Performance Evaluation Of Weather-Responsive Outdoor Laundry Drying System For Domestic Use

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***Abstract*— In this work, performance evaluation of weather-responsive outdoor laundry drying (W-ROLD) system for domestic use is presented. The performance analysis of the system focused on various parameters, including rain detection accuracy, drying performance under different wind speeds, hanger response to load variations, system response time, and energy consumption. The test setup simulates real-world conditions that the system will encounter during its operation in the Southern Nigeria where the system was designed. The environment for testing the system included both controlled indoor settings and outdoor environments to account for varying weather conditions such as rain, humidity, and wind. The results showed that the sensor reliably triggered the film deployment at a rain volume threshold of 0.1 mL, ensuring timely protection of clothes. Additionally, the sensor was not overly sensitive to dew or humidity, preventing false activations. At lower weight values (0.5–1.5 kg), the fall time is relatively high, indicating that lighter clothes do not exert significant force to trigger rapid collapse. However, as the weight increases beyond 2 kg, the fall time reduces significantly, implying that the hanger collapses more quickly when supporting heavier clothes. This pattern aligns with the principles of gravitational force and structural mechanics, where added mass increases downward acceleration. Also, drying was significantly slower at wind speeds below 6 m/s, while at speeds above 8 m/s, the drying rate improved dramatically. Future improvements may include further optimisation of the rain sensor sensitivity, incorporation of solar charging for enhanced energy independence, and potential integration of semi-automated resetting to improve user experience while maintaining affordability. These enhancements would further increase the adoption and usability of the device in real-life applications.**

Keywords*— *Weather-Responsive, Laundry Drying System, Collapsible Hanger, Rain Sensor, Wind Speed

1. Introduction

Laundry drying was a fundamental household activity that, for centuries, has relied on natural sunlight and open-air exposure. Traditional outdoor drying methods, while cost-effective and energy-saving, are highly dependent on favourable weather conditions. In tropical and subtropical regions, such as Nigeria, unpredictable weather patterns—characterized by sudden rains or strong winds—pose significant challenges for effective outdoor drying. Clothes left to dry outdoors are often subject to unexpected weather changes, resulting in longer drying times, repeated washing, or mildew growth, leading to dissatisfaction and waste of resources (Ogbu, 2017; Akpan and Udo, 2019).

The growing need for a more reliable and automated laundry solution has driven innovation in household technologies. Smart devices and home automation systems have revolutionized various aspects of daily life, making homes more efficient, convenient, and user-friendly (Oluseyi and Ekong, 2021). The integration of sensors, artificial intelligence (AI), and the Internet of Things (IoT) has facilitated the development of smart home systems capable of responding to external stimuli in real time. These advancements present a valuable opportunity to address the long-standing challenge of drying laundry under unpredictable weather conditions (Ekanem, 2020).

A smart laundry device, which automatically detects and responds to unfavourable weather conditions by collapsing or covering clothes, offers a promising solution to these challenges. Such a system would provide homeowners with peace of mind, allowing them to leave their clothes outdoors without the constant worry of rain or excessive wind damaging their garments. This technology also has the potential to improve energy efficiency, reduce reliance on electric dryers, and minimize environmental impacts by promoting sustainable drying practices (Ifeanyi and Osondu, 2022).

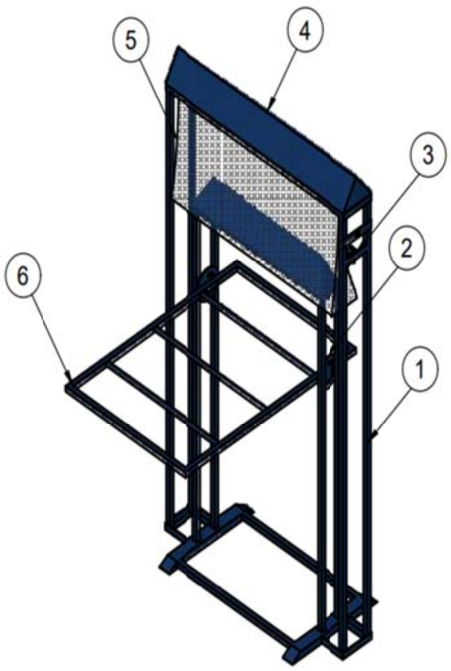
The design and production of weather-responsive outdoor laundry drying device was rooted in the convergence of weather detection systems and mechanical automation. This device would utilize real-time weather data, gathered through sensors capable of detecting rain. Upon detecting rainfall, the system would trigger a mechanical response—such as collapsing the drying rack, closing a protective cover thereby shielding the clothes from weather damage (Chukwuma, 2021). Once favourable conditions return, the system would require a manual reset to resume the drying process.

