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The chemical basis of plant communication: From phytohormones to bioelectrochemical interfaces

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Abstract
Plants possess a natural ability to sense and respond to environmental changes such as light, temperature, touch, and water availability. However, understanding these plant signals has long been a challenge for humans. Recent advances in bioengineering, sensor technology, artificial intelligence (AI), and Internet of Things (IoT) systems have made it possible to decode and interact with plant responses in real time. This review explores the emerging field of plant communication engineering and the development of smart gardening systems. It discusses bioelectrical sensors, AI-based signal processing, robotic plant interaction systems, and light-mediated communication. These technologies enable plants to "speak" through digital platforms, enhancing plant care, sustainability, and eco-friendly agricultural practices. The paper also highlights the potential applications, benefits, and future challenges of this evolving interdisciplinary area that connects biology, engineering, and environmental science.

Keywords: Plant communication, smart gardening, bioelectrical sensors, AI, robotic plants, sustainable agriculture

Introduction
Plants are living, sensitive organisms that continuously interact with their surroundings. They can detect and respond to various environmental stimuli such as light, gravity, temperature, humidity, water, touch, and even sound. These responses help them survive, grow, and reproduce in changing conditions [1]. Through processes like phototropism (response to light), gravitropism (response to gravity), and thigmotropism (response to touch), plants adjust their structure and functions to adapt to their environment. Unlike animals, plants do not have a nervous system, but they use chemical messengers, electrical impulses, and mechanical changes to sense and communicate both within themselves and with neighboring plants [2]. For instance, when a plant is injured or attacked by insects, it releases chemical compounds to warn nearby plants or to attract natural predators of the pests. This remarkable communication ability shows that plants are far more dynamic and aware of their environment than once believed.

In recent years, the integration of engineering and plant biology has opened new pathways for understanding and decoding plant communication. Modern tools such as sensors, artificial intelligence (AI), robotics, and the Internet of Things (IoT) allow scientists to measure and interpret plant signals such as changes in electrical activity, water content, or photosynthetic efficiency to determine their physiological state. These technologies form the foundation of "smart gardening" or "digital botany," where data-driven systems monitor and respond to plant needs in real time. This progress enables humans to interact directly with plants through technology, creating sustainable solutions for precision farming, environmental monitoring, and resource-efficient agriculture [3, 4].

2. Natural Communication in Plants
2.1 Electrical Signalling
Plants generate weak bioelectrical signals in response to stress factors such as drought, light intensity, or mechanical damage. These electrical variations, known as action potentials and variation potentials, can be detected using electrodes. Monitoring such signals helps determine plant health and environmental stress responses.

2.2 Acoustic Communication

Research has shown that plants emit ultrasonic vibrations when under stress, such as dehydration or injury. These sound patterns, though inaudible to humans, may carry information about plant conditions and can potentially be detected using sensitive microphones or sound sensors.

2.3 Chemical Signaling: Plants release volatile organic compounds (VOCs) into the air or root exudates into the soil to signal nearby plants. For example, when attacked by pests, certain plants emit chemicals that trigger defense responses in neighboring plants a form of plant-to-plant warning system [5, 6]. Table:1 shows some of the airborne chemical signals used for plant-plant or plant-insect communication

Table 1: Common Airborne Phytochemicals Involved in Plant Communication

Compound Type	Examples	Function
Terpenoids	Limonene, Pinene, Myrcene	Attract pollinators or repel herbivores; signal neighbouring plants.
Green Leaf Volatiles (GLVs)	Hexenol, Hexenal	Released upon wounding; warn nearby plants of herbivore attacks.
Floral volatiles	Geraniol, linalool	Attract pollinators, guide them to nectar rich flowers,
Phenylpropanoids / Benzenoids	Eugenol, Cinnamaldehyde	Involved in flower scent and defense signalling.
Alkaloids	Nicotine, Caffeine	Act as chemical deterrents and signal defense readiness.
Sulfur Compounds	Allyl isothiocyanate (from mustard plants)	Signal herbivore defense and deter pests.

