Bigint Computing Journal
Volume 4, Issue 2, 2026, pp. 48-53
https://doi.org/10.55537/bigint.v4i2.1827
ISSN: 3032-5374
https://journal.aira.or.id/bigint/index

Analysis of Silica Gel Capability in Suppressing Humidity within Filament Storage Boxes via an Internet of Things-Based Monitoring Application

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ABSTRACT
3D printing filament is highly sensitive to ambient humidity. Moisture absorption by the filament can degrade print quality, causing issues ranging from stringing to complete print failure. This study aims to analyze the ability of silica gel to suppress and maintain humidity stability within a filament storage box using an Internet of Things (IoT)-based monitoring system. The core control system utilizes an ESP32 microcontroller integrated with a DHT11 sensor to detect temperature and relative humidity (%RH) inside the container in real-time. Sensor data is transmitted wirelessly via the ESP32's built-in Wi-Fi connectivity to a Firebase cloud database. Users can remotely monitor storage conditions through an Android application developed using the Kodular platform. The experimental method involved testing humidity reduction performance using varying masses of silica gel within an airtight container. Test results indicate that increasing the mass of silica gel significantly accelerates the rate of humidity reduction and extends the duration for which storage conditions remain stable at the ideal level—below 30% RH. The developed IoT system successfully achieved precise, real-time data synchronization between the hardware and the monitoring application without requiring a local display screen. This research offers a practical solution for 3D printer users to preserve filament quality while providing empirical data on the effectiveness of silica gel quantities as a desiccant.
KEYWORDS: Silica Gel, Filament, ESP32, DHT11, Kodular, Firebase, IoT.

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Article History: Received: 2026-07-15; Accepted: 2026-07-31

1. INTRODUCTION

Fused Deposition Modeling (FDM) 3D printing creates solid objects by melting and extruding plastic filaments layer by layer. The final print quality is highly dictated by the pre-extrusion physical condition of the polymer filament. A major challenge in filament handling is its inherent hygroscopicity, which causes popular materials like Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and PETG to readily adsorb ambient moisture [1]. The materials used in FDM include hygroscopic polymers, such as ABS and PA. Non-hygroscopic polymers include PLA and PP (polypropylene) [2]. In tropical regions like Indonesia, where mean ambient relative humidity (RH) routinely exceeds 70%, unshielded filaments degrade rapidly [3].

When a moisture-laden filament passes through a high-temperature nozzle (200°C–240°C), trapped water molecules rapidly vaporize and cause micro-explosions (popping)[4]. This phenomena introduces visual defects like fine stringing, internal structural voids, weakened interlayer adhesion, and complete nozzle clogging [5]. To preserve material properties, filaments must be stored inside a dedicated dry box maintaining a micro-environment below 30% RH[6].

Silica gel is an economical and highly accessible synthetic desiccant widely utilized to trap moisture via physical adsorption [7]. However, hobbyists and makers frequently deploy arbitrary quantities of silica gel without empirical data regarding mass-to-volume efficiency or desiccant saturation rates[8]. Furthermore, common monitoring setups rely on manual analog hygrometers that require physical inspection of the container, which limits timely intervention. Internet of Things (IoT) frameworks offer an automated solution by facilitating continuous remote data acquisition. Integrating an ESP32 microcontroller with digital sensors allows for seamless environmental logging, while cloud infrastructures like Google Firebase combined with visual programming tools like Kodular accelerate user interface (UI) deployment, [9].

While numerous IoT-based ambient monitoring studies exist, they typically focus on open spaces such as greenhouses, smart homes, or general warehouses, [10]. This study introduces a distinct novelty by focusing on a hyper-confined micro-environment (a 5-liter airtight dry box) and explicitly pairing real-time telemetry with a comparative mass-efficiency evaluation of silica gel. The primary objective of this research is to provide actionable empirical data regarding the exact rate of humidity reduction across different desiccant weights, helping 3D printer users eliminate guesswork when preparing filament storage setups.

2. LITERATURE REVIEW

2.1. 3D Printing Filaments and Hygroscopicity

Filament is the primary material used in FDM 3D printers. The hygroscopic nature of polymer materials causes the plastic's chemical chains to readily bind with water molecules from the air. The primary consequence of moisture-contaminated filament is hydrolysis occurring when the material is melted at high temperatures (200°C–240°C). Trapped water boils, creating gas bubbles and compromising the plastic extrusion exiting the nozzle. Ideal storage requires a humidity-controlled environment—ranging from 15% to 30% RH—to preserve the material's mechanical properties.

