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Interactive Outdoor Learning Center: Smart Irrigation for Hands-On STEM Learning

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Abstract

This project transforms an underused elementary/junior high school courtyard into an interactive outdoor learning space meant to promote interest in STEM and ecofriendly practices. The classroom features custom seating, regional plants, and a mural designed in collaboration with a Northwestern State University creative arts student. The solar-powered automatic watering system is powered by an ESP32 microcontroller and monitors plant health through Bluetooth connection. The layout of the planter boxes and individual irrigation needs were determined through research on plant spacing, soil science, and evapotranspiration. Together, these elements create a low-maintenance environment that teaches environmental science, electronics, and sustainability through hands-on experiences.

Keywords
Smart irrigation, Solar energy, Ergonomics, STEM education, Sustainability.

1. Introduction
Two principles guided the design of our outdoor classroom. First, water is often wasted when using traditional irrigation systems because they run on timers rather than focusing on plant needs which leads to overwatering and inefficient use of resources. Second, hands-on learning helps students understand concepts better than traditional reading and lecture delivery. This explains why schools need to determine smarter ways to teach STEM. This project was created to solve both problems. Our classroom uses a smart irrigation system that waters plants based on real-time moisture readings and creates a learning environment where students can see first-hand how engineering systems work. Another important part of this project is ergonomics; the seating and layout were designed specifically for children ages 6 to 11 to ensure the space is comfortable and safe for learning.

1.1 Objectives
The primary goal of this project was to transform an underutilized courtyard. The objectives were set by our stakeholders to transform the area into an interactive outdoor learning area for the students. On the electronics side of the project, the goals are to develop and build an automated, solar powered, self-sustaining irrigation system capable of minimizing the need for intervention during plant growth. As for the industrial side, the objectives are to design and build ergonomic benches that are adjusted to the average height of a 6-11 year old; Design and build planter boxes that are accessible to the height of the students. Engineering a water storage system for the automated self-watering system; Constructing a solar stand for the solar panels; communicating with school sources to get a mural; and finding chalkboards that are resistant to outdoor weather conditions. By integrating technology and structural design into plant

care, the outdoor environment serves as a bridge between theoretical concepts and real-world applications, encouraging interest in science, technology, engineering, and mathematics (STEM) disciplines.

The main goal of this project is to design a solar powered irrigation system that is functional and educational for students.

- Design a system that monitors soil moisture and waters plants automatically
- Use solar energy to power the system
- Provide real-time feedback using a display
- Design seating based on ergonomic recommendations and data for children ages 6 – 11
- Create an outdoor learning area for students to interact with

2. Literature Review

The studies referenced when designing the classroom demonstrate how gardens can have a positive impact on individuals. For example, Kopeva et al. (2020) shows how sensory gardens can be intentionally designed to support children with disabilities by creating spaces that are both easily accessible and support emotional regulation. Building on this idea, Kong and Chen (2024) explain how participating in school gardens not only increases children's interest in nature but also strengthens their sense of independence. In addition to benefits, Meshram et al. (2024) highlights the role of agricultural technology by demonstrating how sensors can be used to monitor things such as soil and weather conditions to promote healthy plant growth. Combined, these sources suggest that factors such as thoughtful garden design, hands-on learning, and innovative technology can work together to increase the educational and functional value of garden spaces.

3. Methods

During the first planning and design phase, careful consideration was given to the selection of hardware components. The goal was to use cost effective, widely available, and beginner-friendly components without compromising system functionality or reliability. As a result, the Arduino Uno R3 was chosen as the central microcontroller for the prototype. But on behalf of our stakeholder's request for wireless monitoring, we replaced the Arduino Uno R3 with a microprocessor that has Bluetooth and IOT capabilities. To satisfy this request, the ESP32 microcontroller was chosen as the central processing unit due to its integrated Wi-Fi and Bluetooth capabilities, low power consumption, and suitability for Internet of Things (IoT) applications. Compared to traditional microcontrollers, the ESP32 provides significantly greater processing power, cutting the need for external communication modules. This transition enabled seamless integration with mobile-based monitoring platforms, allowing the stakeholder to see system behavior in real time.

