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Effects of sound waves on plants

Possible sustainable agricultural and biotechnological innovations

(https://festival1001notes.com/wp-content/uploads/2021/04/plante-musique-3-815x542.jpg)

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Possible sustainable agricultural and biotechnological innovations

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- Accroître leurs compétences en matière de pratique professionnelle par la mobilisation de connaissances et de techniques, dont les fondements et contenus ont été explorés le plus finement possible afin d'en assurer une bonne maîtrise intellectuelle et pratique,
- Accroître la capacité des ingénieurs en génie de l'aménagement et de l'environnement à innover tant en matière de méthodes que d'outils, mobilisables pour affronter et résoudre les problèmes complexes posés par l'organisation et la gestion des espaces.

La formation par la recherche inclut un exercice individuel de recherche, le projet de fin d'études (P.F.E.), situé en dernière année de formation des élèves ingénieurs. Cet exercice correspond à un stage d'une durée minimum de trois mois, en laboratoire de recherche, principalement au sein de l'équipe Dynamiques et Actions Territoriales et Environnementales de l'UMR 7324 CITERES à laquelle appartiennent les enseignants-chercheurs du département aménagement.

Le travail de recherche, dont l'objectif de base est d'acquérir une compétence méthodologique en matière de recherche, doit répondre à l'un des deux grands objectifs :

- Développer toute ou partie d'une méthode ou d'un outil nouveau permettant le traitement innovant d'un problème d'aménagement
- Approfondir les connaissances de base pour mieux affronter une question complexe en matière d'aménagement.

Afin de valoriser ce travail de recherche nous avons décidé de mettre en ligne sur la base du Système Universitaire de Documentation (SUDOC), les mémoires à partir de la mention bien.

Remerciements

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Introduction

Sound is a mechanical wave that is caused by the movement of air molecules away from the source. This pressure wave causes the surrounding molecules to move back and forth from their equilibrium position. In physics, it is typically measured by its frequency (Hz) and its intensity (dB) (Bhandawat & Jayaswall, 2022). Sound is omnipresent in our daily lives and actually shapes the lifestyles of living organisms. Sound waves have been widely studied, especially as means of communication for animals or humans. This seems quite logical because communication in the animal and Human kingdoms is a key process to live and survive. So, animals and humans have evolved with specific organs to be able to hear, emit and analyze sounds to act in response to these stimuli. Plants, on the other hand, do not have visible and dedicated receiving organs, but we know for a long time that they are able to communicate with each other through chemical signals. Indeed, as sessile living organisms, they must develop means of defense against attacks and threats from their environment (Joshi et al., 2019). So, these observations raise the question if plants are capable of “hearing” and emitting sounds such as other “higher” living organisms to adapt to their surrounding environment.

In the last couple decades, scientists started to study the perception of plants by sound. This field of study is called “phytoacoustics”. By exposing different species to certain sound frequencies, we understood that sound can have an important impact on plants by helping their development. So, if we partially elucidated the effects of sound on plants, the way in which plants perceive these sounds is still the subject of much research. **The purpose of this report is therefore to detail through a state of the art all the existing knowledge around our problem: To what extent plants are impacted by sound and how does it help them to adapt to their environment in rural and urban areas?**

Indeed, while the reception of sounds in living organisms other than plants is done by well-known receptor organs, we will try to understand what mechanisms allow plants to react to acoustic waves, but also to emit such sounds. Finally, we will try to understand to what extent sound influence the adaptation of plants to their environment, particularly in terms of relationships between plants and animals and between plants and anthropic activities.This study will thus allow us to identify gaps of knowledge in the actual source of information and experiences carried out. This will serve as a basis for future research projects on this subject. Indeed, the avenues for further reflection will be clearly identified in this report.

1. The effects of sound in plant development

1.1. The parameters of acoustic waves to which plants are sensitive

In recent years, it has been shown that plants respond to acoustic waves (Khait and al., 2019)(Gagliano and al., 2017). Different effects have been observed on plant development, enzyme activity, gene expression, etc. (Khait et al., 2019). Since we realized that sound could be a great opportunity to improve crop productivity or to fight against certain types of diseases many experiments have been carried out to try to find positive effects on the development of the plant by diffusing all types of sounds (music, natural sounds or fixed frequencies) (Hendrawan et al., 2020)(Fernandez-Jaramillo et al., 2018)(Chivukula&Ramaswamy, 2014). Indeed, sensitivity to particular frequencies, to musical sequences or even to natural noises are elements to be considered when analyzing the work devoted to the impacts of acoustic waves on plants (Khait et al., 2019). In this section, we will therefore focus on the acoustic waves parameters that provoke plant physiological reactions.

To better understand what we are talking about, a soundwave is a simple pressure wave that is caused by the movement of air molecules away from the source. This pressure wave causes the surrounding molecules to move back and forth from their equilibrium position. In physics, four characteristics define a soundwave: the frequency (expressed in Hz), the amplitude (expressed in m), the wavelength (expressed in m) and finally the timber (linked to the shape of the wave) (see figure 1). We can also add the intensity (expressed in dB) as an important parameter to describe a soundwave.

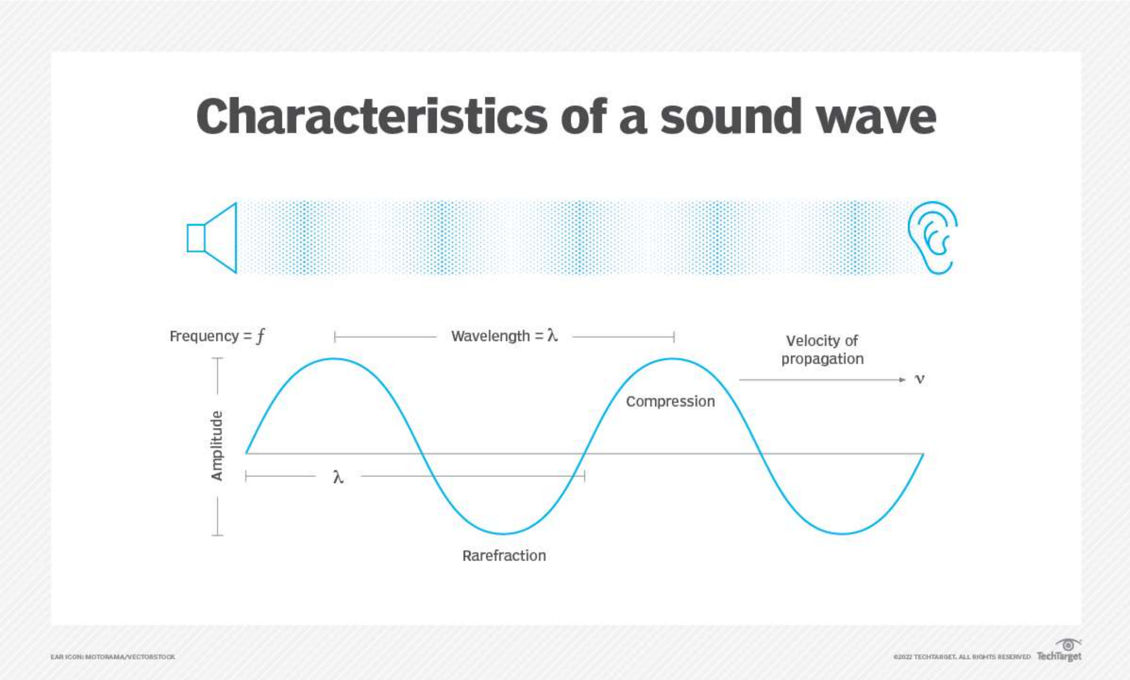

Figure 1 : Illustration of the characteristics of a soundwave

Source: Andrew Zola, TechTarget, 2022

These characteristics mentioned above, are always variable during experimental measurements. To these ones, can be added the time of exposure to the sound source, as well as the distance. An acoustic system has been developed by the university's research center of Agriculture of Qingdao, China (QAU)(Fernandez-Jaramillo et al., 2018). This technology is used to broadcast sounds to plants at very specific frequencies at which the variety of plant studying is sensitive. This could result - once the effects of sound waves will be more understood - in reducing the need for chemical fertilizers (Joshi et al., 2019).

