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THE INFLUENCE OF MUSIC ON PLANT GROWTH IN A SMART GREENHOUSE USING IoT TECHNOLOGY

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Abstract

This paper presents the development and evaluation of an Internet of Things (IoT)-based control system for small-scale greenhouse environments. The core of the system is the Arduino Nano 33 IoT (SAMD21 Cortex-M0, 32-bit), which integrates multiple environmental sensors to monitor temperature, air humidity, soil moisture, and light intensity. Based on user-defined parameters, the system automates plant care actions: activating an LED lighting matrix, powering a ventilation fan, and triggering a water pump for irrigation. System monitoring and control can be performed locally through an LCD interface or remotely via a cloud-based dashboard. Beyond automation, the study investigates the influence of various types of music - such as classical, techno, and meditation - on the germination and growth of lettuce and radish plants. Experimental results indicate that classical and meditation music enhanced plant development, while techno music had a negative effect, despite otherwise optimal environmental conditions. The findings demonstrate the dual potential of IoT systems for smart agriculture: enabling precision environmental control and exploring novel stimuli, such as sound, to support plant growth.

***Key words**: IoT, smart greenhouse, Arduino Nano 33 IoT, plant growth, music influence, environmental control, automation.*

INTRODUCTION

Food insecurity in climate-vulnerable regions, such as Kenya, has intensified the need for automated greenhouse systems capable of maintaining stable internal conditions irrespective of external weather fluctuations. This challenge arises from increasingly erratic climatic conditions that inhibit optimal plant development. While conventional greenhouses partially address this by enclosing crops within controlled environments, they often rely heavily on manual oversight to maintain ideal growth parameters. Prior studies have emphasized the significant impact of environmental factors such as light, temperature, and humidity on plant development under greenhouse conditions (Mitova et al., 2021).

Each greenhouse operates within a specific set of environmental parameters, which vary depending on the species being cultivated (Figure 1).

To support healthy plant growth, conditions such as air temperature, humidity, light intensity, and soil moisture must be maintained within tightly controlled thresholds. Addressing both food insecurity and environmental degradation requires integrated, innovative solutions.

Figure 1. Example of a modern large-scale greenhouse

Recent research has therefore focused on low-cost, microcontroller-based systems that automate environmental monitoring and regulation. Gitonga (2020) developed a prototype utilizing sensors, SMS technology, and Bluetooth connectivity to remotely control greenhouse conditions. However, as Natonis (2023) points out, the increasing deployment of IoT devices introduces new challenges in system configuration, network behavior, and device interoperability, requiring robust architecture and management strategies.

The Internet of Things (IoT) paradigm facilitates the development of smart greenhouses that not only automate internal processes but also allow for remote access and control. While the "Things" aspect focuses on physical devices and user interaction, cloud infrastructure plays a crucial role in processing data and supporting remote communication.

Efficient system design must go beyond enhanced processing power to include scalable architectures that minimize bandwidth consumption and latency. RESTful web services, which operate over the HTTP protocol, can serve as flexible interfaces for these user interactions (Wang, 2017), as illustrated in Figure 2.

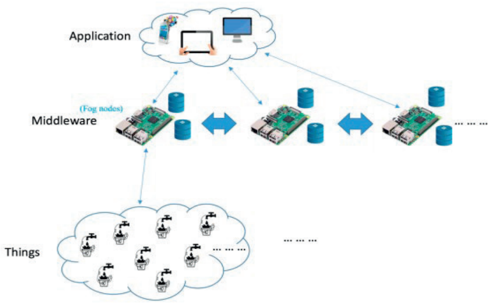

Figure 2. The proposed architecture of the system (Wang, 2017)

Despite these technological advancements, high costs and design complexity have limited the widespread adoption of smart greenhouses. This study proposes the development and testing of an affordable IoT-enabled greenhouse prototype equipped for remote monitoring and environmental automation. In addition to automation, the study explores the use of music as a non-invasive stimulus to enhance plant growth - an emerging area of interest in sustainable agricultural research.

