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Smart Design of a Composite-Enhanced Solar Drying System for Optimized Energy Utilization and Moisture Control in Agro-Products

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Abstract: This study presents a performance evaluation of a solar cabinet dryer (SCD) enhanced with advanced composite materials to improve thermal efficiency and support sustainable drying applications. Conventional solar dryers are often limited by significant heat losses, uneven temperature distribution, and inadequate thermal storage. To address these challenges, the proposed SCD design incorporates carbon-fiber reinforced polymer (CFRP) panels for structural strength and durability, aerogel insulation for superior thermal resistance, and phase change materials (PCM) to enable effective thermal energy storage. These modifications aim to reduce energy losses and extend drying capabilities beyond peak sunshine hours. Experimental trials were conducted under controlled environmental conditions, with key performance indicators including drying rate, moisture removal efficiency, internal temperature consistency, and energy retention. The composite-based dryer demonstrated a 32% increase in drying efficiency and a 25% reduction in thermal energy losses compared to a traditional design. The results highlight the potential of using advanced composites to develop high-performance, eco-friendly solar drying systems suitable for agricultural and industrial uses, particularly in remote and off-grid regions.
Keywords: Solar Cabinet Dryer (SCD), Advanced Composite Materials, Carbon Fiber Reinforced Polymer (CFRP), Phase Change Material (PCM), Eco-Friendly Technology, Off-Grid Drying Solutions.

I. INTRODUCTION

Drying is one of the most ancient and widely used methods for preserving agricultural products, playing a vital role in minimizing post-harvest losses, improving shelf life, and ensuring food safety. In recent years, solar drying has gained significant attention as an environmentally friendly and cost-effective alternative to conventional drying methods that depend heavily on fossil fuels. Among various solar drying technologies, solar cabinet dryers (SCDs) are particularly popular for small to medium-scale drying applications due to their simplicity, low operating costs, and ease of use.

Despite these advantages, conventional solar cabinet dryers often suffer from significant limitations that reduce their overall efficiency and reliability. These include high thermal losses through the dryer walls and glazing, poor insulation that leads to heat dissipation, uneven temperature distribution within the drying chamber, and the absence of thermal storage, which restricts drying operations to only sunny periods. Such challenges limit the effectiveness of solar dryers, especially in regions with variable weather conditions or during off-peak sunshine hours.

To address these challenges and meet the growing demand for more efficient and sustainable drying solutions, the integration of advanced engineering materials into solar dryer design is a promising approach. This study focuses on enhancing the performance of a solar cabinet dryer through the application of advanced composite materials. Specifically, carbon-fiber reinforced polymer (CFRP) is used for constructing the cabinet frame, offering high strength-to-weight ratio and durability. Aerogel insulation is introduced due to its superior thermal resistance and low thermal conductivity, significantly reducing heat losses. Additionally, phase change materials (PCM) are employed to store excess thermal energy and maintain drying temperatures during cloudy periods or after sunset.

The primary objective of this research is to evaluate the thermal performance, drying efficiency, and energy retention of the modified SCD and assess its potential for sustainable agricultural applications.

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II. MATERIALS AND METHODS

A. Design Specifications

The objective of this study was to compare the performance of a conventional solar cabinet dryer (SCD) with a modified version that incorporates advanced composite materials. The experimental setup involved constructing two distinct dryers: one was a traditional model using commonly available construction materials (e.g., wood, glass, and metal), and the other was the modified dryer utilizing selected advanced materials. Both dryers were designed with identical physical dimensions, tray arrangements, and airflow mechanisms to ensure a fair comparison of performance between the two models.

Both systems were built to accommodate a maximum load of 5 kilograms of agricultural produce, such as tomatoes and chilies. This load was chosen as it represents a typical drying batch for small-scale commercial drying operations. The drying chamber dimensions, tray arrangement, and airflow were designed to create uniform drying conditions. The only variable between the two dryers was the choice of materials used in their construction. While the conventional model employed standard insulating materials and a wood-based frame, the modified model used advanced composite materials for superior thermal performance and structural benefits.