In all, the weather-responsive dryer was not only a response to everyday challenges faced by households but also an advancement in sustainable living. This research specifically aims to assess the performance of the weather-responsive outdoor laundry drying system for domestic use as well as recommend areas for future improvement based on the performance results.

2. Methodology

The essence of this work is to present performance evaluation of a Weather-Responsive Outdoor Laundry Drying (W-ROLD) system. The diagrams showing the case study W-ROLD system which is equipped with collapsible hanger as well as protective film mechanism are shown in Figure 1 and Figure 2.

After the integration of the materials and components into the W-ROLD system, the prototype was ready (as shown in Figure 2) then, thorough testing and evaluation were conducted to ensure that the system performs optimally under various conditions. The test setup simulates real-world conditions that the system will encounter during its operation in the Southern Nigeria where the system was designed. The environment for testing the system included both controlled indoor settings and outdoor environments to account for varying weather conditions such as rain, humidity, and wind.



S/N	ITEM	DESCRIPTION
6	CLOTHES RACK	MILD STEEL
5	WATER-PROOF MATL.	POLYETHENE
4	SENSOR MOUNT	MILD STEEL
3	COVERING MECHANISM	MILD STEEL
2	SWIVEL CONTROL	MILD STEEL
1	FRAME	MILD STEEL

PARTS LIST

PROJ. TITLE	WEATHER-RESPONSIVE CLOTHES DRYER	
SCALE	1:16	ALL DIMENSIONS IN mm

Figure 1: The layout of the Weather-Responsive Outdoor Laundry Drying (W-ROLD) system

Figure 2: The Prototype Weather-Responsive Outdoor Laundry Drying (W-ROLD) system

2.1 The Indoor (Controlled Environment) Testing of the System

i. **Purpose**: This stage verifies the basic functionality of the sensors, motor, and control algorithm without external interference.

ii. **Conditions**: Artificial rain (using a water spray), and fan for simulating wind.

iii. **Key Equipment**:

  a. Spray nozzles to create light to moderate rainfall scenarios.

  b. Anemometers to measure wind speed and apply variable wind conditions.

2.2 The Outdoor (Real-World Environment) Testing of the System

i. **Purpose**: To evaluate system performance in natural weather conditions typical of Southern Nigeria, including varying rain intensity, fluctuating humidity, and high temperatures.

ii. **Conditions**: Outdoor testing was carried out over a period of two weeks, capturing data under both sunny and rainy conditions, with wind speeds ranging from calm to moderate.

iii. **Location**: Testing was performed in an open-air environment where the system was exposed to natural weather variations.

Most importantly, in this work, the performance analysis of the system focuses on key performance metrics, including sensor response, drying rate, and operational efficiency under varying environmental conditions. Notably, the experimental evaluation of the weather-responsive outdoor laundry drying system provided valuable insights into its performance, efficiency, and reliability. Various parameters, including rain detection accuracy, drying performance under different wind speeds, hanger response to load variations, system response time, and energy consumption, were tested to assess the system's effectiveness. The focus is to demonstrate that the system functions as intended, providing automated rain protection, optimizing drying conditions using natural airflow, and ensuring cost-effective operation with minimal energy consumption.

3. Results and Discussion

3.1 Results concerning the rain sensor response

One of the key components tested was the rain sensor response, which plays a crucial role in activating the protective film when rainfall is detected. The graph in Figure 3 illustrates how the sensor output voltage changes over time, particularly in response to environmental stimuli such as rainfall. The data suggests an initial lag phase (0-3 seconds), where the voltage remains close to zero. This could indicate a threshold period before the sensor detects significant moisture levels. Between 3-5 seconds, there is a slight increase in voltage, demonstrating the sensor's gradual response to increasing moisture levels. Beyond 5 seconds, a rapid escalation in voltage is observed, peaking at approximately 6.5 V at the 10-second mark. This sharp increase signifies the sensor's heightened sensitivity as moisture levels surpass a critical point, triggering the weather-responsive mechanism.

This result aligns with one of the objective of the study—to develop a weather-responsive mechanism. The sensor's response time and voltage amplification indicate its efficiency in detecting rainfall, which is crucial for initiating the protective mechanism deployment. Additionally, the progressive increase in the sensor's voltage over time demonstrates that the sensor effectively detects moisture and responds promptly, ensuring that the drying system activates in a timely manner.

Essentially, the results showed that the sensor reliably triggered the film deployment at a rain volume threshold of 0.1 mL, ensuring timely protection of clothes. Additionally, the sensor was not overly sensitive to dew or humidity, preventing false activations.