Lai and Wu (2020) found that lettuce seedlings exposed to Gregorian chant, new-age, and waltz music exhibited significant improvements in radicle and hypocotyl elongation, suggesting that certain acoustic frequencies may enhance early plant development. In their experiment involving nine distinct music genres, alfalfa seeds exposed to rock music germinated less effectively, while classical, nature sounds, and waltz promoted germination. Lettuce seedlings responded positively to Gregorian chant, jazz, nature sounds, and new-age music.

This research introduces a user-friendly interface that integrates mobile applications and cloud-based platforms for monitoring and managing greenhouse conditions. By transforming a conventional greenhouse into a smart, responsive system, the study contributes to understanding how IoT automation and acoustic stimuli can jointly promote sustainable, resource-efficient plant growth in controlled environments.

MATERIALS AND METHODS

This section describes the hardware and software components employed in constructing the smart greenhouse prototype. It outlines the configuration of microcontrollers, sensors, actuators, and user interfaces. Additionally, it details the experimental protocol designed to evaluate plant growth under controlled environmental conditions and various musical exposures.

Hardware Components

The smart greenhouse system is built around two primary processing units: the **Arduino Nano 33 IoT** and the **Raspberry Pi 4 Model B**. The Arduino Nano 33 IoT (Figure 3) was chosen for its integrated wireless capabilities and compatibility with the Arduino Cloud platform. During the initial design phase, the Arduino Cloud "Starter Plan" was used to collect sensor data and create a basic dashboard for environmental monitoring. To improve flexibility and system performance, the configuration was later expanded to incorporate a Raspberry Pi.

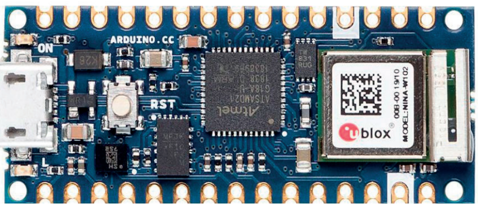

Figure 3. Arduino Nano 33 IoT (Arduino, 2025)

The Raspberry Pi 4 Model B, equipped with 4 GB of RAM, a 16 GB microSD card, built-in Wi-Fi, and a touchscreen display (Figure 4), serves as the local server. This unit manages the graphical interface, local database, and actuator control logic. Its inclusion ensures enhanced system scalability, data security, and offline functionality.

Figure 4. Raspberry Pi 4 Model B (Raspberry Pi, 2025)

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Sensor Specifications

The smart greenhouse prototype integrates three primary sensors to monitor key environmental parameters essential to plant development:

- *DHT11 (Air Temperature and Humidity Sensor)*. This sensor measures ambient temperature and relative humidity. It operates within a temperature range of 0-50°C with ±2°C accuracy, and a humidity range of 20-90% with ±5% accuracy. The DHT11 requires an input voltage of 3.0-5.5 V, communicates through a single digital pin, and consumes between 0.5-2.5 mA during active operation (100-150 µA in standby mode).
- *BMP180 (Barometric Pressure Sensor)*. The BMP180 monitors atmospheric pressure and temperature. It operates between 3.3 V and 5 V and communicates via the I²C protocol through the SDA (A4) and SCL (A5) pins. It measures pressure within the 300-1100 hPa range with an accuracy of ±0.12 hPa and has a minimal current consumption of approximately 3 µA. Its compact form factor (14 mm × 12 mm) enables easy integration into embedded systems.
- *Soil Moisture Sensor*. This sensor uses two conductive probes to assess soil moisture by measuring resistance. It operates at 3.3-5 V and provides an analog output signal ranging from 0 (dry) to 1023 (wet), as interpreted by the Arduino's 10-bit ADC.

The environmental parameters were monitored using a set of three sensors: DHT11 for air temperature and humidity, BMP180 for atmospheric pressure, and a soil moisture sensor. A summary of these sensors and their technical specifications is presented in Table 2.

