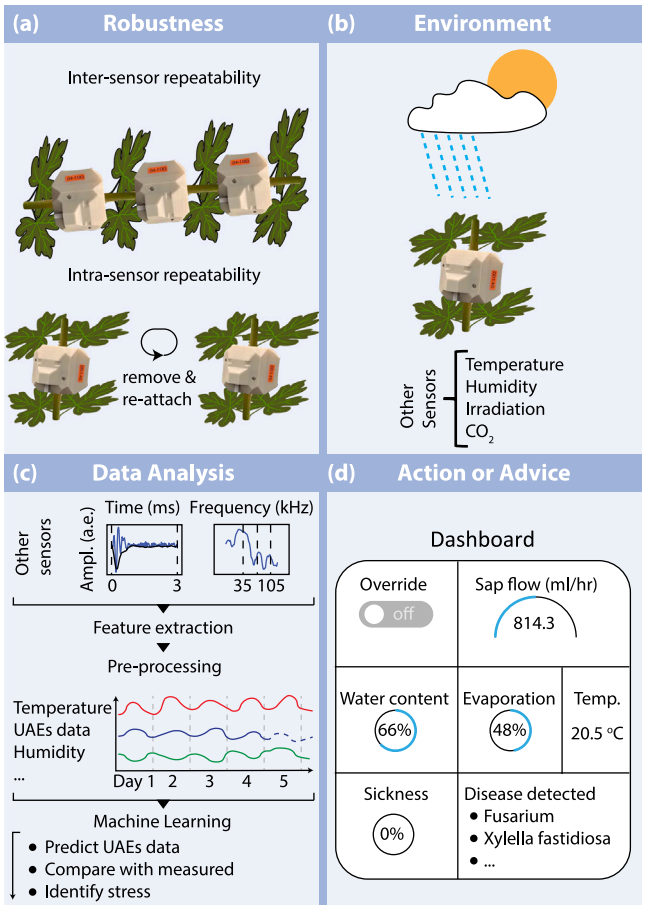


Fig. 2. Plant acoustics technology roadmap: challenges and solutions. **(a)** Robustness is a challenge for ultrasound plant monitoring. Multiple ultrasound sensors on the same plant location should give the same output, i.e. inter-sensor repeatability should be high. Also, remove and re-attaching the same sensor on a plant should give the same output, i.e. intra-sensor repeatability should be high. **(b)** Environment needs to be measured independently as it can affect the output of the ultrasound sensor, e.g. temperature-dependent speed of sound, or serve as co-founding variables in the measurement. **(c)** Data analysis and machine learning tools need to consider output from the UAEs and climatic sensors and fuse them through pre-processing, feature extraction, and clustering to ultimately identify stress. **(d)** Action or advice can be given (i.e. AI) based on a comparison between predicted UAEs data and measured UAEs data next to sap flow, water content and evaporation. These can be estimated directly from the ultrasound sensor output.

2005; Hussain et al., 2023). While cavitation-driven mechanisms are widely supported, the relative contribution of different bubble nucleation processes to the characteristics of ultrasonic acoustic emissions remains an active area of investigation. From a functional perspective, ultrasonic acoustic emissions may therefore reflect the hydraulic risk state of the xylem rather than irreversible damage, providing early information on proximity to cavitation thresholds.

UAEs produced during xylem vessel cavitation serve as valuable indicators of a plant's internal physiological state, especially in response to environmental stressors (Khait et al., 2023; Waqas et al., 2023). However, these acoustic features should be interpreted as indirect and context-dependent indicators of physiological stress rather than direct or universal measures of hydraulic failure. The frequency, amplitude, and duration of these emissions provide critical information about the extent of cavitation and the overall condition of the plant's vascular system (Nardini et al., 2024). For instance, plants under severe water stress or undergoing freeze-thaw cycles may emit more frequent and intense UAEs, signaling a higher degree of cavitation and greater vulnerabilities in their water transport system (Beikircher et al., 2025; Del Stabile et al., 2022).

The relationship between xylem vessel cavitation and sound production is well-documented. Cavitation or air-seeding events produce acoustic emissions, often detected as clicks or bursts of sound (Steppe et al., 2009; Vergeynst et al., 2015). The frequency and intensity of these emissions vary depending on the size of the host vessels and number of such events. Research has shown that these emissions offer a non-invasive, reliable method for assessing plant water stress (Daneshmand et al., 2024). Furthermore, the variability in acoustic emissions between different species suggests that UAEs can be instrumental in studying species-specific responses to environmental stresses, providing valuable insights into the adaptive mechanisms of plants such as stomatal closure, shrinking of xylem vessels, and using water reserves from neighboring xylem parenchyma (Hussain et al., 2023; Gagliano et al., 2012). However, species-specific differences complicate direct comparisons across taxa and limit the transferability of acoustic thresholds between plant types and experimental settings.

Not only passive listening for cavitation enables plant health monitoring; active vibrational and acoustic methods can also be used to probe plant water status. Using these approaches stem water content and vascular tissue thickness can be monitored accurately and in real-time (Kageyama et al., 2008; Lv et al., 2022; Zhdanov et al., 2020). However, most of these techniques have been validated primarily under controlled experimental conditions, and their robustness and scalability under field environments remain to be systematically assessed. Similarly, non-contact acoustics have been applied to leaf-level measurements, enabling the monitoring of leaf turgidity, leaf relative water content, and leaf water potential, using a range of methods (Sano et al., 2015; Fariñas et al., 2024; Castaño-Bernal et al., 2025; Collazos-Burbano et al., 2021; Saglam, 2022).

Environmental factors such as soil moisture, temperature, light intensity, and atmospheric pressure play a significant role in shaping the acoustic emissions of plants (Hölttä et al., 2005; Hussain et al., 2023). The vapor pressure deficit defines how much water can transpire, temperature and light intensity drive the transpiration, and the soil moisture defines the resulting tension in the xylem vessels (Venturas et al., 2017; Olson et al., 2014). Hence, low soil moisture levels increase the frequency of cavitation events, leading to more frequent UAEs (Rosner et al., 2006; Vergeynst et al., 2015). Moreover, temperature variations can affect the physical properties of water and xylem tissues, altering the characteristics and occurrence of cavitation (Tyree et al., 1984; Nijsse et al., 2001; MacMillan et al., 2013). Understanding these environmental influences is essential for accurately interpreting acoustic data and assessing the physiological state of plants under varying conditions (Khait et al., 2023). Consequently, environmental influences must be carefully disentangled from intrinsic plant responses when interpreting acoustic data.