The use of this system for the exposure of plants to sound frequencies allows a significant increase in the productivity and quality of crops (Hendrawan et al., 2020). A frequency of 60 dB would be sufficient to trigger vibrations in the biological structures of plants (Fernandez-Jaramillo et al., 2018) but the frequencies most frequently used during experiments are located in the audible spectrum (20 to 20,000 Hz) and particularly around 100 Hz. Plants are also exposed over long periods (several hours a day) during different phases of plant development : growth, germination, callus growth, hormone synthesis, photosynthesis or even transcription of certain genes (Joshi et al., 2019). Thus, all these different parameters have an effect on the development of plants and can easily be changed using this technology. It also shows that plants would have a regulatory mechanism involving a greater sensitivity to the frequency than to the intensity of the broadcasted sounds (Fernandez-Jaramillo et al.,

2018). Thus, the frequency, and the time of exposure are the two parameters that impact the plants the most. This technology could help to improve plant growth, increase productivity and the quality of certain crops.

However, these "synthetic" sounds do not always reflect natural sounds. Other researchers were then interested in the impact of “white sounds”, that is to say sounds reproducing those that can be found in nature (water flow, buzzing bees, etc.). It is then a question of broadcasting sounds that the plant could encounter in its environment at “realistic” frequencies and intensities (Khait et al., 2019). Yet, it is important to note that in such scenarios, even if the frequencies are selected in ways to recreate “natural” sound, the experiments are realized in closed environments, which means without any unwanted noise. The question of the relation between plants and the sound of their environment will be treated in part 2.2.

Finally, the last avenue of research concerns music. Since the 1990s, some curious farmers were already trying to make their crops “listen” to classical or jazz music to improve the quality of their plants. At this time and level of acknowledgment that comes with it, the reflection was more an hypothesis arguing that if humans and animals were sensitive and could have their favorite types of music, why couldn't plants have their own sensitivity too?”
It should be noted that these farmers, who thought out of the box, had good instincts because it is clear today that music has an impact on plant growth and development (Chivukula & Ramaswamy, 2014). The choice of music is not insignificant because the impacts can be positive or negative depending on the music played and the species of plant studied. An Indian study was carried out to analyze the effects of different types of music on the Chinese rose (Rosa Chinensis). It emerges that Vedic chanting and Indian Classical music are beneficial choices unlike rock, which would prevent the plant from developing at its maximum (Chivukula & Ramaswamy, 2014).

Although there is a consensus that sound waves have an impact on growth and development of many plant species, environmental conditions, not always considered in experiments, can influence physiological responses of the plant. The speed of propagation of sound can for example vary according to the propagation mode, the temperature or ambient humidity (Mohanta, 2018). We can therefore identify a gap of knowledge or the next challenge as understanding what are the thresholds and the best combinations of frequencies /intensity associated with different parameters such as distance, exposure time, to determine the positive and desired effects on the studied plants.

In this part, we have seen that plants are impacted by sound waves, so the question is how the plant receives and perceives this sound. If the question of effects on plants is largely consensus, many questions still arise about the processes behind the reception sound by plants. Which organs, by which chemical or physical processes? This is what we will talk about now.

1.2. The main hypotheses about plant sound reception mechanisms

It seems now clear that plants can respond to acoustic waves and therefore “hearing”. However, the reception mechanisms are still to be clearly identified. Indeed, plants don’t have defined and visible organs dedicated to sound reception such as ears for humans, but it doesn’t mean that they don’t exist or they don’t are important. The natural selection would even act on the different parts of the plant involved in the reception of sounds by changing their shape, structure, or size (Khait et al., 2019), showing how important are the reception organs in plant development. To understand how the plants can understand sounds, it is then a question of trying to understand which parts of the plant are involved but also to understand which vibration translation processes are brought into play to transform external signals into internal signals.

As mentioned before, acoustic waves are mechanical waves, which move in a material medium, here the air or the ground. They propagate thanks to the movement of air molecules (to their compression). During the passage of the sound, the acoustic wave, the air is in vibration. Plants would benefit from mechanoreceptors in their tissues that would allow them to interpret these vibrations. Mechanoreceptors[1] are organs or cells that respond to internal and/or external mechanical stimulation (touch, vibration, etc.). This process of mechano-reception is also documented in plants for their responses to external stimuli (attack by a predator). Several hypotheses have then been put forward concerning the reception processes of plants, based on these processes of mechanoreception, or by reflecting by analogy on the receptor organs of animals.

Between 1998 and 2016, various researchers were interested in the role of calcium and the channels sensitive in the perception of sounds by plants. The concentration of calcium,

[1] Mechanoreceptors are primary sensory structures that provide information about mechanical features of the internal and external environments. They detect stimuli such as touch, pressure, vibration, and sound from the external and internal environments. (Encyclopedia of NeuroSciences, 2009)

essential as plant nutrient, would be linked to specific environmental disturbances and would cause a physiological response (White, 2003). Indeed, the cell walls would be composed of sensitive channels. These channels, sensitive to the vibrations caused by the sound, would modify the tension of the cellular wall. Calcium, that is present in the cell wall and in charge of transmitting exogenous informations would then be a key element in the reaction of plants to these stimuli: the concentration of calcium would be modified which would generate chain signals and therefore a series of physiological answers (Hepler, 2005) (Mishra et al., 2016) (White, 2003).

Other researchers, by analogy to the receptor organs in animals, have been rather interested in the role of flowers in the perception of sounds. I. Khait and his team in 2019 explored the track of flowers as receptors. The large “big bowl” shaped flowers could indeed help to amplify sound. They suggest for example in the case of an external noise produced by a pollinator, that the flower would be the external receiving organ. In fact, the flower of *Oenothera drummondii* (based on its shape and physical properties) could amplify the frequency which includes sounds emitted by the pollinator and does not respond to lower or higher frequencies (see section 2.1.b). The author then suggests the reflection by analogy of the receptor organs in animals, widely documented, which could open new perspectives for the understanding of the process of reception of sounds by plants. (Khait et al., 2019). However, a limit to this hypothesis of the flower as a receptor organ lies in the late arrival of the flower in the plant development. If the flower could, indeed, be an effective receptor, it has been shown that plants perceive sounds from the earliest stages of development before the flower appears. The flower would therefore be complementary to other reception mechanisms.

Although different hypotheses emerge in this field of research, the results presented in the works mainly concern the effects of acoustic waves that improve the development of the plant, mainly for an agronomic application. So there is still a gap of knowledge which is to precise mechanisms that allow plants to interpret sounds (in more detail than what is already present in this report). For the moment, we focus more on the characteristics of sound waves that can be received by plants, than on understanding why and how certain frequencies can be received by plants.

Plants therefore are able to receive sound waves. But is it possible that they themselves emit sound waves? This question of the emission of sound by plants will now be explained.

1.3. Mechanisms of sound emission by plants are still to be clarified

The environment in which plants evolve is full of sounds of all kinds, whether human or “natural” (water, wind, animals, etc.). We have seen that plants were sensitive to these sounds, and that they evolved according to those they perceived. On the other hand, we know that chemical means of communication exist between plants to warn of potential dangers (especially in the event of an attack by herbivores). It would therefore seem consistent to imagine that plants could emit sounds for communication purposes, even if proofs of such intentions are lacking so far (Schöner and al., 2016). Indeed sound propagates faster than chemicals, allows the transmission of a high rate of information and finally provides a more accurate source localization, so that the receiver could be able to determine the signaler’s distance (Wiley&Richards, 1978 and Walker 1998, cited in Gagliano, 2015). Therefore, some scientists even support the idea that chemical signals are less effective than sound signals (Gagliano, 2015). But first thing first, what are the processes involved in the emission of sound by plants?

a. Cavitation

Multiple hypotheses exist regarding acoustic emission in plants but one of the first released and that has been studied multiple times is the process of cavitation. Indeed, the process of xylem cavitation[2] is related in scientific papers since the years 1960 (Borghetti and al., 1989) (Charrier and al., 2015) (Caicedo-Lopez and al., 2021) (Cochard and al., 2008). It is the filling of a xylem vessel or tracheid with air bubbles when the plant transports water from its roots to its leaves that is at the origin of the sound wave (see figure 2). During plant transpiration, the air bubbles interrupt the water conductive system, then the air bubbles burst due to their expansion, which creates tension in the xylem tissues, and finally causes sound vibrations.