Table 1. Central Computing Units Used in the Smart Greenhouse System

Component	Arduino Nano 33 IoT	Raspberry Pi 4 Model B
Function	Sensor interfacing and real-time control	Local server for control and visualization
Specifications	Wireless, ARM Cortex-M0+ core, integrated Wi-Fi	4 GB RAM, Wi-Fi, touchscreen display
Rationale	Easy wireless setup, Arduino Cloud compatible	Custom UI, local database, higher flexibility

Table 2. Environmental Sensors and Their Technical Specifications

Sensor	**DHT11**		**BMP180**	**Soil**
Parameter	Temperature	Humidity	Pressure	Moisture
Measurement Range	0–50°C	20-90%	300-1100 hPa	0-1023 (ADC)
Accuracy	±2°C	±5%	±0.12 hPa	N/A
Voltage	3-5.5 V	3-5.5 V	3.3-5.5 V	3.3-5.5 V

System Configuration and Components

The physical structure of the system is divided into three functional compartments: the experimental chamber, the control panel, and the water reservoir, as shown in Figure 5.

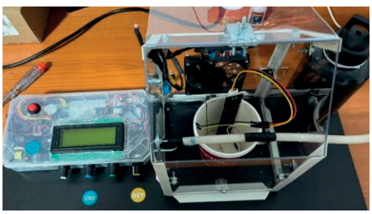

Figure 5. The system setup

- Control panel includes breadboard with all interfacing components:
  - *DS3231 real-time clock (RTC) module* for accurate timestamping of sensor data;
  - *Transistors* to switch actuators (fan, pump, lights);
  - *Potentiometers* to define custom threshold values;
  - *Resistors, jumpers, and wiring* for circuit completion;
- Water tank houses - a submersible pump positioned at its base;
- Ventilation fan - mounted in the main chamber, ensures airflow via small circular vents;

- LED lighting system - 8 UV, 4 red, and 4 sky-blue LEDs simulate daylight spectra to promote photosynthesis.

Experimental Protocol

To investigate the effects of musical stimulation on early-stage plant development, five experimental groups were established. Each group consisted of four Lactuca sativa seedlings (cultivar 'May King'), cultivated under identical environmental conditions inside the smart greenhouse. Musical exposure was administered using a speaker placed at a fixed distance from the seedlings, delivering audio at an average intensity of approximately 65 dB for 3 hours daily over a 9-day period. The auditory conditions applied were:

1. Control group (no music);
2. Techno (aggressive);
3. Classical music;
4. Meditation 432 Hz.

Throughout the experiment, the system continuously logged temperature, humidity, soil moisture, and light intensity. In addition, daily measurements of radicle and hypocotyl length were recorded to assess plant growth dynamics and correlate physiological responses with the respective auditory treatments.

RESULTS AND DISCUSSIONS

Between 2024 and 2025, five experiments were conducted to evaluate the influence of musical stimuli on plant growth within a smart greenhouse prototype.

The tested species included *Lactuca sativa* (cultivars 'May King' and 'Helmut') and *Raphanus sativus* ('Helga'), cultivated under controlled conditions of temperature, humidity, light, and soil moisture.

Each experiment lasted between 7 and 9 days, during which environmental parameters were continuously monitored through an integrated data acquisition system.

The experimental conditions are summarized in Table 3.

Table 3. Experimental setup and conditions

Experiment	**1**	**2**	**3**	**4**	**5**
Species	*L. sativa*	*R. sativus*	*L. sativa*	*L. sativa, R. sativus*	*L. sativa, R. sativus*
Music type	No music	No music	Techno (aggressive)	Classical music	Meditation 432 Hz
Duration	9 days	9 days	9 days	9 days	9 days
Temperature (^{0}C)	Not recorded	20-23	21-24	20-24	23-26
Air humidity (%)	Not recorded	81-84	80-82	82-85	79-84
Soil moisture index	Not recorded	4-5	4-6	4-6	5-6
LED exposure (h/day)	Not recorded	3	3	3	3
Volume (dB)	-	-	~70	~65	~60
Playback	-	-	3 h/day, speaker	3 h/day, speaker	3 h/day, speaker

Plant height – summary by species and experiment

At the conclusion of each experiment, the average plant height was measured to evaluate the effects of musical exposure. Results showed notable differences based on the music type and plant species. The outcomes are presented in Table 4.

