



## A TCS3200/AS7341 Arduino MEGA-Based System for PV Soiling

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### ABSTRACT

With the rapid increase of installed photovoltaic (PV) capacity, especially in countries like Bulgaria, there is a growing need to monitor PV soiling levels to optimize cleaning maintenance for large-scale utility PV parks across multiple locations. While industrial systems like DustIQ track soiling levels using blue-LED and photodetector setups (even at night), educational and open-source alternatives often rely on simpler RGB systems with basic illumination sources, such as the TCS3200 sensor. In this work, we developed an open-source, automated soiling measurement system that integrates both the TCS3200 sensor and an AS7341 spectrometer. The setup is embedded within an Arduino MEGA ecosystem, which features a reference solar panel, an INA219 sensor for estimating solar power generation, a BH1750 sensor for solar intensity recordings, and a DS18B20 sensor for ambient temperature readings. Additionally, a dedicated visualization platform for the TCS3200 and AS7341 data was developed using Processing. The proposed open-source platform serves as a comprehensive educational and research foundation for investigating PV optimization strategies in solar power generation.

**Keywords:** PV soiling, photovoltaic optimization, AS7341 multi-spectral spectrometer, TCS3200 RGB sensor, Arduino MEGA, Processing visualization, predictive maintenance, solar power generation monitoring.

### 1. Introduction

The recent exponential increase in installed photovoltaic (PV) capacity, especially in developing countries such as Bulgaria, now accounts for nearly half of the country's total electrical energy production (Koleva et al., 2026). During the latest severe droughts of 2026, a direct consequence of global weather transitions, this massive PV deployment crucially backed up the nation's baseload energy architecture. With the upcoming climate predictions for the next years, solar power generation will continue to rise in importance to provide electrical energy, increasing the need for continuous monitoring of PV generated power (Koleva et al., 2026). Nevertheless, a massive challenge for big solar parks is PV soiling, which is caused by factors such as soil contamination, among others, on the PV panel surface. This accumulates over time, shadowing the sunlight and preventing it partially or fully from reaching the p-n junction of the solar cell to generate electricity. In this regard, commercial soiling monitoring systems, such as DustIQ (Kipp & Zonen, 2019, Korevaar et al., 2017), have been developed. These systems are typically deployed across multiple strategic locations within a large solar park to accurately map the spatial distribution and rate of soiling accumulation. Market trend projections emphasize the urgency of applying such monitoring technologies by assessing the number of soiling sensors, required per year to satisfy the PV industry needs (Bessa et al., 2021). State-of-the-art open-source automated systems for monitoring soiling are based on: (1) current-voltage measuring devices (Kampira et al., 2022); (2) the TCS3200 RGB sensor (Olorunfemi et al., 2022) or (3) air particulate matter monitoring (Mohammed et al., 2018). The first implementation tracks the I-V characteristic of a PV panel and its degradation due to dirt accumulation. The TCS3200 system illuminates the target surface from within a transparent cover and detects the amount of reflected light via its red, green, and blue photodiode channel matrix, converting the light intensity into a proportional frequency output (Olorunfemi et al., 2022), whereas Mohamed et al., 2018 monitors the particulate matter and humidity in the open air to make correlations to the accumulated dirt on a solar panel. Alternatively, drone recordings, combined with statistical classifiers are used to detect contamination sites on massive PV installations (Czarnecki & Bloch, 2022). An original low-cost solution utilizes free satellite imagery analyzed via Google Earth Engine to compute specialized soil indices and map large-scale dust deposition (Supe et al., 2020).

Alternatively, the AS7341 spectral sensor (ams OSRAM, (2020)) has been used in agricultural monitoring applications, with spectral bands spanning from visible to near-infrared radiation (Rahman et al., 2025), in PV projects as Photosynthetically Active Radiation (PAR) sensor (Bäumker et al., 2021) and for chlorophyll leaf content estimation (Li et al., 2023).

