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Preliminary Design of a Low-Cost Greenhouse with Open Source Control Systems

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Abstract

Food security remains a global challenge, particularly in low-income countries. In Sub-Saharan Africa, one in four are undernourished, and the region has the highest prevalence of hunger in the world. Innovations in low cost greenhouse design have the potential to contribute to increased food security, particularly in areas where global climate change is creating additional variability in local weather patterns. This paper describes the preliminary design of a greenhouse that uses open source control systems. This design takes advantage of the decreasing cost and size of sensors to automate systems that have the potential to increase the efficiency and yield of greenhouses.

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Keywords: greenhouse; integrated controls; Arduino; sensors

1. Introduction

1.1. Motivation

In Sub-Saharan Africa, one in four are undernourished and the region has the highest prevalence of hunger in the world [1]. Food security remains a global challenge, particularly in low-income countries. For example, in Kenya,

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51% of the population lacks access to adequate food supply, and the food that is available is often of poor nutritional quality [2]. As can be seen in Fig. 1, there was a 35.5% prevalence of food inadequacy in 2014. Many households in Kenya are often chronically food insecure. A number of factors challenge food production in Kenya, including changes in climate resulting in unreliable weather patterns and a rapidly increasing population (e.g. from around 4 million people in the 1960s to over 40 million, currently).

Innovations in low cost greenhouse design have the potential to increase food security, particularly in areas where global climate change is contributing to additional variability in local weather patterns. New weather patterns can lead to heavy rains or drought that can disrupt crop production [3]. By increasing agricultural productivity, these innovations can also contribute to economic development, because of the significant role agriculture plays in many developing regions. For example, in Sub-Saharan Africa 65 percent of the labor force is employed through agriculture, generating 32 percent of GDP growth [4].

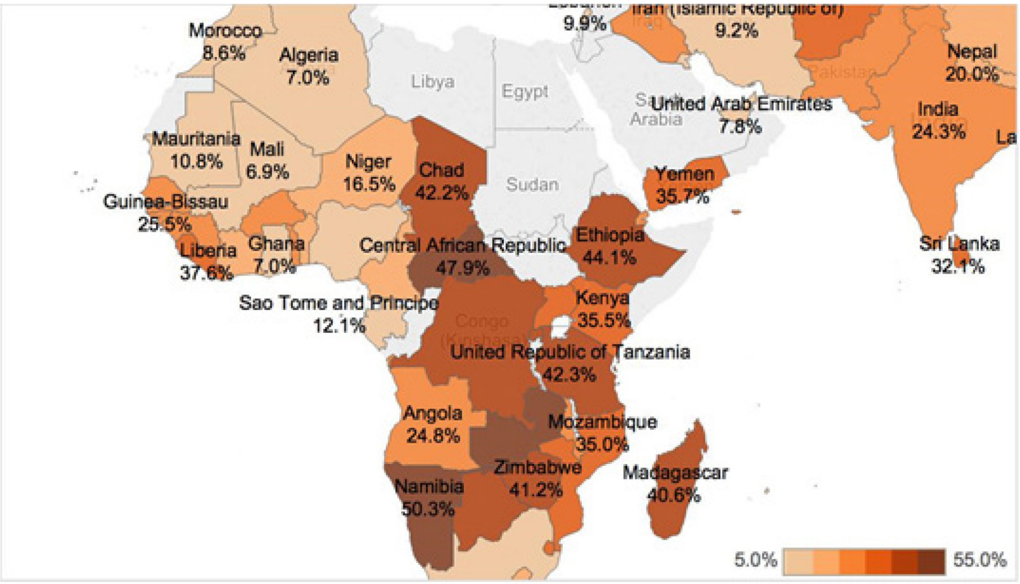


Fig. 1. Prevalence of food inadequacy in 2014 (%) (3-year average). Data Source: [5]

1.2. Existing systems and opportunity for innovation

There are many examples of effective, low-cost greenhouses designed for developing countries. One notable example was created by students from Penn State University’s Humanitarian Engineering and Social Entrepreneurship Program, and features a hoop house structure made from Polypropylene Random Copolymer Type 3 (PPR) [6]. This greenhouse is currently implemented in Kenya. Additionally, there are many commercial companies that develop greenhouses and market the agricultural and economic benefits of greenhouse farming (e.g. Amiran Kenya Ltd in Kenya [15]). However, many of the existing systems lack automation and control systems that are often found in more costly greenhouses. Because of the decreasing cost and size of sensors and microcontrollers in recent years, there is an opportunity to increase the effectiveness of greenhouses by integrating low cost sensors and control systems with low cost greenhouse structures.