Table 4. Average plant height at the end of experiments

Species	**Exp.2 - No music**	**Exp.3 - Techno**	**Exp.4 - Classical**	**Exp.5 - Meditation**
L. sativa	-	2.1 cm	5.7 cm	6.8 cm
R. sativus	6.3 cm	-	6.2 cm	6.5 cm

In the absence of music (Experiment 2), *R. sativus* achieved an average height of 6.3 cm, while lettuce was not included. When exposed to techno music (Experiment 3), *L. sativa* demonstrated significantly stunted growth, averaging only 2.1 cm. In contrast, classical (Experiment 4) and 432 Hz meditation music (Experiment 5) enhanced vertical development in lettuce, with the highest average height recorded under meditation music. *R. sativus* showed more stable growth across treatments, with slight improvements under meditation sound.

Leaf number - summary by species and experiment

Leaf count served as a secondary growth indicator. The average number of leaves per plant is summarized in Table 5.

Table 5. Average number of leaves per plant at the end of experiments

Species	Exp.2 - No music	Exp.3 - Techno	Exp.4 - Classical	Exp.5 - Meditation
L.sativa	-	1-2 leaves	3-4 leaves	4-5 leaves
R. sativus	2-3 leaves	-	3-4 leaves	3-4 leaves

Results indicate a correlation between musical exposure and foliar development. *L. sativa* exposed to techno music developed fewer leaves, while those exposed to classical and meditation music exhibited significant improvements in leaf formation.
R. sativus also showed slightly increased leaf counts under musical conditions compared to the control, with minimal variation between the classical and meditation groups.
These outcomes suggest that harmonic and soothing music may positively influence physiological processes such as photosynthetic efficiency and hormone regulation, contributing to improved plant morphology.

Environmental parameters comparison across experiments
To confirm that observed differences in plant growth were attributable to music rather than environmental variability, average environmental conditions were compared across Experiments 2 through 5. These values are presented in Table 6.

Table 6. Environmental conditions across experiments (average values)

Experiment	Exp.2 - No music	Exp.3 - Techno	Exp.4 - Classical	Exp.5 - Meditation
Temperature (^{0}C)	21.8	22.3	21.9	22.7
Air humidity (%)	82.0	81.5	82.2	81.7
Soil moisture index (0-6)	4.3	4.5	4.4	4.6
Light index (0-10)	1.4	1.6	1.5	1.7

The environmental data confirm that all parameters remained within optimal ranges throughout the trials, with only slight variations. Temperatures were consistently maintained between 21.8°C and 22.7°C, air humidity levels stayed above 80%, and soil moisture remained within the ideal index range of 4 to 5.
Light intensity, though low due to indoor conditions, was supplemented uniformly by a calibrated LED matrix.
These results support the conclusion that differences in plant development are attributable to auditory stimuli rather than uncontrolled environmental factors.

Graphical interpretation of monitored variables
To evaluate the consistency of environmental control and its potential interaction with music exposure, the daily evolution of four key parameters - temperature, air humidity, soil moisture, and light intensity - was graphically analyzed across Experiments 2 to 5. These results are presented in Figures 6 to 9.
Figure 6 shows the daily temperature profiles for the four experiments. Despite minor fluctuations, all temperature values remained within the optimal growth range of 20-26°C. The highest average temperatures were recorded in Experiment 5 (meditation music). However, no thermal stress was observed, indicating that the system maintained an effective microclimate, even with modest variation.

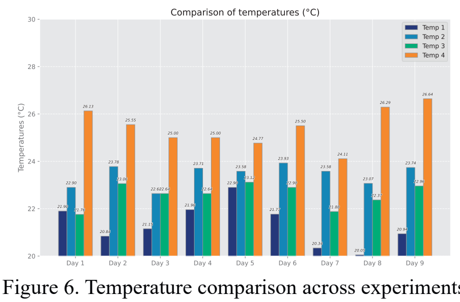

Figure 6. Temperature comparison across experiments

As shown in Figure 7, relative humidity levels remained above 70% throughout all experiments. The most stable and elevated values were recorded during Experiment 4 (classical music), suggesting that the enclosed environment efficiently retained moisture. This stable humidity may have supported the enhanced growth observed under classical music exposure.