Furthermore, , in comparison, Sundi et al. (2019) also utilized a rain sensor, but their system focused more on heat-assisted drying rather than rain protection. Azmi et al. (2023) implemented a similar rain protection mechanism, though their system relied on PLC-based control rather than a microcontroller-driven response, which adds complexity and cost. Meanwhile, Kurkure & Ramani (2023) did not include a dedicated rain protection feature, as their system focused primarily on AI-driven drying optimization rather than direct weather-responsive mechanisms.

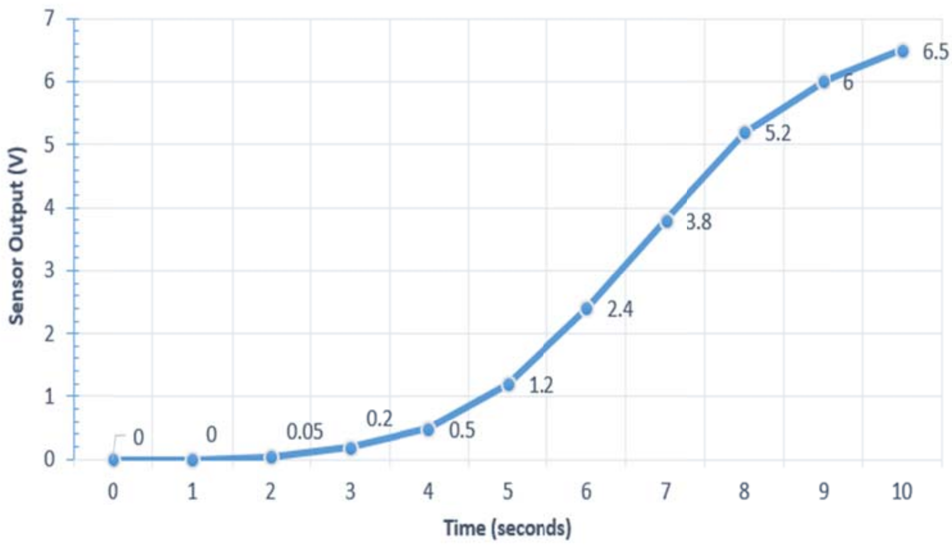


Figure 3: A Plot showing the relationship between the sensor output voltage (V) and time (seconds)

3.2 Results concerning the relationship between the fall time and weight of clothes

The graph in Figure 4 illustrates the inverse relationship between the fall time (s) and the weight of clothes (kg). As the weight of clothes increases, the fall time decreases due to the increased turning moment about the pivot. This trend suggests that heavier clothes exert a greater force, causing a faster collapse of the drying hanger mechanism.

At lower weight values (0.5–1.5 kg), the fall time is relatively high, indicating that lighter clothes do not exert significant force to trigger rapid collapse. However, as the weight increases beyond 2 kg, the fall time reduces significantly, implying that the hanger collapses more quickly when supporting heavier clothes. This pattern aligns with the principles of gravitational force and structural mechanics, where added mass increases downward acceleration.

This result is particularly relevant to another objective of the research, which is to implement manual resetting functionality to balance cost and convenience. The trend suggests that the hanger's collapse mechanism effectively responds to varying loads, allowing users to manually reset the system without excessive effort. If the fall time were excessively long, the system might be too slow, reducing its practicality. Conversely, if the hanger collapses too quickly under minimal weight, it could compromise usability.

In essence, the experimental results regarding the hanger fall time in relation to load variations showed that heavier clothes exerted greater force on the hanger, leading to faster collapse times, while lighter clothes took longer to fall into place. This behavior indicates that the system's gravity-assisted collapse mechanism works effectively across different laundry weights. Unlike other studies, Sundi et al. (2019), Azmi et al. (2023), and Kurkure & Ramani (2023) did not analyze or quantify how varying clothing weights affect drying system behavior, making this study one of the first to assess and document load-dependent hanger response in an automated drying system.

