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Agrivoltaic System Designing for Sustainability and Smart Irrigation

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Abstract: This project focuses on designing an agrivoltaic system integrated with smart irrigation to promote sustainable agriculture and efficient resource management. The system combines solar photovoltaic (PV) panels with agricultural land to generate renewable energy while cultivating crops, thereby achieving dual land utilization. The solar panels provide electricity for powering irrigation pumps and IoT based sensors, which monitor soil moisture, weather data, and crop conditions in real time. A smart irrigation mechanism uses this data to automate water distribution, ensuring crops receive the right amount of water at the right time, minimizing waste and reducing water consumption. Additionally, the shading effect of solar panels reduces soil evaporation and heat stress on crops, leading to improved crop yield and resilience against climate variability. Surplus solar energy can be stored or sold back to the grid, creating an extra source of income for farmers. This project aims to demonstrate an energy efficient, water saving, and climate smart agricultural model that is scalable for both small and large farming operations, addressing the pressing challenges of food security, water scarcity, and sustainable energy production.

Keywords: Agrivoltaic System, Smart Irrigation, Solar Photovoltaic (PV), Internet of Things (IoT), Sustainable Agriculture.

I. INTRODUCTION

Agriculture today is facing many serious challenges such as climate change, increasing water scarcity, rising energy costs, and the growing demand for food. Farmers often depend on electricity or diesel to run irrigation systems, which increases expenses and harms the environment. At the same time, there is a strong need to adopt farming methods that use resources efficiently an d support long-term sustainability. This makes it important to combine modern technology with traditional farming practices. One promising solution is agrivoltaics, which allows farmers to use the same land for both agriculture and solar power generation. In this system, solar panels are installed above the crops so that electricity can be produced without reducing the area available for cultivation. The panels also provide partial shade, which helps reduce water loss from the soil, lowers field temperature, and protects crops from extreme heat. This creates a better growing environment and can improve crop productivity.

Water management is another major concern in farming. Traditional irrigation methods often lead to overwatering and unnecessary water loss. With the help of IoT-based sensors, it is now possible to monitor soil moisture, temperature, and weather conditions in real time. A smart irrigation system can use this information to supply the right amount of water at the right time, ensuring healthy crop growth while conserving water. This project focuses on developing an agrivoltaic system combined with a smart irrigation setup powered by solar energy. The electricity generated from the solar panels is used to run irrigation pumps and sensor systems, making the entire system energy-efficient and self-sustaining. In addition to reducing water and energy costs, any extra electricity can be stored or supplied to the grid, providing additional income for farmers. Overall, this project aims to promote a practical and scalable solution for sustainable, climate-smart agriculture that benefits both farmers and the environment.

II. STUDY AREA

The study area selected for this agrivoltaic system design project is located in Karaparambu, Malappuram district, Kerala, India. This region has a strong agricultural background, where farming is not just an occupation but a way of life for many families. Paddy cultivation is the most common practice here, reflecting the area’s fertile soil, reliable water resources, and well-established farming traditions. With the growing need for renewable energy and the increasing pressure on available land, this site offers an ideal opportunity to explore how solar power generation can be integrated with agriculture. Instead of using land exclusively for either farming or energy production, the concept of agrivoltaics allows both activities to coexist, making better use of limited land resources. The total area of the site is 50 cents, and it is currently under active paddy cultivation. The land has never been used for industrial or commercial purposes, ensuring that its agricultural quality remains intact. The size of the land is adequate for designing a systematic solar panel layout while still providing sufficient space for crop growth and routine farming activities.

The surrounding area mainly consists of open farmland, with no tall buildings or dense tree cover. This ensures good solar exposure throughout the day with minimal shading, which is highly beneficial for solar power generation. A nearby well serves as a dependable source of irrigation, supporting farming activities year-round. Additionally, the site is easily accessible by local roads, making it convenient for transporting agricultural inputs, harvested crops, and solar equipment. The terrain is flat and level, which simplifies the installation of solar panels and helps in achieving uniform shade distribution over crops. The region experiences a tropical monsoon climate characterized by moderate to high solar radiation, warm temperatures, and high humidity. The soil type, predominantly clayey and silty loam, is well suited for paddy cultivation and can also support various shade-tolerant crops under an agrivoltaic system.


Fig. 1 Study Area

III. LAND SURVEY

The land survey was carried out using Differential Global Positioning System (DGPS) to obtain accurate measurements of the field. The DGPS method is a highly accurate technique used for site surveys in agrivoltaic system design. Unlike normal GPS, DGPS provides very precise location data by correcting errors using a reference base station. This high level of accuracy is important in agrivoltaic projects where solar panels and agricultural activities must be planned carefully on the same land. In a DGPS survey, a base station is first set up at a known fixed location. This station receives satellite signals and generates correction data. A rover unit is then moved across the project site to collect field data. The correction signals from the base station are applied to the rover readings, which greatly improves accuracy by reducing errors caused by atmospheric conditions and satellite signal disturbances.

Using the DGPS rover, the exact boundaries of the land are mapped, and the total area is calculated accurately. DGPS is also used to collect elevation data across the site, which helps in preparing contour maps and understanding slope, drainage, and surface conditions. This information is essential for deciding the alignment of solar panels, foundation design, and water management. As per the DGPS survey conducted at the site, the total measured area is 2025.6 square meters, which is equivalent to approximately 50.05 cents of land.