2. System description and preliminary results

This paper describes the preliminary design of a low-cost greenhouse that uses open source control systems designed for use in communities outside of Nairobi, Kenya. The microcontroller and structure of the greenhouse system are designed to enable optimized growing conditions for crops such as tomatoes, capsicum, and onions. Fig. 2 illustrates the subsystems of the greenhouse, which include a:

- rainwater catchment system that supplements water supply,
- photovoltaic cell and battery array to power electronics and pumping,
- polyethylene-covered hoop structure,
- a control system that uses an Arduino microcontroller for regulating and monitoring climate variables, such as temperature, humidity, and soil moisture, which influence agricultural success.

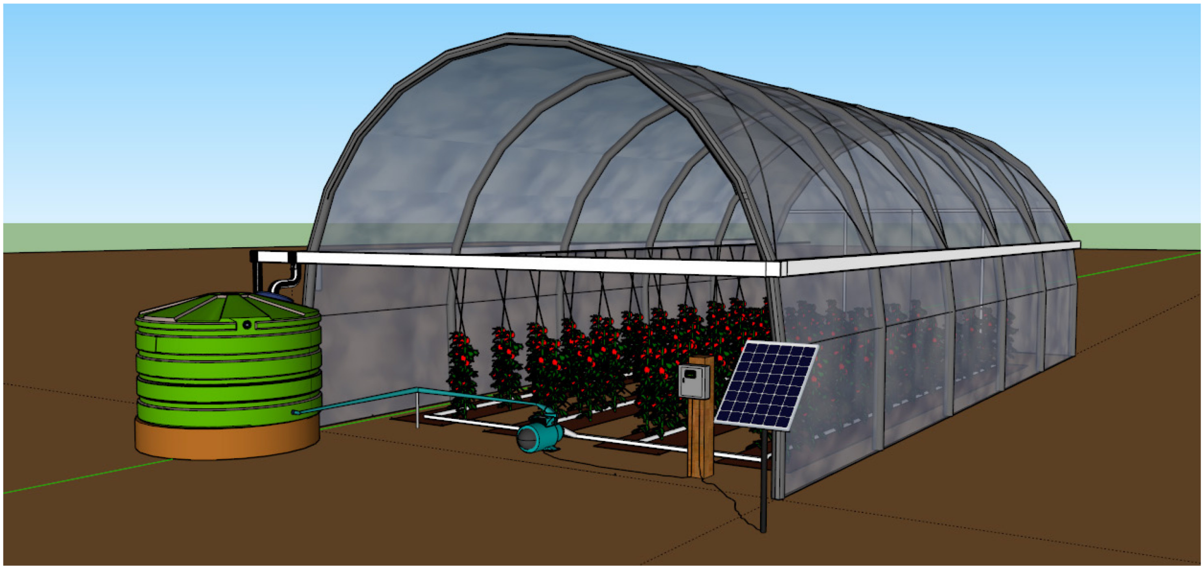


Fig. 2. 3D Render of the Hoop House with Integrated Systems

2.1. Controls

The control system collects information from the greenhouse environment in order to regulate its climate to maintain optimal growing conditions. The integrated system is composed of sensors (i.e. for soil moisture, temperature, and humidity), a microcontroller, and a power supply. A network included in the design allows for off-site control, and enables users to receive alerts and transmit commands to the control system.

2.1.1 Microcontroller-Sensor Assembly

The system uses Arduino, an open-source hardware and software platform, for the microcontroller because of its relative low-cost, large user community, and adaptability. Fig. 3 shows the software flowchart for the Arduino microcontroller program logic. The program is set to run every 20 minutes during daylight hours to gather enough information to properly maintain the environment, while minimizing power usage.

