Low-Cost Light Sensors for Indoor Agriculture

Introduction

Hydroponic Salonova lettuce under full-spectrum LED grow lights.

Optimal light intensity is critical for maximizing agricultural production, maintaining plant health, and managing electricity costs for indoor growing operations. While inadequate light levels typically result in low plant yield, receiving too much light can be a contributing factor to issues such as tip burn in hydroponic lettuce, which is caused by a calcium deficiency when the rate of growth is too high and transpiration is reduced by high humidity (Figure 1).

The wavelength or color of light can also be controlled to produce a range of results in plants. A common type of grow light is the full-spectrum light, which provides significant amounts of blue and red light, which plants generally use for photosynthesis. These fixtures also add green, orange, and far-red wavelengths, which can further increase photosynthetic activity and plant weight, as well as optimize energy usage (Li et. al., 2020). Other light fixtures focus on supplying just red, blue, or a combination. The ability to generate specific lighting compositions can create specific responses, such as providing only blue to reduce the time to flowering in strawberries (Yoshida et. al., 2016).

The range of light wavelengths that is useful to plants is referred to as the Photosynthetically Active Radiation (PAR) range. PAR is measured with a quantum light meter, which counts the number of photons, or light particles, within the PAR range hitting the sensor and is commonly expressed in units of micromoles per square meter per second (μmol/m²/s). This quantity is referred to as the Photosynthetic Photon Flux Density (PPFD). A mole (mol) is simply a unit to count the photons, and there are one million micromoles (μmol) in each mole.

The PPFD, or light intensity, is used to determine the total light provided to plants over the course of a day. This parameter is the Daily Light Integral (DLI) and is expressed in units of mol/m²/d. The DLI is calculated by multiplying the PPFD by the duration of time in hours (T) that the plant receives light and then performing a unit conversion by multiplying by a factor of 3,600 (seconds in one hour) and dividing by a million to convert from units of micromoles to moles.

As an example, hydroponic lettuce requires 14 - 17 mol/m2 PAR each day. Over a 16-hour light period, the PPFD would need to fall between 243 - 295 μmol/m²/s. The DLI determination for an indoor operation using grow lights is very simple, since the light intensity does not change over the course of the day.

$$\mathrm{DLI}\left[\frac{\mathrm{mol}}{\mathrm{m^2 d}}\right] = \mathrm{PPFD}\left[\frac{\mu\mathrm{mol}}{\mathrm{m^2 s}}\right] \cdot \mathrm{T[hr]} \cdot \frac{3600\left[\frac{\mathrm{s}}{\mathrm{hr}}\right]}{1{,}000{,}000\left[\frac{\mu\mathrm{mol}}{\mathrm{mol}}\right]}$$

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The use of light sensors is necessary to appropriately set intensity controls and grow light mounting heights to achieve an ideal DLI. Quantum meters that measure PPFD can be expensive. The unit used for this work was purchased for $270 and is one of the least expensive devices available. In this study, we developed a low-cost alternative and tested the ability of phone apps to make PPFD measurements.

Figure 1. (a) Tip burn on new leaves of lettuce. (b) Etiolated (tall) stems of lettuce that receive inadequate light.

Phone Apps

There are several apps available for download for Android and iOS devices that will produce a PPFD reading using the built-in ambient light sensor on the face of a phone or tablet (Table 1). While the app is running, the on-screen PPFD reading is not continually updated and will generally display a new value only when there is a significant change in the light level. Temporarily blocking, moving, or rotating the device is often necessary to make a new measurement. Notable features within the apps include the ability to calculate DLI from the PPFD measurement and the option to select the type of source such as sunlight, full spectrum, or red light. Two of the apps reviewed can also apply a single-point calibration for an additional adjustment. Other useful features within these apps (Table 1) include the ability to lock or save a reading and record the position where the measurement was taken.

TABLE 1. Features of Android and iOS phone and tablet apps capable of PPFD measurements.