[2] “Cavitation describes the birth and radial oscillation of gas and vapor bubbles in a liquid subjected to a vacuum. If this depression is high enough, the pressure can become lower than the saturation vapor pressure, and a vapor bubble is likely to be born.” Définition on : https://www.techno-science.net/definition/1311.html

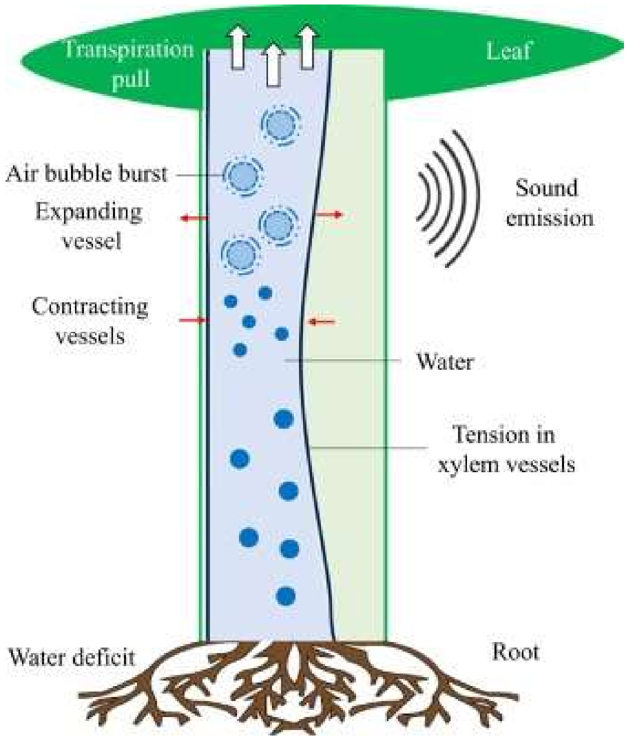

Figure 2 : Physiology of sound emission in plants as a result of tension in xylem vessels

(Bhandawat & Jayaswall, 2022)

This mechanism that transmits the force necessary for the circulation of water in the xylem is responsible for the production of sound waves (Laschimke and al., 2006). The induced tension in the xylem vessel walls causes vibrations, these can be detected by audio receivers. That is how, in 1989 M. Borhetti and his team started to “listen” to a Picea abies under environmental conditions, in this case under water stress (Borghetti and al., 1989). As the phenomenon of xylem cavitation is directly related to the amount of water circulating in the vessels, and this creates a vibration detectable by sound devices, they concluded that ultrasonic receivers were a good way to study the state of stress water in plants and prevent droughts.

Nonetheless, cavitation is not always due to drought stress, it could also occur when some plant species freeze. Indeed, ice cavitation also happens through ice nucleation (Charrier and al., 2015). This is interesting in the way that plants currently have to face freezing temperatures, especially in alpine and boreal areas. The process of cavitation through ice nucleation is quite similar to the process that occurs during drought stress. During freezing, dissolved gases are trapped as bubbles in the forming ice. This is because the solubility of gas is lower in ice than in liquid. The bubbles then expand at lower negative tension. In this way, ice formation and increase in pressure due to volume changes cause tensions in the xylem that generate cavitation, and thus acoustic emissions (Charrier and al., 2015). This

study also demonstrates that the propagation of water in the plant is not delayed by anatomy, which means that even in large and ramified structures such as trees, acoustic emission would be a functional warrant system.

The sound wave production is described in this part for "small plants" but is it similar for plants with particular morphology? What about cavitation in these more complex structures?

b. Other hypotheses

Sound wave emission mechanisms are certainly not limited to the specific case presented above. Indeed, although several studies (Kikuta and al., 1997 and Laschimke and al., 2006) agree that the plant emits waves between 10 and 300 KHz, the mechanisms to produce sound waves are not unanimous or are multiple. Here are the others most documented hypotheses.

An hypothesis led by Zweifel and Zeugin (2008) consists in saying that the sound waves produced by the plant come from the respiration of the plant and the metabolism allowing the creation of the xylem and phloem.

In another study, growing corn roots generated structured spike-like sound different from that of cavitation (Gagliano, 2012), a year later, this same author made the hypothesis that that the waves come from the agitation of the organelles that are different structures inside the cells, contained in the cytoplasm such as for example the mitochondria and the cytoplasm. (See figure 3) (Gagliano, 2013).

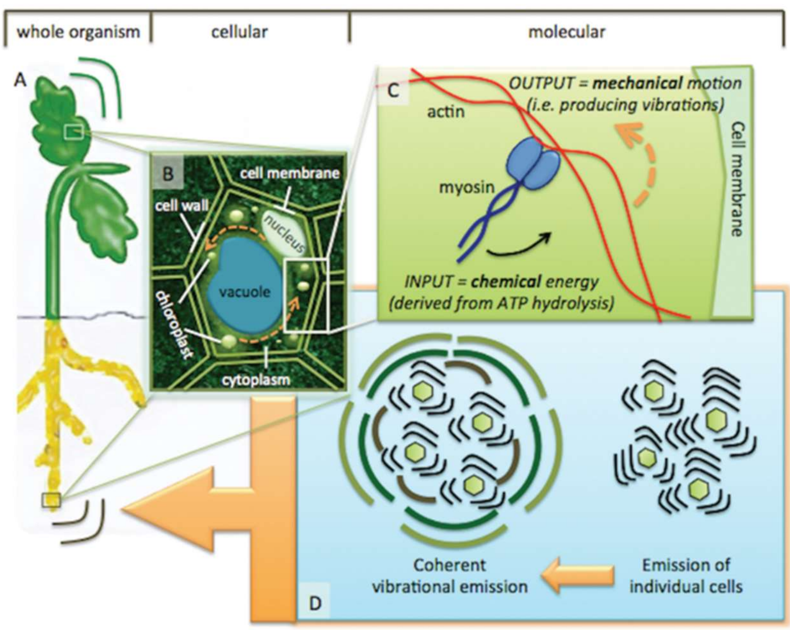

Illustration of the theory of M. Gagliano about the cellular origin of sound emission by plants: (A) sound emission to neighbor, (B) cytoplasmic movements, (C) motor protein myosin movements create cytoplasmic streaming, (D) individual cells receive neighbor cell's vibration and coordinate themselves into an synchronize and strongest vibration (Gagliano, 2013)

Figure 3 : Illustration of the theory about the agitation of organelles as sound emission process

Finally, the last hypothesis put forward by Rosner and al. (2006), explains that these waves can come from a rapid drop in pressure within the xylem which would be due to environmental stress. An experiment on corn roots (Gagliano and al., 2012) confirmed the emission of sound waves by the plant when it was in a situation of environmental stress (immersed in water).

We have seen that plants emit sound, but the proposed hypothesis explains this emission of sound through structural phenomenon. Moreover, plants can vibrate due to their environment that mechanically stimulates them (wind, water, buzz etc.) and some of the effects produced on plants with mechanical stimulus are similar to those produced by acoustic emissions. Indeed, both sound vibrations and touch produce mechanical waves… So, we could argue that, considering the moving environment, an overlap in the mechano-stimuli of touch and sound is likely to occur. But even if these two sensory systems have similarities, we have seen that plants have very specific responses to sound vibrations that are different from touch. Then, the soundwaves stimulus seems to be different from touch (Mishra and al., 2016).

A question on this topic could be: does the plants intentionally emit sound? Yet evidence for communication purposes of such sounds is lacking so far. This constitutes a gap of knowledge, so it would be interesting to understand better the reception's mechanism to distinguish waves from mechanical harm stress.

As we have seen, many researchers are sure that plants emit sound. The question after that would be why. Why do plants emit and receive sound? What are the beneficial or negative effects of sound waves on the plant? This is what we will try to understand in this part.