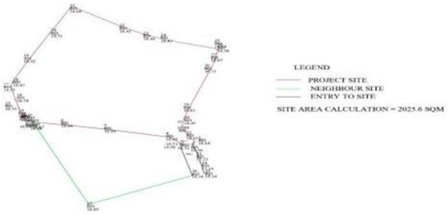


Fig. 2 Surveyed Land

IV. SOIL TESTS

A. *Soil pH Test*

Soil pH indicates the acidity or alkalinity of soil and plays a vital role in determining soil fertility and crop productivity. In agrivoltaic systems, where crops are grown beneath solar photovoltaic panels, soil pH assessment is essential because shading and altered moisture conditions can influence soil chemical properties. Soil pH affects nutrient availability, microbial activity, and overall plant health; hence, it must be evaluated before system design. The objective of the soil pH test is to determine whether the soil is suitable for the proposed crops and to identify the need for soil amendments. Most crops grow well in slightly acidic to neutral soils with a pH range of 6.0–7.5. Soil samples are collected from a depth of 15–20 cm, air-dried, sieved, and mixed with distilled water.

The pH of the suspension is measured using a calibrated pH meter. The test result indicates whether the soil is acidic, neutral, or alkaline and helps in crop selection and soil management. If required, corrective measures such as liming or organic amendments are recommended. Thus, the soil pH test is a simple and essential analysis for ensuring sustainable crop production in agrivoltaic systems.

The electrometric method is a simple and accurate way to determine the pH of soil using a pH meter. It works by measuring the electrical potential difference between a glass electrode (which responds to hydrogen ions) and a reference electrode placed in a soil-water mixture. This difference is automatically converted into a pH value by the instrument. To test the soil, the sample is first air-dried, ground, and sieved. About 20 g of soil is mixed with 40 ml of distilled water (1:2 ratio) and stirred well. After allowing the mixture to stand for about 30 minutes, the calibrated pH meter electrodes are immersed in the suspension, and th e stable reading is noted. The pH value is directly displayed on the meter. This method helps identify whether the soil is acidic, neutral, or alkaline, which is important for crop growth and nutrient availability. The pH of the sample determined by electrometric method was found to be 6.17. The soil is moderately acidic in nature. Such pH is suitable for most agricultural crops; however, phosphorus availability may be reduced under acidic conditions. Liming may be recommended if sensitive crops are cultivated.

Table 1 Result of pH Test

SL No.	pH using electrometric method
1	6.17

Fig. 3 Digital pH Meter

B. *Soil Moisture Content Test*

Soil moisture content refers to the amount of water present in the soil and is a key factor affecting plant growth and irrigation planning. In agrivoltaic systems, partial shading from solar panels reduces evaporation and alters soil moisture conditions, making moisture assessment important for efficient system design. The objective of this test is to evaluate the water-holding capacity of the soil and its suitability for the proposed crops. Soil samples are collected from a depth of 15–20 cm and weighed immediately to obtain the wet weight. The samples are then oven-dried at 105–110°C for 24 hours, and the dry weight is recorded. Moisture content (%) = (Weight of water / Weight of dry soil) × 100.The results help determine irrigation requirements and drainage needs. Proper moisture management ensures healthy crop growth and supports sustainable agricultural practices under agrivoltaic systems.

The soil moisture content test by oven dry method is a simple laboratory test used to find how much water is present in a soil sample. It is considered the most accurate method for determining moisture content in soil mechanics. In this test, a small amount of wet soil is taken in a clean container and weighed. Then the sample is kept in an oven at 105°C to 110°C for about 24 hours to remove all the moisture. After drying, the soil is cooled and weighed again. The loss in weight represents the amount of water that was present in the soil. The moisture content is calculated by dividing the weight of water by the weight of dry soil and multiplying by 100. Although this method takes time, it is reliable and widely used in laboratories for accurate results. The moisture content of the soil determined by oven dry method was found to be 28%. This indicates that the soil is moist with high water holding capacity. Such moisture condition may be attributed to fine texture or high organic matter content. Proper drainage should be ensured to avoid waterlogging.

Table 2 Result of Soil Moisture Content Test

SL NO.	Sample No.	1
1	Weight of container with lid (w1) gm	24g
2	Weight of container with lid + wet soil (w2) gm	88g
3	Weight of container with lid + dry soil (w3) gm	74g
4	Water moisture content = [(w2-w3)/(w3-w1)] *100	28%

Fig. 4 Oven

C. *Organic Carbon Test*

Soil organic carbon is an important indicator of soil fertility and health. It influences nutrient availability, soil structure, water retention, and microbial activity. In agrivoltaic systems, maintaining adequate organic carbon is essential for sustaining crop productivity under modified microclimatic conditions. The objective of the organic carbon test is to assess soil fertility and determine the need for organic amendments. The test is commonly conducted using the Walkley and Black wet oxidation method. Soil samples collected from the root zone are air-dried, sieved, and chemically oxidized using potassium dichromate and sulfuric acid. The remaining dichromate is titrated to calculate organic carbon content. The results classify soil as low, medium, or high in organic carbon. Medium to high organic carbon level is desirable for agrivoltaic systems to ensure good crop performance and long-term soil sustainability.