App	Operating System	Light Source Settings	Adjust / Calibrate	DLI Calc.	Mapping	Hold Mode	Data Logging
Photone	Android, iOS	Yes	PPFD	Yes	Paid	Yes	No
PPFD Meter	Android	Yes	Lux	Yes	Yes	Yes	Yes
Tent Buddy	Android	Yes	No	Yes	No	No	No
Galactica	iOS	No	No	No	No	Yes	Yes
Light Meter	iOS	Yes	No	Yes	No	Yes	No

Figure 2. Screenshots of PPFD and DLI measurements with the (a) PPFD Meter app, (b) Photone app and (c) ambient light sensor on phone face.

Custom PPFD Meter

Overview

The custom PPFD meter was designed to be cost effective and simple to build and assemble (Figure 3). Its two main components are the light sensor and a microcontroller that communicates with the sensor and displays readings to the user. The sensor is positioned at the top of a 3D printed case that can be handheld or mounted to a tripod or articulating arm with a ¼″-20 threaded mount. The Adafruit ESP32 S2 TFT Feather microcontroller selected can send readings to a computer through a USB connection or wirelessly over WiFi and Bluetooth, and has a built-in LCD screen to display measurements in real time to the user. The connection to the sensor also does not require soldering. Other components include a cable connecting the sensor and microcontroller, USB cable for data transfer and to upload the code to run the microcontroller, mounting screws, and an acrylic diffuser for the sensor (Table 2).

The three-part case was 3D printed with a filament deposition printer (Pulse XE). The main body incorporates

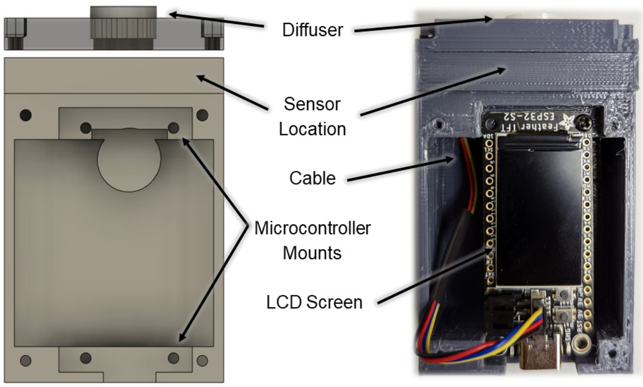

Figure 3. CAD drawing of case and 3D printed prototype of device equipped with AS7341 sensor.

mounting holes to secure the microcontroller and sensor to the case. The 3D printed cap contains a pocket to hold a circular light diffuser that scatters light from oblique sources or extreme angles that might otherwise cast a shadow on the sensor from the edges of the sensor chip package. A rectangular plate covers the main compartment of the case to protect the microcontroller. Metric M2.3, 2.5 or 2.6 self-tapping screws attach the sensor, microcontroller, cap, and cover plate to the main body.

Table 2. Component costs for custom PPFD meter. The acrylic sheet and screws will be purchased as quantities larger than required for this project. The portion of costs allocated to each device is rounded up to $1.

Components	Cost
AS7341	$16
Adafruit Feather ESP32 S2-TFT	$25
Qwiic Cable	$1
Acrylic Sheet	$1
USB-C Cable	$5
3D Printed Case	$2
M2.6 Self Tapping Screws	$1
Total	**$51**

Light Sensitivity

Light particles, or photons, travel in oscillating waves. The distance between peaks in those waves is referred to as the wavelength and is measured in nanometers (nm). The AS7341 (ams AG) sensor selected for this device features eight overlapping light measurement channels (respectively centered at 415, 445, 480, 515, 555, 590, 630, and 680 nm), which together span the entire 400 - 700 nm PAR range (Figure 3). The sensor is more sensitive to, or more