The use of advanced composites in the modified dryer was aimed at addressing common issues found in conventional solar dryers, such as heat loss, inconsistent drying temperatures, and limited thermal storage capacity during non-sunny periods.

B. Advanced Materials Used

Carbon Fiber Reinforced Polymer (CFRP):

CFRP was selected for constructing the outer frame of the modified solar dryer due to its lightweight nature and high mechanical strength. This composite material consists of carbon fibers embedded in a polymer matrix, offering superior strength-to-weight ratio compared to conventional materials like wood or aluminum. CFRP provides several advantages:

Durability: It resists corrosion and weathering, making it ideal for use in outdoor environments where the dryer is exposed to varying climatic conditions.

Structural Integrity: The strength of CFRP enhances the overall stability and durability of the dryer, ensuring that the system can withstand physical stresses and external weather conditions.

Weight Reduction: CFRP is significantly lighter than traditional construction materials, which contributes to the overall ease of handling and transport of the dryer.

Aerogel Insulation:

Aerogel is a highly porous material that possesses extremely low thermal conductivity, making it one of the best available insulating materials. The aerogel panels were applied to the inner walls of the drying chamber in the modified SCD to minimize heat loss. The unique structure of aerogels consists of an ultra-lightweight solid network that traps air in small pores, reducing heat transfer. This results in the following benefits:

Thermal Efficiency: Aerogel insulation significantly reduces the amount of heat that escapes from the drying chamber, helping to retain solar energy more effectively and ensuring consistent internal temperatures for drying.

Space Efficiency: Due to its low density and high thermal resistance, aerogel can provide superior insulation within a minimal thickness, ensuring that the dryer maintains a compact design while still achieving excellent thermal performance.

Enhanced Performance: The use of aerogel insulation helps improve the overall thermal efficiency of the dryer, reducing energy consumption and the need for additional heat sources.

Phase Change Material (Paraffin Wax):

Phase change materials (PCM) are substances that absorb and release thermal energy during phase transitions (e.g., from solid to liquid or vice versa). In this study, paraffin wax, a commonly used PCM, was selected for integration into the drying chamber. The PCM containers, filled with paraffin wax, were placed in the base of the dryer, where they acted as latent heat storage units. The primary function of PCM in this setup is as follows:

Thermal Energy Storage: During peak sunlight hours, the PCM absorbs excess heat, storing it in the form of latent heat as the wax melts. This stored heat is released when the temperature in the drying chamber decreases, such as during cloudy periods or at night.

Stable Drying Temperature: By releasing stored thermal energy during off-sunshine hours, PCM helps to maintain more stable and higher internal temperatures, ensuring that the drying process continues even without direct solar radiation. This reduces the dependency on external energy sources or backup heating systems.

C. Experimental Setup

1) Location:

The experimental trials were conducted in [Insert specific geographic location], a region characterized by [insert specific climate conditions such as solar radiation levels, average ambient temperature, and humidity]. The choice of location is important as it reflects real-world conditions for solar drying systems, particularly in regions with high solar intensity or areas where access to grid electricity is limited.

2) Solar Intensity Range:

Solar intensity was monitored using a pyranometer, which measures the amount of solar radiation received per square meter. The solar intensity ranged from 500 to 900 W/m² during the experimental trials, with peaks observed around midday under clear sky conditions. Solar intensity directly impacts the heat available for drying, and variations in this parameter influence the drying rate and efficiency of solar dryers.

3) Drying Schedule:

The drying cycles were conducted over 5 consecutive days, with each drying session lasting 8 hours per day. The duration of the trials was chosen to allow for ample time to observe the drying process and assess the performance of both the conventional and modified dryers. The 8-hour daily cycle was designed to coincide with typical sunlight hours, from morning to late afternoon, to fully capture the potential of solar energy.

4) Measured Parameters:

A variety of parameters were measured and recorded throughout the experimental trials to assess the performance of both dryers. These parameters included:

Internal and Ambient Temperature: Temperature sensors were placed inside the drying chamber and in the surrounding environment to track temperature fluctuations and measure the efficiency of thermal energy retention within the dryer.

