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PLANT HEALTH MONITORING USING ACOUSTICS

Jerome Vande Velde[1*] **Bruno da Silva**[2] **Abdellah Touhafi**[1]
Laurent Segers[2]
[1] Department of Engineering Technology (INDI), Vrije Universiteit Brussel, 1050 Brussels, Belgium
[2] Department of Electronics and Informatics (ETRO), Vrije Universiteit Brussel, 1050 Brussels, Belgium

ABSTRACT

Plants respond and adapt to changes in their surroundings through various mechanisms, including chemical signals like volatile organic compounds and mechanical signals, producing acoustic signals. Advances in acoustic sensing technologies have increasingly revealed the potential for using sound-based methods to monitor and assess plant health. This work synthesizes the current state of the art in plant acoustics research, highlighting how ultrasonic and audible signals emitted by plants can serve as valuable indicators of physiological status. It further explores data-processing methods, including machine learning and signal analysis, that transform raw acoustic data into actionable insights. The review concludes by identifying key technical and conceptual challenges, including the need for standardized monitoring protocols, robust sensor networks, and improved interpretations of acoustic signatures under varied environmental conditions.

Keywords: *bio-acoustics, plant health, ultrasound plant monitoring, instrumentation*

1. INTRODUCTION

Wether in house plants, horticulture or forest management, plant health is a crucial but hard to monitor parameter. physiological changes can be hard to measure and are often running behind on the facts. Bio-acoustic plant monitoring could prove key in achieving anomaly detection, when plant show abnormal behavior, and potentially even recognize the signatures for characterization. Enabling robust bio-acoustic capturing technologies could prove the next step in this increasingly prominent research topic. With this research we hope to shed light on acoustic capturing technologies, their current use in bio-acoustic research and the future possibilities it could provide. This publication offers a survey on used bio-acoustic capturing technology. Firstly, in Section 2, we provide a background of bio-acoustic emissions generated in plants. The evolution and trends are also highlighted. Afterwards, Section 3 reviews the used hardware in bio-acoustic research. Then, In Section 4 we offer more information about the currently existing sound capturing technologies. Section 5 provides highlights possibilities to optimally capture acoustic emissions emanating from plants, along with the extractable parameters. Finally, Section 6 concludes this publication with a discussion.

**Corresponding author*: *Jerome.Antoine.B.Vande.Velde@vub.be.*

2. BACKGROUND

Research on plant acoustics started several decades ago. Plants are known to use negative pressure in their vascular system to transport fluids from the root system to the stems and leaves. The biological processes involving liquids under negative pressure are known to be vulnerable to cavitation, which can be triggered when plants are subjected to different forms of stress. These stresses can be categorized into two main types: abiotic and biotic stress [1]. Abiotic stresses are caused by non-living environmental factors, such as drought, lack of nutrients, and others, which negatively affect plant growth and development. In contrast, biotic stresses are caused by living organisms such as herbivores and parasites that feed on plants, pathogens such as fungal and bacterial infection, or viral diseases. Plants exhibit several types of measurable biomarkers indicating current biological processes, states, or conditions [2]. These biomarkers can be retrieved via molecules, biochemical activities, physiological signals or structural changes that provide objective evidence of normal or abnormal processes such as responses to stressors, diseases, environmental conditions, or therapeutic interventions. Monitoring these biomarkers offer a practical way to assess biological changes and diagnose potential harmful situations. One of such biomarkers is acoustic emission. It is not known if this biomarker is intended or even captured by other plants [3]. When evapotranspiration rates exceed root water intake the tension in the xylem sap increases. Above a threshold the xylem metastability is disrupted and this results in a cavitation, a sudden formation of a gas bubble. This cavitation expands the xylem, and generates a ultrasonic sound [4]. Xylem embolism, the presence of air in the xylem, can result in a substantial impairment of transportation of water though the xylem, and can be correlated to plant dying due to drought stress. JA Milburn et al. desmonstrated in 1966 that cavitation in the xylem could be detected with an apparatus to detect vibrations [5]. Milburn correlated the 'click' with the water status of the measured plant. In 1988 Weier et al. [6] and in 2023 Waqas et al. [7] correctly point out that embolisms in the xylem can be caused by stress factors due to frost, tobacco mosaic virus infections and plant cutting stress as well. Hussain at al. [8] and Son et al. [3] pointed out that information about the ability of plants to emit stress related acoustic cues has remained enigmatic, and asks for more research about the different mechanism that create sound in plants. Likewise, Linus et al. [9] points out that there is a potentially invalid assumption that all emitted acoustic emissions stem from the loss in the hydraulic conductivity in the xylem. Vergeynst et al. [10] notes that the number of cavitation related acoustic emitted signals significantly exceeded the number of vessels in the branch. Multiple acoustic emission types can be found in and around plants. One of these sources includes the emission of the growing and expanding root system in the soil [11, 12]. Besides describing the causes plants exhibit acoustic emissions, Khait et al. [7] describe that depending both the patterns and the occurrences of the emitted sound, depend on the type stress plants undergo. The measurements performed by Khait et al. also demonstrate that the detected volume of certain acoustic emitted patterns approximates 60 dBSPL at a distance of 10 centimeters. Waqas et al. [13] also conclude that crops emit specific acoustic patterns while experiencing nutrient deprivation.