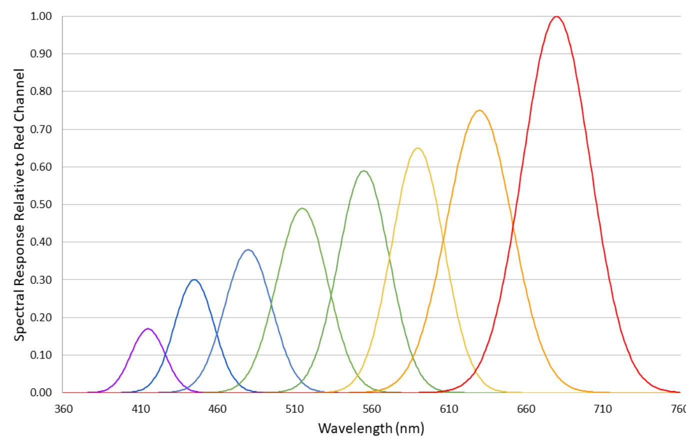

Figure 4. Eight light measurement channels of the AS7341 sensor which span the PAR range. Higher values indicate increased sensitivity to detect light photons at the specified wavelength. Adapted from the manufacturer's data sheet (ams OSRAM Group, 2020).

likely to detect, photons at longer wavelengths, such as red and orange. The photons counted by these eight channels are added together to make the PPFD measurement.

The sensor was purchased from a third-party manufacturer, Adafruit Industries, which packages the sensor as more of a turnkey product, in which other necessary components have been integrated into a circuit along with the sensor. This type of product minimizes the number of individual components required and eliminates the need to solder electronic components. Software libraries and examples for the Arduino and Python programming environments are provided.

Diffuser

The AS7341 sensor is particularly sensitive to the relative position of the light source, especially when it is not directly above the sensor. Readings taken at the edge of the grow lights were observed to deviate significantly by simply rotating the sensor. Light must pass through a small circular window in the sensor body (Figure 5c) to reach the sensor array and light from oblique sources must be scattered as to not be blocked from hitting the entire sensor array. A nominally ¼” thick translucent white acrylic sheet was laser cut into a circle and installed with 1 mm of the acrylic protruding up from the surface of a cap covering the sensor.

The diffuser also had the effect of limiting light transmission or reducing the amount of light that reaches the sensor, allowing the device to be used with a wider range of light intensities without saturating the photosensors on the AS7341. The translucent acrylic lowered the average observed deviation caused by rotation or light direction to 5 µmol/m²/s with full spectrum LEDs through an intensity of 688 µmol/m²/s. It is possible to omit the diffuser when working with lower levels of light or when the sensor is placed further away from the light source.

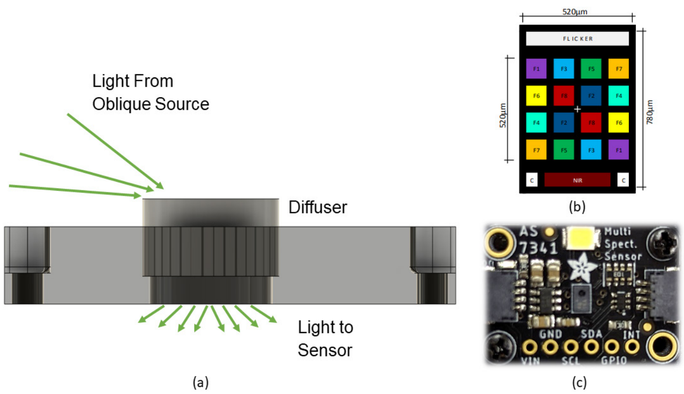

Figure 5. (a) Light traveling through the diffuser in the sensor cap. (b) Layout of sensor array, reproduced from the manufacturer’s data sheet (ams OSRAM Group, 2020), and (c) Pinhole window to sensor array (on rectangular AS7341 microchip at center of sensor circuit board).