The implications of climate change, including more frequent extreme weather events and altered precipitation patterns, further underscore the importance of monitoring UAEs (Waqas et al., 2023; Del Stabile et al., 2022). As plants increasingly face droughts, temperature extremes, and other environmental stresses, the ability to detect stress responses through acoustic emissions becomes critical for managing agricultural and natural ecosystems (Ziv et al., 2018; Daneshmand et al., 2024; Beikircher et al., 2025; Bhandawat and Jayaswall, 2022). Early detection of plant stress via UAEs can provide timely interventions and aid in developing strategies to mitigate the adverse effects of climate change on plant health, productivity, and overall resilience (Hussain et al., 2023; Nardini et al., 2024). However, realizing this potential will depend on reliably distinguishing stress-specific acoustic responses from background environmental variability across contrasting climatic conditions.

Beyond their potential as stress indicators, an emerging area of research explores the concept of "plant alerts", where plants emit

signals in response to threats or environmental changes. Some studies suggest that plants might use acoustic emissions as a form of signaling, potentially warning neighboring plants or attracting beneficial organisms (Gagliano et al., 2012; Goldstein and van de Meent, 2015; Schöner et al., 2016; Polajnar et al., 2012). For example, increased acoustic activity in response to herbivore may signal nearby plants to activate defense mechanisms (Khait et al., 2023). While the mechanisms behind this potential signaling remain under investigation, these findings open new avenues in understanding inter-plant communication and ecological interactions. At present, however, these observations remain largely hypothesis-driven, and the existence, mechanisms, and ecological relevance of acoustic signaling in plants are not yet established.

Taken together, these considerations underscore that ultrasonic acoustic emissions primarily reflect biophysical processes in plant hydraulics, while their biological interpretation and ecological relevance require careful, context-dependent validation.

4. Production and perception of sounds by plants

Plants produce UAEs through a range of biological activities beyond xylem vessel cavitation. These include cellular metabolism, growth processes, and responses to environmental factors such as wind or mechanical damage (Gagliano et al., 2012; Berardi et al., 2017; Beikircher et al., 2025). The characteristics of these emissions, such as their frequency and amplitude, can vary widely depending on the biological process and environmental context (Waqas et al., 2023). For example, sounds produced during growth may offer insights into the rate and pattern of development, while emissions linked to metabolic activities might reflect shifts in cellular function or energy status (Hussain et al., 2023; Nardini et al., 2024). Together, these observations suggest that plant-generated acoustic signals can serve as non-invasive, real-time indicators of physiological activity, although their specific biological origins are often difficult to disentangle (Daneshmand et al., 2024; Khait et al., 2023).

The possibility that plants can perceive and respond to sounds, despite lacking traditional auditory organs, is an intriguing yet somewhat controversial topic in plant science (Son et al., 2024; Gagliano et al., 2012; Goldstein and van de Meent, 2015). Although plants are capable of emitting sounds, evidence supporting their ability to perceive these sounds over long distances remains limited. Current understanding suggests that plants are more likely to respond to substrate-borne vibrations rather than airborne sound, as no specialized auditory receptors have been identified (Woodhouse and Goldstein, 2013). Substrate vibrations, which propagate through the ground or plant structures, are thought to be more effective in conveying information due to their direct physical interaction with plant tissues (Brancheriau and Baillères, 2002; Shimmen and Yokota, 2004). Some research indicates that plants can detect mechanical vibrations or environmental changes caused by sound stimuli, potentially through mechanosensitive pathways, involving changes in membrane potential or cytoskeletal dynamics (Gagliano et al., 2012; Berardi et al., 2017). Such responses may enable plants to adjust growth or stress responses, including altering growth patterns, activating stress-related genes, or initiating defensive responses to specific vibrational signals, such as those generated by herbivory (e.g., insect chewing) or environmental threats (e.g., wind or rain) (Khait et al., 2023; Daneshmand et al., 2024). Nevertheless, these responses are best interpreted as mechanosensory phenomena rather than auditory perception in the conventional sense. Studies suggest that plants can distinguish between different types of vibrations, using them as cues to optimize survival strategies (Waqas et al., 2023). This highlights the possibility that plants have evolved mechanisms to interpret and react to vibrational cues, even in the absence of specialized auditory receptors, underscoring the complexity of plant sensory systems (Gagliano et al., 2012; Woodhouse and Goldstein, 2013).

A well-established example of plant ultrasonic-vibration occurs during buzz pollination, where pollinators, such as bumblebees, use rapid muscle contractions to generate vibrations that dislodge pollen from flowers. During this process, ultrasonic emissions from plants arise as a byproduct of the mechanical interaction between the pollinator and floral structures (Berardi et al., 2017). These vibrations are transmitted through the flower's structure as a substrate-borne signals and partially radiated into the air as acoustic emissions, creating a complex signal that may serve ecological functions, such as communication or pollen release optimization (Goldstein and van de Meent, 2015). Studies suggest that these ultrasonic emissions could provide feedback to pollinators or even influence plant–pollinator interactions by reflecting pollen availability, rather than serving as intentional communication signals (Berardi et al., 2017). The association between ultrasound emissions and buzz pollination highlights the intricate biomechanical and ecological dynamics of plant–pollinator interactions, offering insights into how plants and pollinators have co-evolved to optimize reproductive success (Vallejo-Marin, 2019).

Despite growing interest in plant sound production and responsiveness, the mechanisms by which plants perceive and process acoustic or vibrational stimuli remain incompletely understood. It is often unclear whether observed responses are triggered directly by mechanical stimulation or indirectly through downstream physiological processes such as cytoplasmic streaming or mechano-transduction pathways (Goldstein and van de Meent, 2015; Woodhouse and Goldstein, 2013; Shimmen and Yokota, 2004). Clarifying these mechanisms is essential for distinguishing between passive physical responses and biologically meaningful signal processing, and represents an important direction for future research into plant behavior, communication, and environmental sensing.

5. Opportunities for plant acoustics in plant breeding and cultivation

An integrated conceptual framework linking ultrasonic sensing, data analytics, biological interpretation, and agricultural decision-making is summarized in Fig. 3. This framework illustrates how plant acoustic information progresses from data acquisition to biologically meaningful interpretation and, ultimately, to actionable decisions across different deployment contexts. The opportunities discussed below represent specific applications of this framework in plant cultivation and breeding.

Growing Plants with Sound: The Ultrasonic Aeroponics Revolution: Ultrasonic aeroponics, pioneered by LettUs Grow, is an active sound-based approach used in controlled environment agriculture, in which high-frequency vibrations generate a fine mist from nutrient-rich water. This mist is delivered directly to plant roots suspended in air, enabling efficient oxygen and nutrient uptake (Gagliano et al., 2012; Daneshmand et al., 2024). Compared with conventional soil-based or hydroponic systems, ultrasonic aeroponics can reduce water consumption and accelerate growth, making it an attractive option for vertical farms and greenhouses where environmental parameters are tightly controlled (Beikircher et al., 2025; Hussain et al., 2023; SharathKumar et al., 2020; van Delden et al., 2021). Experimental trials indicate substantial growth gains, in some cases approaching a doubling of growth rates, although such outcomes depend strongly on species and growth conditions (Waqas et al., 2023; Nardini et al., 2024).