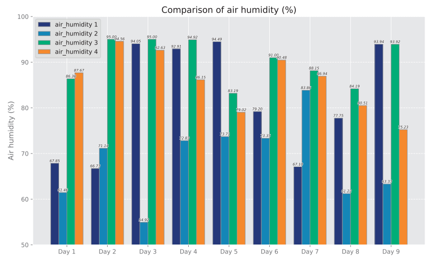

Figure 7. Air humidity comparison

Figure 8 presents soil moisture index trends, with values ranging from 0 (dry) to 6 (high moisture).

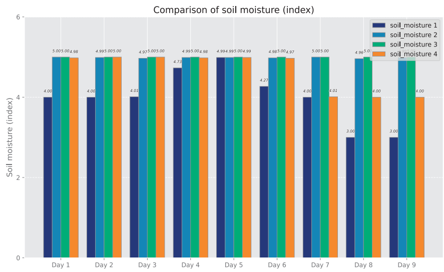

Figure 8. Soil moisture index

Most experiments maintained a consistent range between 3 and 5. Slightly more variability was observed in Experiment 3 (techno music), which may have contributed to the reduced plant growth and germination observed in that group.

Figure 9 depicts natural light levels across experiments, measured on a scale from 0 (complete darkness) to 10 (full daylight). Due to the shaded placement of the setup, natural light intensity remained low (~1.5). However, consistent supplemental lighting from the LED matrix ensured adequate photosynthetic conditions across all trials.

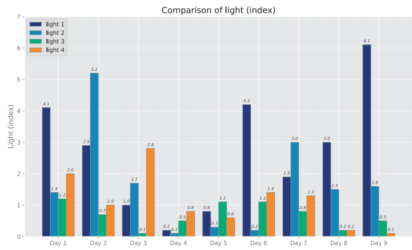

Figure 9. Light index comparison

Final comparative interpretation of prototype versions and music effects

To consolidate the findings, a final comparative analysis was conducted across all prototype versions, including earlier trials without musical treatment (Experiments 1.1 and 1.2) and later ones incorporating music (Experiments 3-6). Environmental variables were compared and visualized in Figures 10 to 14, with corresponding color codes provided in Table 7.

Table 7. Analysis - the legend of colours

Analysis - the legend of colours	
Analysis 1.1	Dark blue
Analysis 1.2	Steel blue
Analysis 3	Mediumseagreen
Analysis 4	Dark orange
Analysis 5	Salmon
Analysis 6	Orchid

All temperature values across experiments remained within the optimal range. Slightly elevated mean temperatures were recorded in Experiments 5 and 6 (meditation and classical music), yet these did not adversely affect plant growth, demonstrating effective thermal regulation by the system (Figure 10).

Experiment 4 (classical music) and Experiment 5 (meditation music) exhibited the most stable and elevated air humidity values (Figure 11).

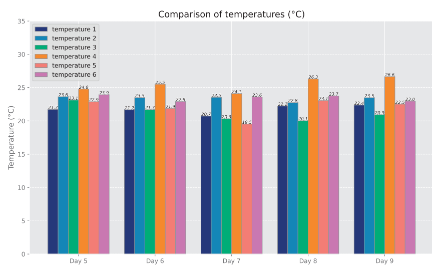

Figure 10. Comparative temperature trends

These findings support the hypothesis that stable humidity levels may contribute to improved germination and plant vigor. Greater variability was observed in Experiments 1.1 and 3 (no music and techno music), potentially correlating with less robust growth.

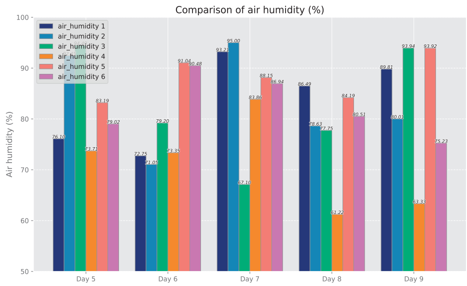

Figure 11. Comparative air humidity trends

Soil moisture remained within optimal levels in most experiments. However, Experiment 3 (techno music) exhibited lower and more fluctuating values, which may have hindered seedling development (Figure 12). This reinforces previous observations of suboptimal plant performance under techno exposure.