Grow Lights

The custom PPFD sensor and the apps were calibrated and tested with Spider Farmer SF1000 full spectrum and Mars Hydro Pro II Epistar 120 (red and blue) Light Emitting Diode (LED) grow lights. The light compositions of these units were also evaluated with an UPRtek MK350N spectrometer, which measures the light intensity at individual wavelengths across the PAR range. The light spectrum emitted by these grow lights are shown in Figure 6. The full-spectrum light fixture provides light at wavelengths throughout most the 400 – 700 nm PAR range, while other fixture targets specific light requirements for blue and red light.

The AS7341 can generate a similar, low-resolution graphic for eight wavelengths in this range. Bars indicating the relative light intensities of each color sensor of the AS7341 have been overlaid onto the corresponding spectra from the spectrometer.

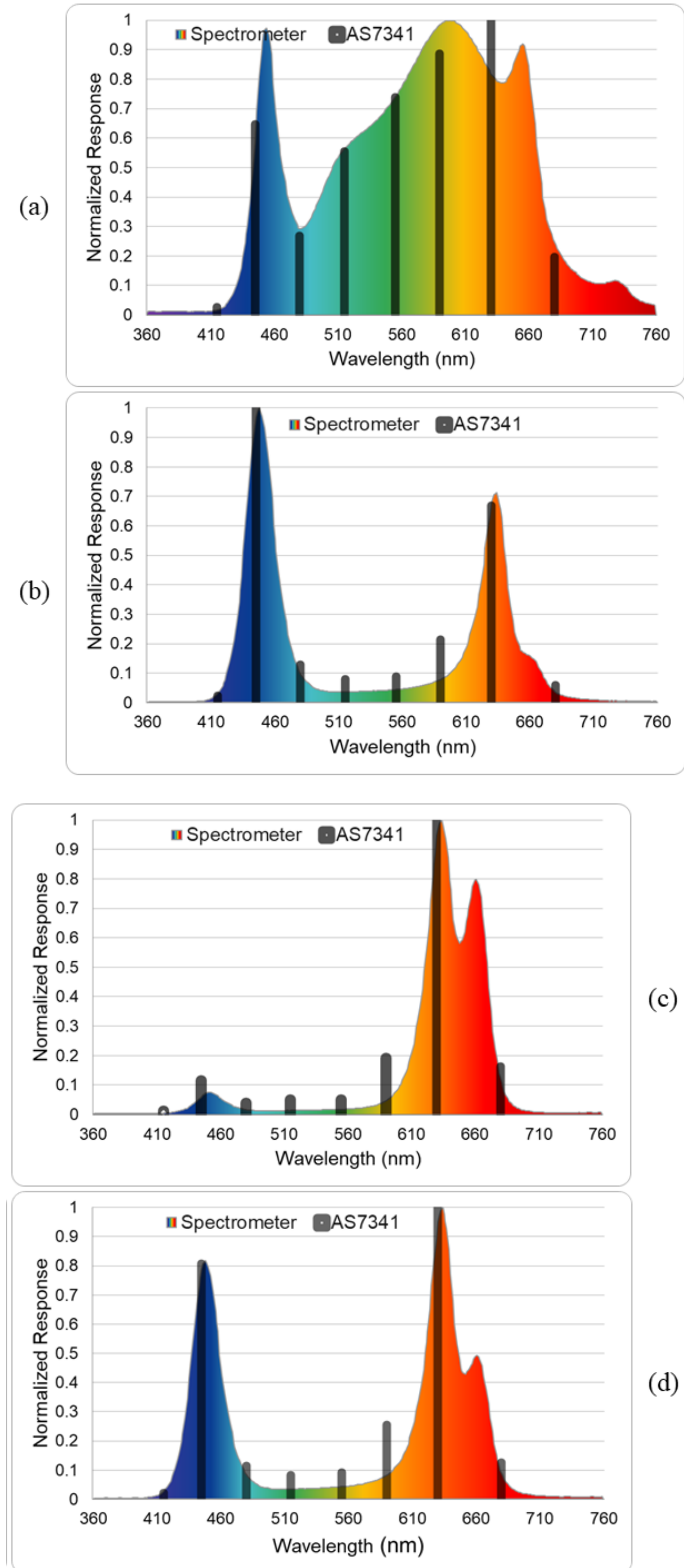

Figure 6. Relative response as measured by the UPTrek 350N spectrometer (curve) and AS7341 (bars) for (a) Spider Farmer SF1000 and Mars Hydro Pro II Epistar 120 using the (b) blue, (c) red, and (d) blue and red settings.