1.4. Sound provokes different effects observed at different scales

The various studies carried out on the subject have shown that repeated sounds played over long periods in various stages of development involved different plant responses, to different levels (see table 1). I.Khait grouped these responses into 8 standard responses (Khait et al., 2019) : simulation of seed germination, plant growth, delayed ripening, increase in cellular energy balance, modification of endogenous hormone levels, modification of cell cycles, modification of enzymatic activities, root metabolism … In this field of research (relations between sound and plants), most of the studies focus on the effects of sound on plant metabolism, mostly for agricultural purposes. Many studies have been conducted on this subject, but it now seems difficult to aggregate all these results, as the effects are multiple and the experimental variables numerous. Furthermore, the difficulty lies in the cause-and-effects relationships: cell cycles can for example involve plant growth. An interesting avenue would

then be to classify the responses depending on their level: genetic, cellular, molecular as well as their physiological and phenotypic responses.

There is still little data concerning the expression of genes resulting from the diffusion acoustic waves, however the research of Jeong and his team (2014) provides some clues. Indeed, by exposing rice plants for 4 hours to frequencies between 50Hz and 1kHz, they found that sound regulated “Rubisco subunit” gene expression as well as the cytoplasmic protein aldolase (ald). These genes being photosensitive genes, the sound could represent an alternative to light as a genetic regulator (Jeong et al., 2008). Other studies conducted on different plant species have attempted to establish the link between the modification of gene expression and treatment with sound waves. Thus, on Aradiposis, 17 genes were upregulated after long exposures to sound frequencies. Another study demonstrated that in *Dendrobium candidum*, four genes were expressed in different ways in response to acoustic waves (Fernandez-Jaramillo et al., 2018). In general, most of the genes expressing themselves after exposure to sound are so-called defense genes, that is, they are involved in plant stress response processes as well as means of signal transduction. It is important to focus on the impact of sound on gene expression because it is related to the biological functions of plants. Indeed, the variation in gene expression may depend on different environmental factors and cause physiological changes and development in plants (See section 3.1.).

Sound also greatly influences the root development of different species. (Fernandez-Jaramillo et al., 2018) (Gagliano et al., 2017) (Kim et al., 2021) (Joshi et al., 2019). But root growth and development are related to cell division which increases the number of cells and therefore the length of the roots. This cell division depends on two factors which can be influenced by sound: the expression of genes but also hormones (Fernandez Jaramillo et al., 2018). First, and as we have seen before, acoustic waves can have an impact on gene expression. Genes involved in cell division are no exception. Indeed, when *Arabidopsis a* is exposed to soundwaves of approximately 100 Hz, it was observed that strong upregulation of genes associated with root cell division in this plant (Kim et al., 2021).

Another important parameter for cell division and root growth is Acid acetic-indole (AIA). If the concentration of AIA decreases, then the growth of callus (structure helping to vegetative propagation) is inhibited. Again, experiments have shown a link between the exposure of the *Chrysanthemim* to sound and the activity of the AIA. Indeed, at frequencies of 800 Hz and 100 dB, AIA activity increases in this plant species, which helps its roots grow (Yiyao et al., 2002). Therefore, sound has an impact at the cellular level of plants, and ultrasound can even cause repairable damage to cells. Indeed, ultrasound can reduce the

stability of cells and alter their membranes, but also release DNA from the cell nucleus (Fernandez-Jaramillo et al., 2018).

In the field of the invisible, other responses can be triggered in plants due to their exposure to sound waves. To return to the main effects mentioned in the reviews, the impact on the activity of enzymes is often noticed. Studies on *Dendrobium candidum* were conducted (Fernandez-Jaramillo and al., 2018) and it has been shown that enzyme activity increased during sound exposure, but this effect was canceled directly at the end of the sound diffusion. The increase in the production of polyamides accompanied by an increase in the concentration of dioxygen (O2) could also be observed when plants were exposed to sound. Finally, the sound can also imply a larger accumulation of salicylic acid, beneficial for their defenses against some pathogens (Fernandez-Jaramillo et al., 2018) (see an example in section 3.1).

All these responses at the cellular, molecular, and genetic scales generate physiological changes in plants (see Table 1). If the growth of roots has already been mentioned, other effects have been observed. Sound can affect the aperture of stomata, improving plant development (Hendrawan et al., 2020), (see section 2.2.). Flower nectar can be sweetened by broadcasting natural sounds like the buzzing of bees (Veits et al., 2019), (see section 2.1). The size, color of the leaves of certain plants such as red lettuce can also be impacted (Hendrawan et al., 2020) by certain acoustic frequencies. Finally, music would also be a mean of significantly improving the resistance of plants against certain diseases or against environmental threats (such as drought) (Khait et al., 2019), (see section 3.2). The interest of all these experiments is then to find what frequencies, at what intensities for the species studied, make it possible to observe advantageous responses for the plant. Indeed, we can easily imagine the interest of the propagation of sound in crops to improve their productivity.

Table 1 : Different effects of soundwaves on plants (E. Audiffren, 2022)

State of development	Species	Sound / Frequency	Effect of sound	Reference
Flowering	*Oenothera drumondii*	Bee sound	Sweeter nectar	Veits and al., 2019
Sprouting	*Pisum sativum*	Water flowing in a pipe	Root growth towards the sound source	Gagliano and al., 2017
2 weeks	*Arabidopsis thaliana*	200 Hz	Root growth towards the sound source	Rodrigo-Moreno and al., 2017
Unknown	*Lactuca sativa var*	3-5 kHz	Increase in weight up to 25.63%	Hendrawan and al., 2020
Unknown	*Lactuca sativa var*	0.3-6 kHz	Plant's increase in height	Hendrawan and al., 2020
Unknown	*Rosa Chinensis*	Violin	Plant's increase in height	Chivukula Ramaswamy, 2014
Unknown	*Lactuca sativa var.*	3-5 kHz	Better stomatal opening	Hendrawan ans al., 2020
Sprouting	*Rice seeds*	400 Hz	Better germination rate	Bochu and al., 2003

We have seen in this part that the plant reacts at different levels (genetic, cellular, molecular, physiological, and phenotypic) when it is exposed to sound waves. It would be interesting to study whether other reactions at other scales exist, particularly at the level of plant behavior by studying "plant ethology".

We have seen that plants were able to receive and emit sound waves. The reception of sound (the mechanisms into play and the effects) is more documented than the effects and mechanisms of sound emission by plants. This is also due to all the potential applications in agronomy of such mechanisms. This first understanding is a step forward in the understanding of the plant world. However, it remains to be determined to what extent the perception and emission of sound can be useful for the plant, which is still poorly understood.

2. Communication between plants and their natural environment

2.1. Sound as a means of communication between plants and animals

a. Active communication to facilitate pollination

Angiosperm plants use pollination to ensure their reproduction. This involves a pollinating insect which, by feeding on the plant's nectar, carries pollen with it. When this same pollinator is in contact with another plant, the pollen transported by the insect will settle in the second flower and thus allow fertilization. This is the classic reproductive process in angiosperm plants. However, this process is ultimately more complex and involves other factors, including sound (De Luca and al., 2012; Khait and al., 2019). Indeed the pollinating insect is not randomly chosen by the plant and the pollen is not transported by the pollinator in a providential way. Indeed, as explained in part 1.2 and 1.3, plants pick up and react to the sounds of their environment. In the case of plant pollination by insects, sound communication is called “Buzz pollination” and more than 20,000 plant species use it in nature (De Luca and al., 2012). We will now see more details and explanations about this Buzz pollination effect.

As said just before, the plant needs to transmit its gametes via pollen to other plants. Pollen in plants that use vibratile pollination is contained in the anthers, that are the upper parts of the stamen (see figure 4).

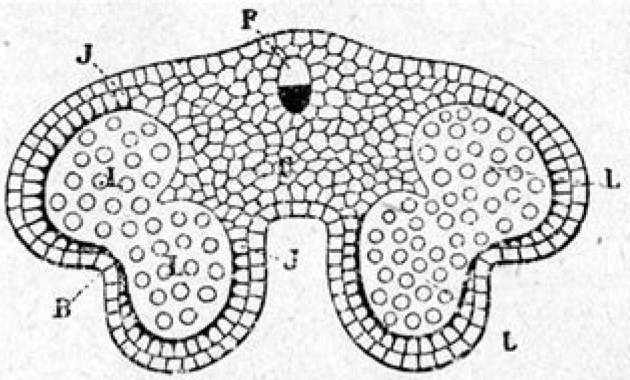

Fig. 404. — Coupe transversale d'une anthère mûre.
L, loge renfermant les grains de pollen ; J, assise mécanique ; F, faisceau libéro-ligneux ou nervure du connectif ; B, sillon externe entre les deux sacs polliniques d'un même côté.