Beyond commercial deployment, ultrasonic aeroponics provides a highly controllable experimental platform for studying plant physiology and development (Khait et al., 2023). For example, combining aeroponic cultivation with acoustic monitoring and simultaneous measurements of photosynthesis could help disentangle links between growth dynamics and mechanical or vibrational stimuli. As this technology advances, it may support the optimization growth conditions and the design of more resource-efficient food production systems (Del

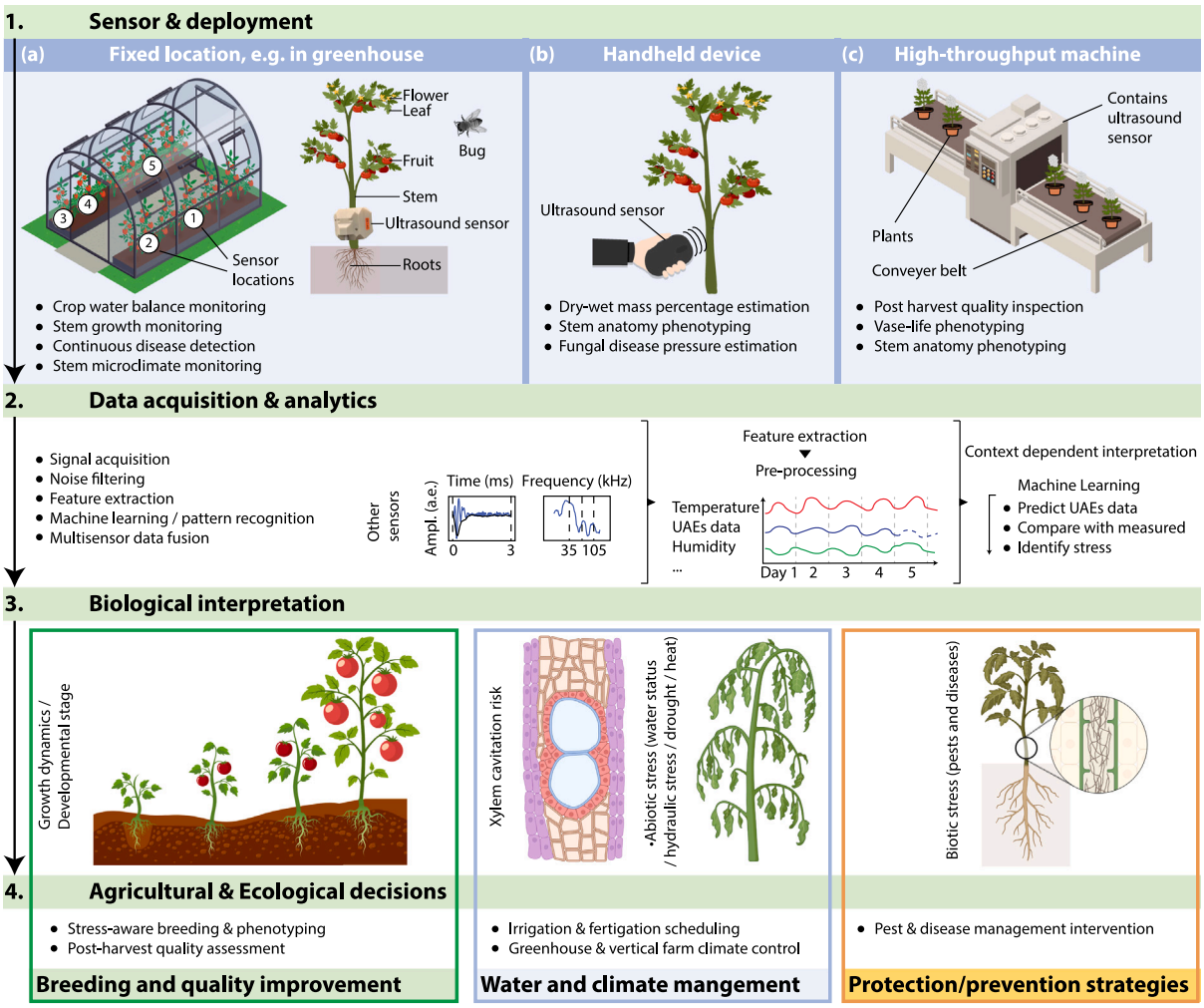


Fig. 3. Integrated conceptual framework for plant ultrasonic acoustic emissions (UAEs), linking sensing technologies, data analytics, biological interpretation, and agricultural decision-making across increasing deployment readiness. The figure illustrates the progression of UAE monitoring systems from research to application across increasing technology readiness levels, and shows how plant acoustic information is translated from data acquisition to actionable agricultural and ecological decisions through four interconnected layers. **1. Sensor & deployment** depicts representative UAEs monitoring configurations across increasing technology readiness, including fixed installations, handheld devices, and high-throughput systems. **(a)** Fixed-location systems, for example in greenhouses, enable applications such as crop water balance monitoring, stem growth assessment, early and continuous disease detection, and stem microclimate monitoring. **(b)** Handheld devices offer advantages for field applications, including dry–wet mass percentage estimation and fungal disease pressure assessment. **(c)** High-throughput systems enable the rapid screening of large numbers of plants for post-harvest quality inspection, vase-life phenotyping, and stem anatomy phenotyping. **2. Data acquisition & analytics** summarizes the processing pipeline common to all deployment modes, including signal acquisition, noise filtering, feature extraction, multisensor data fusion, and machine-learning-based pattern recognition. **3. Biological interpretation** translates acoustic features into biologically meaningful states, including xylem cavitation risk and hydraulic status (abiotic stress), growth dynamics and developmental stage, and biotic stress related to pest or disease pressure. **4. Agricultural & ecological decisions** illustrates how these interpreted biological states inform management and selection strategies, such as irrigation and fertigation scheduling, greenhouse and vertical farm climate control, stress-aware breeding and phenotyping, post-harvest quality assessment, and pest and disease management interventions.

Stabile et al., 2022; Venturas et al., 2017). By increasing yields and reducing agriculture's environmental impact, ultrasonic aeroponics can contribute to enhanced food security while promoting more efficient and sustainable agricultural practices globally (Hussain et al., 2023; Woodhouse and Goldstein, 2013). However, its broader applicability will depend on economic feasibility, system robustness, and scalability beyond controlled environments, particularly for staple field crops.