2.2. Silica Gel as a Desiccant

Silica gel is a form of silica synthetically produced from sodium silicate. This material possesses a structure of extremely small pores (nanopores) that provides a large specific surface area, enabling it to absorb water molecules through physical adsorption. Silica gel does not undergo a physical change in state when absorbing water; however, it has a maximum absorption capacity (approximately 30–40% of its own weight) before becoming saturated and losing its ability to reduce ambient humidity.

2.3. Monitoring System Hardware

ESP32: A low-cost, low-power system-on-a-chip (SoC) microcontroller developed by Espressif Systems. The ESP32 features integrated Wi-Fi and Bluetooth capabilities, making it a preferred choice for IoT architectures as it does not require additional communication modules to connect to the internet [11].

DHT11 Sensor: A digital sensor designed to measure air temperature and relative humidity. It incorporates a resistive humidity sensing element and an NTC (Negative Temperature Coefficient) temperature sensing component, offering a humidity measurement range of 20–90% RH with an accuracy of ±5%.

2.4. Software and Cloud Computing

Firebase Realtime Database: A cloud-hosted database provided by Google. Data is stored in JSON format and synchronized in real-time across all connected clients. This characteristic makes it ideal for IoT applications requiring instant data updates without high latency [13].

Kodular: A web-based Android app development platform that utilizes a visual block-based programming system (drag-and-drop), built upon the MIT App Inventor framework. The platform enables the rapid and interactive design of IoT monitoring application interfaces (UI) without requiring mastery of complex textual programming languages [14].

3. METHODOLOGY

3.1. Research Workflow

This research begins by identifying the issue of moisture absorption in filaments, followed by a literature review on desiccants and IoT. Subsequent steps involve designing the hardware and software systems, testing system integration, conducting experiments with varying silica gel masses, and analyzing the data to draw conclusions.

In summary, the system's data exchange workflow is illustrated by the following block diagram:

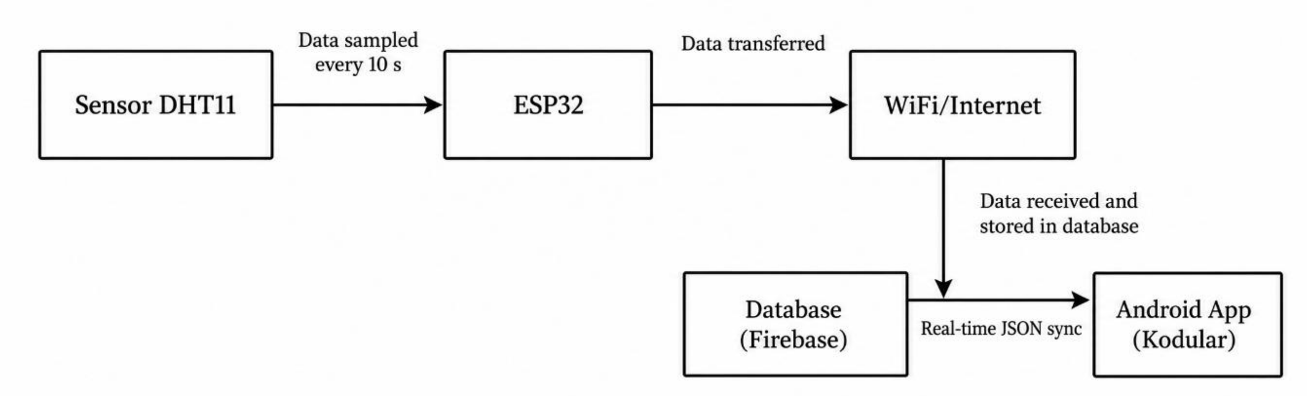

Figure 1. Block Diagram

To ensure data reliability, a functional check of the DHT11 sensor was performed alongside a baseline mechanical hygrometer inside a controlled chamber. The raw environment values were transmitted by the ESP32 every 10 seconds. To smooth out high-frequency sensor noise, the values reported every 30 minutes in the final results represent the mathematical average of the 180 raw data packets received during that specific 30-minute block window.

3.2. Materials and Experimental Boundary Conditions

The experimental environment was strictly bound by the following fixed parameters to ensure consistency:

3.2.1. Hardware

The hardware consisted of an ESP32 NodeMCU microcontroller, a DHT11 temperature and humidity sensor, female-to-female jumper wires, an airtight plastic dry box, one roll of 3D printer filament (PLA+), an Android smartphone for application testing, and a laptop or PC for programming the microcontroller.

3.2.2. Software

The software consisted of Arduino IDE for writing the ESP32 program code, Firebase Realtime Database as cloud data storage, and Kodular Creator for designing the Android monitoring application.

3.2.3. Experimental Materials

The experimental materials consisted of bulk white silica gel and a digital scale with 0.1-gram accuracy for measuring silica gel mass.