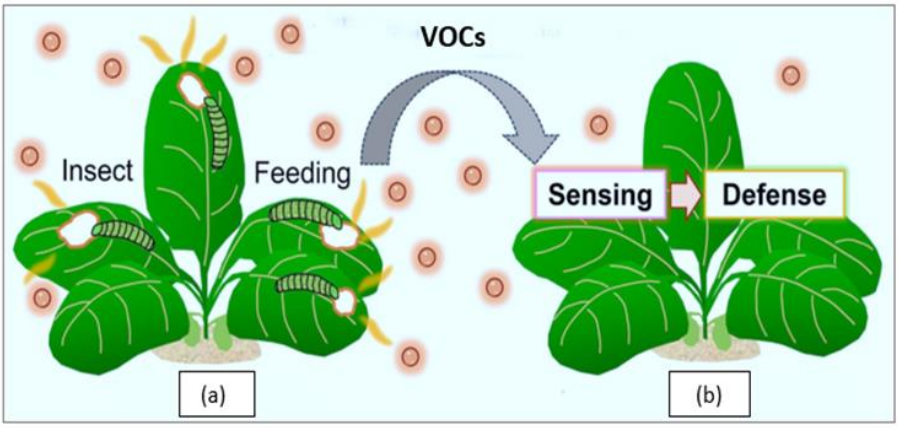
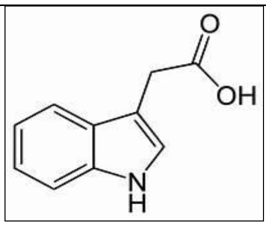
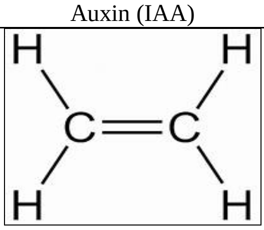
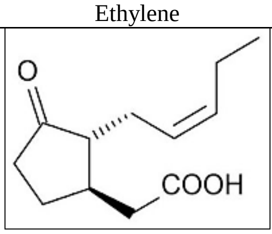
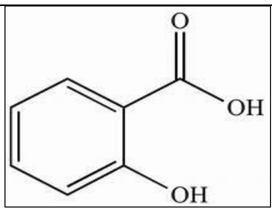
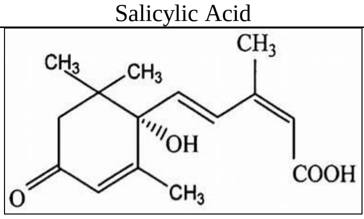


Fig 1: Plants emit volatile organic compounds (VOCs) into the air to communicate and signal with neighbouring plants: a) affected plant b) neighbour plant

Table 2: Major plant hormones and chemical signals with their triggers and physiological responses [7, 8]

Chemical / Hormone	Type	Trigger	Response
 Auxin (IAA)	Growth hormone	Light, gravity	Bending toward light, root growth
 Ethylene	Gas hormone	Touch, injury, stress	Leaf folding, ripening, senescence
 Jasmonic Acid	Defense hormone	Wounding, herbivory	Produces defense compounds

 Salicylic Acid	Defense signal	Pathogen attack	Activates immune response
 Abscisic Acid	Stress hormone	Drought, cold	Closes stomata, conserves water
Volatile Organic Compounds (VOCs)	Airborne signal	Herbivore or pathogen attack	Warns neighbouring plants
Calcium Ions (Ca^{2+})	Cellular messenger	Touch, mechanical stress	Rapid leaf movement

2.4 Photoreception and Light Response

Light not only powers photosynthesis but also serves as a communication channel. Plants sense specific wavelengths blue and red for growth and flowering and respond to light patterns by changing orientation or metabolism. Excessive or insufficient light can generate stress signals detectable by sensors [9, 10]. Some of the plant species and its sensitivity to light and touch is given in table: 3

Table 3: Examples of daylight-sensitive plants and their unique responses [11].