3.1 Irrigation System Design

The design of the automated irrigation system is an improvement of the first prototype, using improved sensing capabilities, distributed control architecture, renewable energy integration, system protection mechanisms, and remote monitoring functionality. The system is designed to care for multiple planting zones while monitoring soil and environmental conditions. This system improves irrigation accuracy, reduces water consumption, and supports the development of a fully automated plant care system that can run with little to no human intervention over long periods of time.

At the systems core, the ESP32 continuously monitors incoming data from multiple sensors and works to control logic for irrigation across four independent zones. Each zone has a capacitive soil moisture sensor that provides continuous analog readings of moisture content within the soil. These sensors are preferred over resistive alternatives due to their improved durability, reduced exposure to corrosion, and more stable long-term performance. Each sensor is assigned an irrigation zone, implementing localized environmental monitoring and preventing reliance on a single average soil condition. The circuit diagram for the irrigation system design is shown in Figure 1.

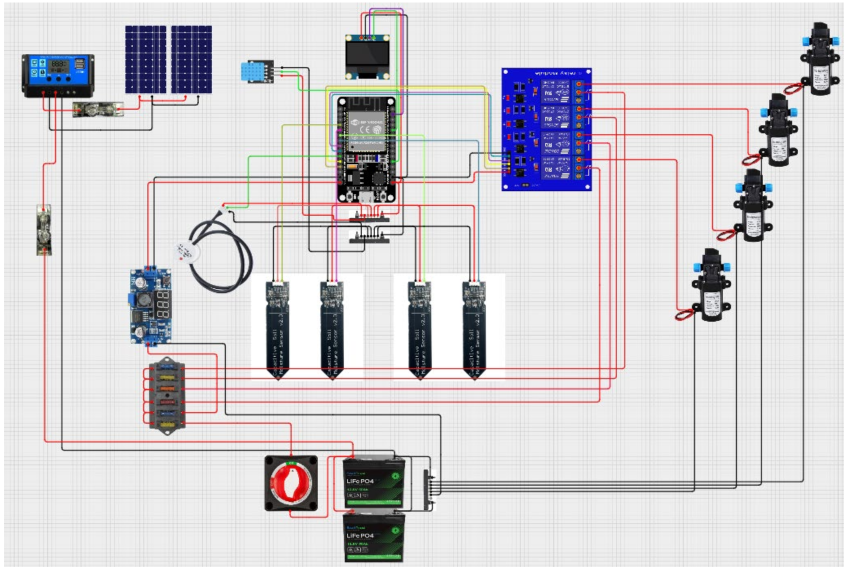

Figure 1. Circuit diagram for the irrigation system design

Here is the pseudocode for the Irrigation System

```
START
Initialize sensors, relays, Wi-Fi, display, and server
WHILE true DO
        Read soil moisture, temperature, humidity, and tank level
        FOR each zone DO
                IF tank level = LOW THEN
                        Pump = OFF
                ELSE
                        IF pump timeout reached THEN
                                Pump = OFF
                        ELSE IF soil = DRY
                                        AND cooldown OK
                                        AND active pumps < 2 THEN
                                Pump = ON
                        END IF
                END IF
        END FOR
        Update OLED display
        Send data to web server and Blynk
        Delay 2 seconds
END WHILE
END
```

Each irrigation zone has an independent 12V DC, 4-amp, water pump connected through a relay module, which each of them is connected to the 12v 100Ah solar power station. The relay acts as an electrically isolated switch, allowing low voltage control signals from the ESP32 to safely use higher voltage pump circuits. Prevent quick drainage of the battery system; the ESP32 will not allow more than two pumps to run at the same time. When a soil moisture sensor detects that moisture levels have fallen below the set point, the ESP32 activates the corresponding relay, turning on the pump and starting water delivery to that specific zone. Once soil moisture levels return to an acceptable level, the relay is disengaged, shutting off the pump. This closed-loop feedback control system ensures efficient irrigation, prevents water waste, and supports best soil conditions for plant growth.

Environmental monitoring is enhanced through the integration of a DHT22 temperature and humidity sensor. DHT22 provides more exact and stable readings than lower-cost alternatives, enabling reliable measurement of ambient environmental conditions. Even though it does not directly control irrigation decisions in the current implementation, the data it provides is critical for understanding environmental influences such as evaporation rates, humidity-driven water demand, and overall plant stress conditions. This added dataset shows a foundation for future system improvements, including adaptive irrigation scheduling and predictive control algorithms based on environmental modeling.