The in-house method for determination of total carbon using a muffle furnace is based on the Loss on Ignition (LOI) principle, which estimates total carbon content by measuring the weight loss of a dried soil or solid sample after combustion at high temperature. In this method, the sample is first air-dried, ground, and sieved (usually through a 2 mm sieve) to obtain a uniform representative sample. A clean, dry crucible is heated at 105°C, cooled in a desiccator, and weighed (W_1). Approximately 5–10 g of the prepared sample is added to the crucible and dried in a hot air oven at 105°C for 24 hours to remove moisture, then co oled in a desiccator and weighed again (W_2). The dried sample is then ignited in a muffle furnace at 550°C for about 4 hours, during which organic carbon is oxidized to carbon dioxide (CO_2), resulting in a reduction in mass. After ignition, the crucible is cooled gradually, placed in a desiccator to reach room temperature, and weighed (W_3). The loss in weight between the oven-dried sample (W_2) and the ignited sample (W_3) represents the organic matter content. Organic matter percentage is calculated using the formula $OM\% = [(W_2 - W_3) / (W_2 - W_1)] \times 100$, and total carbon percentage is estimated by dividing the organic matter percentage by 1.724 (Van Bemmelen factor), assuming organic matter contains approximately 58% carbon. The analysis should be performed in duplicate with proper quality control measures such as balance calibration and temperature verification of the furnace. Precautions include avoiding overheating above 600°C, preventing moisture absorption before weighing, and handling hot crucibles carefully. This method is simple, economical, and suitable for routine laboratory estimation of total carbon in soil, sediment, sludge, and other solid environmental samples.

The total organic carbon content of the sample determined by in-house furnace method was found to be 22.72%. This value indicates that the sample contains a very high amount of organic matter. Such high carbon content is generally observed in peat, compost, sludge, or highly organic soils. If the sample represents mineral agricultural soil, the value should be reconfirmed to rule out analytical or procedural errors.

Fig. 5 Muffle Furnace

D. Total Nitrogen Test

Total nitrogen is a key indicator of soil fertility, as nitrogen is essential for plant growth, chlorophyll formation, and crop yield. In agrivoltaic systems, altered microclimatic conditions such as partial shading and improved soil moisture can influence nitrogen availability and microbial activity. Therefore, assessing total nitrogen helps evaluate soil nutrient status and long-term nitrogen supply to crops. The main objective of the total nitrogen test is to determine the overall nitrogen content of soil and its suitability for selected crops. The test assists in identifying nitrogen deficiency or sufficiency and supports proper fertilizer and org anic manure planning. Total nitrogen is commonly determined using the Kjeldahl method, which involves acid digestion, distillation, and titration to calculate nitrogen content. Soil samples are collected from the root zone (15–20 cm), processed, and analyzed in the laboratory. Results are expressed as a percentage of dry soil weight. Adequate nitrogen levels are essential for healthy crop growth in agrivoltaic systems, particularly for leafy vegetables and legumes, while balanced nitrogen management promotes sustainable farming practices.

The IS 6092 (Part 2 / Sec 2) method is used to determine the total nitrogen content in soil. Nitrogen is one of the most important nutrients for plant growth, so measuring it helps us understand the fertility status of the soil. This method is based on the well-known Kjeldahl principle. In this test, a known quantity of air-dried and sieved soil is taken and digested with concentrated sulphuric acid along with a catalyst. During digestion, the organic nitrogen present in the soil is converted into ammonium form. The process is continued until the solution becomes clear, which shows that digestion is complete. After digestion, the mixture is diluted and made alkaline by adding sodium hydroxide. This releases ammonia gas from the solution. The ammonia is then distilled and collected in a receiving solution containing a standard acid. The amount of ammonia collected is determined by titration.

From the volume of acid used in titration, the percentage of nitrogen in the soil is calculated. This method gives dependable results when the digestion and distillation steps are carried out carefully. The nitrogen value obtained helps in assessing soil fertility and planning suitable fertilizer applications for better crop growth. The total nitrogen content of the sample determined as per IS 6092 Part 2 (Sec-02) was found to be 0.028%. This indicates that the soil falls under the low nitrogen category. Such nitrogen content is insufficient for optimum crop growth, and nitrogen fertilization is recommended to improve soil fertility.

Fig. 6 Borosil Labquest KDI040 Auto matic Kjeldahl Distillation Unit

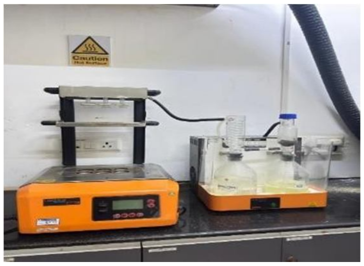


Fig. 7 Borosil Kjeldahl Oracle Digester

E. Total Phosphorus Test

Total phosphorus plays an important role in energy transfer, root development, and overall plant growth. In agrivoltaic systems, changes in soil moisture and temperature under solar panels can affect phosphorus availability. Hence, total phosphorus testing is necessary to assess soil fertility and ensure optimal crop performance. The objective of the test is to determine the total phosphorus content of the soil and evaluate its suitability for proposed crops. The test is carried out by acid digestion followed by colorimetric analysis, commonly using the molybdenum blue method, where phosphorus concentration is measured using a spectrophotometer.