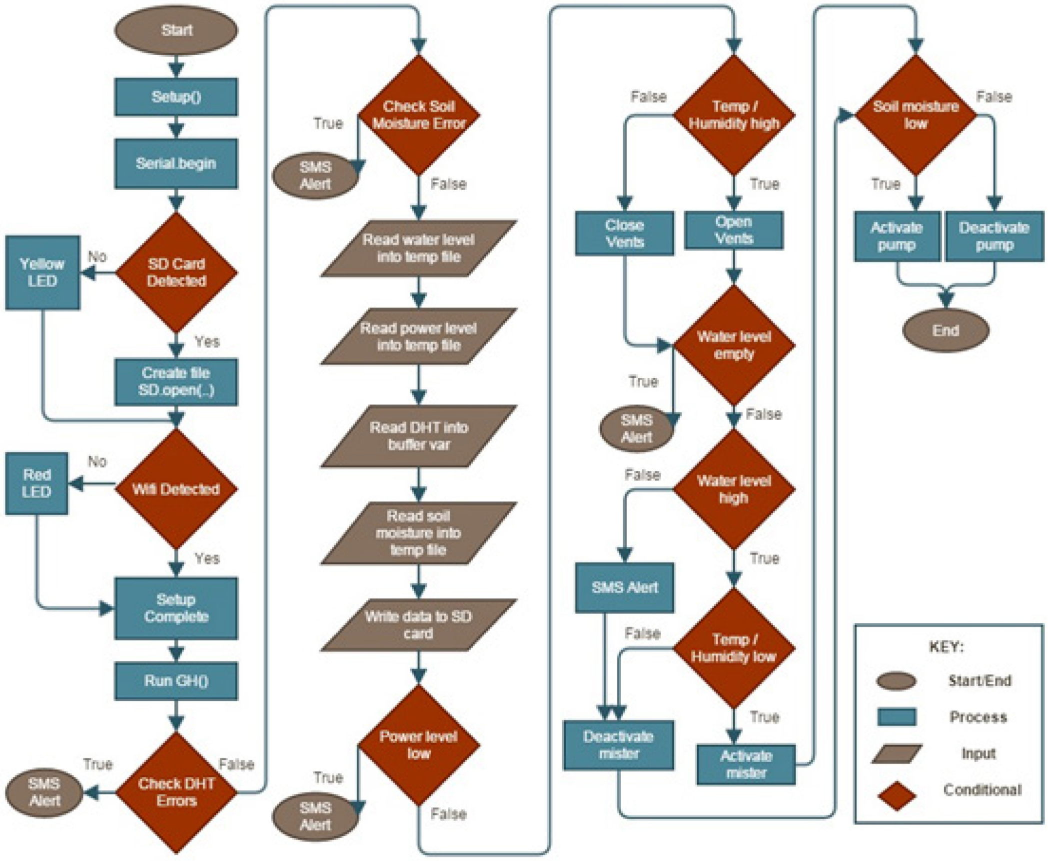


Fig. 3. Software Flowchart for the Arduino Program

The program begins by detecting the data storage and network connections. It then checks the humidity/temperature and soil moisture sensors for errors, and sends an SMS alert to the user if either are not operational. If both are functioning correctly, the program reads the level of the water storage tank, percentage of power remaining in the battery, and the status of the soil bays. After the sensors take the necessary readings, the program then monitors the power level. If the power level is low, an SMS alert is sent so that a worker can manually address the problem. With sufficient power, the program proceeds to perform a temperature and humidity check, which informs the Arduino whether to open the vents if levels are high, or close the vents if levels are low. Next, the program analyzes the water level to indicate whether or not the microcontroller can conduct further operations. If no water remains in the tank, the program sends an SMS alert, but does not proceed to perform any following procedures. If an adequate amount of water is in the tank, the Arduino activates the misters if the humidity levels are low. High temperature and humidity readings cause the microcontroller to deactivate the misters. The program finishes by examining the soil moisture levels, which prompts the Arduino to activate the pump if the levels are low or deactivate the pump if the levels are high. If the water level check reveals a low amount of remaining water in the tank, the program sends an SMS alert and deactivates the misters, but still examines the soil moisture data and activates the pump if needed. See Appendix 1 for a sample of the Arduino code in the program.

2.1.3 Power Supply

Several renewable and off-grid power sources were considered for the project, including solar, hydroelectric, and wind. A photovoltaic-based power system was chosen because of geographic constraints of the project and its versatility across varying locations. Electricity generated from the photovoltaic is stored in a lead-acid battery [8] due to its low cost and the stationary nature of the greenhouse. A step down converter regulates the battery's voltage to supply the Arduino with power. The system is sized to handle the loads generated from the motors of the irrigation pump and ventilation system.