3. REVIEW OF BIO-ACOUSTICS SOUND CAPTURING TECHNOLOGY

The goal of this survey is to investigate the technologies employed in bio-acoustics recording devices through a comprehensive review of existing literature. Publications were selected based on the following criteria: 1) The publication must analyze sound emissions from plants. 2) The publication must include a description of the hardware used. 3) The reported measurements must have been conducted by the authors themselves, rather than relying on external data. Our review specifically highlights the technologies used to capture ultrasonic recordings of sounds emitted by plants. From an extensive pool of over 2844 publications related to bio-acoustics signals in plants, we curated a selection of accessible, well-cited papers to form the basis of our analysis. Analysis of publication trends reveals that the number of papers describing ultrasonic emissions of the xylem has approximately doubled every decade since the 1970s, as indicated by Google Scholar data. If current trend persists, we anticipate this exponential growth to continue throughout the present decade. Given the impracticality of reviewing all identified publications, our final selection was informed by their prominence in the top Google Scholar results and citation frequency in relevant studies. Several factors constrained our data collection and analysis. A significant challenge arose when examining older publications before internet came up, where detailed specifications of older equipment were often only available in physical documentations. Although independent verification was frequently impossible, we have reported the original information as best as available. Consequently, hardware information presented in our survey primarily derives from the publications themselves, leading to observable variability in the reported frequency ranges for identical equipment. Additionally, many promising bio-acoustics studies lacked detailed hardware descriptions and could therefore not be included in our study. Numerous publications also primarily discussed data from earlier studies, highlighting a greater general interest in bio-acousticss than original empirical research. Finally, restricted access to certain publications limited our ability to conduct a complete comprehensive analyses. From the selected studies, we ex-

Table 1. Publications cited in our survey listing the mentioned plants and the respective conditions that were analyzed, together with the used equipment and frequency ranges mentioned in the corresponding publication.

Year	Author	Plant	Condition	Instrumentation	Frequency range
1983	Tyree et al [14]	Eastern White Cedar	Dehydration	B&K 8312 broad band transducer	100–1000 kHz
1986	Tyree et al [15]	Corn	Dehydration	B&K 8312 broad band transducer	100+ kHz
1988	Weiser et al [6]	multiple tree stems	Freezing	MC500 Transducer	350-700 kHz
1989	Tyree et al [16]	Thuja & Maple	Dehydration	B&K 8312 broad band transducer	up to 1200 kHz
1996	Ikeda et al. [17]	Pine	Parasite	AE 904US PZT transducer	100–1000 kHz
1998	Sherwin et al. [18]	Myrothamnus flabellifolius	Dehydration	B&K 8314 broad band transducer	800 kHz (resonance)
2003	Kikuta et al [19]	multiple	Freezing	I15I ultrasound acoustic sensor	150 kHz (resonance)
2006	Lashimke et al [20]	elm	Dehydration	SE-45 mass-loaded piezoelectric sensor	20-120 kHz
2009	Steppe et al [21]	unknown	Dehydration	VS150-M passive piezoelectric AE sensor	100-300 kHz
2015	Nolf et al [22]	16 woody species	Dehydration	150 kHz resonant sensors (R15)	150 kHz (resonance)
2020	Oletic et al. [23]	grapevine	Dehydration	VS600-Z1, AE1045S & VS150-M	100–500 kHz, 100–1500 kH & 100–500 kHz
2022	Lamacque et al [24]	lavender	Dehydration & rehydration	ISD9203B	1 kHz–3 MHz
2022	Dutta et al [25]	ten plant species	Dehydration	M500-USB ultrasound microphone	10 kHz and 150 kHz
2023	Khait et al [7]	Tomato & Tobacco	Dehydration & cut	Condenser ultrasound microphones	20–150 kHz