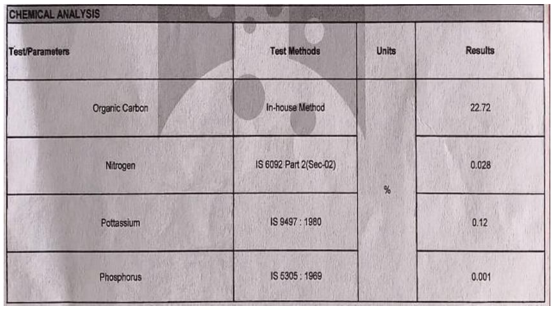
Soil samples collected from the root zone are processed and analyzed, and results are expressed in percentage or ppm. Adequate phosphorus is especially important for root, tuber, and legume crops. Proper interpretation of test results helps in planning balanced fertilizer application and maintaining sustainable soil fertility in agrivoltaic systems. The total phosphorus content in the soil was determined according to IS 5305:1969. In this method, the soil sample is digested using strong acids to convert the phosphorus into a soluble form. The soil was first air-dried, powdered, and sieved through a 2 mm sieve. About 1 g of the sample was taken and digested with acids by heating until the solution became clear. After cooling, the solution was filtered and made up to a known volume with distilled water. A portion of this solution was treated with ammonium molybdate reagent to develop a colour. The intensity of the colour, measured using a spectrophotometer, indicates the amount of phosphorus present. The final result was calculated using a standard calibration curve and expressed as percentage (%) or mg/kg (ppm), following proper safety precautions during the test. The phosphorus content of the sample determined as per IS 5305:1969 was found to be 0.001%. This value indicates that the soil falls under the low phosphorus category. The soil is deficient in phosphorus and requires phosphorus fertilization for optimum crop growth.

F. Total Potassium Test

Total potassium is an essential soil nutrient that supports enzyme activation, water regulation, stress resistance, and crop productivity. In agrivoltaic systems, modified soil moisture and temperature conditions may influence potassium uptake, making potassium assessment important for balanced nutrient management. The objective of the total potassium test is to evaluate the soil’s potassium reserves and determine its suitability for crop cultivation. The test is performed by digesting or extractin g soil samples and measuring potassium concentration using a flame photometer or atomic absorption spectrophotometer.

Soil samples are collected from 15–20 cm depth, processed, and analyzed. Results are expressed in percentage or ppm. Adequate potassium levels improve crop quality, disease resistance, and water-use efficiency. The total potassium test supports effective nutrient management and sustainable agrivoltaic system design. The total potassium content in the soil sample was determined according to IS 9497:1980. In this method, the soil is digested using strong acids to release all the potassium present in it. The potassium in the solution is then measured using a flame photometer, where the intensity of the flame colour indicates the potassium concentration. First, the soil sample was air-dried, powdered, and sieved through a 2 mm sieve. About 0.5–1 g of the prepared sample was taken for digestion. Nitric acid and hydrofluoric acid were added, and the mixture was heated carefully. After partial digestion, perchloric acid was added and heating was continued until the sample was completely digested. The digested solution was cooled, filtered, and made up to a known volume with distilled water. The flame photometer was calibrated using standard potassium solutions, and the sample reading was recorded. The potassium content was calculated from the calibration curve and expressed as percentage (%) or mg/kg (ppm). All safety precautions were strictly followed while handling the acids to ensure safe and accurate testing. The potassium content of the sample determined as per IS 9497:1980 was found to be 0.12%. This indicates that the soil falls under the medium potassium category. The soil is moderately fertile with respect to potassium, but additional potassium fertilization may be required depending on crop demand.

Fig. 8 Flame Photometer



CHEMICAL ANALYSIS			
Test/Parameters	**Test Methods**	**Units**	**Results**
Organic Carbon	In-house Method	%	22.72
Nitrogen	IS 6092 Part 2(Sec-02)		0.028
Pottassium	IS 9497 : 1980		0.12
Phosphorus	IS 5305 : 1969		0.001

Fig. 9 Test Result

G. *Test Result Analysis*

The soil sample was analyzed to check its suitability for cultivating turmeric under the solar panels and paddy in the remaining field area. The soil pH was found to be 6.17, which indicates that the soil is slightly acidic. This pH range is generally suitable for both turmeric and paddy cultivation. However, in slightly acidic soils, the availability of phosphorus may be lower, so proper nutrient management may be required. The moisture content of the soil was 28%, showing that the soil has a good water holding capacity. This is beneficial for both crops, as turmeric requires consistently moist soil and paddy needs sufficient water during its growth stages. In the agrivoltaic system, the shade from the solar panels can also help reduce evaporation and maintain soil moisture. However, proper drainage should be maintained to prevent waterlogging, especially in the turmeric cultivation area. The organic carbon content of the soil was found to be 22.72%, indicating high organic matter in the soil. High organic matter improves soil fertility, enhances microbial activity, and helps retain moisture, which supports healthy crop growth. This is particularly beneficial for turmeric cultivation. The nitrogen content of the soil was 0.028%, which falls under the low category. Nitrogen is important for plant growth, so the soil will require nitrogen fertilizers or organic manure to support better growth of both turmeric and paddy. The phosphorus content was 0.001%, which is very low. Since phosphorus is essential for root development and plant growth, phosphorus fertilization will be necessary to improve crop productivity. The potassium content of the soil was 0.12%, which falls under the medium category. This indicates that the soil has a moderate amount of potassium, but additional potassium fertilizers may be applied depending on crop needs. Overall, the soil has good moisture retention and high organic matter, which supports sustainable crop cultivation. However, the soil is low in nitrogen and phosphorus, so proper fertilization and smart irrigation management will be required for efficient cultivation of turmeric and paddy in the agrivoltaic system.