Monitoring Plant Health and Stress: UAEs hold considerable promise for monitoring plant health and stress in both agricultural production and breeding contexts. Acoustic monitoring can provide continuous, real-time information on plant status, enabling early detection of water stress, nutrient imbalances, or disease before visible symptoms emerge (Khait et al., 2023). Such early warning capability could support more targeted and efficient management of inputs, including irrigation and fertilization. (Waqas et al., 2023; Daneshmand et al., 2024).

In precision agriculture, where minimizing stress and optimizing resource use are central goals, UAEs may complement existing sensing technologies (Hussain et al., 2023; Beikircher et al., 2025). Analysis of acoustic signals can reveal subtle physiological changes associated with stress progression (Nardini et al., 2024; Del Stabile et al., 2022) or developmental stages such as fruit ripening (Landahl and Terry, 2020; Yan et al., 2023). This approach could improve agricultural efficiency and sustainability by reducing waste and enhancing plant resilience (Venturas et al., 2017; Olson et al., 2014). However, reliable interpretation requires careful calibration across species and environments, as acoustic responses are inherently context-dependent.

Acoustic monitoring systems can be integrated into existing agricultural infrastructure, enabling continuous observation at the crop

or canopy scale (Waqas et al., 2023) as illustrated in Figs. 3a and 3b. Such integration can support more informed decision-making and timely responses to environmental change, with potential benefits for crop health and productivity (Hussain et al., 2023; Daneshmand et al., 2024). However, the practical value of these systems depends on sensor robustness, reliable data processing pipelines, and validation under realistic field conditions. As these challenges are addressed, plant acoustics may become a useful component of sustainable and efficient crop management strategies (Khait et al., 2023; Woodhouse and Goldstein, 2013).

Ultrasound as an Eco-friendly bug repellent: Ultrasound has been explored as an eco-friendly approach to pest control, using high-frequency sound waves to deter insects or other pests without chemical inputs (Goldstein and van de Meent, 2015; Woodhouse and Goldstein, 2013). Some devices emit ultrasonic frequencies that are inaudible to humans but disruptive to insects, potentially interfering with their communication, navigation, or feeding behavior (Berardi et al., 2017; Shimmen and Yokota, 2004). This concept is often linked to observations that plants emit ultrasonic signals during stress responses or biotic interactions with pollinators and herbivores (Khait et al., 2023; Gagliano et al., 2012). While some studies report deterrent effects for specific pests, results remain inconsistent, as many insects appear to habituate to ultrasonic stimuli over time (Goldstein and van de Meent, 2015). Consequently, ultrasound-based repellents are currently best viewed as complementary rather than standalone pest-management tools, despite there appeal due to their non-toxic nature and minimal environmental impact (Woodhouse and Goldstein, 2013; Beikircher et al., 2025). Further research is required to identify optimal frequency ranges, exposure patterns, and ecological contexts, potentially informed by naturally occurring plant acoustic emissions (Daneshmand et al., 2024).

Plant Breeding Programs: In plant breeding, UAEs offer opportunities as non-destructive physiological markers associated with stress resistance, hydraulic performance and overall vigor (Khait et al., 2023; Waqas et al., 2023). Therefore, we foresee the integration of acoustic sensing into high-throughput phenotyping platforms, as illustrated in Fig. 3c. By comparing acoustic responses under controlled stress conditions, breeders may identify genotypes with favorable hydraulic traits (Hussain et al., 2023; Nardini et al., 2024). For example, plants exhibiting fewer or delayed acoustic emissions under drought conditions may possess more efficient water transport systems or enhanced drought tolerance (Venturas et al., 2017; Rosner et al., 2006).

Incorporating acoustic measurements with genomic and conventional phenotypic data could strengthen breeding strategies aimed at resilience and yield stability (Daneshmand et al., 2024). By selecting plants with specific acoustic responses to stress, breeders can pinpoint key traits linked to resilience and productivity (Del Stabile et al., 2022; Beikircher et al., 2025). Such integration of acoustic data with genomic and phenotypic information can enhance breeding strategies, enabling the development of crops that are more adaptable to changing environmental conditions (Waqas et al., 2023; Gagliano et al., 2012). This approach not only improves agricultural efficiency but also supports sustainable food production by fostering the crops that can thrive under multiple stressors (Hussain et al., 2023; Woodhouse and Goldstein, 2013).

One particular field of breeding where UAEs can play an important role is that of ornamental flowers. Flowers are desired to have a long vase-life, which has been shown to be related to vascular properties and growing conditions such as relative humidity (Nijsse et al., 2000; Damunupola et al., 2011; Daneshmand et al., 2024; Twumasi et al., 2005; Verdonk et al., 2023; Aliniaeifard and Van Meeteren, 2016). This complex interplay between genotype and phenotype (Fanourakis et al., 2021; Olson et al., 2014; Blackman et al., 2019) can potentially be better understood using UAEs, as this approach is non-destructive and can be applied during growth rather than only post-harvest. Recent work on ornamental cut chrysanthemums indicates that UAEs are promising predictors of vase-life under post-harvest conditions (Bieling et al. under review).

6. Discussion: Strengths, limitations, and future applications

The present literature (summarized in Tables 1 and 2) highlights two defining facets of plant acoustics research: first, diverse set of *applications* ranging from drought monitoring to plant breeding and pest control, and second, a rapidly evolving landscape of *sensor technologies* enabling such applications. Together, these tables provide a concise overview of current achievements, while also revealing important gaps in biological interpretation, technological maturity, and field validation. Here, we critically discuss the strengths and limitations of existing approaches and outline pathways toward future applications in agriculture and plant science.

Across crops and stress conditions, UAEs have consistently emerged as early indicators of physiological stress. As shown in Table 1, UAEs have been detected in tomato, maize, wheat, grapevine, and cut flowers under drought, freeze–thaw, and disease pressure, often hours or days before visible symptoms appear. Passive detection enables non-invasive monitoring when stress occurs, while active ultrasound techniques allow precise probing of leaf water status and structural integrity of vascular tissues. Table 2 further illustrates the breadth of available technologies, ranging from piezoelectric probes to airborne microphones and laser vibrometers, each tailored to specific experimental contexts. Together, these findings highlight the versatility of plant acoustics as a physiological monitoring tool across scales and applications.

At the same time, both tables underscore persistent and non-trivial limitations. On the application side (Table 1), many findings remain crop- or condition-specific and lack broad validation under field trials. Quantitative relationships such as correlations (e.g., R^2 between UAEs and vase-life, or reductions in insect activity) are encouraging but are often based on relatively small sample sizes and short experimental durations. Moreover, it remains unclear which ultrasonic frequency bands encode specific physiological information, an issue that warrants systemic investigation. On the technology side (Table 2), reproducibility and robustness remain major challenges: piezoelectric probes are highly sensitive but strongly dependent on sensor–plant contact; microphones offers scalability but are vulnerable to environmental noise; and laser vibrometers provide high resolution yet are largely confined to controlled laboratory settings due to practical constraints and high costs. These trade-offs illustrate that no single technology currently meets all requirements for robustness, scalability, and non-invasiveness.