In this work, we present an automated Arduino-based soiling detection system, which incorporates an RGB-based TCS3200 sensor, a VIS-NIR AS7341 spectrometer, a PV panel linked to an INA219 current-voltage meter device, a BH1750 for light intensity and DS1820 for ambient temperature recordings. The data visualization is realized in Processing for both spectral sensors, which optimizes the data assessment in real-time. The proposed open-source system can serve as a basis for future educational and research projects within the field of PV power monitoring.

## 2. Materials and Methods

Figure 1 presents the electrical schematic of the developed environmental and optical characteristics monitoring system, controlled by an Arduino Mega 2560 microcontroller board (Arduino, Monza, Italy). The circuit includes several peripheral modules connected either directly to the microcontroller or via a breadboard used for power distribution and communication lines.

The BH1750 digital ambient light sensor (Rohm Semiconductor, Kyoto, Japan) is connected to the I<sup>2</sup>C bus, providing ambient light level data measured in lux. The AS7341 spectral sensor (ams OSRAM AG, Premstaetten, Austria) is integrated into the same I<sup>2</sup>C bus, detecting light radiation across eight visible spectrum channels, as well as via additional Clear and Near-Infrared (NIR) channels. The INA218 power monitoring sensor (Texas Instruments, Dallas, Texas, USA) is also connected to the I<sup>2</sup>C bus to track the electrical parameters of the system. Consequently, the system enables simultaneous measurement of the physical environment, total illuminance, and the spectral distribution of the captured light.

The TCS3200 color recognition sensor (ams OSRAM AG, Premstaetten, Austria) is retained as a separate optical measurement component. It is interfaced with the digital I/O pins of the Arduino via the S0–S3 control lines and the OUT frequency output. This sensor utilizes a photodiode array composed of red, green, blue, and clear (unfiltered) photodiodes to generate a frequency output signal proportional to the intensity of the detected light.

Temperature is measured using a DS18B20 digital probe (Analog Devices Inc. / Maxim Integrated, Wilmington, Massachusetts, USA), connected via the 1-Wire single-conductor interface. The communication line is equipped with a pull-up resistor, which is required for the proper operation of the sensor.

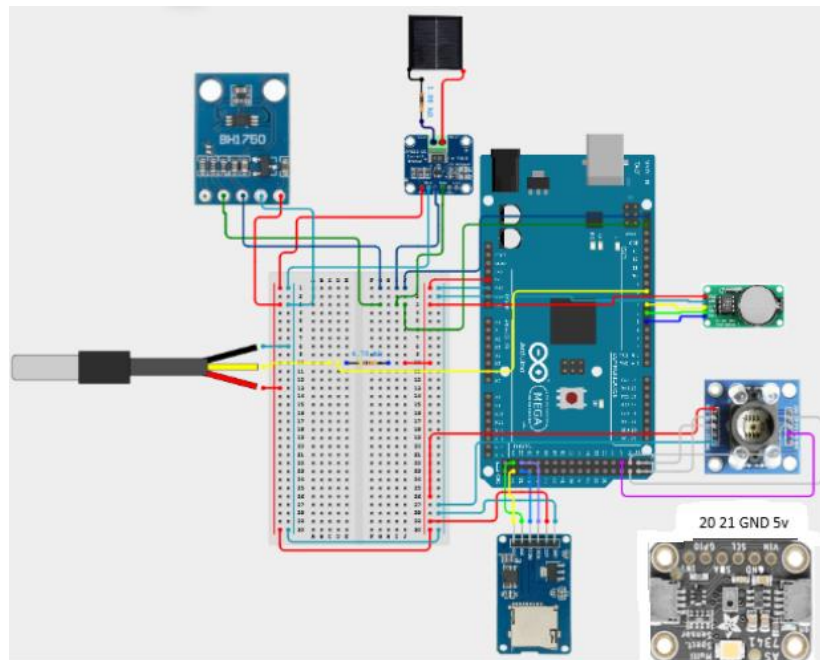


**Fig. 1 - Electrical schematic of the soiling monitoring system based on TCS3200 and AS7341 optical/spectral sensors.**

All related codes can be downloaded from (Tsvetkov & Tolstosheeva, 2026). The realized laboratory prototype, assembled on a standard breadboard to validate the hardware integration, is shown in Fig.2.