V. DETERMINATION OF CROP

Based on the soil test results obtained from the laboratory analysis, turmeric was selected as the most suitable crop for cultivation on the site. The decision was made by considering the soil properties such as organic carbon content, nitrogen, phosphorus, and potassium levels, along with the site conditions and availability of irrigation. The soil test result shows that the organic carbon content is 22.72%, which indicates that the soil is very rich in organic matter. High organic carbon improves soil fertility, enhances microbial activity, and increases moisture retention capacity. Turmeric is a rhizome crop that grows well in soils rich in organic matter and requires loose, fertile soil for proper rhizome development. Therefore, the high organic carbon content in the soil makes it highly suitable for turmeric cultivation. The nitrogen content in the soil is 0.028%, which is considered low. Nitrogen is important for the vegetative growth of plants, especially for the development of leaves and stems.

However, this deficiency can be easily corrected by applying organic manure or nitrogen fertilizers during cultivation. Hence, the low nitrogen level does not restrict turmeric cultivation. The phosphorus content is 0.001%, which is also low. Phosphorus plays a vital role in root and rhizome development. This deficiency can be improved by applying fertilizers such as rock phosphate or DAP during planting. With proper nutrient management, the phosphorus requirement for turmeric can be effectively satisfied. The potassium content of the soil is 0.12%, which is at a moderate level. Potassium is important for improving crop quality, disease resistance, and the development of healthy rhizomes. The presence of moderate potassium in the soil supports good turmeric growth and yield. The soil pH value is 6.17, which indicates that the soil is slightly acidic. Turmeric grows best in slightly acidic to neutral soils with a pH range of about 5.5 to 7.0. Therefore, the existing pH level of the soil is suitable for turmeric cultivation and supports proper nutrient availability and plant growth. The soil moisture content is 28%, which indicates good moisture retention in the soil. Adequate soil moisture is essential for turmeric cultivation as it helps in proper rhizome development and healthy plant growth. The presence of sufficient moisture in the soil, along with irrigation facilities, further supports the cultivation of turmeric. In addition to soil conditions, site conditions also favor turmeric cultivation. Turmeric grows well in partially shaded environments and can tolerate reduced sunlight. Since the land is located under solar panels with a height of about 1.5 m, crops that can grow under partial shade are more suitable. Turmeric has a plant height of around 60–90 cm and can grow comfortably under such conditions.

VI. AGRIVOLTAIC SYSTEM DESIGN

The solar panels are installed on elevated structures at a height of about 1.5 m above the ground. This height allows farming activities to be carried out beneath the panels without any disturbance. Such a system combines solar energy generation with agriculture, making better use of the available land. A 10-kW solar photovoltaic (PV) system is used to generate electricity by converting sunlight into electrical energy. The electricity produced can be used for agricultural purposes such as running irrigation pumps and charging electric farming tools like sprayers, tractors, and crop cutters. This helps reduce electricity costs and supports the use of renewable energy in farming. The system can produce around 50 kWh of energy per day assuming an average of 5 peak sun hours. After considering energy losses, about 30 kWh of usable energy per day is available. The extra energy can be stored in batteries, used to operate farm equipment, or sold to the electricity grid, which can provide additional income for the farmer. In this setup, 13 solar panels are installed at the beginning portion of the paddy field. Each panel is mounted at a height of 1.5 m with an inclination angle of 12°. The top portion of the panel faces north and the bottom portion faces south, which helps improve solar energy generation. Turmeric is cultivated under the solar panels because it grows well in partial shade. The shade from the panels helps retain soil moisture and supports better crop growth. The remaining area of the field is used for paddy cultivat ion, ensuring that the land is used efficiently for both energy production and agriculture. Each solar panel occupies about 60 square feet of area, and for 13 panels the total area required is about 780 square feet, which is approximately 1.8 cents of land. This shows that only a small portion of the land is needed for solar installation while the rest can still be used for farming.

Fig. 10 Agrivoltaic System Design

VII. SMART IRRIGATION DESIGN

In this project, a smart irrigation system is incorporated into the agrivoltaic setup to improve water management and support sustainable farming practices. Agrivoltaics allows crops to be grown beneath or between solar panels, enabling the same piece of land to be used for both agricultural production and solar energy generation. Because the land is used for two purposes, proper irrigation management becomes very important to ensure healthy crop growth while maintaining the efficiency of the solar power system. The smart irrigation concept used in this project focuses on supplying water only when it is actually needed. By observing soil conditions and environmental factors, irrigation can be managed more efficiently. This helps maintain the right amount of moisture in the soil for crop growth while avoiding unnecessary water usage.