A mini-OLED display is incorporated into the system to provide present feedback on the operation's status. The display presents key system information, including soil moisture readings for each zone, pump activation states, Tank status, and relative temperature/humidity. By providing live visual feedback, the OLED display enhances usability and allows users to quickly verify system performance without requiring external devices. It also serves as an important diagnostic function during system calibration, troubleshooting, and testing phases by providing direct observation of sensor, relay, and pump behavior.

In addition to local monitoring, the system has remote monitoring capabilities through the Blynk IoT platform. Blynk enables informational communication between the ESP32 and a mobile application, allowing the stakeholder to check system's conditions from anywhere with internet access. Through this interface, users can see real-time soil moisture levels, environmental conditions, and pump activity across all irrigation zones. This functionality directly satisfies the stakeholder's request for mobile accessibility.

The power system is designed for off-grid operation using renewable energy sources to ensure long-term autonomous functionality. The system uses two 100W solar panels connected in parallel, supporting a stable 12V nominal system voltage while increasing current output capacity. The solar energy generated is routed through a charge controller, which plays a critical role in regulating battery charging, preventing overcharging, and protecting against deep discharge conditions. This ensures safe and efficient energy management between the solar array and the energy storage system.

Energy storage is provided by one 12V 100Ah $LiFePO_4$ battery. The $LiFePO_4$ battery chemistry was selected due to its high thermal stability, long cycle life, consistent discharge capabilities, and improved safety compared to traditional lithium-ion batteries. This makes it more suitable for continuous, unattended outdoor operation where reliability is a top priority. The equations we used are shown below.

Battery Capacity Equation:

$$C_{Total} = 100Ah \qquad \text{Equation (1)}$$

Total Energy:

$$E = V \times Ah = 12v \times 100Ah = 1200Wh \qquad \text{Equation (2)}$$

To ensure proper voltage regulation for low power electronics, a DC-DC buck converter is used to step down the 12V battery output to a stable 5V supply. This regulated output is used to power the ESP32 microcontroller and its low voltage components. The use of a buck converter improves system efficiency while protecting sensitive electronics from voltage fluctuations that may occur within the solar power system.

Multiple layers of protection and safety mechanisms are included in the system design to ensure reliable and safe operation. A battery and solar cut off switch are installed to allow manual disconnection of the entire system during maintenance, troubleshooting, or emergency situations.

To further increase electrical safety and the protection of all components, fuses are installed throughout the system. Specifically, fuses are placed on the battery output line, solar panel input line, and each individual water pump circuit. This multi-fuse design ensures that overcurrent conditions are isolated at the source, preventing potential failures and minimizing damage to the system. By protecting both solar power generation and electronic components, the system has a higher level of electrical reliability, safety, and failure tolerance.

A non-contact liquid level sensor is installed on to the water tank continuously checks water availability without direct contact with the liquid. This sensor ensures that the irrigation pumps are only activated when enough water is present in the tank. By preventing dry run conditions, the system protects pump integrity, reduces mechanical wear, and supports long term operational lifespans.

Power distribution within the system is carefully structured to ensure stability and efficiency. Solar panels feed into the charge controller, which manages energy flow into the battery storage system. The batteries then supply power to the system to load through the bus bar pathways. The buck converter draws directly from the battery bank to provide a stable 5V rail for the ESP32 and low-power electronics, ensuring consistent performance regardless of fluctuations in solar generation or load demand.

4. Results and Discussion

4.1 Ergonomics Design

For the Ergonomics side of the project, our team designed a bench that ensured students feel comfortable and improve their ability to learn. Using anthropomorphic data and recommendations from credited sources for ergonomics, our benches will be suitable and comfortable for a wide range of students. More specifically, we gained data using the largest measurement in the ranges of 6 to 11-year-olds to find the Max shoulder to shoulder breadth shown below in Figure 2. For seat height, we relied on recommended ranges to ensure the bench works comfortably for smaller and larger students, allowing proper support across different sizes.