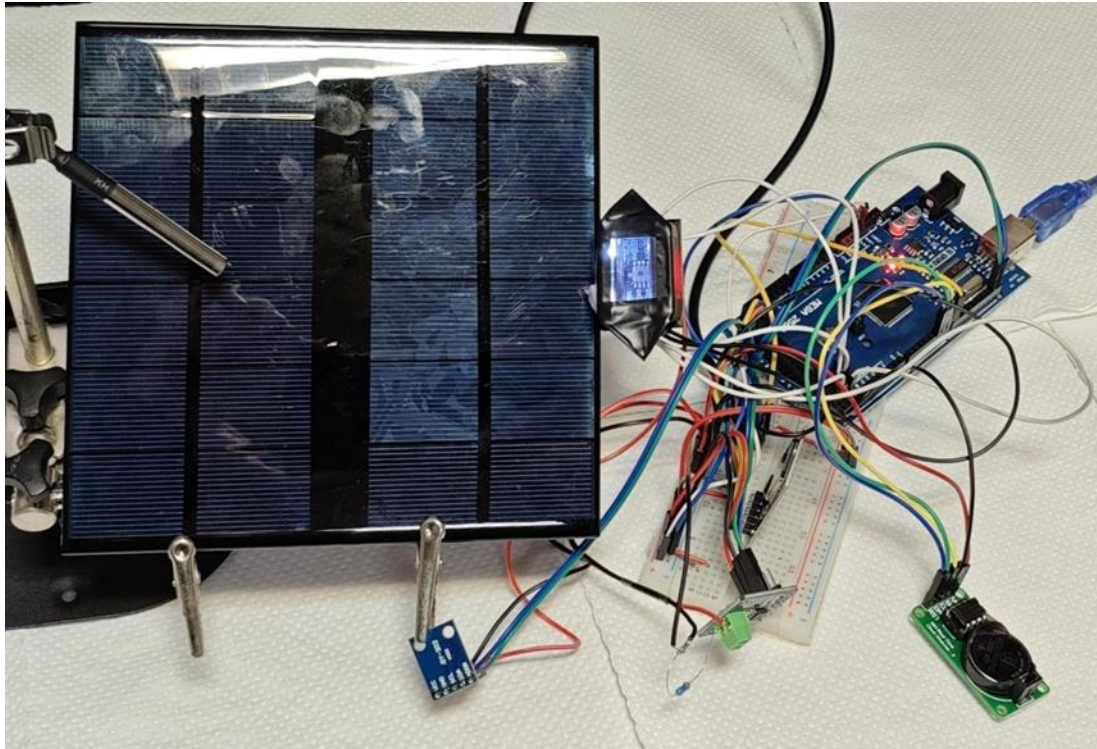


Fig. 2 - Realized breadboard prototype of the developed soiling system.

### 3. Results and Discussion

#### 3.1 TCS3200 soiling level detection indoors

Figure 3 presents the first initial experiment, obtained indoors with the TCS3200 sensor. The left panel of the Figure illustrates the experimental setup under initial, unsoiled conditions, while the right panel displays the baseline frequency output for the Red, Green, Blue, and Clear channels. The measurements were conducted indoors under 400 lx fluorescent lighting to establish the reference values before any soil accumulation.