Figure 4 : Transverse section of a mature anther : explanation of its structure

(Pizon Antoine, 1930. *Précis d'histoire naturelle.* Lib. Octave Douin ed., 622 p., p. 534)

The anther contains the pollen. Its openings, which are too small for insects, only let the pollen out[3]. It is the stimulation of the anthers by a vibratory sound wave that allows the pollen to come out. In order to maximize its chances of fertilizing as many other plants as possible, it must maximize its pollen production, especially because not all the pollen is devoted to reproduction. Indeed, part of the pollen recovered by the pollinating insect is kept by it as a reward, for example, for bees, pollen is used as a source of protein for juveniles (De Luca and al., 2012). The plant must therefore produce twice as many gametes and this is for this reason that sound communication is very useful to plants. De Luca and al. (2012) tested different buzzing sounds of pollinating insects on plants and analyzed the plant responses. The pollinating insect studied is the buff-tailed bumblebee (bombus terrestris) and the plant studied is a solanaceae, Solanum rostratum. The scientists isolated the following factors to determine which had an effect on the plant: the amplitude, the duration of exposure and the frequency of the buzz. They have shown that the amplitude of the sound wave and, to a lesser extent, the duration of exposure have an influence on the quantity of ejected pollen. However, it appeared that a high amplitude and a long exposure time could, on the contrary, reduce the yield. The frequency, which was the third parameter tested, revealed no impact on pollen production. Indeed, all the frequencies of the range of pollinating insects are received in the same way by the plant. Only the very high frequencies between 700 and 1000 hertz had a negative impact on the pollen yield, however these frequencies absolutely cannot be emitted by pollinating insects. The anthers therefore operate in stages, above a certain frequency level, it stops the pollen distribution process.

For pollinating insects such as bumblebees, a strategy is put in place to collect as much pollen as possible. This is based on the fact that the production of pollen is stronger when the amplitude of the wave is greater. In bumblebees, it is mainly the heaviest ones that take care of collecting pollen. According to De Luca and al. (2012), the heaviest are also those that emit sound vibrations with the greatest amplitudes. Thus, thanks to their size, they can collect more pollen than the smaller ones, which will be responsible for collecting nectar or staying in the nest to take care of the larvae. Therefore, it is more profitable to send large bumblebees to collect pollen in view of their ability to eject pollen to collect it.

Plants must also compete with neighboring plants to attract as many pollinators as possible. It is essential for their reproduction to guarantee the visit of a maximum number of pollinators. For this they have adopted a strategy based on the sound signals emitted by

[3] Definition and explanation of anthers on : https://www.aquaportail.com/definition-14236-sonication.htmlhttps://www.aquaportail.com/definition-14236-sonication.html

pollinators. In their paper, (Veits and al.,2019), the scientists experimented with exposing the plant *Oenothera drummondii* to different sounds and measured the concentration of sugar in the nectar. They measured this concentration for natural, synthetic sounds of different frequencies and compared them. They obtained as a result that the plant reacts in less than 3 minutes to a sound vibration transmitted by the air. It has thus been demonstrated that *Oenothera drummondii* produced sweeter nectar after being exposed for 3 minutes to the sound of buzzing of bees or to synthetic sounds reproducing them (Veits et al., 2019). The flower would be the receiving organ of these vibrations and would allow the response of the plant, namely an increase in the production of nectar. Several sounds were tested and the response was similar when the sound came from the beating of a bee's wing or when it came from an artificial sound with the same frequency but not the same temporal pattern. Thus (Veits et al., 2019), deduces that it is the frequency of sound that is mainly captured by the flower and that it is sufficient to induce a reaction (sweeter nectar, delivery of pollen) from the plant. The reaction according to the experiment is a 1.2% increase in sugar concentration in the nectar. Even though this variation in concentration is minimal, it is still detected by pollinating insects. (Afik and al., 2006; Whitney and al., 2008). For the plant, the increase in sugar in the nectar allows it to increase its chances of visit and the duration of visit by pollinators but also to increase the tendency that a pollinator visits flowers of the same species and therefore improves its chances of reproduction.

This process of Buzz pollination is really interesting to understand the progress of coevolution between flowers and pollinators. This question hasn’t been studied yet but could be a start to improve our knowledge in plant evolution. One other question that the Buzz pollination raises is the influence of sound on cultivated or autogamous plants which are not completely dependent on pollination. Do they also have anther mechanism to deliver some pollen even if its survival doesn’t depend on pollen? (De Luca and al., 2012)

b. Passive communication, a key element to attract bats

Passive communication or passive acoustic signaling in plants relates to their relationship with animals such as bats. Indeed, in this relationship, plants are simply the communication support of bats by reflection of their sound. Some plants are dependent on bats because they allow very good dispersal of the plant's seeds over long distances. Their fertilization therefore depends on the presence of pollinating insects, in this case for passive communication, bats. According to the study “Acoustic interactions between plants and animals” by Michael and Caroline Schöner (2018), it appears that plants associated with bats

have evolved in order to adapt "to the echolocation systems of bats by providing reflectors, which attract mutualistic animal partners" (Michael and Caroline Schöner, 2018).

The interest of plants is to attract bats, so it is in their interest to have "acoustically attractive" flowers to feed bats with nectar (Michael and Caroline Schöner, 2018). Indeed, bats emit sounds and locate nectar and plants thanks to the sound that comes back to them. Thus, the plant, thanks to the acoustic reflection of its flower, communicates its position to bats, in order to promote its fertilization. Bats are good partners for plants because, according to the study by Kalko and Condon (1998), they can disperse seeds over long distances without damaging them.

In a study that Michael and Caroline Schöner conducted in 2016, they investigated the different reflections of sound by plants depending on the shape of plant organs. Indeed, the sound that propagates in the middle of plants is very diffuse and difficult to pick up by bats. This is why some plants have a special shape that concentrates the sound information so that it is better perceived by the animal. The figure 5 presents the different plant forms with sound transmission efficiency. The neotropical vine Marcgravia evenia's leaves are used because it is a bat-pollinated plant. Figures (a) and (b) represent the shape of its leaves in the form of plate and foliage respectively. Another carnivorous plant, the *paleotropical Nepenthes hemsleyana* has been studied because it is fertilized by bat droppings. Figure (c) shows the back wall of the pitchers of the plant. Finally, figure (d) represents the leaf of the plant *N. rafflesiana*, which is the closest plant to *N. hemsleyana* (c), but which has no relation to bats.

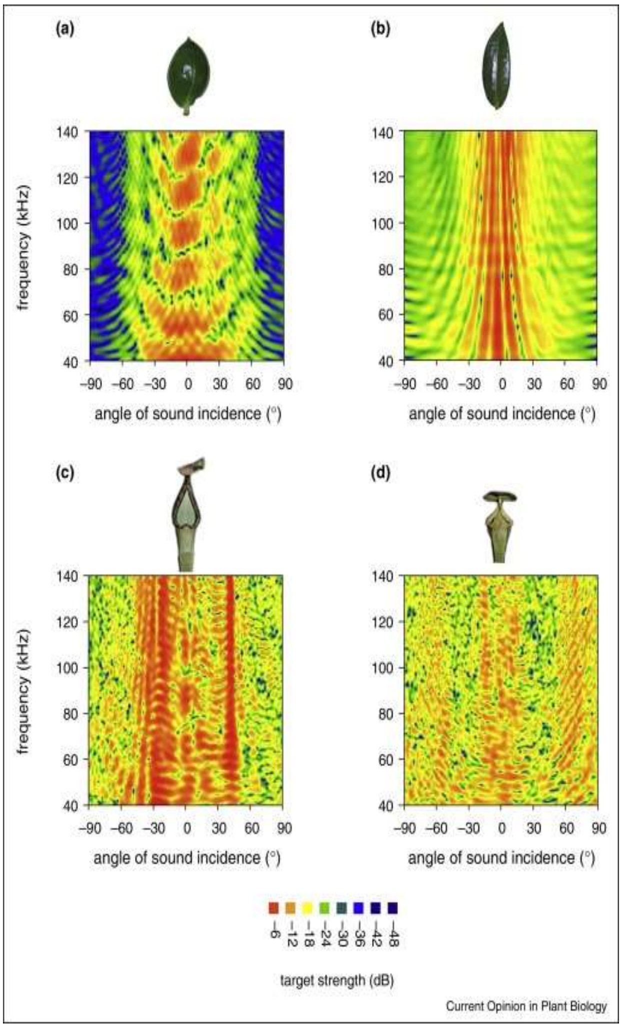

Figure 5 : Passive acoustic signaling in two unrelated plant species.