As a result, water resources can be used more carefully and efficiently. One of the natural advantages of the agrivoltaic system is the partial shading provided by the solar panels. This shade helps in reducing soil temperature and slowing down the rate of water evaporation from the soil. Because of this condition, crops grown under the panels generally require less water than crops grown in open fields. This not only helps conserve water but also creates a more favorable microclimate for certain crops. Another benefit observed in the system is the use of solar energy to support irrigation activities. The solar panels installed in the field can supply the electricity needed to operate irrigation pumps and control units. This reduces the dependence on conventional electricity or fuel-powered pumps, which in turn lowers operational costs and makes the system more environmentally friendly.

A. Capacitive Soil Moisture Sensor V1.2

The Capacitive Soil Moisture Sensor V1.2 is used to measure the moisture content present in the soil without directly exposing metal probes to water. It operates based on the principle of capacitance, which changes depending on the amount of water in the soil. When the sensor is inserted into the soil, the soil acts as a dielectric material between the two conductive plates inside the sensor. The moisture present in the soil affects its dielectric constant. Wet soil has a higher dielectric constant than dry soil, and as the moisture level increases, the capacitance of the sensor also increases. The internal electronic circuit of the sensor converts this change in capacitance into a corresponding analog voltage signal. This output voltage varies according to the moisture level present in the soil. The analog signal is then transmitted to a microcontroller such as the Arduino Uno or other IoT devices, which read and process the data to determine the soil moisture condition. Based on the sensor readings, the system can identify whether the soil is dry or sufficiently moist. If the soil moisture level falls below the required limit, the microcontroller automatically turns on the water pump. Once the pump is activated, water from the well flows through the pipes provided for the drip irrigation system. This ensures that the crops receive the required amount of water. When the soil moisture reaches the desired level, the pump is turned off, preventing excess water usage and improving water efficiency in the irrigation system.

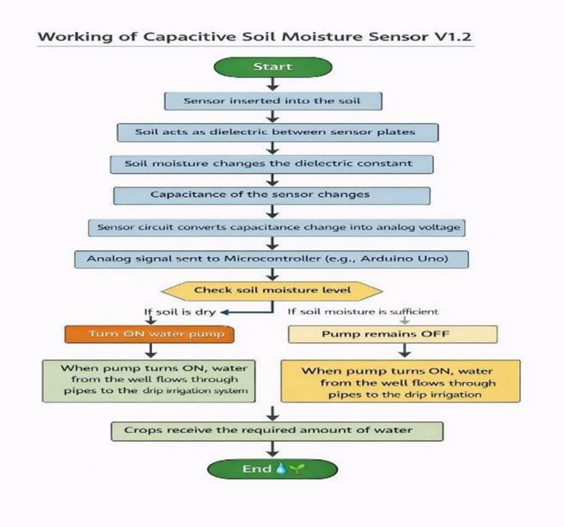


Fig. 11 Working of Capacitive Soil Moisture Sensor V1.2

B. DHT22 Temperature and Humidity Sensor

The DHT22 Temperature and Humidity Sensor is a digital sensor used to measure temperature and relative humidity in the environment. It is widely used in weather monitoring, smart agriculture, and IoT systems. The sensor contains two main sensing elements: a capacitive humidity sensor and a thermistor for temperature measurement. The humidity sensing element consists of a moisture-holding substrate placed between two electrodes. When the surrounding air contains moisture, water vapor is absorbed by the substrate, which changes its electrical capacitance. This change in capacitance is measured by the internal circuit and converted into a humidity value. For temperature measurement, the sensor uses a thermistor, whose electrical resistance changes with temperature. As the temperature of the surrounding air increases or decreases, the resistance of the thermistor changes accordingly. The internal microcontroller inside the sensor measures this resistance change and calculates the corresponding temperature. The sensor has a built-in signal processing chip that converts both temperature and humidity measurements into a digital signal.

This digital data is then transmitted through a single data pin to a microcontroller such as the Arduino Uno. The microcontroller receives this digital data, processes it, and displays or uses it for further applications. In smart irrigation or agricultural monitoring systems, the data helps monitor environmental conditions and can be used to control irrigation, ventilation, or other automated systems.