S.No	Plant Name (Scientific Name)	Type of Sensitivity	Visible Response or Special Behavior	Interesting Fact
1	Mimosa pudica (*Touch-me-not*)	Touch / Vibration	Folds leaves instantly when touched or shaken.	Reacts within seconds; regains position in 10-15 minutes.
2	Maranta leuconeura (*Prayer plant*)	Light (Day/Night)	Raises leaves at night and lowers them in the morning.	“Prays” daily — follows circadian rhythm.
3	Desmodium gyrans (*Telegraph plant*)	Light / Temperature	Small leaves move in circular motion every few minutes.	Famous “dancing plant,” even reacts to sound waves.
4	Oxalis triangularis (*Purple shamrock*)	Light / Touch	Folds its purple leaves in darkness or when touched.	Often used for classroom plant experiments.
5	Samanea saman (*Rain tree*)	Humidity / Light	Leaves close before rain or at night.	Known as “five o’clock tree” due to daily leaf closure.
8	Codariocalyx motorius (*Dancing grass / Semaphore plant*)	Sound / Light	Side leaflets “dance” faster under sunlight or sound.	Responds to music or rhythmic sound vibrations.
10	Boehmeria nivea (*Chinese nettle*)	Touch	Slight leaf vibration when touched.	Related to nettle plants, but non-stinging variety.
11	Trifolium repens (*White clover*)	Light / Gravity	Leaflets adjust to follow sunlight direction.	Exhibits slow, graceful movement toward light.
12	Phaseolus vulgaris (*Bean plant*)	Light (Phototropism)	Bends toward light source.	Classic example of plant motion due to auxin distribution.
13	Helianthus annuus (*Sunflower*)	Light (Heliotropism)	Flower head follows the sun’s movement.	Symbol of phototropic plant behavior.
15	Codiaeum variegatum (*Croton plant*)	Temperature / Stress	Leaves change color with stress, light, or age.	Used for environmental sensing and color research.

3. Emerging Engineering Techniques for Plant Communication:

3.1 Bioelectrical Sensors: Miniature electrodes are attached to plant leaves or stems to measure electrical potential changes. These sensors transmit data to computers or smartphones through wireless modules. The data are analyzed to assess plant hydration, stress level, or disease conditions. For instance, a drop in electrical conductivity may indicate water stress.

3.2 Artificial Intelligence (AI) Integration

Machine learning algorithms are now being used to interpret complex plant signals. By analyzing sensor data, AI systems can predict plant needs, automate irrigation, and even simulate plant “emotions” such as stress or comfort. Some mobile applications can send real-time alerts like “Water me” or “Too much light.”

3.3 Robotic Systems (Flora Robotica)

The Flora Robotica project combines living plants and robotic systems that grow together in symbiosis. Robots use light and tactile cues to guide plant growth in desired directions, forming living structures such as self-repairing green walls, bridges, and adaptive architecture.

3.4 Light-Based Communication
Recent experiments show that light pulses, including lasers and LEDs, can influence plant signaling pathways. By controlling the intensity and wavelength of light, researchers can trigger specific physiological responses, enabling two-way communication between humans and plants.

3.5 IoT and Smart Gardening Apps
Smart gardening systems use IoT-based sensors embedded in soil or leaves. These sensors monitor temperature, humidity, pH, and nutrient levels, transmitting data to cloud-connected apps. Users receive updates and care suggestions, making home and urban gardening more interactive and sustainable [12-14].

4. Devices for Monitoring Plant Communication
Scientists have developed several innovative devices to detect and interpret the electrical and biochemical signals plants use to communicate and respond to their environment. These technologies bridge the gap between plant biology and engineering, enabling real-time monitoring and interaction with plant systems.

4.1. Plant Wave
Plant Wave is a commercially available device that captures the electrical activity of plants and converts it into sound. By attaching electrodes to the plant, it detects bioelectrical signals and translates them into musical tones, allowing users to "listen" to their plants' responses. This tool is used for both scientific research and artistic exploration. The main components of Plant Wave include the electrodes for signal detection, an amplifier to boost the signals, a processor to translate them into sound, an output device to produce the audible tones, and a power source, usually a battery, for portability [15].