(Schöner, M. G., & Schöner, C. R.,2016)

We observe on the results that the leaves from plants associated with bats have a greater reflection of multidirectional sound waves. On the contrary, the leaves of *N. rafflesiana* (d) send back the sound waves in a diffuse and not very intense way. In the case of this example, it is the leaves that reflect the sound waves, but in other cases it can be the flowers or the hairs of the cactus that act as a reflector. Based on the study “Echoes of bat-pollinated bell-shaped flowers: remarkable for nectar-producing bats?” by Von Helversen and al. (2003), there are bell-shaped flowers pollinated by bats, whose specific shape makes it possible to return long-lasting echoing sounds easily identifiable by the bat. This is the case for example of *Markea neurantha*.

Finally, in a study conducted by Korine and al. (2005), it was shown that fruits can also be detected by bats using sound waves. Fruits that hang along a single stalk, without leaves and other sources of wave scattering, are easily located. However, this also has disadvantages for the plant because it has to use a lot of energy to make a fruit at the end of a leafless stem (loss of photosynthesis).

It would be interesting to continue research on this subject of communication between plants and animals, in particular by studying different species of plants, trees, etc. Is all the plant world able to communicate with sound or only a few species have developed this ability? Similarly, we may wonder what are the ecological, environmental parameters that allow sound communication? Finally, studying sound communication in plants in an evolutive approach would be interesting.

2.2. Sound as an asset for plants to better adapt to their environment

It is well-known that chemical signals exist between plants as an alert to potential dangers such as herbivore attacks. Nevertheless, as we mention in this paper, recent studies have shown that the chemical processes wouldn’t be the only ones that come into play for communication purposes (Schöner and al., 2016)(Mishra and al., 2016)(Bhandawat & Jayaswall, 2022). It would even be less efficient than sound signals between plants (Gagliano, 2013). More than a means of communication, perceiving sound is also a way for plants to better adapt to their environment.

As seen previously in part 1.2 and 1.4, the plant can emit and receive sound waves. This is very useful because it allows communication between plants via sound. One hypothesis of communication between plants is that the stressed plant emits sound waves in order to warn neighboring plants (Falik et al., 2011). Thus, non-stressed neighboring plants

can trigger stress reaction mechanisms and thus better defend themselves. This is particularly the case in the event of drought, plants that receive a sound signal of water stress can in anticipation close their stomata in order to protect themselves against drought (Mishra and al.,2016).

In a study by Appel and al (2014), the interaction of the plant with herbivorous insects was studied. For the study, the caterpillar of *P. rapae* was taken as a herbivorous insect and the plant studied is *A. thaliana*. It has been shown that the caterpillar, by consuming the leaves of the plant, when chewing, produces a sound wave that the plant receives and which is transmitted to the whole plant. These vibrations induced by herbivores are well differentiated from other vibrations such as the wind by the plant. The reception of vibrations allows the plant to be alerted and thus to react. It produces an audible warning signal to warn other plants and also produces a chemical defense (Appel and al., 2014). It has not yet been studied whether the plant defends itself against herbivorous insects using sound waves. Indeed, it remains to be proven that the sound emitted by the plant has a deterrent impact on insects. However, the sound waves produced by the herbivore are amplified by the plant in order to prevent symbiotic species protecting the plant. These protective species such as ants are attracted to the plant to defend it by chasing the attacker (Chamberlain and al., 2009).

In 2013, an encouraging study conducted by Michel Renton and Monica Gagliano - one of the first scientists to start studying phytoacoustics (the sound of the plant) - showed how a basil plant stimulates the germination of chilli seeds, recognizing the presence of neighbouring, even when all signaling pathways between plants, except sound (chemical, touch and light) were blocked. Figure 6 shows the results of the experiment.

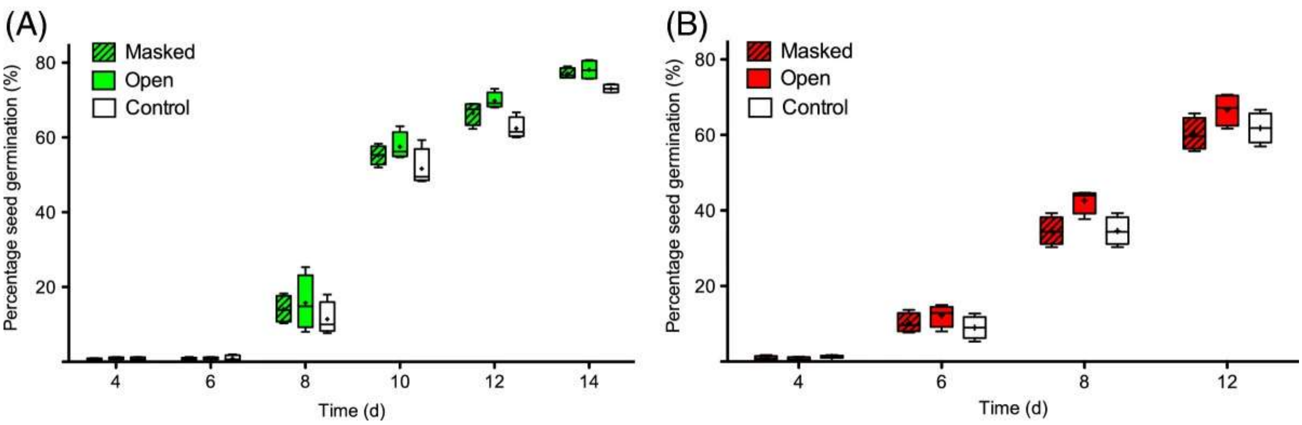

Figure 6 : Effects of the presence of a neighboring (A) basil and (B) chilli plant on the percentage of chilli seeds germinating over time

(Galliano and Renton, 2013)

On graph A, we find the experiment where the neighboring plant of pepper seeds is basil, whereas on graph B, the chilli seeds have a chilli plant as a neighbor. The experiment

was carried out masked (chemical signals, touch and light blocked), in an open environment and in a room with a controlled environment. According to the p-value, the germination rate of chilli seeds when the basil was masked or not did not change. Thus, neither light, nor touch, nor chemical substances influenced the growth of the seeds, so it is likely that the plants detected their neighboring presence by auditory signals. Such knowledge of the presence and identity of its neighbors is an advantage for the plant and allows it to put a growth strategy in place. Indeed, in the experiment we observe that in the presence of basil (A) the seeds grew quickly, while in the presence of chilli (B) the growth was slower. According to (Galliano and Renton, 2013), the plant responds, according to competition from neighboring plants, chilli is a competitive plant for chilli seeds, so it moderates its growth while basil is a "friendly" plant. The plant has a response “tailored to the specific identity of the neighbor (friend or foe)” (Galliano and Renton, 2013).

The capture of sound waves has yet other advantages for the plant, this time at the root level. In the research work of Monica Gagliano, the roots of maize plants have been shown to bend to push towards a sound source simulating the sound of water (Gagliano et al., 2017). This demonstrates a certain ability of plants to adapt to their environment through sound. When the presence of water is more rare or distant, the plant thanks to the acoustic waves can survive and grow optimally to reach the water (Bhandawat and al., 2022).