PPFD Calibration

The raw photon counts of the sensors were converted to actual PPFD values through a calibration process that used a quantum meter (Spectrum Technologies Solar Electric Quantum Meter #3415FSE) as the reference for PPFD, with settings for electric and solar light. The electric light setting was used with all grow lights, regardless of type. A mounting bracket kept the angle, height, and position of the reference meter and light sensors consistent to ensure that all devices were exposed to the same light conditions when under an LED grow light. A range of PPFD through a maximum of 700 µmol/m²/s, typical for indoor agriculture, were produced by changing the light intensity, height of the grow light, and horizontal position under the light. Readings from the reference meter and AS7341 were recorded when each was centered on nine positions designated on a grid below the light fixture. (Figure 7).

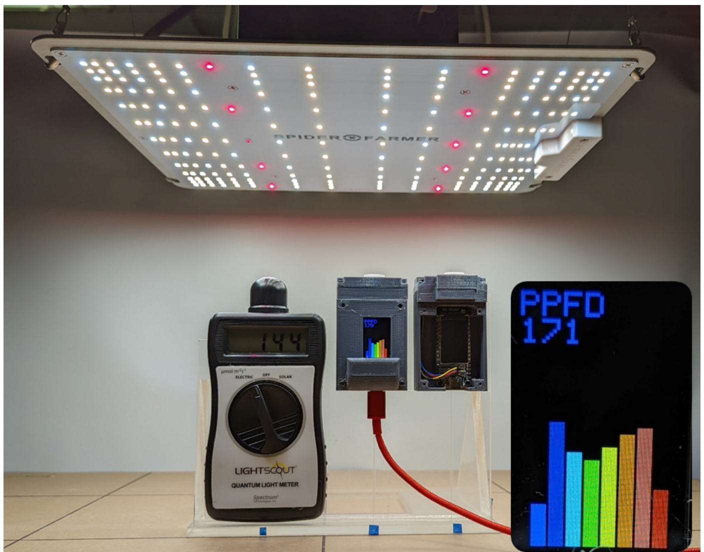

Figure 7. Mounted reference meter and AS7341 sensor under the Spider Farmer SF1000 full-spectrum grow light with enlarged view of sensor LCD display showing the PPFD reading and light composition.

Readings from both the reference meter and AS7341 were observed to increase consistently as the light intensity was raised. This type of proportional or linear relationship shown in Figure 8 for full-spectrum LED indicates that the conversion of photon count to PPFD reading can accomplished with the formula for a straight line. The PPFD value is calculated by multiplying the sensor photon count by the slope of the line and then adding that product to the offset or y-intercept value. For example, the raw photon count of the AS7341 must be divided by 32.75. The resulting value is a PPFD reading in units of µmol/m²/s. In this particular calibration result, there is no significant offset between the sensor output and quantum meter reading (Figure 8).