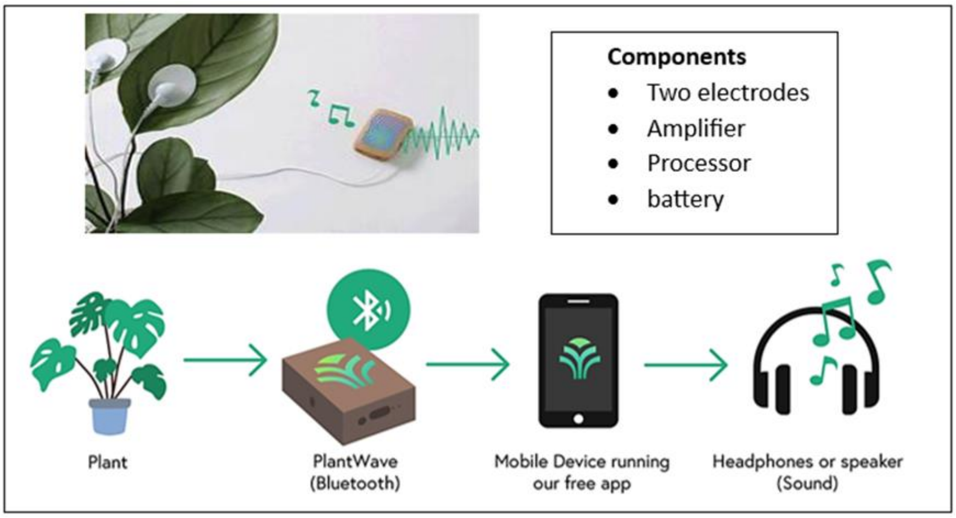


Fig 2: Schematic of how the plant wave device converts bioelectrical signals into sound.

4.2. Conformable Electrodes: Researchers at Nanyang Technological University developed a device that uses soft, conformable electrodes to interface with plants like the Venus flytrap. These electrodes can both read electrical signals from the plant and send small stimuli to trigger actions, like making the trap close. This two-way communication system allows scientists to interact with plants in real-time, opening up new possibilities for plant-based robotics and smart environmental monitoring [16].

4.3. Multi-Electrode Arrays: At Linköping University in Sweden, researchers made very thin films with many tiny electrodes that can bend and fit onto the surface of plant leaves. These multi-electrode arrays can detect electrical signals from different parts of the leaf at the same time. This helps scientists see exactly how plants send and process signals when they respond to things like touch, light, or stress, giving a detailed picture of plant "communication [17].

4.4. SpikerBox: The SpikerBox is a low-cost device designed to detect and amplify the electrical signals (action potentials) in plants. It has been used in educational settings to demonstrate plant responses to various stimuli, such as touch or light, providing insights into plant neurobiology

4.5. Motion Leaf
Motion Leaf utilizes millimeter-wave radar sensors to monitor the subtle vibrations of plant leaves. By analyzing these vibrations, the system can assess plant health and detect stress factors like water scarcity, offering a non-invasive method for precision agriculture. These devices represent a significant advancement in our ability to understand and interact with plant systems, paving the way for innovations in sustainable agriculture, environmental monitoring, and bio-inspired technologies [18, 19].

5. Benefits and Applications
- **Enhanced Plant Health:** Continuous monitoring helps detect stress early, improving growth and yield.
- **Water Conservation:** Smart irrigation systems deliver water only when required, reducing waste.
- **Disease Detection:** AI-driven systems can identify early symptoms of diseases and nutrient deficiencies.
- **Urban Green Design:** Robotic plant systems support vertical gardens and bioarchitectural designs.
- **Sustainable Agriculture:** Minimizes chemical use, optimizes resources, and promotes eco-friendly practices [20].

5. Challenges and Future Directions

Despite rapid advancements, several challenges remain:

- **High Cost and Maintenance:** Advanced sensors and AI systems are expensive for large-scale adoption.
- **Signal Complexity:** Plant responses vary across species and environmental conditions, making standardization difficult.
- **Data Interpretation:** Translating plant signals into accurate "messages" requires complex algorithms.
- **Two-Way Interaction:** Future research must focus on developing systems that allow plants to not only "talk" but also "respond" to human or machine inputs.

In the future, smart cities could include living networks where plants and robots work together. Plants could send signals about their environment like soil moisture, sunlight, or air quality and robots could respond immediately to adjust conditions, such as watering the plants, controlling light, or cleaning the air. This combination of nature and technology would help create sustainable and eco-friendly cities.

6. Conclusion

The intersection of biology, engineering, and digital technology has redefined how humans understand and care for plants. Smart gardening systems using bioelectrical sensors, AI, robotics, and IoT enable a new era of plant-human communication. These technologies promise more efficient, sustainable, and intelligent agricultural practices while deepening our connection with nature. As research advances, the dream of co-living with "talking plants" in self-sustaining green cities is becoming a scientific reality.

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Conflict of interest

The authors declare no conflict of interest.

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