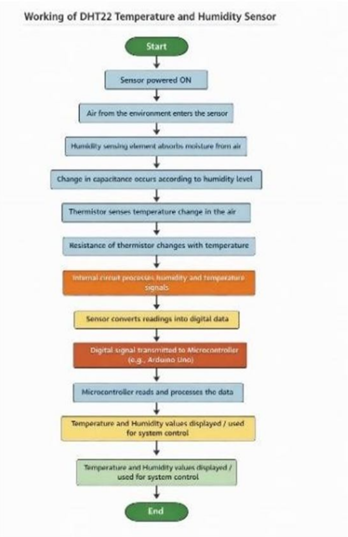


Fig. 12 Working of DHT22 Temperature and Humidity Sensor

C. NDVI Plant Health Sensor

The NDVI Plant Health Sensor is used to monitor plant health by measuring how plants reflect different wavelengths of light. It works based on the Normalized Difference Vegetation Index, which indicates the health and growth condition of plants.Plants absorb most of the red light from sunlight for photosynthesis and reflect a large portion of near-infrared (NIR) light. Healthy plants absorb more red light and reflect more near-infrared light, while unhealthy or stressed plants reflect less near-infrared light. The NDVI sensor contains optical sensors that measure the intensity of red light and near-infrared light reflected from the plant leaves. When the sensor is placed above the crop, it captures the reflected light from the plant canopy. The sensor then processes these two values using the NDVI formula: NDVI = (NIR − Red) / (NIR + Red). This calculation produces a value between −1 and +1. Higher NDVI values indicate healthy and dense vegetation, while lower values indicate poor or stressed plants. The calculated NDVI value is transmitted to a microcontroller such as the Arduino Uno or other IoT systems. The microcontroller processes this information and helps farmers monitor crop health, detect stress early, and make better decisions about irrigation, fertilization, and crop management in smart agriculture systems.

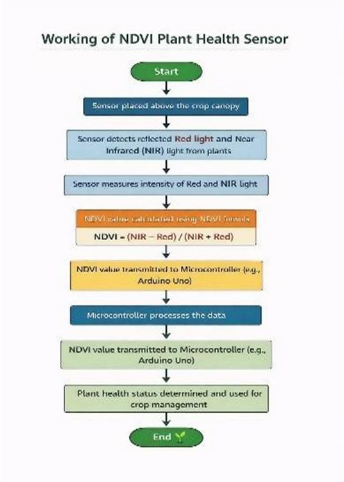


Fig. 13 Working of NDVI Plant Health Sensor

D. Drip Irrigation

In this agrivoltaic system, drip irrigation is provided to supply water efficiently to the crops grown beneath the solar panels. In this method, water is delivered slowly and directly to the root zone of the plants through small pipes and emitters placed near each crop. This ensures that the plants receive water exactly where it is needed, reducing water loss due to evaporation or runoff. Drip irrigation is very suitable for agrivoltaic systems because the solar panels create partial shading over the field. This shading helps reduce soil temperature and slows down the evaporation of water from the soil. When drip irrigation is used along with this condition, the water requirement of the crops can be managed more efficiently. Another advantage of drip irrigation is that it helps maintain proper soil moisture for plant growth. The system can also be connected with smart irrigation technologies such as soil moisture sensors, which help monitor the soil condition and supply water only when necessary. This reduces water wastage and ensures that crops receive the right amount of water at the right time.

E. Utilization of Solar Energy

In this agrivoltaic system, the solar panels installed above the field generate electricity that is used for multiple agricultural purposes. The solar energy produced is primarily used to operate the drip irrigation system, which supplies water efficiently to the crops grown beneath the panels. This helps ensure proper irrigation while reducing dependence on conventional electricity sources. The generated solar power is also used for the operation of sensors such as soil moisture sensors and weather monitoring sensors. These sensors continuously monitor field conditions and provide real-time data that helps in managing irrigation and crop growth more effectively. The solar energy supports the operation of an electric tractor (EV tractor) and other electric farming tools used in the field. This reduces the need for diesel-powered equipment, making the farming process more environmentally friendly and cost-effective. After meeting the energy requirements of irrigation, sensors, and farming equipment, the remaining or surplus energy generated by the solar panels is supplied to a nearby EV charging station located close to the agricultural plot. This allows the extra electricity produced in the system to be utilized efficiently while also supporting electric vehicle charging infrastructure.

Fig. 14 Final Output of the Project

VIII. RESULT AND ANALYSIS

Traditional farming mostly depends on diesel-powered tractors and irrigation pumps for field operations. In many farms, irrigation is carried out manually, and farmers usually rely on experience rather than accurate measurements of soil moisture or water levels. Because of this, water is sometimes applied more than necessary, which leads to water wastage and higher energy consumption. At the same time, the increasing cost of diesel makes farming more expensive. For instance, a diesel tractor typically consumes about 3 liters of diesel per hour. If it is used for around 4 hours a day, the daily fuel cost can reach approximately ₹1,140, depending on the diesel price. Over the course of a year, this expense can add up to nearly ₹2.8–3 lakh, which becomes a significant cost for farmers. Similarly, irrigation pumps often run on diesel or grid electricity, and farmers usually do not have real-time information about soil moisture, water levels in tanks, or fertilizer availability. As a result, irrigation and nutrient management may not always be efficient.

In contrast, the agrivoltaic system with smart irrigation offers a more modern and efficient approach to farming. In this system, a 10 kW solar power plant is installed above the crops, allowing the same land to be used for both agriculture and electricity generation. The solar panels can produce about 40–45 kWh of electricity per day, depending on sunlight availability. A portion of this energy is used to operate the smart irrigation system, where sensors measure soil moisture, water levels, and fertilizer concentration. The collected data is then sent to an IoT dashboard, allowing farmers to monitor field conditions in real time. With this system, the irrigation pump works automatically only when the soil moisture drops below the required level. This helps prevent unnecessary watering and significantly reduces water wastage.

In addition to irrigation, the solar energy generated can also be used to charge an electric tractor, which may require around 20 kWh of energy per day, and to operate electric agricultural tools that consume around 5–10 kWh per day. Even after meeting the energy needs of irrigation and farm equipment, some surplus solar energy may still remain. This extra energy can either be stored in batteries for later use or supplied to the electricity grid, creating an additional benefit for farmers.