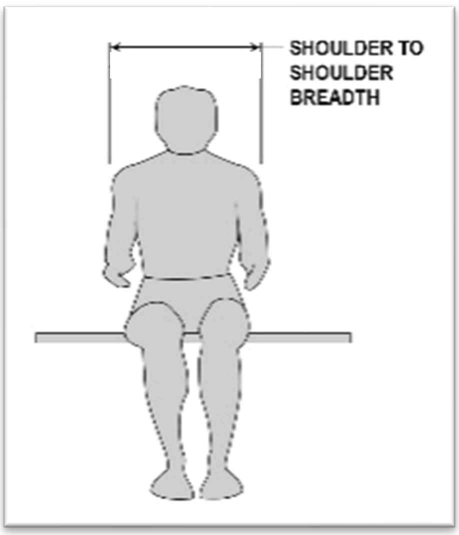

Figure 2. Shoulder to shoulder breadth is used for determining the bench size

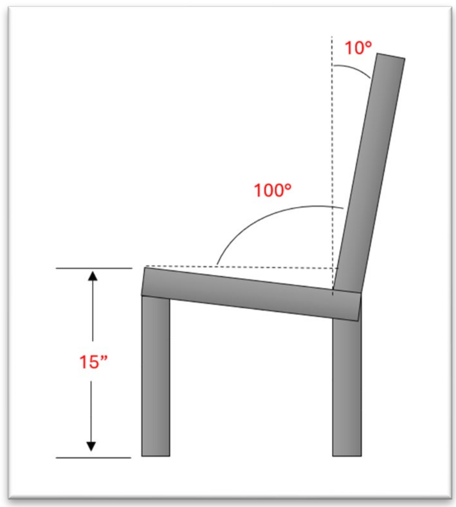

Figure 3. Chair Dimension Design

For the learning area for the students, when designing the benches we wanted to find acceptable and comfortable dimensions that support student safety and allows for focus on learning activities. Based on recommended seat heights from accredited sources, a seat height of 15” is suggested for the ranges of 6- to 11-year-old leg height, which is shown below in Figure 3.

According to Brezlin the recommended angle between the backrest and seat should be between 100° to 105°, with a seat inclination of 10° to 15° (Brezlin, n.d.). Having an inclination and seat tilt helps with improving posture, overall sitting comfort, and keeps the user grounded.

Another design consideration was finding seat width based on shoulder-to-shoulder breadth data from the measure of Man and Women. Data for 11 year olds in the 98th percentile was used to ensure the design accommodates larger students (Tilley 1993). To balance material constraints while accommendating this measurement, a 72 in board was devided into 24 in sections, allowing for 3 to 4 students per bench, as shown in the design below In Figure 4. Additionally, based on an estimated class size of 20 to 25 students, approximately 6 to 7 benches would be required. However, we decided to apply 6 chairs to the courtyard based on spacing requirments and material avaiability.

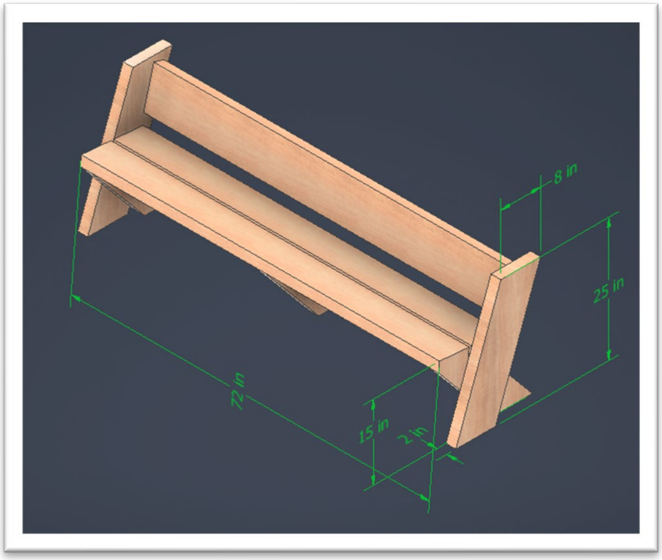

Figure 4. Bench Design

4.2 Soil Characterization, Plant Selection, and Ecological Design

To design a system that is both educationally valuable and age appropriate, this project applies ecological engineering elements to turn natural processes into real-world learning. In an article by ScienceDirect, ecological engineering is described as "'the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both'" (Mitsch and Jorgensen 2003). In this project, these concepts are implemented by treating soil, plants, and water as connected processes that shape how the system performs. By viewing soil composition, plant growth, and water flow as purposeful interactions that provide educational opportunities instead of passive elements, the system serves as a miniature ecological model that students can observe. This is ideal in a school setting as it is a sustainable, low-cost way for students to explore various STEM topics in a non-traditional way. Through hands-on learning approaches, children are exposed to scientific practices that promote sustainability.