Now that it has been shown that inter and intraspecific (between plant/plant and plant/animals) acoustic communication in plants exist, it is still to be understood for what purposes plants communicate between each other through acoustic signals.

It remains to be seen how the plant can react in the event of sound wave overstimulation. Can it sort out all the waves, how is it chosen to favor one wave over another? These are things that would be interesting to study.

Phytoacoustics was quickly perceived as a field of research that could quickly be applied to the field of agronomy. Many research works are now focused on looking for visible positive effects in plants. The workload remains greater, that the plants can discriminate the sound waves and that the sound can cause negative effects. However, finding the right frequency/intensity combinations for each plant species studied offers great prospects for agronomy in the coming years. Indeed, this could make it possible to develop crop productivity, strengthen the fight against certain diseases, while limiting the use of fertilizers or pesticides. However, we saw that plants have certain thresholds above which sound can be detrimental to its development. So, because plants are everywhere in our everyday life, we can therefore easily imagine that anthropogenic sound waves could have a negative effect on their development...

3. Relationship between plants and anthropic sounds

3.1. Impact of city noises on plants

Plants are increasingly present in urban areas. They are used as an element of the structuring, decorative landscape, to cool cities. However, studies such as those by Iannace and al. (2021) suggest that plants can also play a role in the acoustic attenuation of urban noise. In town, for example, certain plants are the first to be exposed to noise and sound waves. Instead of looking at what plants bring to the city, one can ask what impact sound waves have on plants.

This is what Kafash and al. (2022) proposes to study in their study “Traffic noise induces oxidative stress and phytohormone imbalance in two urban plant species”. This study shows that car traffic noise is perceived as an environmental stress by plants. Indeed, it has been observed that the reactions induced by sound waves are stress response mechanisms. In particular, it was observed that after a 16-hour exposure to traffic noise (about 73 dB) for a period of 15 days, the species S. splendens and T. patula were affected in several ways.

Firstly, it appeared a delay in the growth of the plants with in particular a reduction in the biomass of 27% for *S. splendens* and 17% for *T. patula* (measurements relative to the fresh weight). On the phytohormone side, there have also been changes. Indeed, levels of phytohormones such as indole 3-acetic acid (IAA), gibberellic acid (GA3), zeatin and salicylic acid (SA) were significantly reduced. Conversely, phytohormones such as jasmonic acid (JA) and abscisic acid (ABA) increased significantly.

The loss of biomass previously observed is mainly explained by the decrease in the growth phytohormones IAA, GA3 and zeatin because these hormones, when present, increase plant cell division and expansion. The response of plants through the regulation of plant hormones shows its plasticity and its ability to react to stress. IAA is a very important hormone for the plant's response to stress, according to Wolters and Jürgens (2009), it is this hormone that mainly limits the damage to the plant from external environmental factors. In a study, Bartoli and al. (2013) suggested that the strong reduction of auxin such as IAA is a mechanism that allows a greater ability of plants to adapt and resist environmental stress such as stress caused by sound waves generated by road traffic.

The other hormones that have been impacted by the sound waves are also very important. According to a study by Finkelstein and al. (2008), the phytohormones ABA and

GA3 would have a link and an effect depending on their relative proportions. If, as is the case in the study (Kafash and al., 2022), the ABA content increases and that of GA3 decreases, then the ABA/GA3 ratio results in an increase in the DELLA protein. This protein is when it accumulates in plants thanks to the ABA/GA3 ratio, it leads to a high tolerance to biotic and abiotic stresses. Thus, in the study (Kafash and al., 2022) the combination of the phytohormones ABA and GA3 can increase the tolerance of plants to environmental stress generated by road traffic. The increase in the plant hormone ABA coincides with the decrease in zeatin. According to a study by Sreenivasulu and al. (2012), it was confirmed that ABA is at the heart of the plant's response to stress (physiological response, embryo dormancy, changes in physiological mechanisms and reprogramming of the plant). expression of genes…). A study by Hassanien and Li (2020) confirmed the results of (Kafash and al., 2022) by also observing in a strawberry species, an increase in ABA following environmental stress due to sound waves which once again confirms the primordial role of the plant hormone ABA.

In Kafash's study, SA (salicylic acid) is negatively impacted by increased ABA. According to Thevenet and al. (2017), SA is also a very important plant hormone for environmental stress response. Finally, it was observed that the JA content increased significantly following the exposure of the plant to sound waves, which is consistent because this hormone allows the plant to react in the event of cell damage due to environmental stresses.

Apart from hormones, experiment (Kafash and al., 2022) has also shown that exposure to sound waves from road traffic caused in plants “an increase in the rate of formation of H202 as well as an increase in oxidative damage to biomembranes, marked by an increase in MDA (malondialdehyde) content” (Kafash and al., 2022). The increase in the rate of formation of H2O2 which is a reactive oxygen species (ROS), can be toxic and cause damage to proteins, lipids, DNA and others, this is called oxidative stress. According to Ghotbi-Ravandi et al (2021), H2O2 is a reactive oxygen species that is very harmful to plants because it has a longer half-life than that of oxygen and is rather stable, which allows it to spread into tissues and can cause peroxidation of membrane lipids which is “one of the most harmful processes that occur in cells, which impairs membrane fluidity and integrity, increases solute leakage from the cell and inactivates membrane protein complexes” (Garg & Manchanda, 2009). MDA content is an indicator of lipid peroxidation, and in the study (Kafash and al., 2022), MDA levels increased significantly following exposure to sound waves. Thus, the noise of road traffic increased the peroxidation of lipids, which is also consistent with the increase in the level of H2O2. To combat this phenomenon, the plant has a defense mechanism called the antioxidant system. The plant has an ability to trap and eliminate ROS such as H2O2. This happens thanks to antioxidant enzymes which have a protective role by breaking down H2O2

molecules. Thus, a high activity of these enzymes shows a strong ability to resist environmental stress such as road traffic noise.

Thus, the study (Kafash and al., 2022) showed that the plants studied have great plasticity in the face of environmental stresses thanks to hormones and enzymes. Plants therefore have the plastic capacity to live in an urban environment. However, because of the mechanisms they must put in place to resist environmental stresses due to sound waves in this case, plants can develop less, create biomass and grow optimally.

Few studies have been carried out on this subject of the noise impact of cities on plants. However, as seen in this section, car noise has a detrimental effect on plants. Thus, it would be interesting to study other city processes that emit sound waves and study their impact on plants to complete this gap of knowledge. It would also be interesting to study how it would be possible to reduce the amount of sound waves received by plants in the city.

3.2. Agriculture perspectives

Agriculture is a field confronted with environmental hazards and yield pressure. Farmers to control diseases, crop pests and other environmental factors resort to the use of pesticides. These chemical techniques are effective for the most part, however the big counterpart is their harmful aspect for humans. Bioengineers are therefore looking for more natural ways to continue to maintain good quality agricultural production without major yield losses.

The ability of plants to capture sound waves and to emit them in turn is a faculty that has greatly interested researchers in the quest for a substitute for pesticides. This is notably the case of Fernández-Jaramillo and al. (2018) in his study “Effects of acoustic waves on plants: an agricultural, ecological, molecular and biochemical perspective”. Acoustic vibration, of a certain frequency as previously explained in part 3.1, can constitute an environmental stress and therefore induce defense and plasticity mechanisms in the plant, adaptation to the external environment and to other frequencies, the sound wave can stimulate the plant and allow faster growth ((Collins, 2001), (Khait et al., 2019), (Hendrawan et al., 2020)).

Choi and al. 2017 in a study “Positive regulatory role of sound vibration treatment in Arabidopsis thaliana against Botrytis cinerea infection”, showed that exposure of the Arabidopsis plant to a sound wave of 1000 Hz, allowed it to become resistant to “infection with a necrotrophic fungal pathogen, B. cinerea” (Choi and al. 2017). The plant was able to produce a stronger response thanks to a greater activation of its genetic defenses. This same study showed the same effects on bean, corn, tomato, and cucumber plants. Their tolerance to environmental stress was improved thanks to the sound stimulation which, as said in part 3.1,

itself represents an environmental stress for the plant. The sound vibrations modify the expression of certain genes, the level of phytohormone, the activity of enzymes (Li, 2008), which prepares the plant to defend itself against a future attack.