tracted detailed information with respect to the equipment utilized to detect acoustic emissions. Table 1 includes researchers, types of studies, utilized hardware, and reported frequency ranges, with studies that span more than four decades to observe technological trends. Table 2 synthesizes the identified instrumentation by their core technologies, highlighting the historical dominance of piezo-based instrumentation. The widespread adoption of piezo technology can be attributed to its accessibility and ease of use, particularly for researchers lacking specialized acoustic engineering expertise. However, a significant limitation of piezo sensors is their narrow frequency sensitivity, making them effective for detecting acoustic events ("clicks") rather than characterizing their spectral properties. Recent advances in electret and condenser-type microphone technologies mark a pivotal transition toward more sophisticated acoustic analyses, such as acoustic spectroscopy. Compared with piezo-based instrumentation, electret condenser microphones offer superior capabilities for detailed spectral characterization. This technological shift is exemplified by recent works: Dutta et al. [25] provided an acoustic analysis of biomarkers, while Khait et al. [7] successfully distinguished plant stress type conditions, such as cutting and dehydration, based on acoustic signal characteristics. Employing conventional microphone outputs that capture continuous sound enables the use of advanced acoustic processing techniques. For instance, Khait et al. [7] conducted peak frequency analyses and measured sound intensity (recording a dehydrating tomato at $61.6 \pm 0.1 dB_{\text{SPL}}$ with a peak frequency of $49.6 \pm 0.4 kHz$). Furthermore, technologies such as acoustic cameras [26] could enhance future research capabilities by enabling precise spatial localization and temporal tracking of acoustic biomarkers, as well as detailed studies of plant tissue acoustics.

Table 2. Publications grouped by the used instrumentation and corresponding utilized technology

Year	Papers	Instrumentation	Technology
1983	[14–16]	B&K 8312 broad band transducer	Piezo based
1988	[6]	MC500 Transducer	Piezo based
1996	[17]	AE 904US PZT transducer	Piezo based
1998	[18]	B&K 8314 broad band transducer	Piezo based
2003	[19]	I15I ultrasound acoustic sensor	Piezo based
2006	[20]	SE-45 mass-loaded piezoelectric sensor	Piezo based
2009	[21]	VS150-M passive piezoelectric AE sensor	Piezo based
2015	[24]	ISD9203B	Piezo based
2020	[23]	VS600-Z1, AE1045S & VS150-M	Piezo based
2022	[25]	M500-USB ultrasound microphone	Electret
2023	[7]	CM16 Condenser ultrasound microphones	Condenser

4. ACOUSTIC EMISSION CAPTURING TECHNOLOGIES

Several types of sensors exist to capture acoustic information. Many of these sensors are able to operate in both the audible and ultrasound ranges. While most sensors are intended for audible sound, there is a niche sector for ultrasonic capturing. These sensors do vary significantly in there ultrasonic ranges as they vary in their intended applications. To capture ultrasonic plant sounds one can typically find the piezo electric based sensors, the electret and condenser sensor families and the MEMS based sensors. While these sensors usually offer a rapid solution, several options also utilize acoustic sensors based on the laser reflection and on fiber optics.