3.3. Testing and Experimental Procedures

Eksperimen dilakukan dengan metode komparatif unjuk kerja penyerapan uap air

The experiment was conducted using a comparative performance method of moisture absorption, utilizing 3 (three) different variations of silica gel mass:

The experiment compared four conditions: Test A without silica gel as the control or baseline, Test B using 50 grams of silica gel, Test C using 100 grams of silica gel, and Test D using 150 grams of silica gel.

Each testing session is carried out through the following steps:

Each testing session followed the same procedure. The storage box was left open in an open room for 15 minutes so that the humidity inside the box equaled the initial room humidity of approximately 70%–80% RH. The filament and the predetermined silica gel mass were then inserted, the box was closed tightly until airtight, and the ESP32 system was activated. The Kodular application and Firebase automatically recorded the decrease in humidity, while formal observations and data logging were conducted every 30 minutes for 6 hours for each variation.

4. RESULTS AND DISCUSSION

4.1. Network and Cloud Integration Testing

Upon boot, the ESP32 successfully connected to the local Wi-Fi gateway with an average handshake latency of 3.4 seconds. Data payload delivery achieved a 0% packet loss metric. The JSON data structure inside the Firebase console updated dynamically without latency, organized under flat keys as illustrated below:


```json
{
 "filament_drybox_1": {
  "current_humidity": 27,
  "current_temperature": 28.2,
  "timestamp_minutes": 60
 }
}
```


The Kodular Android application synchronized with the Firebase database listener instantly. Toggles or value updates on the database populated the smartphone screen interface smoothly without requiring manual UI refreshes.

4.2. Desiccant Mass Performance Evaluation

The averaged environmental parameters across the 6-hour test duration for all four test cases are structured in Table 1.

Table 1. Humidity and Temperature Decay Tracking Across Desiccant Masses

Time (Min)	Case A: 0g (Control)	Case B: 50g	Case C: 100g	Case D: 150g
0	76% RH / 27.5°C	75% RH / 27.6°C	77% RH / 27.5°C	76% RH / 27.5°C
30	76% RH / 27.6°C	58% RH / 27.8°C	45% RH / 28.0°C	38% RH / 28.2°C

Time (Min)	Case A: 0g (Control)	Case B: 50g	Case C: 100g	Case D: 150g
60	75% RH / 27.6°C	46% RH / 27.9°C	33% RH / 28.1°C	27% RH / 28.3°C
90	75% RH / 27.5°C	39% RH / 28.0°C	28% RH / 28.2°C	22% RH / 28.4°C
120	75% RH / 27.7°C	34% RH / 28.1°C	24% RH / 28.2°C	*20% RH / 28.5°C**
150	76% RH / 27.6°C	29% RH / 28.2°C	22% RH / 28.3°C	*20% RH / 28.4°C**
180	75% RH / 27.5°C	28% RH / 28.2°C	21% RH / 28.3°C	*20% RH / 28.5°C**
210	76% RH / 27.6°C	28% RH / 28.1°C	20% RH / 28.2°C	*20% RH / 28.4°C**
240	75% RH / 27.5°C	27% RH / 28.3°C	20% RH / 28.4°C	*20% RH / 28.5°C**
270	76% RH / 27.6°C	27% RH / 28.2°C	20% RH / 28.3°C	*20% RH / 28.4°C**
300	75% RH / 27.6°C	27% RH / 28.2°C	*20% RH / 28.4°C**	*20% RH / 28.5°C**
330	76% RH / 27.5°C	28% RH / 28.3°C	*20% RH / 28.3°C**	*20% RH / 28.5°C**
360	76% RH / 27.6°C	28% RH / 28.2°C	*20% RH / 28.3°C**	*20% RH / 28.4°C**

Note: Bold values denote the exact timestamp where internal conditions successfully dropped below the ideal filament preservation threshold (<30% RH). Asterisks (*) indicate data points that fall below the sensor's official factory measurement floor (20% RH).

4.3. Technical Analysis and Sensor Boundaries

Data in Table 1 shows that humidity readings for Cases C and D flatline at 20% RH, reflecting the DHT11 sensor's 20% floor restriction rather than a continuous decrease below this value. These measurements indicate that the environment has reached an ultra-dry state, representing a measurement saturation point rather than high-precision data.

The compiled telemetry tracking over the 360-minute experiment window across all test cases is graphically plotted in Fig. 2.