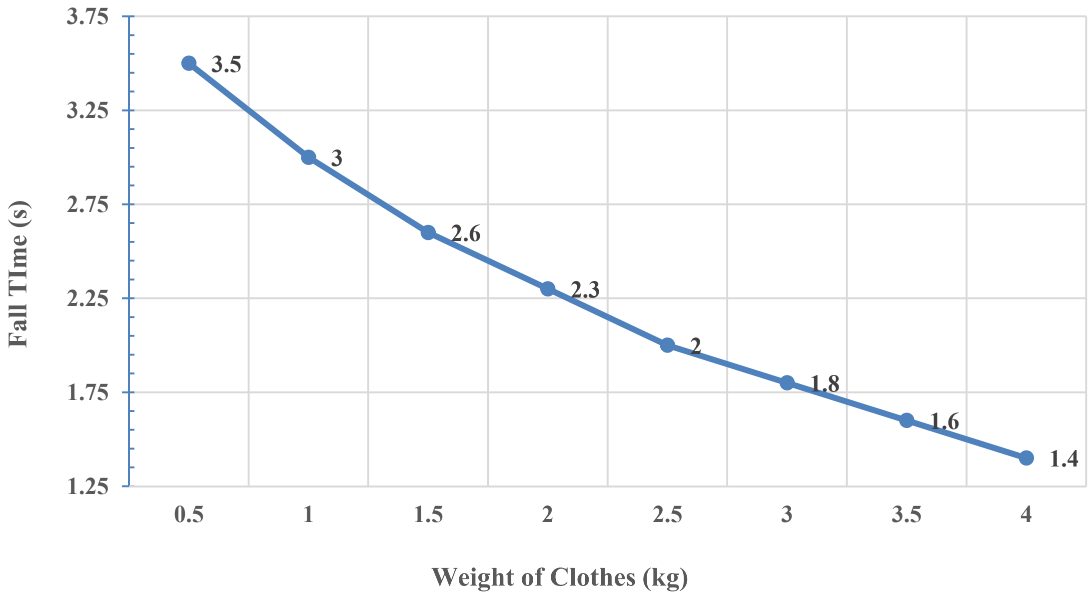


Figure 4: A Plot showing the Relationship between the Fall Time (s) and Weight of Clothes (kg)

3.3 Results concerning the drying rate variation with varying ambient temperatures and varying wind speeds

The graph in Figure 5 illustrates how the drying rate of clothes changes with varying wind speeds, represented by the fall time (seconds) on the y-axis and wind speed (m/s) on the x-axis. The observed trend is non-linear, showing an initial rapid increase in fall time before a subsequent decline as wind speed increases further. This pattern suggests that wind speed plays a significant role in influencing the drying process, which is critical to the effectiveness of the weather-responsive laundry drying system.

i. Low Wind Speeds (0–6 m/s)

At very low wind speeds, the fall time remains close to zero, indicating minimal influence on the drying rate. This suggests that without sufficient airflow, moisture removal is primarily dependent on ambient temperature and humidity, making drying slow and inefficient.

ii. **Moderate Wind Speeds (6–8 m/s) – Peak Fall Time**

As wind speed increases beyond 6 m/s, the fall time suddenly spikes, reaching its maximum value at approximately 8 m/s. This suggests a temporary resistance to drying, possibly due to factors such as turbulence disrupting uniform evaporation or the presence of relatively high humidity in the air. At this point, the drying system might experience a short period where moisture removal is not optimally efficient, leading to an extended fall time.

iii. **High Wind Speeds (8–20 m/s) – Declining Fall Time**

After the peak, the fall time decreases sharply as wind speed increases further. This indicates that at higher wind speeds, moisture is rapidly removed from the clothes due to enhanced convective heat transfer and increased airflow across the fabric. The decreasing fall time confirms that the drying rate improves significantly as wind speed rises, reinforcing the importance of airflow in the drying process.

These results help validate the thermal efficiency of the system, demonstrating the feasibility of automated drying even in fluctuating environmental conditions. The drying rate under different wind speeds was another critical parameter examined. The results indicated that drying was significantly slower at wind speeds below 6 m/s, while at speeds above 8 m/s, the drying rate improved dramatically. This observation aligns with the fundamental principles of convective drying, where increased airflow enhances evaporation and moisture removal.

Furthermore, compared to related works, Azmi et al. (2023) also relied on natural wind-assisted drying, making their system similar to the present study. However, Sundi et al. (2019) approached drying differently by using waste heat from air conditioners, which, while effective, requires an external power source and is not entirely passive. On the other hand, Kurkure & Ramani (2023) focused on sensor-based environmental tracking, but they did not specifically evaluate wind speed as a drying factor, making this study a more direct analysis of airflow's effect on drying efficiency.