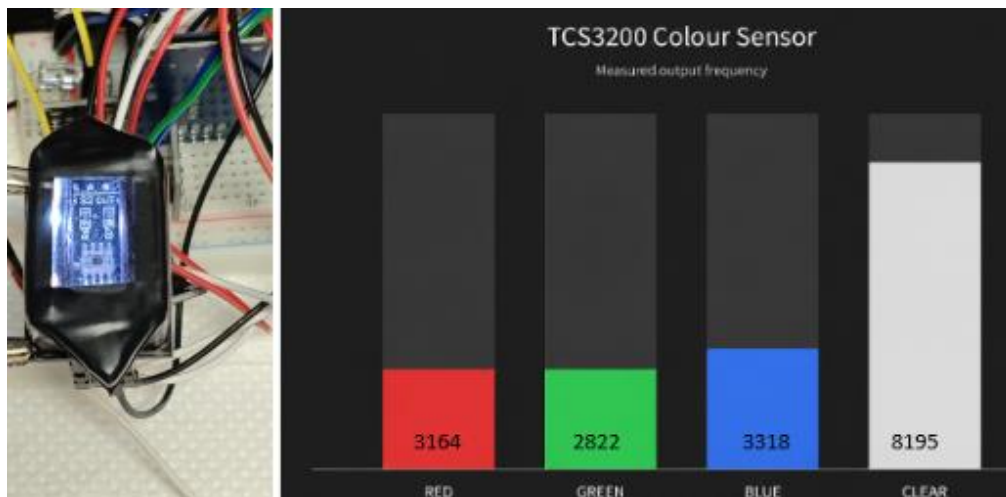


Fig. 3 - The TCS3200 sensor baseline frequency outputs under 400 lx indoor fluorescent lighting (no soiling).

Figure 4 shows the TCS3200 sensor output under two levels of contamination: light soiling (left) and heavy soiling (right). As the soiling level increases, the frequency values for the Red, Green, Blue, and Clear sensor channels drop. This reduction clearly proves that the system can detect different levels of surface pollution.



Fig. 4 - Comparison of TCS3200 sensor frequency outputs for RGB channels under mild and heavy soiling levels in indoor conditions.

### 3.2 TCS3200 soiling level detection outdoors vs. indoors

Figure 5 compares the sensor output between indoor and outdoor conditions in the left and right plots, respectively. The ambient light intensity at noon mid of July in Bulgaria is significantly higher than indoor lighting. Because of this, the signal attenuation caused by soiling is much larger outdoors. This greater drop in frequency makes the sensor more sensitive to surface contamination under bright outdoor conditions, especially the RED and CLEAR sensor channels.

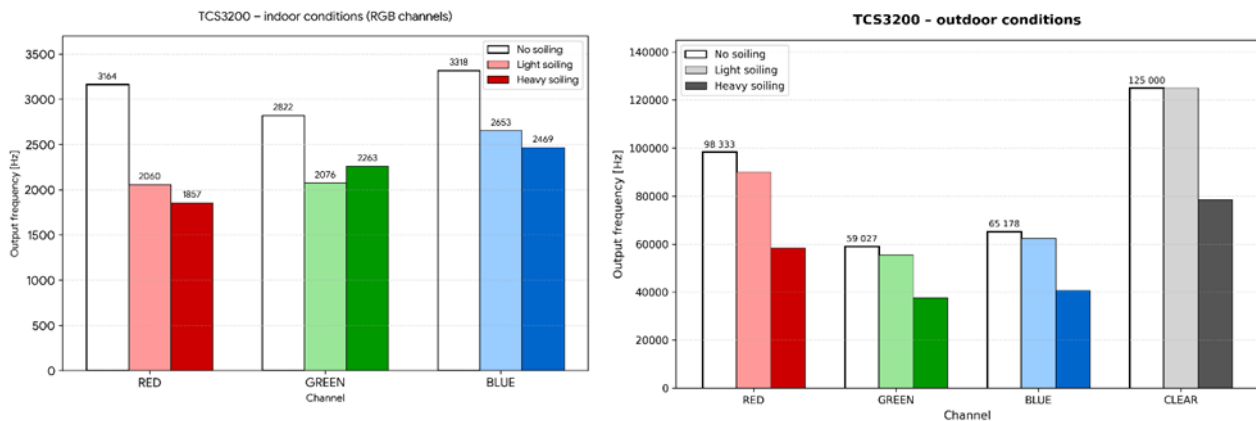


Fig. 5 - Comparison of TCS3200 sensor frequency outputs under indoor (left plot) and outdoor (right plot) lighting conditions.