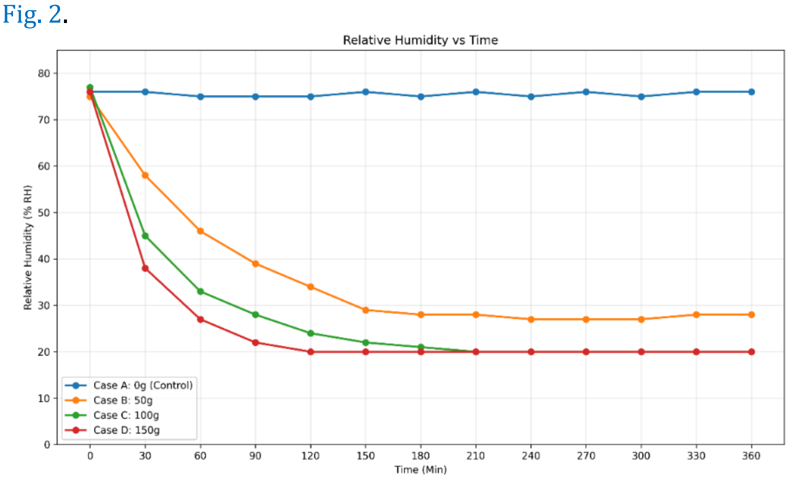

Figure 2. Environmental relative humidity decay profiles inside the 5-liter dry box across a 6-hour timeline.

4.4. Analysis of the Humidity Reduction Rate

To compare the performance of each treatment, the average humidity reduction rate was calculated up to the first measurement below 30% RH.

The formula used is:

$$v = \frac{RH_{initial} - RH_{final}}{t} \quad (1)$$

Case B – 50 g

$$v = \frac{75 - 29}{150} = 0.307\ \%RH/minute$$

Case C – 100 g

$$v = \frac{77 - 28}{90} = 0.544\ \%RH/minute$$

Case D – 150 g

$$v = \frac{76 - 27}{60} = 0.817\ \%RH/minute$$

The results can be summarized as follows:

Table 2. Humidity Reduction Rate

Case	Silica Gel Mass	Average Humidity Reduction Rate until <30% RH
A	0 g	Not reached
B	50 g	0.307 %RH/minute
C	100 g	0.544 %RH/minute
D	150 g	0.817 %RH/minute

Based on these values, Case D has an average humidity reduction rate approximately 2.66 times higher than Case B, while Case C has a rate approximately 1.77 times higher than Case B.

This indicates a tendency that increasing the mass of silica gel improves the system's ability to reduce air humidity.

Across the treatments, the observed decline in relative humidity demonstrates a clear mass-dependent desiccant response: 50 g, 100 g, and 150 g reached the <30% RH threshold in 150, 90, and 60 minutes, respectively, while the control remained at 75%–76% RH. This pattern is consistent with the adsorption function of silica gel described in previous desiccant studies [7], [8] and reinforces the importance of humidity control for moisture-sensitive 3D-printing filaments reported in prior filament studies [1], [6]. However, the apparent plateau at 20% RH for the 100 g and 150 g treatments should not be interpreted as precise measurement below that level because it corresponds to the DHT11 lower measurement boundary; therefore, the results support 100–150 g as the best-performing range among the tested conditions rather than a universal optimum.

5. CONCLUSION

An IoT-based environmental monitoring system utilizing an ESP32 microcontroller and a DHT11 sensor was successfully deployed to track moisture reduction within a 5-liter filament storage dry box. The experimental results over a 6-hour test window show that increasing desiccant mass increases the rate of humidity reduction. Case A (0g control) remained stagnant at 75%–76% RH. Case B (50g) required 150 minutes to cross the ideal threshold of <30% RH, Case C (100g) required 90 minutes, and Case D (150g) achieved the fastest reduction in 60 minutes. For a 5-liter storage volume, a desiccant load of 100g to 150g provides the best performance among the tested conditions, maintaining an ultra-low moisture environment over the 6-hour monitored period. However, readings recorded below 20% RH must be understood as structural indicators of an ultra-dry state rather than precise measurements due to the hardware tracking boundaries of the DHT11 sensor.

DECLARATIONS

Artificial Intelligence Use

Generative AI was used only to assist with language editing during manuscript revision. The authors reviewed the final text and remain responsible for the article content, analysis, and conclusions.

Author Contributions

Harlan Kurnia AR: Conceptualization, methodology, system development, experimentation, data collection, formal analysis, visualization, and writing—original draft. Yustria Handika Siregar: Supervision, conceptual guidance, methodology review, validation, and writing—review and editing. All authors reviewed and approved the final manuscript.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

Ethics Approval / Ethical Clearance

Not applicable. This study did not involve experimental research involving human participants or animals. The experiments were limited to environmental humidity monitoring and silica gel performance evaluation within a filament storage container.

Data Availability Statement

The data supporting the findings of this study are presented within the article, including the experimental humidity measurements and performance analysis. The research methods and experimental procedures are described in the manuscript. Additional supporting materials may be obtained from the corresponding author upon reasonable request.

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