$$\text{PPFD} = \frac{\textbf{sensor output}}{\textbf{slope}}$$

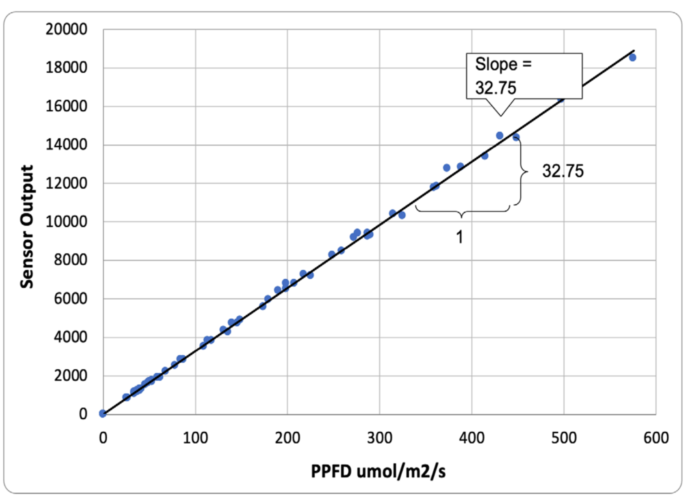

Figure 8. Linear relationship between the AS7341 sensor photon count and reference quantum meter. The conversion to PPFD is accomplished by multiplying the photon count by the slope of the line and adding the y-intercept as an offset.

Results

For full-spectrum LEDs, the average error or difference between reference meter and calibrated AS7341 reading was determined with a root mean squared error calculation and found to be 7 µmol/m²/s. When converted to the DLI using a 16-hour light duration (Equation 1), the average projected error is 0.4 mol/m²/d. The results for all light sources are shown in Figure 9.

The PPFD Meter and Photone apps were tested using a Google Pixel 6 phone. The "5000K + 630 nm" light preset setting within the PPFD Meter app was used with all LED fixtures. For the Photone app, the "Full Spectrum" setting was selected for the full spectrum fixture and "Red/Blue" was selected for all other fixtures. These apps do not provide raw photon count measurements at specific wavelengths, as the AS7341 sensor does, but displays the photon count for the entire sensitivity range of the sensor as a PPFD reading. Any calibration performed simply