4.1 Piezo electric sensors

Piezo electric based transducers are based on a crystal structure which exhibits voltage differences when forces are applied on both sides of the transducer [27, 28]. Oppositely, the same transducers can be used to produce mechanical movements by applying voltage differences on both sides. Piezoelectric based transducers generally offer high sensitivity but require a direct force to be applied. One can use piezoelectric elements directly into the circuitry, however, several vendors propose a piezo based sensor which includes electronics encased into one metallic sensor. These sensors are usually current based and require the user to provide a certain amount of current (i.e. 10 mA to 30 mA) for the sensor to operate. The output signal is provided on the same wire. Piezoelectric elements usually require an amplification circuitry and an analog to digital converter (ADC) to digitize the transducers' signals. The piezoelectric transducer usually exhibit a resonance frequency peak with a narrow frequency range, while the current based piezo sensors, with a compensation circuit, offer flatter and wider frequency ranges. The price tag of small piezoelectric elements vary from 3 to 5 euros, while the current based sensors can cost up to a few thousands of euros. Depending on the model, the frequencies can ranges from a few Hertz up to 1 MHz and even beyond [29].

4.2 Electret and condenser microphones

Electret and condenser microphones both operate on a very similar principle. Both types of microphones rely on the principle of a charged diaphragm sliding inside a metallic casing [30, 31]. The output voltage of theses sensors varies accordingly to the distance between the diaphragm and the bottom of the casing. Electret and condenser microphones usually offer a near flat frequency response over the proposed frequency ranges. Condenser based microphones are typically used in situations where high fidelity audio recordings are required. This type of sensor, however, usually require a high bias voltage which can be as high as 200 V, making these unpractical for small and low-power embedded electronics applications. Electret microphones, in contrast, have a pre-charged diaphragm which removes the burden of high bias voltages. Moreover, electret microphones usually also contain a small amplifying circuitry. These advantages makes electret microphones the preferred option for small embedded electronics. The downside of the electret microphones can be found in phantom noises, the noise induced by the precharged diafragma, and lower signal-to-noise ratio (SNR). The electret microphones can be found for less than 10 euros, while high grade condenser microphones can reach 100 euros, and even more. Small electret microphones are usually rated to to 20 kHz. However, depending on the type, both types of microphones usually reach 100 kHz and beyond while keeping a near flat frequency response [32, 33].

4.3 MEMS microphones

A more recent type of microphones is based on microelectromechanical systems (MEMS). These sensors are one of the smallest microphones available on the market, with sizes of only 3 mm to 5 mm per side [34]. MEMS microphones are based on a silicon material based diaphragm which is allowed to oscillate inside a small chamber. The distance between the diaphragm and a reference material correlates to the measured voltage across this sensor. The obtained signals are usually very small. Therefore, a small amplifying circuitry is included inside the transducer allowing the obtained signals to be used in a conventional conditioning circuitry. Compared to previous types of microphones, MEMS are typically operated from supply voltages ranging from 1.8 V up to 3.3 V. Since MEMS microphones are silicon based, it is possible to include conversion circuits so that a digital output can be provided, removing the need for dedicated ADCs. Aside of the analog MEMS microphones, one can find digital I2S and digital PDM microphones. Pulse density modulated microphones operate on a bus with clock speeds ranging from 1 MHz up to 4.8 MHz. On each bus, one or two microphones can be connected in stereo mode. Each microphone provides a modulated 1-bit signal representing the density of the signal. This signal must be demodulated at receivers' side to obtain useful signals. Not all platforms offer an integrated PDM demodulater. I2S microphones alleviate this shortcoming by providing the demodulated acoustic data directly on a similar bus. MEMS microphones are the favorite choice for portable devices such as smartphones, tablets, etc. MEMS microphones primarily target consumer markets. Therefore, most MEMS microphones are specified for frequencies between 20 Hz and 20 kHz. A very limited number analog and PDM based microphones are able to operate up to 100 kHz. MEMS microphones are typically available for less than 5 euros. The frequency response of MEMS microphones is 'flat' enough for most consumer grade applications. These sensors, however, exhibit a resonance peak which is due the size of the sensors' chamber, known as the Helmholtz resonance [35].