IX. CONCLUSION

This project successfully demonstrates the design of an agrivoltaic system integrated with smart irrigation to support sustainable and efficient agricultural practices. By combining solar photovoltaic panels with crop cultivation, the system enables dual use of land, allowing farmers to generate renewable energy while continuing agricultural production. This approach helps improve land productivity and promotes the use of clean energy in farming. The integration of IoT-based sensors for monitoring soil moisture, weather conditions, and crop status enables better decision-making in irrigation management. The smart irrigation system ensures that water is supplied only when required, which helps reduce water wastage and maintain proper soil moisture for healthy crop growth. At the same time, the partial shading provided by solar panels helps lower soil temperature and reduce evaporation, creating a more favorable microclimate for crops.

Another important outcome of this system is the efficient utilization of solar energy. The electricity generated from the solar panels can power irrigation pumps, sensors, and other agricultural equipment. Any surplus energy can be stored or supplied to the grid, providing an additional economic benefit to farmers. This project highlights the potential of agrivoltaic systems to ad dress key challenges in agriculture such as water scarcity, high energy costs, and environmental sustainability. By integrating renewable energy with smart irrigation technology, the system offers a practical solution for improving farm productivity while conserv ing natural resources. Therefore, agrivoltaic farming can be considered a promising and scalable model for future sustainable agriculture.

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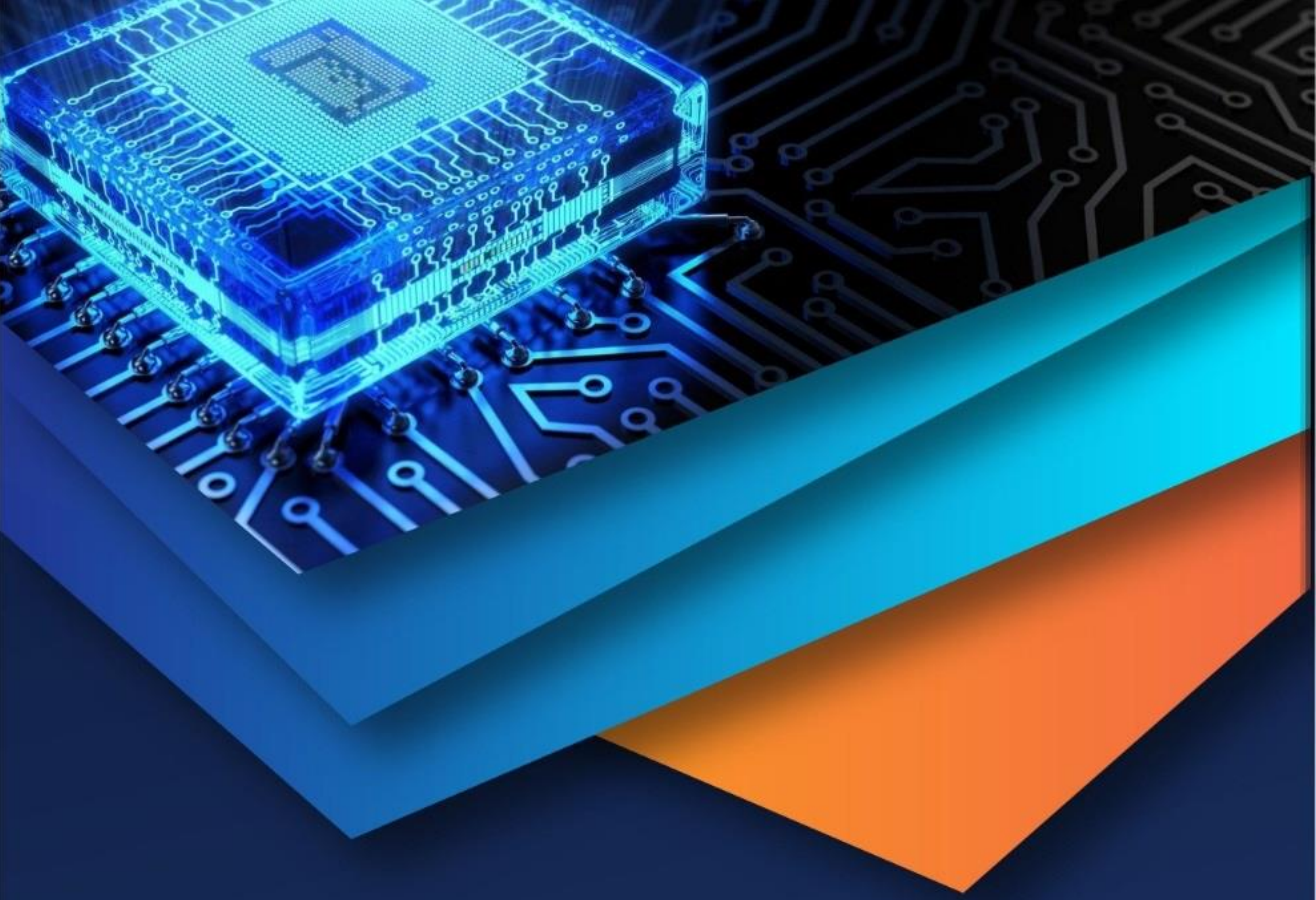

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