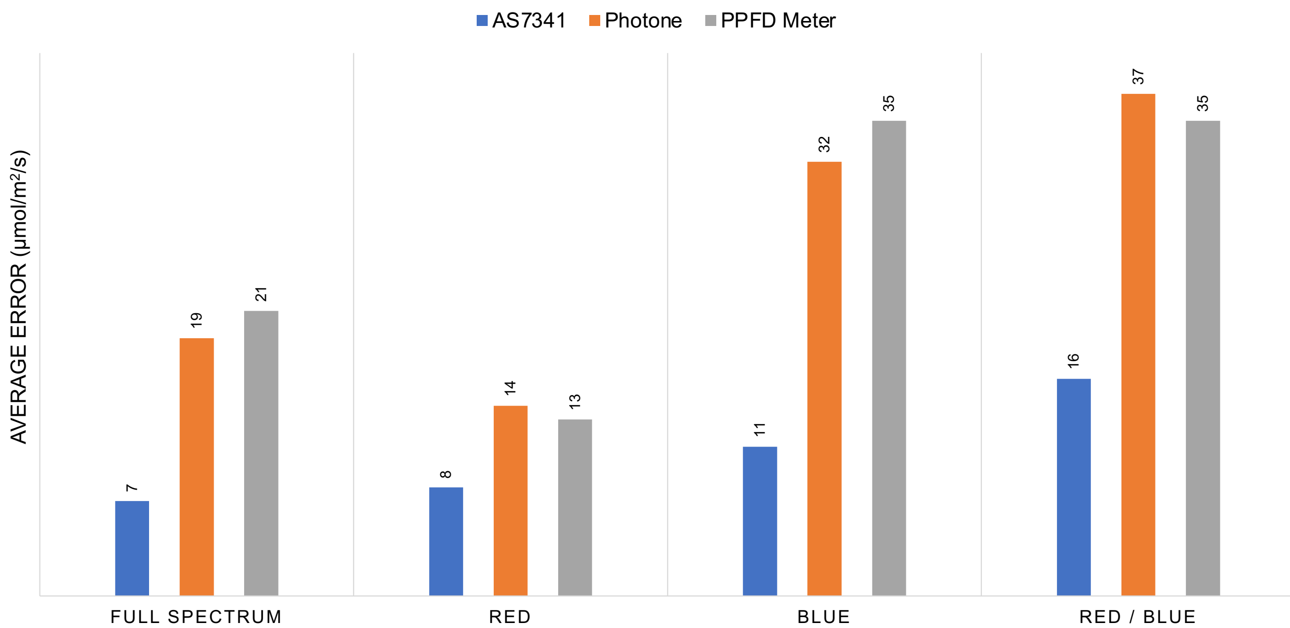

Figure 9. Average error in the calibrated PPFD readings from the AS7341 and Google Pixel 6 running the Photone and PPFD Meter apps with LED grow lights.

corrects the app's PPFD reading to align with the reference meter PPFD reading more closely.

With full-spectrum LEDs, the phone apps had observable errors of 27 and 47 µmol/m²/s for Photone and PPFD Meter respectively, with no changes to the default calibration. Use of the single-point calibration feature within the Photone app did not improve the result over the entire range tested, although it did improve the results at light levels near the point of calibration. The adjustment feature within the PPFD Meter app was not used, as that was required to be performed in light units of lux, which weights photons from different wavelengths differently to more closely approximate the perception of "luminance" by human vision. With an external calibration, the average error was brought down to 21 and 19 µmol/m²/s for these apps, but this calibration cannot be entered into the app so that the calibrated values are displayed on the phone screen. The observed errors for the other LEDs are summarized in Figure 9.

Simplified Calibration

While the use of more measurements improves the accuracy of the calibration, this process can be completed with just two calibration points, provided that the light intensities are within the dynamic range in which the sensor behaves linearly. In contrast, 117 calibration points were generated for the above calibration result. If a two-point calibration is conducted, it is recommended that the sensor is positioned directly under the fixture to avoid very oblique illumination through the sensor view ports. A careful two-point calibration did not significantly increase the observed average error, adding on average approximately 2 µmol/m²/s to the error measuring full-spectrum LEDs at distances of 8-12 inches from the fixture. Two-point calibration calculations can be performed without the use of a spreadsheet. Equation 3 is used to calculate slope, and the sensor readings must be divided by the slope to convert the photon count to PPFD (equation 2). The first or lower pair of readings for the two-point calibration is denoted by the subscript 1, where Q1 and S1 are the reference quantum reading and AS7341 sensor reading respectively. Likewise, Q2 an S2 are the reference and AS7341 readings at the higher calibration point.

$$\text{slope} = \frac{(S_2 - S_1)}{Q_2 - Q_1}$$

Summary

A low-cost (~$51) PPFD device to measure photosynthetic active radiation was constructed with readily available electronic components, required no soldering, and is housed in a 3D printed case. The device can be mounted with a ¼"-20 threaded adapter and left in place to continually monitor light levels. Calibrated PPFD readings were displayed in real time to an LCD screen and exported to a computer through a USB connection. The results were on average accurate to within 7 µmol/m²/s (PPFD) or 0.4 mol/m² (DLI 16-hour) when measuring lighting from full spectrum LEDs. This sensor is also capable of providing a low-resolution determination of the light composition. Future versions will incorporate wireless transmission of results and a battery for cordless operation. 3D drawing files for a case are available for download.

Two phone apps were also evaluated as PPFD sensors. Both averaged accuracies of 21 μmol/m²/s (PPFD) or 1.2 mol/m²/d (DLI 16-hour) after calibration over a 700 μmol/m²/s range, which can be improved if the usage range is narrowed. With proper technique, these devices can be sufficient to maintain lighting in indoor agricultural systems to achieve recommended DLI ranges.

Resources

3D printer files for the case for the PPFD meter can be downloaded from Thingiverse (5528849).

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Disclaimer

Mention of any product or company should not be considered a recommendation over alternatives that may also be suitable. The results obtained with the sensors described may not be achieved under all conditions. Adjustments should be made to account for differing conditions such as the sensor selected, grow lights used, and other environmental factors.

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