4.4 Other acoustics measurement techniques

Other technologies for capturing acoustics exist but are less commonly used in embedded electronics. Dynamic microphones are based on a diaphragm attached to a coil which induces a current flow once it is moved relative to a fixed magnet. These microphones tend to be both physically larger in size and heavier compared to the aforementioned microphones. These microphones, therefore, typically capture acoustic signals below 10 kHz and are less susceptible to capture low amplitude signals. Other types of acoustic signals capturing techniques rely on the optical properties of materials. A first technique is to capture the reverberated amount of light on a reflective vibrating surface. While acoustic waves propagate through a medium, these waves reverberate on reflective materials which in turn vibrate accordingly. The lost amount of reflected light due to these vibrations is captured and translated into audible signals. While it generally works to capture sound from a distance, it is unknown if this technique suits ultrasound measurements. A second technique relies on measuring the vibration perceived by a long fiber optic cable. Fiber optics a primarily utilized to transport digital information in an optical manner. Fiber optics, however, are in some situations sensitive to vibrations. These vibrations can cause the receiving end of the cable to perceive the emitted signal differently. These differences allow to calculated the vibrations encountered by the light waves traveling the fiber. This technique is mainly used in seismology with fiber optics with distances up to 50 km.

5. USED TECHNOLOGY IN ACOUSTIC PLANT MONITORING

In Section 4, several researchers have described multiple methods used to capture acoustic signals from bioacoustics plants. Depending on the plant species and the type of desired plant stressor, a suitable set of microphone technology and acoustic acquisition is to be selected. However, the proposed solutions in Section 4 are insufficient to entirely capture the complexity of acoustic signals emitted by plants. Section 3 lists some sensors that were used in the performed research, but omits the backend electronics to read-out the sensor, information that can often be found in the listed publications. To detect an acoustic emission for analysis, one should collect information about amplitude, wave patterns and the emitted frequencies to characterize the cause of the emission given the uniqueness of the acoustic emission based on the physiology of the plant. Microphone types such as the electret and condenser often exhibit the ability to capture a very wide range of acoustic frequencies, including the ultrasound ranges. Aside of the microphones, an appropriate acquisition system is to be provided. This system should provide the ability to capture acoustic signals on a long term basis. Plants exhibit acoustic events at a non-predictable and sparse time interval. Therefore, the system must be able to trigger on these sparse acoustic events. Once captured the acoustic information is to be logged with an appropriate timestamp. All these possible solutions listed in Section 4 are often complex and may be outside the typical biologist's expertise. Alternatively, there are turnkey system solutions where all the electronics are integrated into a single user friendly device that connects directly to a computer via a USB cable. While these solutions may have limitations for ultrasound recordings, they frequently offer reliable, user-friendly operation. Finally, another viable approach is to use a simple power supply and an oscilloscope. These devices can be programmed remotely using virtual instrumentation software, offering great flexibility in data acquisition. Due to the nature of the emitted sound described in Section 3, we know that the loudness of such emissions can be very weak. If a plant emits a 60 dB acoustic emission, measured at 10 cm from the source, we can calculate that at 1 m the sound will be less than 30 dB before even calculating the attenuation by the air. This volume is below the noise floor of most of the shelf microphones. Based on the described measurements, the choice of microphone technology as described in Section 4 can play impact to provide a cheap solution. Alternatively, a distributed set of microphone can help detect and perhaps locate the acoustic emission in a plant. To enhance scalability solution cheaper on the shelf solutions are preferable. Finally, given the infrequent acoustic bursts, using local processing (edge-computing) can help avoid overloading a central processing solution from a massive work-load. By carefully evaluating the trade-offs among these readout solutions, researchers can select the most appropriate instrumentation to fully capture and analyze the diverse acoustic signals emitted by plants. Using appropriate instrumentation to extract more, or higher-quality, acoustic parameters leads to more robust and reliable information for signal analysis. Modern machine learning and general artificial intelligence are highly dependent on a diverse set of input features. To effectively apply these techniques, it is preferable to generate large datasets, enabling models to more accurately predict the state of plant stress or other conditions. The typical data collection rates associated with acoustic recordings of plants highlight the need for standardized protocols. Such standardization would facilitate easier sharing of measurement results between the recording scientists and data scientists, promoting the development of effective tools for plant monitoring based on acoustic signatures.