### 3.3 AS7341 soiling level detection outdoors

Figure 6 shows the initial output of the AS7341 sensor under unsoiled outdoor conditions. A key advantage of this sensor is its broad spectral coverage. It measures the entire visible light spectrum across eight distinct channels. Additionally, it detects the Near-Infrared (NIR) region through a dedicated spectral channel. This expanded capability provides valuable data for advanced optical analysis.

Figure 7 demonstrates the outdoor performance of the AS7341 sensor. A major advantage of this sensor is its built-in LED on the shuttle board, though this experiment deliberately drove the sensor without active internal illumination. By relying 100% on ambient outdoor solar radiation, the setup shows extreme sensitivity to pure shadowing effects. Even the addition of a clean transparent cover, used to shield the device from direct contamination, triggers a clear signal reduction. This passive solar tracking approach reveals larger absolute signal drops in the CLEAR and Near-Infrared (NIR) bands due to their high baseline daylight amplitudes. Unlike commercial systems like the DustIQ Soiling Monitoring System which use active internal blue LEDs to run measurements at night to establish a cloud-free, seasonally stable baseline, this experimental configuration functions purely via ambient light transmittance. However, the AS7341 retains the long-term benefit of being software-upgradable to activate its onboard LED, enabling future active night-time monitoring modes similar to the DustIQ system.

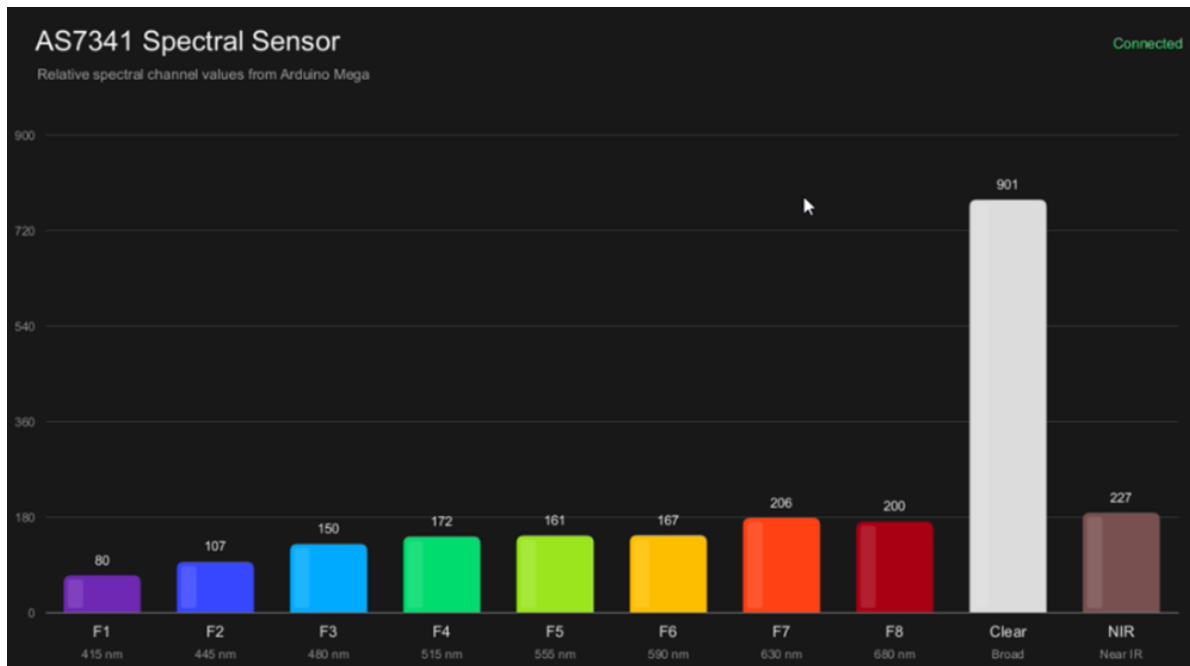


Fig. 6 - AS7341 sensor baseline spectral output under unsoiled outdoor conditions, showing visible light and Near-Infrared (NIR) channels.