Since soil acts as the foundation for all the ecological processes within the system, we first had to analyze both the physical and functional characteristics of the soil. All soils are composed of a combination of minerals, organic matter, water, and air, which causes different soil types to have unique textures (Mississippi State University Extension Service 2026). Soil texture is important as it directly impacts water retention, drainage, root penetration, and the availability of nutrients to aid in plant growth (Natural Resources Conservation Service 2026). A key factor in determining what soil to use for this project was determining the ratio of different sediments within various soil types (clay, sand, and silt). To do so, we referred to a soil texture triangle and concluded that we would move forward using silty loam. Silty loam is considered one of the top choices for plants due to its ability to retain moisture, optimize drainage, provide necessary nutrients, and allow plant roots to burrow deeply thus leading to healthier plant development (Silva 2026).

After establishing soil type, the next step was to estimate the amount of water needed to properly support plant growth. To do so, we had to use the concept of evapotranspiration, or how much water plants lose due to their climate, to get a rough idea of how much water each plant typically needs to thrive (U.S. Geological Survey 2026). Every plant uses water differently, which meant we had to consider crop coefficients to figure out the specifics for each plant (Nazareth Torres et al. 2021). With all of this in mind, we had to apply our findings to silty loam (balanced drainage and good water retention) to determine irrigation frequency to avoid over-watering or water loss. Based on these factors, the system was designed with three watering zones to allow for consistent moisture without over saturation. This ensures that every plant receives adequate water without compromising water drainage.

With the system's core established, the last step was to consider how the system promotes sustainability and student learning. Sustainability was a key consideration throughout the entire design process and influenced factors such as soil selection, water use, and overall functioning. By choosing to use silty loam and balancing our irrigation approach, the project reduces unnecessary resource usage while supporting the long-term health of the plants. These choices reflect ecological engineering principles by focusing on resilience, efficiency, and using natural resources responsibly.

Beyond environmental benefits, we intentionally designed the system to serve as an educational tool that promotes hands-on learning. This project addresses an accessibility gap by providing access to laboratory-based STEM experiences in a rural education setting. Through activities such as monitoring soil moisture, observing the growth of plants, and exploring water movement, young students are introduced to foundational scientific practices in a non-traditional, accessible way.

By merging sustainability with experimental learning methods, the system encourages students to use critical thinking to consider natural resources, caring for the environment, and how various ecological processes are connected. This approach supports both academic learning and a deeper appreciation for sustainability practices and the natural environment.

4.3 Site Design Change and Wood Selection

Material selection was an important part of the construction process for the planter boxes, benches, and water storage stand. Selecting materials that could withstand Louisiana's outdoor conditions while still remaining practical and cost effective was a major consideration throughout the project. Pine wood was chosen for the planter boxes because of its easy workability and ability to be customized to fit the dimensions required for the courtyard layout. Originally, the team hoped to use naturally rot-resistant lumber, but availability and budget constraints limited those options.

The team was able to acquire donated treated 2x8x8 lumber from a local wood preserving company that specializes in treated lumber commonly used for docks and freshwater retaining walls. This material was beneficial because the planter boxes and benches will remain exposed to rain, humidity, and other outdoor elements throughout the year. Using treated lumber helped improve the durability and expected lifespan of the structures while also reducing overall project costs through donated materials. The benches were constructed using the same treated lumber to maintain consistency in appearance and provide additional resistance to weathering and moisture exposure.

The water storage stand did not use the donated treated lumber and was instead constructed using scrap lumber pieces that were available in the Engineering Building woodshop. Reusing available materials helped reduce project costs while also demonstrating the importance of minimizing waste and finding practical uses for existing resources. Due to site modification caused by a bathroom addition, the original installation area was relocated from one grass site to an alternate grass location. This change was made to accommodate construction constraints while maintaining suitable conditions for the self watering system and greenhouse installation which is seen in Figure 5.