6. DISCUSSION

Capturing more complex high-frequency plant bio-acoustics data offers augmented research possibilities. Transitioning from piezo-based emission detectors to electret or condenser microphones could allows for the acquisition of more detailed acoustic emissions data. It is, however, still unclear which parameters are significant to detect the causes of plant stress. A more exhaustive data collection could reveal a variations in acoustic emission parameters associated with the different stress factors. Adopting electret and condenser microphones may be the next step in advancing bio-acoustics analysis by moving beyond simple emission frequency measurements to include parameters such as volume, waveform shape, spectral range, and even the spatial origin of the sound. These additional measurement parameters could enable a more robust and accurate differentiation of the causes of plant stress. Moreover, many studies have raised important yet understudied questions about previous research. Demey et al. [36] and Hussain et al. [8] have posed significant queries regarding the findings of Khait et al. [7]. The growing volume of publications highlights the repeated calls for further research and improvement of earlier work. Enhanced acoustic recording equipment can significantly elevate plant bio-acoustics research by capturing data with greater clarity and precision. With improved sensitivity and a broader frequency range, these devices enable researchers to detect subtle nuances in plant-generated sounds that might otherwise be overlooked, leading to more thorough studies and stronger conclusions based on robust, high-quality data. Notably, although fundamentally an acoustic engineering problem, bio-acoustics remains notably isolated within biotechnology. Improved measurement techniques and instrumentation could significantly contribute to resolving many of the open questions and help bridge this disciplinary gap.

7. BIBLIOGRAPHY

[1] Kareem A Mosa et al. “Introduction to plant stresses”. In: *Plant stress tolerance: an integrated omics approach* (2017), pp. 1–19.

[2] Richard Karban. “Plant behaviour and communication”. In: *Ecology letters* 11.7 (2008), pp. 727–739.

[3] Jin-Soo Son et al. “Is plant acoustic communication fact or fiction?” In: *New Phytologist* 242.5 (2024), pp. 1876–1880.

[4] John S Sperry and Melvin T Tyree. “Mechanism of water stress-induced xylem embolism”. In: *Plant physiology* 88.3 (1988), pp. 581–587.

[5] John A Milburn and RPC Johnson. “The conduction of sap: II. Detection of vibrations produced by sap cavitation in Ricinus xylem”. In: *Planta* 69 (1966), pp. 43–52.

[6] Russell L Weiser and Stephen J Wallner. “Freezing woody plant stems produces acoustic emissions”. In: *Journal of the American Society for Horticultural Science* 113.4 (1988), pp. 636–639.

[7] Itzhak Khait et al. “Sounds emitted by plants under stress are airborne and informative”. In: *Cell* 186.7 (2023), pp. 1328–1336.

[8] Muzammil Hussain et al. “Plants can talk: a new era in plant acoustics”. In: *Trends in plant science* 28.9 (2023), pp. 987–990.

[9] Linus De Roo et al. “Acoustic emissions to measure drought-induced cavitation in plants”. In: *Applied Sciences* 6.3 (2016), p. 71.

[10] Lidewei L Vergeynst et al. “Cavitation: a blessing in disguise? New method to establish vulnerability curves and assess hydraulic capacitance of woody tissues”. In: *Tree Physiology* 35.4 (2015), pp. 400–409.

[11] Tomohide Shimotashiro et al. "Non-destructive method for root elongation measurement in soil using acoustic emission sensors". In: *Plant production science* 1.1 (1998), pp. 25–29.

[12] CD Durairaj, L Okushima, and S Sase. "ASIMULATED INVESTIGATION TO MEASURE ACOUSTIC EMISSIONS CAUSED BY ROOT GROWTH". In: *Transactions of the ASAE* 43.6 (2000), pp. 1905–1910.

[13] Muhammad Waqas, Dominique Van Der Straeten, and Christoph-Martin Geilfus. "Plants' cry'for help through acoustic signals". In: *Trends in plant science* 28.9 (2023), pp. 984–986.

[14] Melvin T Tyree and Michael A Dixon. "Cavitation events in Thuja occidentalis L.? Ultrasonic acoustic emissions from the sapwood can be measured". In: *Plant Physiology* 72.4 (1983), pp. 1094–1099.

[15] Melvin T Tyree et al. "Detection of xylem cavitation in corn under field conditions". In: *Plant Physiology* 82.2 (1986), pp. 597–599.

[16] MT Tyree and JS Sperry. "Characterization and propagation of acoustic emission signals in woody plants: towards an improved acoustic emission counter". In: *Plant, Cell & Environment* 12.4 (1989), pp. 371–382.