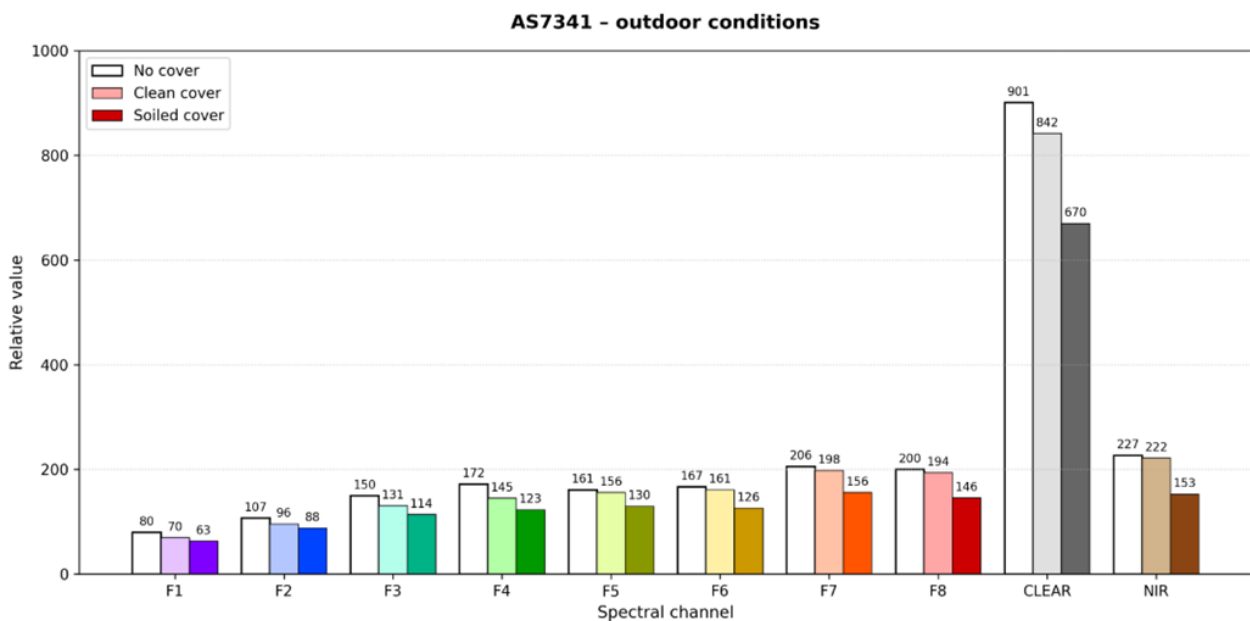


Fig. 7 - AS7341 sensor spectral output under outdoor daylight conditions across distinct protective cover and contamination levels (F1–F8 visible, CLEAR, and NIR bands).

#### 4. Conclusion

This work presented the development of an open-source, Arduino Mega-based system to automatically detect soiling levels by means of a TCS3200 RGB sensor and AS7341 spectrometer. Outdoor measurements under real conditions revealed that the multi-spectral AS7341 sensor provides superior diagnostics due to its broader coverage of eight visible channels and a dedicated Near-Infrared (NIR). This architecture allows the system to be upgraded to active nighttime monitoring modes similar to commercial DustIQ systems, eliminating daytime cloud anomalies and seasonal solar variances to maintain a stable baseline reference, and it can be used in future educational and research initiatives.

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