Several strategies can help address these challenges. First, standardized measurement protocols are essential to ensure comparability across crops, environments, and sensor types. Second, data-fusion approaches that combine acoustic signals with environmental variables (temperature, relative humidity, soil moisture) and physiological metrics (sap flow, stomatal conductance) can substantially improve our understanding of plant health. Third, as shown in Table 2, emerging technologies such as MEMS microphones and optical fiber sensors hold promise for scalable deployment in greenhouses and fields, but require further engineering to balance sensitivity with robustness. Finally, machine learning approaches offer a clear path forward: algorithms trained on multi-modal datasets may enable robust feature extraction from noisy acoustic streams and shift plant acoustics from reactive monitoring toward predictive decision support.

Looking ahead, plant acoustics is poised to contribute beyond drought detection alone. In breeding, UAE-based phenotyping (Table 1) may accelerate the identification of stress-tolerant genotypes and varieties with extended vase-life. In cultivation systems, integration with ultrasonic aeroponics offers opportunities for both fundamental physiological studies and yield optimization. Ultrasound-based pest management remains attractive due to its eco-friendly nature, although current evidence suggests effectiveness is limited and species-specific. Perhaps most compelling is the ecological dimension: UAEs may reveal novel aspects of plant–plant and plant–animal interactions, including signaling responses to herbivory and pollination. Realizing these opportunities will require close interdisciplinary collaboration between engineers, crop physiologists, and data scientists alongside rigorous validation across environments and scales.

Table 1
Summary of reported applications of plant acoustics, based on literature cited in this manuscript.

Application	Crop/Plant	Active/ Passive	Key finding	Limitations	Sources
Drought and water stress detection	Tomato, Wheat, Maize, Grapevine	Passive	UAEs increase significantly under drought; frequencies typically 20–200 kHz; detection possible within 1–3 m; cavitation events correlated with xylem tension (−1 to −2 MPa).	Signal overlap with mechanical noise; variability across species; sensitivity to environment.	Tyree et al. (1984), Venturas et al. (2017), Hussain et al. (2023), Waqas et al. (2023)
Freeze–thaw stress monitoring	Conifers, Grapevine	Passive	Increased UAE bursts during freeze-thaw cycles; frequency and intensity correlated with embolism formation.	Difficult to separate freeze-induced UAEs from other stress sources; requires low-noise conditions.	Beikircher et al. (2025), Del Stabile et al. (2022)
Nutrient stress	Herbaceous crops	Passive	UAE patterns correlate with nutrient deficiencies; early stress detection before visible symptoms.	Weak quantitative benchmarks; still exploratory; confounding by water stress.	Khait et al. (2023), Waqas et al. (2023)
Disease and pathogen attack	Tomato	Passive	Early increase in UAEs observed under fungal infection.	Limited validation in field; requires larger sample sizes.	Daneshmand et al. (2024)
Buzz pollination	Bumblebee–tomato interaction	Both	Pollinator vibrations (100–400 Hz) induce ultrasonic emissions in flowers; enhances pollen release by up to 2× .	Mechanistic link between plant emission and pollinator behavior still unclear.	Berardi et al. (2017), Vallejo-Marin (2019)
Leaf water content/turgor monitoring	Arabidopsis, Tomato	Active	Ultrasound reflection/transmission used to estimate leaf water potential; accuracy within ±0.1 MPa.	Requires contact probes or precise alignment; limited to lab conditions so far.	Sano et al. (2015), Collazos-Burbano et al. (2021), Saglam (2022)
Stem water content and vascular thickness	Woody plants (e.g. Cherry, Oak)	Active	Acoustic velocity correlates with stem water content and tissue thickness; repeatable real-time monitoring.	Hardware-intensive; not yet scalable to field.	Kageyama et al. (2008), Lv et al. (2022), Zhdanov et al. (2020)
High-throughput phenotyping	Cut flowers, Post-harvest fruit	Passive	UAEs predict vase-life (differences up to 3–5 days between varieties); post-harvest inspection possible.	Mostly destructive setups; integration into breeding pipelines still under development.	Nijsse et al. (2000), Damunupola et al. (2011), Twumasi et al. (2005), Verdonk et al. (2023), Aliniaeifard and Van Meeteren (2016)
Ultrasonic aeroponics	Lettuce, Herbs	Active	Ultrasonic fogging accelerates root nutrient uptake; growth rates up to 2× higher; water use reduced by ∼70%.	High power demand; scaling challenges for large greenhouses.	Beikircher et al. (2025), Hussain et al. (2023)
Pest deterrence (ultrasound repellent)	Multiple insect species	Active	Certain frequencies (> 20 kHz) reduce insect activity or feeding rates by 20%–40%.	Mixed effectiveness; insects may adapt; species-specific responses.	Goldstein and van de Meent (2015), Woodhouse and Goldstein (2013)

Table 2
Summary of sensor technologies for plant acoustic monitoring.

Sensor type	Frequency range	Detection capability	Limitations	Sources
Piezoelectric contact sensor	20–300 kHz	High sensitivity to cavitation events; detection depth in xylem 1–2 cm.	Invasive (requires bark removal or tight contact); species-dependent coupling; sensitive to mounting.	Tyree and Sperry (1988), Rosner et al. (2006)
Airborne ultrasound microphone	20–200 kHz	Non-invasive; detects UAEs from 1–3 m distance; applicable to woody and herbaceous plants.	Signal-to-noise ratio drops outdoors; requires shielding against ambient noise.	Khait et al. (2023), Waqas et al. (2023)
Laser Doppler vibrometer	10 Hz–1 MHz	Contactless measurement of stem or leaf vibrations; resolution ∼nm.	Expensive; requires stable lab environment; limited scalability in field.	Vogler et al. (2015), Shah et al. (2017)
Capacitive MEMS microphones	20–100 kHz	Portable, low-cost, scalable; useful for wireless sensor networks.	Sensitivity lower than piezo sensors; requires advanced filtering for noisy environments.	Del Stabile et al. (2022), Beikircher et al. (2025)
Ultrasonic transducer (active probing)	100 kHz–10 MHz	Can measure stem water content, vascular thickness, and leaf turgor; real-time monitoring.	Requires coupling medium or close contact; higher power use; less non-invasive.	Kageyama et al. (2008), Lv et al. (2022), Zhdanov et al. (2020)
Optical fiber acoustic sensor	10 kHz–1 MHz	Immune to electromagnetic noise; suitable for integration in greenhouses.	Still experimental for plants; expensive; fragile.	Rae and Brown (2016), Hoskins (2007)