[17] Takefumi IKEDA. "Xylem dysfunction in Bursaphelenchus xylophilus-infected Pinus thunbergii in relation to xylem cavitation and water status". In: *Japanese Journal of Phytopathology* 62.6 (1996), pp. 554–558.

[18] Heather W Sherwin et al. "Xylem hydraulic characteristics, water relations and wood anatomy of the resurrection plant Myrothamnus flabellifolius Welw." In: *Annals of Botany* 81.4 (1998), pp. 567–575.

[19] Silvia B Kikuta and Hanno Richter. "Ultrasound acoustic emissions from freezing xylem". In: *Plant, Cell & Environment* 26.3 (2003), pp. 383–388.

[20] Ralf Laschimke, Maria Burger, and Hartmut Vallen. "Acoustic emission analysis and experiments with physical model systems reveal a peculiar nature of the xylem tension". In: *Journal of plant physiology* 163.10 (2006), pp. 996–1007.

[21] Kathy Steppe, F Zeugin, and R Zweifel. "Low-decibel ultrasonic acoustic emissions are temperature-induced and probably have no biotic origin". In: *New Phytologist* (2009), pp. 928–931.

[22] Markus Nolf et al. "Xylem cavitation resistance can be estimated based on time-dependent rate of acoustic emissions". In: *New Phytologist* 208.2 (2015), pp. 625–632.

[23] Dinko Oletic et al. "Time-frequency features of grapevine's xylem acoustic emissions for detection of drought stress". In: *Computers and electronics in agriculture* 178 (2020), p. 105797.

[24] Lia Lamacque et al. "Detection of acoustic events in lavender for measuring xylem vulnerability to embolism and cellular damage". In: *Journal of Experimental Botany* 73.11 (2022), pp. 3699–3710.

[25] Satadal Dutta et al. "Ultrasound pulse emission spectroscopy method to characterize xylem conduits in plant stems". In: *Research* (2022).

[26] Dick Dobler and Gunnar Heilmann. "Perspective of the acoustic camera". In: *INTER-NOISE and NOISE-CON congress and conference proceedings*. Vol. 2005. 6. Institute of Noise Control Engineering. 2005, pp. 2491–2498.

[27] G. Gautschi. *Piezoelectric Sensorics: Fundamentals and Applications*. Springer, 2001. ISBN: 9783642003814.

[28] James F Tressler, Sedat Alkoy, and Robert E Newnham. "Piezoelectric sensors and sensor materials". In: *Journal of electroceramics* 2 (1998), pp. 257–272.

[29] Physical Acoustics. *Model ISPK15I*. Technical datasheet. URL: https://www.physicalacoustics.com/content/literature/sensors/Model_ISPK15I.pdf (visited on 03/26/2025).

[30] Gerhard M Sessler and James E West. "Foil-electret microphones". In: *The Journal of the Acoustical Society of America* 40.6 (1966), pp. 1433–1440.

[31] GM Sessler and JE West. "Electret transducers: a review". In: *The Journal of the Acoustical Society of America* 53.6 (1973), pp. 1589–1600.

[32] *Ultrasound Microphones*. URL: https://avisoft.com/ultrasound-microphones/ (visited on 03/26/2025).

[33] Senscomp. *Series 600 Instrument Grade Ultrasonic Sensor Specification*. URL: https://senscomp.com/wp-content/uploads/2022/11/Series-600-Instr-Grade-Ultrasonic-Sensor-Spec-01Oct22.pdf (visited on 03/26/2025).

[34] Marc Fueldner. "Microphones". In: *Handbook of silicon based MEMS materials and technologies*. Elsevier, 2020, pp. 937–948.

[35] Knowles. *Knowles SPU0410LR5H QB Datasheet*. URL: https://www.mouser.be/datasheet/2/218/Knowles_SPU0410LR5H_QB-2935249.pdf (visited on 03/26/2025).

[36] Marie Liesbeth Demey, Ratnesh Chandra Mishra, and Dominique Van Der Straeten. "Sound perception in plants: from ecological significance to molecular understanding". In: *Trends in Plant Science* 28.7 (2023), pp. 825–840.