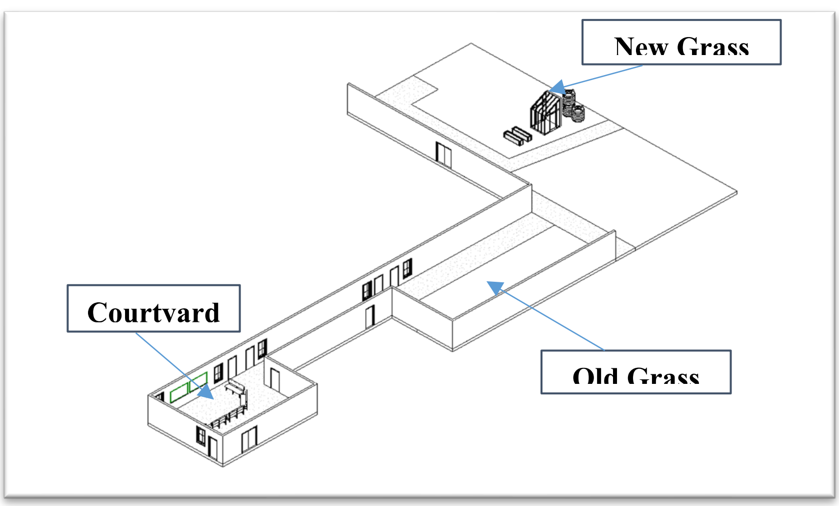

Figure 5. CAD design showing the layout of the courtyard with old and new grass areas

4.4 Planter box and Chair Placements

A seating layout was developed to determine the placement and spacing of benches within the available area. The arrangement was designed to accommodate the calculated bench capacity of 6-7, while maintaining adequate spacing for student movement and accessibility. However, the bench layout in practicality may change because of spacing and material constraints. A diagram of the final layout of the courtyard is shown below in Figure 6.

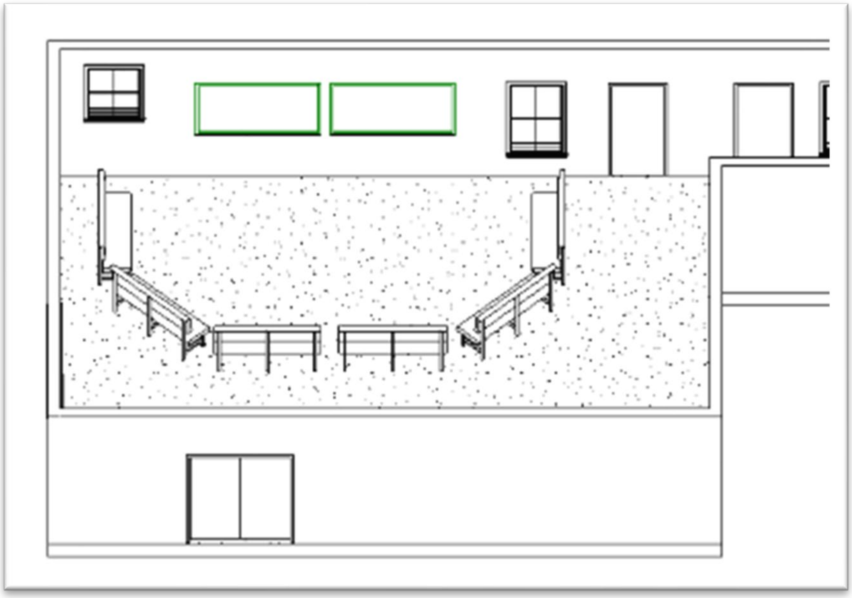

Figure 6. Layout of Courtyard

Another implementation of the project is the planter box. The planter boxes will be constructed using 2x8x8's-foot treated dimensional lumber as the primary material. This decision was based on standard lumber availability and sponsorships to simplify cutting and assembly. The design is a basic rectangular structure made to have enough planting space while reducing material waste. Specific dimensions were selected to allow efficient use of full board lengths, reducing the need for excessive cutting or leftover material which is shown below Figure 7.