7. Future directions and conclusion

Future research in plant acoustics offers several promising directions, including deeper investigation of acoustic emissions in plant–plant and plant–animal interactions, the development of improved acoustic sensing technologies and analytical tools, and the deployment of acoustic monitoring techniques across both natural and agricultural ecosystems. Advancing our understanding of the diversity and origins of plant acoustic phenomena is essential for moving from proof-of-concept studies toward biologically meaningful interpretation and practical application. Such progress has the potential to yield novel insights into plant physiology while supporting more sustainable approaches to agriculture and environmental management. The inher-

ently interdisciplinary nature of plant acoustics research remains one of its defining strengths. Effective progress will require sustained collaboration among plant physiologists, engineers, data scientists, and ecologists, integrating expertise in plant biology, sensor design, signal processing, and ecological theory. Importantly, plant acoustics should not be viewed as a standalone diagnostic tool, but rather as a complementary component of multi-sensor monitoring frameworks that include environmental and physiological measurements, providing a holistic understanding of plant–environment interactions. Interdisciplinary efforts to date already demonstrate the value of this approach across agriculture, ecology, and conservation.

Despite the promising potential of plant acoustics, several critical challenges must be addressed before plant acoustics can be broadly adopted. Improving the sensitivity and specificity of acoustic detection remains essential, particularly given the high variability of ultrasonic acoustic emissions across species, developmental stages, and environmental conditions. Standardization of recording protocols, sensor deployment, and analytical workflows is essential to ensure reproducibility and comparability across studies. Moreover, comprehensive validation under diverse and realistic field conditions is required to establish UAEs as reliable indicators of plant health and stress beyond controlled environments.

Looking ahead, the future of plant acoustics lies not in any single technology or application, but in the integration of robust sensing, rigorous data analysis, and biologically grounded interpretation. By addressing current challenges through coordinated technological innovation and interdisciplinary research, plant acoustics can evolve from an emerging research topic into a practical and informative component of smart agriculture, plant breeding, forestry, and ecosystem management. In doing so, it holds potential to contribute meaningfully to the sustainability and resilience of plant systems in a changing world.

CRediT authorship contribution statement

Malleshaiah SharathKumar: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **T.J. Bieling:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **B.B. de Klerk:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **S. Dutta:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **G.J. Verbiest:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

MSK acknowledges Deliflor Chrysanten B.V. TJB, BBdK, SD, and GJV acknowledge the 4TU Plantenna project. During the preparation of this work, the authors used OpenAI in order to polish the written text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data availability

No data was used for the research described in the article.

References

Agrawal, Megha, Prasad, Abhinav, Bellare, Jayesh R., Seshia, Ashwin A., 2016. Characterization of mechanical properties of materials using ultrasound broadband spectroscopy. Ultrasonics 64, 186–195.
Aliniaeifard, Sasan, Van Meeteren, Uulke, 2016. Stomatal characteristics and desiccation response of leaves of cut chrysanthemum (*Chrysanthemum morifolium*) flowers grown at high air humidity. Sci. Hort. 205, 84–89.
Ashby, Michael F., 1983. The mechanical properties of cellular solids. Met. Trans. A 14, 1755–1769.
Ashby, Michael F., 2006. The properties of foams and lattices. Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 364 (1838), 15–30.
Beikircher, Barbara, Held, Magdalena, Losso, Adriano, Mayr, Stefan, 2025. New insights into a sensitive life stage: hydraulics of tree seedlings in their first growing season. New Phytol. 245 (2), 577–590.
Berardi, Umberto, Iannace, Gino, Di Gabriele, Maria, 2017. The acoustic characterization of broom fibers. J. Nat. Fibers 14 (6), 858–863.
Bhandawat, A., Jayaswall, K., 2022. Biological relevance of sound in plants. Environ. Exp. Bot. 104919.
Blackman, Chris J., Li, Ximeng, Choat, Brendan, Rymer, Paul D., De Kauwe, Martin G., Duursma, Remko A., Tissue, David T., Medlyn, Belinda E., 2019. Desiccation time during drought is highly predictable across species of eucalyptus from contrasting climates. New Phytol. 224 (2), 632–643.
Boudon, Frederic, Chopard, Jerome, Ali, Olivier, Gilles, Benjamin, Hamant, Olivier, Boudaoud, Arezki, Traas, Jan, Godin, Christophe, 2015. A computational framework for 3d mechanical modeling of plant morphogenesis with cellular resolution. PLoS Comput. Biol. 11 (1), e1003950.
Brancheriau, Loic, Baillères, Henri, 2002. Natural vibration analysis of clear wooden beams: A theoretical review. Wood Sci. Technol. 36 (4), 347–365.
Castaño-Bernal, Jose L., Mejía, Maria Sara, Ealo-Cuello, Joao L., 2025. Leaf water dynamics in Coffea Arabica using noncontact ultrasonic intensity measurements. Results Eng. 25, 104074.
Caupin, F., Herbert, E., 2006. Cavitation in water: a review. C. R. Phys. 1000–1017.
Collazos-Burbano, David Alejandro, Cuello, Joao Luis Ealo, Villagrán-Muniz, Mayo, 2021. Ultrasonic wave propagation for smart agriculture: an Arabica Coffee case of study. In: 2021 IEEE UFFC Latin America Ultrasonics Symposium. LAUS, IEEE, pp. 1–4.
Damunupola, J.W., Ratnayake, K., Daryl, C. Joyce, Donald, E. Irving, 2011. Characterisation of xylem conduits and their possible role in limiting the vase life of cut acacia holosericea (mimosaceae) foliage stems. Funct. Plant Biology 38, 614–623.
Daneshmand, B., Gholami, M., Etemadi, N., Ehtemam, M.H., 2024. The water relation parameters are associated with the genotypic differences in the vase life of cut rose flowers. Postharvest Biology Technol. 211, 112829.
Del Stabile, F., Marsili, V., Forti, L., Arru, L., 2022. Is there a role for sound in plants? Plants 11 (2391), 1–13.
Dutta, Satadal, Bieling, Thijs J., Verbiest, Gerard J., 2022. Studies on the evaporation induced acoustic emissions from 3d-printed bio-inspired microfluidic vessels. R. Soc. Open Sci. 10 (12), 231029.
Dutta, S., Chen, Z., Kaiser, E., Matamoros, P. Malcolm, Steeneken, P.G., Verbiest, G.J., 2022. Ultrasound pulse emission spectroscopy method to characterize xylem conduits in plant stems. Research 2022, 9790438.
Dutta, S., van den Berg, T., Koning, M., Bij de Vaate, I., Bieling, T.J., Kaiser, E., Verbiest, G.J., Fan, Q., van Klink, A., Steeneken, P.G., ten Veldhuis, M.-C., 2025. Comparison of multiple plant sensors aimed at early detection of drought stress in the greenhouse. Agricult. Water. Manag. 315, 109535.
Fanourakis, D., Papadopoulou, E., Valla, A., Tzanakakis, V.A., Nektarios, P.A., 2021. Partitioning of transpiration to cut flower organs and its mediating role on vase life response to dry handling: A case study in chrysanthemum. Postharvest Biology Technol. 181, 111636.
Fariñas, Lola, Sancho-Knapik, Domingo, Peguero-Pina, José J., Gil-Pelegrín, Eustaquio, Álvarez-Arenas, Tomás E. Gómez, 2024. Origin and development and applications of air-coupled broadband ultrasounds for the study of tissues and water relations in plant leaves: A review. IEEE Open J. Ultrason. Ferroelectr. Freq. Control..
Gadalla, Ataf, Dehoux, Thomas, Audoin, Bertrand, 2014. Transverse mechanical properties of cell walls of single living plant cells probed by laser-generated acoustic waves. Planta 239, 1129–1137.
Gagliano, Monica, Mancuso, Stefano, Robert, Daniel, 2012. Towards understanding plant bioacoustics. Trends Plant Sci. 17 (6), 323–325.
Gibson, L., 2005. Biomechanics of cellular solids. J. Biomech. 38 (3), 377–399.
Gibson, L., 2012. The hierarchical structure and mechanics of plant materials. J. R. Soc. Interface 9 (76), 2749–2766.
Gibson, L., Ashby, M.F., 1982. The mechanics of three-dimensional cellular materials. Proc. R. Soc. A 382 (1782), 43–59.
Goldstein, R.E., van de Meent, J.-W., 2015. A physical perspective on cytoplasmic streaming. Interface Focus. 5 (4).
Gomez, B., Repetto, C., Stia, C., Welti, R., 2007. Oscillations of a string with concentrated masses. Eur. J. Phys. 28 (5), 961.
Hölttä, T., Vesala, T., Nikinmaa, E., Perämäki, M., Siivola, E., Mencuccini, M., 2005. Field measurements of ultrasonic acoustic emissions and stem diameter variations, new insight into the relationship between xylem tensions and embolism. Tree Physiol. 25 (2), 237–243.