2.1.3 Data transfer considerations

The Arduino microcontroller can use several methods to store and transfer data, including cellular networks and Ethernet/WiFi. The design of the control system includes the creation of a local wired (i.e. Ethernet) network that is connected over a cellular data network using a cellular Global System for Mobile Communication (GSM) data modem. The top cellular network providers in Kenya (i.e. Safaricom Limited, Airtel Networks Kenya Limited, and Telkom Kenya), who combined hold 96.1% of the market share, all use GSM technology [7].

2.2. Greenhouse

The structural elements of the greenhouse contribute the most to the overall cost, and thus provide the greatest potential for cost reduction. Thus, to minimize the cost of the system, it is important to have a simple, robust design that requires minimal material and complexity.

2.2.1 Structure

The greenhouse will be 8m by 30m, with 2m vertical walls and an arch extending 2m above the vertical wall for an overall height of roughly 4m. The vertical walls were sized with respect to the average height of the tomato plant, allowing for sufficient growing room and working conditions when planting and harvesting. This height also allows for a simple trellis system made by tying twine from sidewall to sidewall, which can be used to support tomatoes and other tall crops. Concerning the arch height, 2m was selected to achieve an optimal balance between structural integrity and water catchment, which is largely a function of slope. The 2m arch yields a 1:2 slope, which is adequate for a rooftop water harvesting system [14].

A "hoop" design rather than a "gable" design was chosen to reduce the need for costly structural fittings, to mitigate the effect of wind loading, and to simplify the on-site assembly process. A hoop design was selected because in multiple tests of different geometries in SolidWorks Flow Simulation (Fig. 4), it was found to require the least structural material to handle the associated wind loading due to its aerodynamics. A low-pressure system above the structure from the effect of wind accelerating along the arch saves the structure from excessive downward forces and prevents buckling of the vertical walls. This phenomena is governed by the Bernoulli Principle (Equation 1) where a pressure drop (P) occurs when the velocity of air along the roof (v2) exceeds the velocity of the air along the sidewall (v1). Because of the low coefficient of drag of the arch, v2 is greater than v2 would be for a gable house, and thus the pressure drop is greater and the downward force due to wind is lesser.