Scientists are very interested in the potential of sound on plants. Profits in agriculture, as said before, are very attractive. This is why researchers such as Sternheimer[4] (1980) have developed music that would stimulate plant growth based on the molecular level of the plant. The sound sequences of the music are not random: they are carefully constructed melodies. Each note is chosen to correspond to an amino acid in a protein with the complete melody corresponding to the entire protein. Physically, amino acids are large molecules that are present in all cells. The wave relationships between the waves associated with the masses of these amino acids are in a harmonic relationship. And so naturally when a protein is produced and synthesized on a ribosome in a cell, there is emission of a series of frequency pulses. This means that sounds sequenced in the correct order sound unique and harmonize with the internal structure of a specific type of plant. Each type of plant has a different sequence of notes to stimulate its growth. According to New Scientist[5], "Sternheimer claims that when plants 'hear' the appropriate tune, they produce more of this protein. He also writes tunes that inhibit protein synthesis." In other words, it would stimulate the growth of desirable plants, and inhibit that of undesirable plants (weeds for example). Thus, Sternheimer translated into audible vibrations of music the quantum vibrations that occur at the molecular level when a protein is assembled from its constituent amino acids. Using simple physics, he is able to compose music that achieves this correlation. Sternheimer told New Scientist that each musical note in a proteody is a multiple of an original frequency emitted when an amino acid joins the protein chain. He says playing the right notes stimulates the plant and increases growth. This idea is particularly attractive because it can lead to the eventual obsolescence of fertilizers used to stimulate plant growth. This new method would be cheap and relatively easy to supply worldwide, avoiding many of the problems associated with the extraction, shipping, environmental and economic costs of chemical fertilizers. Playing the right melody stimulates the formation of vegetable proteins. "The length of a note is the actual time it takes for each amino acid to come after the next," according to Sternheimer, who studied quantum physics and math at Princeton University. In his experiments, he claims that tomatoes exposed to his proteodies were two and a half times larger than those that had not been treated. Some of the plants on display were even sweeter in addition to being much bigger! At the molecular level, the musical sequences stimulated two proteins responsible for tomato growth, cytochrome C

[4] Video of an interview with Sternheimer by "Collectif CLPU" : https://www.dailymotion.com/video/xaw07l
[5] Article on Sternheimer theory : https://www.newscientist.com/article/mg14219271-500-good-vibrations-give-plants-excitations/

and thaumatin (a flavoring compound). Even more interesting: Sternheimer claims to have stopped the mosaic virus, which is harmful to tomato plants, by playing sequences of notes that inhibited the enzymes required by the virus. The note sequences used by the inventor are very short and should only be played once. For example, the sequence for cytochrome C is only 29 seconds long. According to Sternheimer, "on average there are four amino acids played per second" in this series. The inventor also issued a warning for those who repeat his experiments. He warns to be careful with sound footage as it can affect people. "Don't ask a musician to play them," he says. Sternheimer reported that one of his musicians had difficulty breathing after playing the Cytochrome C tune.

Another experiment conducted by Sternheim could provide clues to fight against pollution in the city thanks to algae[6]. Indeed, after having stimulated the algae for 10 minutes a day with music composed of proteoids associated with proteins allowing carbon fixation and oxygen production, we observe the appearance of oxygen bubbles and when we measure, the quantity of oxygen emitted is sixteen times greater than that of unstimulated algae. Thus, the presence of algae in the city with photosynthesis stimulated by music would re-oxygenate cities.This theory of Sternheimer is questionable because there was not a lot of experimentation about. That is why in 2018, a team from the university of Cergy[7] in France studied this theory with cucumber plants which confirmed Sternheimer's theory.

Finally, exposure of plants to sound waves in agriculture would work like a vaccine by preparing plants to defend themselves through changes in internal mechanisms. In short, it allows “to give plants a controlled stress, causing an activation of the defense against a particular disease or pest. “(Fernández-Jaramillo and al., 2018). It is therefore a solution for the fight against pesticides at a lower cost, good for the environment, good for human health, while keeping plants resistant to their environment.

Applications of sound to plants can still be discovered. Similarly, the advantages that can be drawn from it for a more sustainable agriculture are also to be explored. It would also be interesting to retest the experiments of theories like those of Sternheimer to understand all the parameters and make it a reproducible protocol on a large scale to transform our agriculture.

[6] Les effets de la musique sur les plantes http://esev.e-monsite.com/pages/les-effets-de-la-musique-sur-les-plantes.html

[7] Reporterre - Comment la musique fait pousser les plantes, 2018. Available on : https://reporterre.net/VIDEO-Comment-la-musique-fait-pousser-les-plantes

Conclusion

The objective of this report was therefore to answer the question: How do plants react to their sound environment in rural and urban settings? From this subject, we were able to identify the main parameters that come into play but also to highlight the lack of knowledge on certain points, which could be the subject of future research. Thus, plants interact with sound in multiple ways, whether the effects are positive or negative. These interactions with sounds are due to the development of sensitive mechanical channels that are responsible for the detection of sound vibration.

As we have seen, plants are frequency selective and not all sounds can generate physiological responses. Perceiving sound allows plants to be aware of their environment, to adapt to potential threats, and to predict future situations such as drought.

On the other hand, sound has an important impact on molecular and genetic levels which implies different physiological responses such as plant growth, disease resistance, pollinators attraction etc. Thus, this capacity of plants is a precious reserve of sustainable innovations in the field of agriculture with the stimulation of food production, the fight against diseases, drought and parasites.

But sound is also used as a means of communication in the plant's kingdom but also to communicate with animals. Plants are able to emit sounds, but it is still to be identified if it is intentional, and if yes, for what purposes they emit sounds. The mechanisms of sound emission are also still poorly understood even though some new hypotheses emerged these recent years.

Nonetheless, even if sound can have really interesting effects on plants, it could also have negative impacts. Environmental sounds, and particularly cars in urban areas, or agricultural vehicles in rural environments can be detrimental to their development and understanding the impacts that certain sound waves can have on plants could allow us to better protect them.

Finally, it becomes clear that sound application is promising to cope with food challenges in a middle-term perspective. Yet, further research is needed to be able to see the big picture and to understand all the mechanisms into play (mostly during sound emission) and all the positive effects sound can have on plant development. It is also an interesting opportunity to better understand the impacts of human activities on plants (regarding sound) and to find new solutions to protect biodiversity in urban areas. This study allowed us to identify the main gaps of knowledge which constitute interesting lines of thought to further deepen research and understanding of the plant world.

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Effects of sound waves on plants: Possible sustainable agricultural and biotechnological innovations

Abstract:

Living organisms need to know their environment to live in. Almost all living organisms such as vertebrates evolved in order to perceive and emit sound frequencies. Until recent years plants were regarded as unable to produce or perceive sound, mostly because they don't have visible and dedicated organs for such purposes. Nonetheless, major advancements have been made towards understandings of sound emission and reception in plants. The purpose of this review is to understand the role of sound in plants development and evolution but also to highlight the gaps of knowledge that need to be documented for better understanding of the subject. Plants can emit sound, but it is still unclear if this mechanism is intentional or not, and several hypotheses exist regarding how they do it. Plants are also receptive to sound and frequency-selective which means that sound frequencies can have various effects on plants that occur at genetic, molecular, and physiological levels and that can be either beneficial or detrimental for plant development. This is a precious reserve for sustainable innovations in the field of agriculture with the possibility to improve crop productivity, to fight against diseases, drought, and parasites without use of pesticides. It is also a way to better understand how plants adapt to their environment using surrounding noises.
The main challenge in agronomy is now to find the best combination of frequency, intensity, and time of exposure for selected species. Nonetheless, it is also an opportunity to study the potential negative impacts that sound can have on plants in urban areas (such as the sound of cars). As promising as this field of research may sound, further research is needed to better understand the different mechanisms that exist for plant emission and reception, and if sound emission "in natura", that could interfere with surroundings sound, could be really efficient for plant growth.

Key words: Sound wave; Plants; Animals; Sound communication; Perception; Acoustics