Hoskins, P.R., 2007. Physical properties of tissues relevant to arterial ultrasound imaging and blood velocity measurement. Ultrasound Med. Biol. 33 (10), 1527–1539.
Hussain, Muzammil, u Rahman, Muhammad Khashi, Mishra, Ratnesh Chandra, Van Der Straeten, Dominique, 2023. Plants can talk: a new era in plant acoustics. Trends Plant Sci. 28 (9), 987–990.
Kageyama, K., Watanabe, E., Kato, H., 2008. Non-destructive measurement of vascular tissue development in stems of miniature tomato using acoustic method. J. Solid Mech. Mater. Eng. 2 (12), 1487–1496.
Khait, I., Lewin-Epstein, O., Sharon, R., Saban, K., Goldstein, R., Anikster, Y., Zeron, Y., Agassy, C., Nizan, S., Sharabi, G., Perelman, R., Boonman, A., Sade, N., Yovel, Y., Hadany, L., 2023. Sounds emitted by plants under stress are airborne and informative. Cell 186, 1328–1336.
Kolkman, R.G., Klaessens, J.H., Hondebrink, E., Hopman, J.C., de Mul, F.F., Steenbergen, W., Thijssen, J.M., van Leeuwen, T.G., 2004. Photoacoustic determination of blood vessel diameter. Phys. Med. Biol. 49 (20), 4745.
Landahl, S., Terry, L.A., 2020. Non-destructive discrimination of avocado fruit ripeness using laser doppler vibrometry. Biosyst. Eng. 194, 251–260.
Lizzi, F.L., Feleppa, E.J., Alam, S.K., Deng, C.X., 2003. Ultrasonic spectrum analysis for tissue evaluation. Pattern Recognit. Lett. 24 (4–5), 637–658.
Lv, D., Zi, J., Gao, M., Xi, R., Huang, X., 2022. Detection of water changes in plant stems in situ by the primary echo of ultrasound rf with an improved aic algorithm. Sensors 23 (1), 20.
MacMillan, C.P., O'Donnell, P.J., Smit, A.-M., Evans, R., Stachurski, Z.H., Torr, K., West, M., Baltunis, J., Strabala, T.J., 2013. A survey of the natural variation in biomechanical and cell wall properties in inflorescence stems reveals new insights into the utility of arabidopsis as a wood model. Funct. Plant Biology 40 (7), 662–676.
Migliori, A., Darling, T.W., 1996. Resonant ultrasound spectroscopy for materials studies and non-destructive testing. Ultrasonics 34 (2–5), 473–476.
Milburn, J.A., Johnson, R., 1966. The conduction of sap: II. detection of vibrations produced by sap cavitation in ricinus xylem. Planta 69, 43–52.
Moebius, F., Canone, D., Or, D., 2012. Characteristics of acoustic emissions induced by fluid front displacement in porous media. Water Resour. Res. 48 (11).
Nakade, D., Dhadse, S., 2024. The plant bioacoustics: A system of plant-sound relationship. Plantae Sci. 7 (1), 1–8.
Nardini, Andrea, Cochard, Hervé, Mayr, Stefan, 2024. Talk is cheap: rediscovering sounds made by plants. Trends Plant Sci. 29 (6), 662–667.
Nijsse, J., van der Heijden, G.W.A.M., van Ieperen, W., Keijzer, C.J., van Meeteren, U., 2001. Xylem hydraulic conductivity related to conduit dimensions along chrysanthemum stems. J. Exp. Bot. 52, 319–327.
Nijsse, J., van Meeteren, U., Keijzer, C.J., 2000. Air in xylem vessels of cut flowers. Acta Hortic. 517, 479–486.
Olson, M.E., Anfodillo, T., Rosell, J.A., Petit, G., Crivellaro, A., Isnard, S., León-Gómez, C., Alvarado-Cárdenas, L.O., Castorena, M., 2014. Universal hydraulics of the flowering plants: vessel diameter scales with stem length across angiosperm lineages, habits and climates. Ecol. Lett. 17, 988–997.
Ongaro, F., De Falco, P., Barbieri, E., Pugno, N., 2016. Mechanics of filled cellular materials. Mech. Mater. 97, 26–47.
Pintelon, R., Guillaume, S., Vanlanduit, P., De Belder, K., Rolain, Y., 2004. Identification of young's modulus from broadband modal analysis experiments. Mech. Syst. Signal Process. 18 (4), 699–726.
Polajnar, J., Svensek, D., Cokl, A., 2012. Resonance in herbaceous plant stems as a factor in vibrational communication of pentatomid bugs (heteroptera: Pentatomidae). J. R. Soc. Interface 9 (73), 1898–1907.
Ponomarenko, A., Vincent, O., Pietriga, A., Cochard, H., Badel, E., Marmottant, P., 2014. Ultrasonic emissions reveal individual cavitation bubbles in water-stressed wood. J. R. Soc. Interface 11 (20140480).
Rae, P., Brown, E., 2016. Some observations on measuring sound speeds in polymers using time-of-flight. Exp. Tech. 1085–1097.
Rosner, Sabine, Klein, Andrea, Wimmer, Rupert, Karlsson, Bo, 2006. Extraction of features from ultrasound acoustic emissions: a tool to assess the hydraulic vulnerability of Norway spruce trunkwood? New Phytol. 171 (1), 105–116.
Saglam, S., 2022. How the physical properties of the leaves of common plants affect dependent acoustic characterization in urban areas of Istanbul, Turkey. Contemp. Probl. Ecol. 15 (5), 566–578.
Sano, M., Nakagawa, Y., Sugimoto, T., Shirakawa, T., Yamagishi, K., Sugihara, T., Ohaba, M., Shibusawa, S., 2015. Estimation of water stress of plant by vibration measurement of leaf using acoustic radiation force. Acoust. Sci. Technol. 36 (3), 248–253.