$$\Delta P = \frac{\rho({v_1}^2 - {v_2}^2)}{2} \qquad (1)$$

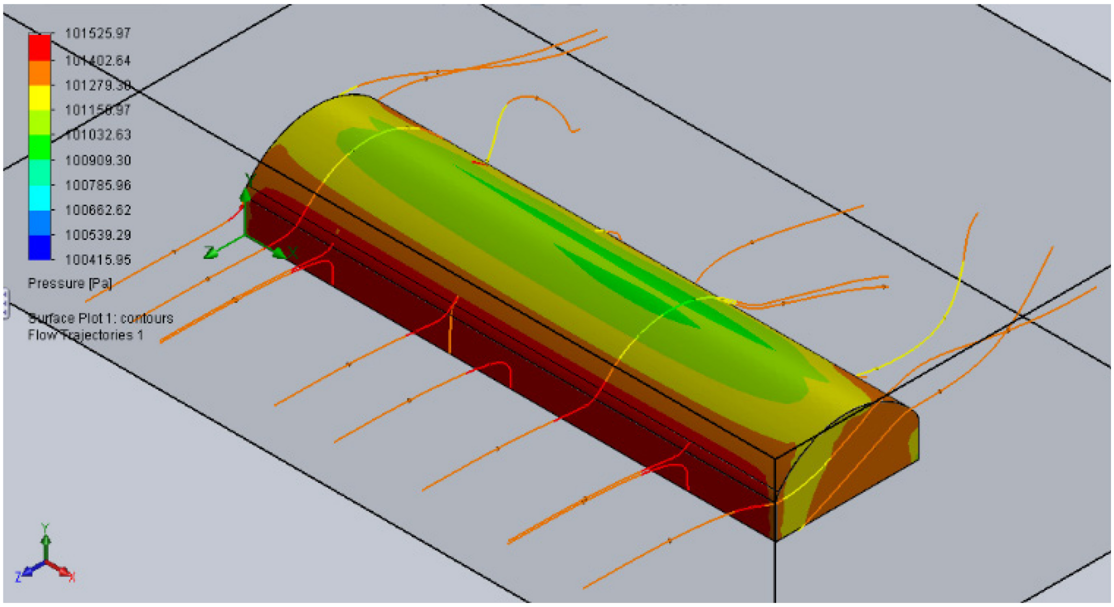
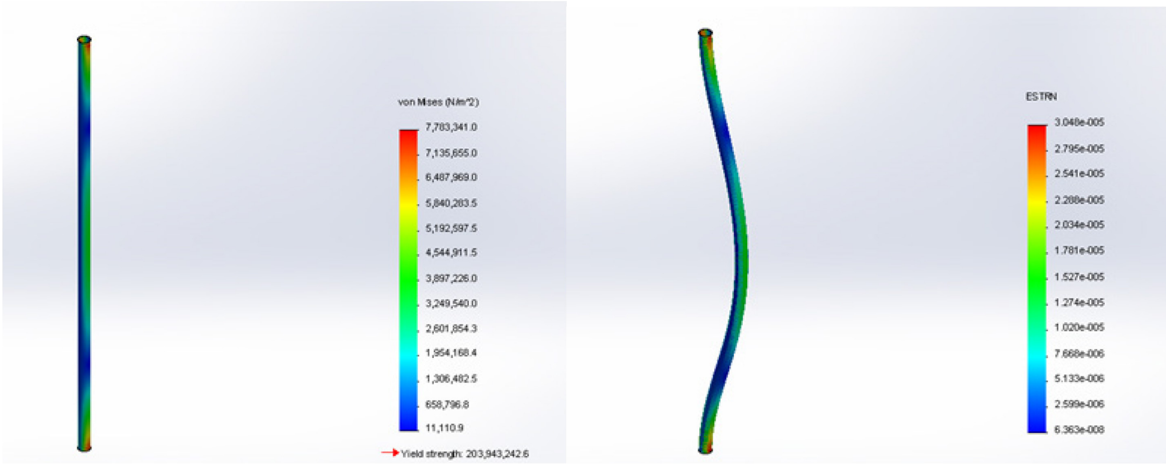


Fig. 4. SolidWorks Flow Simulation Results of 40mph (18m/s) Wind

As previously stated, SolidWorks Flow Simulation was used to determine the maximum anticipated wind load on the greenhouse. As can be seen in Fig. 4, even in maximum (gale) wind conditions, a low-pressure system relieves the vertical walls from excessive downward forces (i.e. only the orange and red sections exceed atmospheric pressure). The Flow Simulation results were then used to perform Static Load Simulation in SolidWorks. The Static Load Simulation was used to select an optimal pipe size and material for the design. Standard sizes of galvanized steel pipe were tested, until a minimally sized pipe that maintained a safety rating of two was found. Thus, 1.5" Schedule 10 (12 gauge), triple-galvanized steel pipe will be used, as it is commonly available and thus inexpensive relative to more unique pipe sizes. When deciding on the optimum pipe size, the maximum pressure from flow simulation was imported to a Finite Element Analysis (FEA) and tested on pipes of different sizes. The FEA allowed for more precise calculations and understanding of the stresses that will be present on the greenhouse. The sizes to be tested were determined by availability and cost of fittings. The FEA shown in Fig. 5 below represents 1.5" schedule 10 galvanized pipe, with twice the maximum wind loading applied. The figure shows that the selected pipe can handle the wind-loading expected in Kenya.



(a) (b)

Fig. 5. (a) True Scale Deformation of Vertical Support Beam and (b) 1000:1 Scale Deformation of the Vertical Support Beam

2.2.2 Glazing

The design uses a polyethylene glazing (6mm thick and single-layered) because of the consistent and moderate temperatures in Kenya. The primary criteria for decided on glazing material is light transmittance rather than insulation, which allows for the use of a single layer of polyethylene. A 6mm polyethylene glazing has a Photosynthetically Active Radiation (PAR) value of 88% [9]. Because the side curtains will automatically raise and lower for ventilation by automated controls, mesh netting will be used on the sidewalls between the glazing and the vertical walls. This will protect the crops from insects when the side curtains are raised and lowered. To the tendency of the glazing to billow in the presence of the low-pressure system created by wind accelerating along the arc, it will be tied from one vertical support to another on the opposite sidewall. This will form a crisscross pattern that will prevent stretching and tearing in windy conditions, and will minimally affect the cost and light transmittance of the design.