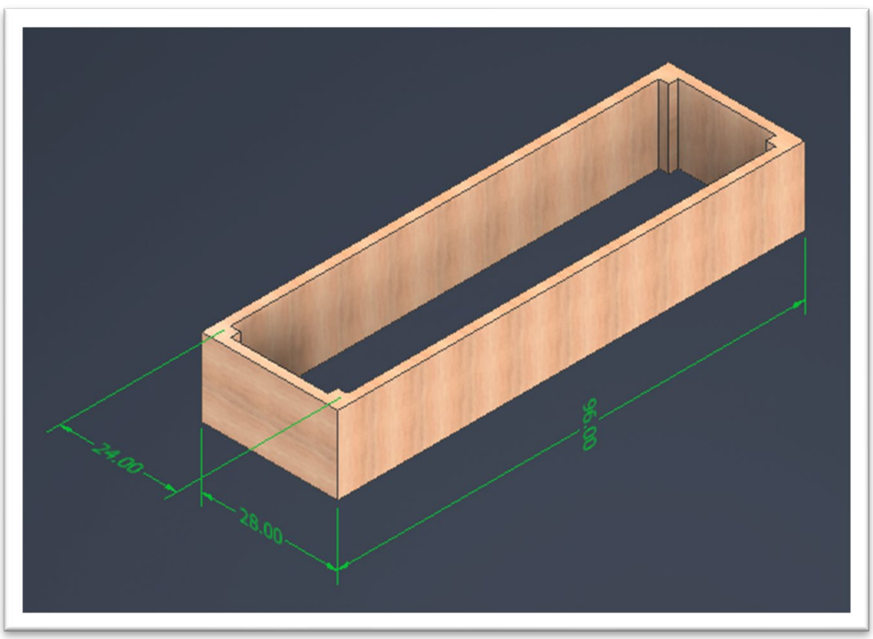

Figure 7. Planter Box Design

4.5 Irrigation System

For Electronics, the irrigation system (Figure 8) can run on its own for 12.2 hours at full use, based on our battery and current calculations as shown in Equation 3 & 4. The integration of soil moisture sensors ensures plants are only watered when they need it, instead of running on a timer. This helps cut down on wasted water. Using separate watering zones also makes it more efficient since each area gets water based on its own needs. The solar power setup allows the system to run without needing an outside power source.

Figure 8. The irrigation system developed for this project

Total Current:

$$I_{Total} = (2 \times 4A) + 0.2A = 8.2A \qquad \text{Equation (3)}$$

Total System Run Time:

$$t = \frac{100Ah}{8.2A} \approx 12.2\ hours \qquad \text{Equation (4)}$$

The design process resulted in a finalized plan for a soil-plant-water system that employs both ecological engineering principles and educational goals. Through the analysis of soil texture, silty loam was ultimately selected as the most suitable medium because of its balanced drainage, water-holding capabilities, and ability to foster healthy root development. Considerations of water requirements led to a three-zone irrigation design intended to provide consistent moisture while avoiding oversaturation. Although construction of the system is not yet complete, the final design plan integrates soil selection, irrigation planning, and plant needs into a design that is cohesive and is expected to function as a stable, low-input model for classroom use. Once implemented, the system is expected to effectively support plant growth and provide students with a multitude of opportunities to observe ecological processes in a hands-on environment.

5. Conclusion

The project focused on creating an outdoor learning space that brings together a solar-powered irrigation system with custom seating and planter boxes designed for student use. The irrigation system automatically waters the plants based on real-time soil readings and uses solar power which makes it both efficient and environmentally friendly. It also included remote monitoring, which allows the system to be easily monitored. When designing the physical space, we gave special attention to the body measurements of children aged six to eleven to ensure that the benches promote comfort, accessibility, and practicality. The layout of the courtyard was carefully planned to best use the available space while ensuring the environment is both welcoming and functional. The soil selection and watering methods were chosen to foster healthy plant growth and reduce the amount of water that is wasted. By combining principles of engineering, sustainability, and education, this project provides an engaging space that encourages hands-on learning.

Overall, the completed system shows how an outdoor classroom can function as both a meaningful learning environment and positive upgrade to a previously underused courtyard. The finished space promotes student interaction, supports sustainable practices, and offers an engaging, real-world approach to STEM learning.

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