Schenk, H.J., Steppe, K., Jansen, S., 2015. Nanobubbles: a new paradigm for air-seeding in xylem. Trends Plant Sci. 20 (4), 199–205.
Schöner, M.G., Simon, R., Schöner, C.R., 2016. Acoustic communication in plant–animal interactions. Curr. Opin. Plant Biol. 88–95.
Shah, D.U., Reynolds, T.P., Ramage, M.H., 2017. The strength of plants: Theory and experimental methods to measure the mechanical properties of stems. J. Exp. Bot. 68 (16), 4497–4516.
SharathKumar, M., Heuvelink, E.P., Marcelis, L.F.M., 2020. Vertical farming: Moving from genetic to environmental modification. Trends Plant Sci. 25 (8), 724–727.
Shimmen, T., Yokota, E., 2004. Cytoplasmic streaming in plants. Curr. Opin. Cell Biol. 16 (1), 68–72.
Son, Jin-Soo, Jang, Seonghan, Mathevon, Nicolas, Ryu, Choong-Min, 2024. Is plant acoustic communication fact or fiction? New Phytol. 242 (5), 1876–1880.
Steeneken, P.G., Kaiser, E., Verbiest, G.J., ten Veldhuis, M.-C., 2023. Sensors in agriculture: towards an internet of plants. Nat. Rev. Methods Prim. 3 (1), 60.
Steppe, Kathy, Zeugin, F., Zweifel, R., 2009. Low-decibel ultrasonic acoustic emissions are temperature-induced and probably have no biotic origin. New Phytol. 928–931.
Twumasi, P., van Ieperen, W., Woltering, E.J., Emons, A.M.C., Schel, J.H.N., Snel, J.F.H., van Meeteren, U., van Marwijk, D., 2005. Effects of water stress during growth on xylem anatomy, xylem functioning and vase life in three zinnia elegans cultivars. In: VIII International Symposium on Postharvest Physiology of Ornamental Plants, vol. 669, pp. 303–312.
Tyree, M.T., Dixon, M.A., Tyree, E.L., Johnson, R., 1984. Ultrasonic acoustic emissions from the sapwood of cedar and hemlock : an examination of three hypotheses regarding cavitations. Plant Physiol. 75, 988–992.
Tyree, Melvin T., Sperry, John S., 1988. Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress?: Answers from a model. Plant Physiol. 88 (3), 574–580.
Vallejo-Marin, M., 2019. Buzz pollination: studying bee vibrations on flowers. New Phytol. 224 (3), 1068–1074.
van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R.S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R.E., Stanghellini, C., van Ieperen, W., Verdonk, J.C., Vialet-Chabrand, S., Woltering, E.J., van de Zedde, R., Zhang, Y., Marcelis, L.F.M., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Nat. Food 2, 944–956.
van Ieperen, W., van Meeteren, U., Nijsse, J., 2002. Embolism repair in cut flower stems: a physical approach. Postharvest Biology Technol. 25, 1–14.
Venturas, M.D., Sperry, J.S., Hacke, U.G., 2017. Plant xylem hydraulics: What we understand, current research, and future challenges. J. Integr. Plant Biology 59 (6), 356–389.
Verdonk, J.C., van Ieperen, W., Carvalho, D.R.A., van Geest, G., Schouten, R.E., 2023. Effect of preharvest conditions on cut-flower quality. Front. Plant Sci. 14, 1281456.
Vergeynst, L.L., Sause, M.G., Hamstad, M.A., Steppe, K., 2015. Deciphering acoustic emission signals in drought stressed branches: The missing link between source and sensor. Front. Plant Sci. 6 (494).
Vogler, H., Felekis, D., Nelson, B.J., Grossniklaus, U., 2015. Measuring the mechanical properties of plant cell walls. Plants 4 (2), 167–182.
Waqas, Muhammad, Van Der Straeten, Dominique, Geilfus, Christoph-Martin, 2023. Plants' cry'for help through acoustic signals. Trends Plant Sci. 28 (9), 984–986.
Warner, M., Thiel, B., Donald, A., 2000. The elasticity and failure of fluid-filled cellular solids: Theory and experiment. Proc. Natl. Acad. Sci. 97 (4), 1370–1375.
Woodhouse, F.G., Goldstein, R.E., 2013. Cytoplasmic streaming in plant cells emerges naturally by microfilament self-organization. Proc. Natl. Acad. Sci. 110 (35), 14132–14137.
Yan, D., Luo, L., Zhang, P., Liu, W., Wang, J., Lu, Q., Luo, S., 2023. Vibration analysis and experimental study of the effects of mechanized grape picking on the fruit–stem system. Biosyst. Eng. 82–94.
Zhdanov, O., Blatt, M.R., Cammarano, A., Zare-Behtash, H., Busse, A., 2020. A new perspective on mechanical characterization of arabidopsis stems through vibration tests. J. Mech. Behav. Biomed. Mater. 104041.
Zimmermann, M.H., 2013. Xylem Structure and the Ascent of SAP. Springer Science & Business Media.
Zimmermann, U., Haase, A., Langbein, D., Meinzer, F., 1993. Mechanisms of long-distance water transport in plants: a re-examination of some paradigms in the light of new evidence. Phil. Trans. R. Soc. Lond. B 19–31.
Ziv, C., Zhao, Z., Xia, Y., 2018. Multifunctional roles of plant cuticle during plant-pathogen interactions. Front. Plant Sci. 391051.
Zweifel, R., Zeugin, F., 2008. Ultrasonic acoustic emissions in drought-stressed trees – more than signals from cavitation? New Phytol. 179 (4), 1070–1079.