2.2.3 Foundation

A solid foundation is crucial to the success and longevity of the structure. When designing and implementing the foundation, such specifications as site location, topography, climate, wind speeds, and type of soil need to be taken into consideration. After benchmarking various systems, steel rebar rods (0.5” x 48”) were selected to be used in the foundation of the greenhouse. Specifically, two 0.5” holes will be drilled into the bottom of each vertical sidewall pole and the rebar rods will be inserted in a “+” pattern and tamped approximately three feet into the ground. Simple construction systems of this kind have proven to be sufficient concerning strength, corrosion, expense, and maintenance costs for greenhouses of similar size [11].

2.2.4 Water System

The water system must provide the greenhouse crops with an ample water supply, even with fluctuations in rainfall. The water system is comprised of three main elements: collection, storage, and conveyance.

Collection: A *roof rainwater-catchment system* is ideal for an off-grid and low-cost greenhouse, because it is relatively inexpensive compared to alternative collection methods and complementary to the structure [10]. The roof catchment system utilizes the large surface area of the greenhouse to capture rainfall, which is carried to a storage tank via a guttering system. In turn, the guttering system also mitigates erosive water accumulation on the sides of the greenhouse [10]. However, as a result of the inconsistent nature of rain, roof catchment is unreliable as the sole source of water collection, making supplemental water supply necessary for crop health.

Storage: A *plastic water tank*, between 500 and 1,000 gallon capacity, holds collected water for later irrigation. The plastic tank material reduces the time and money associated with installation, allows for easy internal access for cleaning, and is location independent [10]. The relatively small size range of the tank is important to ensure complete flushing of the water, which discourages the growth of bacteria and algal blooms that can compromise the integrity of drip lines and lead to crop disease [12].

Conveyance: A *drip method* enables efficient irrigation of greenhouse crops by delivering water based on readings from soil moisture sensors. This irrigation style uses drip lines with emitters, spaced according to the location of plants to facilitate consistent watering throughout the greenhouse. Additionally, drip lines reduce the likelihood of excess watering and plant diseases associated with wet foliage, which can occur with alternative methods like sprinklers [13].

In a similar water system developed for a greenhouse by Iowa State University that utilizes roof catchment to collect and store rainwater, it was able to provide 40 to 70 percent of the irrigation needs in a growing season, reducing the costs associated with supplemental water supply [10].

3. Future Work and Conclusions

There are three main areas that involve future work relating to controls, including the installation and control of appropriate motors, the configuration of SMS commands for use in Kenya, and exploring the possibility of incorporating local weather forecasts into the greenhouse's water supply usage.

A 1:8 scale prototype of the greenhouse design is currently being constructed as a proof of concept for the integration between structure and controls. This prototype will provide a microclimate to test aspects of the system, including water harvesting and irrigation, automated ventilation, and temperature and humidity control. From the results of testing, iterations will be made through data analytics to optimize the growing variables, debug potential flaws, and evaluate whether increases in costs associated with automation result in increases in productivity or efficiency.

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Appendix A. ***Sample of Arduino Code from program***

```
void setup()
{
    LCD.setHome();              //set the cursor back to 0,0.
    LCD.clearScreen();          //clear screen.
    pinMode(motor1, OUTPUT);
    pinMode(validtempLED, OUTPUT);
    Serial.begin(9600);
    //heading for serial monitor
    Serial.println("Greenhouse Status");
    Serial.print("Humidity (%),\t");
    Serial.print("Temperature (C),\t");
    Serial.print("Temperature (F),\t");
    Serial.println("SoilMoisture%");
    LCD.setBacklight(0);

    Serial.println("Initializing Card");
    pinMode(CS_pin, OUTPUT);
    if(!SD.begin(CS_pin))
    {
        //Serial.println("Card Failed");
        digitalWrite(YellowLED, HIGH);
        return;
    }
    Serial.println("Card Ready");

    // attempt to connect to an open network:
    Serial.println("Attempting to connect to open network...");
    status = WiFi.begin(ssid);

    // if you're not connected, stop here:
    if ( status != WL_CONNECTED) {
        Serial.println("Couldn't get a wifi connection");
        digitalWrite(RedLED, HIGH);
    }
    // if you are connected :
    else {
        Serial.print("Connected to the network");
    }
}
```

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