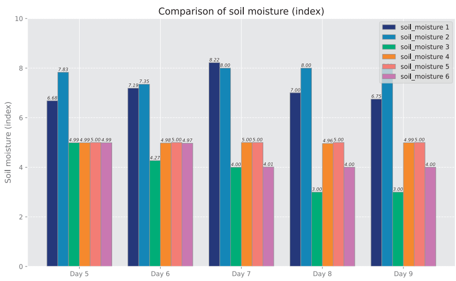

Figure 12. Comparative soil moisture trends

Light levels were consistently low throughout all experiments due to limited natural lighting. The LED matrix effectively compensated for this limitation. Slightly higher light index values were recorded in Experiment 4, possibly due to better placement and reflectivity within the setup (Figure 13).

Atmospheric pressure readings remained relatively stable across all trials (Figure 14). Slight increases were noted in Experiment 5, but no direct influence on plant development was observed. While atmospheric pressure is not typically a manipulated variable in greenhouse conditions, its consistency supports the overall environmental stability of the experimental setup.

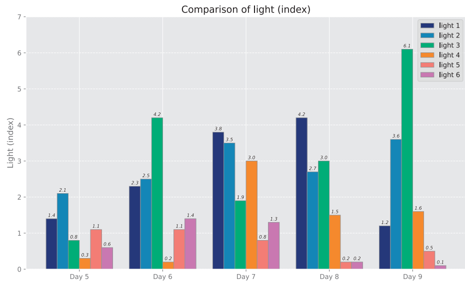

Figure 13. Comparative light intensity

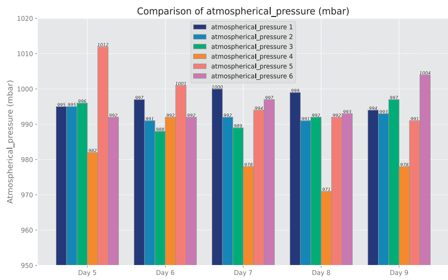

Figure 14. Comparative atmospheric pressure

CONCLUSIONS

The developed smart greenhouse prototype demonstrated effective control over key environmental parameters, outperforming traditional non-automated systems in maintaining stable conditions conducive to plant growth. The integration of sensor-based automation, cloud connectivity, and remote monitoring significantly enhances the system's potential for scalability and full automation in future applications.

Experimental results confirmed that music, particularly classical and meditation genres, served as a notable non-invasive stimulus influencing the physiological development of plants. Lettuce (*Lactuca sativa*) and radish (*Raphanus sativus*) responded positively to harmonic sound treatments, exhibiting increased plant height and greater leaf production under stable environmental conditions.

A detailed analysis of Figures 10-12 revealed a strong interdependency between temperature, air humidity, and soil moisture. Elevated temperatures correlated with increased humidity

- likely due to condensation effects within the enclosure - which in turn helped sustain optimal moisture levels. These dynamics were especially evident in Experiments 4 and 5 (classical and meditation music), where environmental consistency aligned with enhanced plant growth outcomes.

By contrast, Experiments 1.1 and 1.2 (no music) recorded slightly lower values for temperature and humidity, along with less vigorous plant development. This contrast suggests that musical stimulation may play a supportive role in enhancing plant physiological responses, possibly through mechanisms involving hormone regulation or photosynthetic efficiency.

Light intensity, shown in Figure 13, exhibited minimal variation across trials due to the continuous use of an LED lighting matrix. Although natural light contributions were low, consistent artificial lighting maintained photosynthetically active radiation levels sufficient for healthy growth. Observed phototropic behavior, where plants oriented toward the light source, further confirmed its effectiveness.

Atmospheric pressure, illustrated in Figure 14, remained stable across experiments. While no direct relationship was established between pressure fluctuations and plant morphology, its consistency reinforced the environmental control achieved by the prototype. Manipulating this variable for research purposes would require substantial structural modifications and was deemed impractical for small-scale implementations.

Collectively, these findings underscore the complex interplay between environmental variables and plant development. They highlight the value of precision agriculture tools, especially IoT-enabled systems, in advancing sustainable cultivation practices.

Despite its promising results, the study presents several limitations. The small sample size, short experiment duration, and limited variety of music genres constrain the generalizability of the findings. Future research should explore larger-scale prototypes, a broader range of plant species, and more diverse auditory stimuli to deepen our understanding of how environmental and acoustic factors synergistically influence plant development.

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