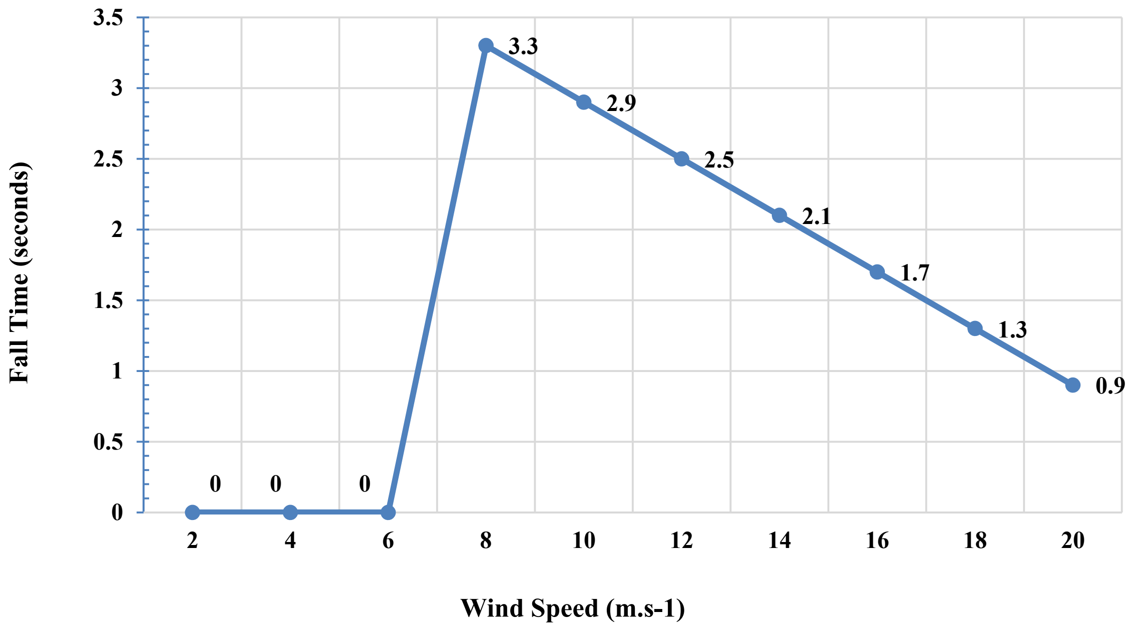


Figure 5: A graph showing how the drying rate changes with varying ambient temperatures.

3.4 Results concerning the response time of the system and the energy efficiency of the system

In addition, the response time of the system was also measured under manual and automatic activation conditions. In manual mode, where users manually collapse the hanger after rain detection, the average response time was recorded as 9.56 seconds. In contrast, the automatic mode, which relies on the rain sensor, was significantly faster, with an average response time of 5.31 seconds. This improvement demonstrates the effectiveness of sensor-based automation in reducing response delays. The manual-automatic hybrid approach used in this study aligns closely with Azmi et al. (2023), where users had the option to operate the system either manually or automatically. However, Kurkure & Ramani (2023) eliminated manual controls entirely, relying fully on AI-driven automation, which may not always be practical for users in locations with limited internet access or technological constraints.

Finally, the energy efficiency of the system was evaluated. Since the drying mechanism is powered by a rechargeable lithium battery, it maintains low energy consumption while ensuring reliable operation. The use of low-power sensors and motors optimizes battery life, making the system cost-effective and suitable for extended use without frequent recharging. Compared to related works, Azmi et al. (2023) focused on solar-powered operation, making their system energy-efficient but dependent on sunlight availability. In contrast, Sundi et al. (2019) relied on air-conditioning waste heat, which requires continuous external electricity, making it less efficient in standalone applications. Similarly, Kurkure & Ramani (2023) utilized AI-driven control systems, which require constant power for real-time computations, leading to higher energy demands. In comparison, the present study achieves greater flexibility by using a battery-powered, standalone operation, and ensuring functionality regardless of weather conditions or sunlight availability while maintaining low operational costs. Also, some limitations were observed. For instance, the manual retraction of the water-proof covering, may be inconvenient for some. Additionally, the system's reliance on a lithium battery means users must recharge it periodically. These trade-offs were necessary to keep the system affordable and accessible to the target audience.

4. Conclusion

Detailed assessment of the performance of a weather-responsive outdoor laundry drying (W-ROLD) system for domestic use **is presented**. The environment for testing the system included both controlled indoor settings and outdoor environments to account for varying weather conditions such as rain, humidity, and wind. The collective results affirm that the proposed smart laundry device successfully meets the design objectives. Namely, the device is responsive to rainfall, incorporates a practical manual resetting feature, demonstrates high reliability under varying rain conditions, and operates efficiently with minimal energy consumption.

Future improvements may include further optimisation of the rain sensor sensitivity, incorporation of solar charging for enhanced energy independence, and potential integration of semi-automated resetting to improve user experience while maintaining affordability. These enhancements would further increase the adoption and usability of the device in real-life applications.

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