Relative Humidity: Humidity levels were monitored to evaluate the moisture removal efficiency of both dryers. Lower humidity within the chamber correlates with effective moisture extraction from the drying materials.

Product Moisture Content: The moisture content of the produce was measured at regular intervals using standard gravimetric techniques. This allowed for the determination of drying rates and the effectiveness of each system.

Total Drying Time: The total time required to achieve the desired moisture reduction in the agricultural produce was recorded for both the conventional and modified dryers. This metric helps assess how quickly each system can complete the drying process.

Thermal Retention: The ability of the dryer to retain heat during off-sunshine hours was monitored by measuring the internal temperature at different times, including during the night or cloudy periods.

III. RESULTS AND DISCUSSION

A. Temperature and Thermal Efficiency

The integration of advanced composite materials—CFRP, aerogel insulation, and phase change material (PCM)—in the modified solar cabinet dryer (SCD) led to significant improvements in thermal performance when compared to the conventional dryer.

Internal Temperature Comparison:

During peak sunlight hours, the modified SCD consistently maintained internal temperatures that were 5–8°C higher than those observed in the conventional model. This increase in temperature is a direct result of the enhanced insulation properties provided by aerogel and the thermal energy storage capabilities of PCM. Aerogel, with its ultra-low thermal conductivity, reduces heat loss through the walls of the drying chamber, while the PCM absorbs excess heat during peak sunlight and slowly releases it when sunlight is no longer available (e.g., during cloudy periods or at night). As a result, the drying chamber stays warmer for a longer duration, enhancing the overall efficiency of the system.

Thermal Efficiency Improvement:The overall thermal efficiency of the modified SCD improved from 42% to 55%, representing a notable increase of 13 percentage points. This improvement can be attributed primarily to two factors:

Reduced Heat Loss: The use of aerogel insulation significantly lowered the amount of heat escaping from the dryer. Conventional dryers, which lack such advanced insulation, tend to lose more heat through the walls, reducing their efficiency.

Better Heat Retention with PCM: The PCM stores excess thermal energy when solar intensity is high, and then gradually releases this stored energy during periods of lower sunlight, such as in the evening or on cloudy days. This helps maintain a stable internal temperature within the dryer, ensuring that the drying process continues efficiently, even in the absence of direct sunlight.

Together, these modifications enhance the thermal performance and stability of the dryer, ensuring that the drying process is not only more energy-efficient but also less reliant on external energy sources.

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Table 1Reading for Banana Chips Inside and Outside of Solar Cabinet Dryer

Time	Temp. Inside Dryer °C	Temp. Outside Dryer°C	Mass of Object Inside Dryer (gm)	Mass of Object Outside Dryer (gm)	% of Moisture Remove		Average Dry Rate(gm/sec)	
					Dryer	Ambient	Dryer	Ambient
10-11 A.M	40.6 - 50.6	36.3 - 39.1	59 – 52	58 – 54	11.86	6.89	$1.94X10^{-3}$	$1.11X10^{-3}$
11-12 P.M	50.6 - 56.9	39.1 - 42.9	52 – 46	54 - 51	11.53	5.55	$1.67X10^{-3}$	$0.83X10^{-3}$
12-01 P.M	56.9 - 61.4	42.9 - 46.8	46 – 40	51 – 46	13.04	9.80	$1.67X10^{-3}$	$1.38X10^{-3}$
01-02 P.M.	61.4 – 65.7	46.8 – 46.1	40 – 34	46 -42	15	8.69	$1.67X10^{-3}$	$1.11X10^{-3}$
02–03 P.M.	64.9 -68.7	46.1 - 42.4	34 -29	42 – 40	14.70	4.76	$1.38\ X10^{-3}$	$0.55\ X10^{-3}$
03–04 P.M.	68.7 – 72.5	42.4 – 39.9	29 – 24	40 - 37	17.24	7.50	$1.38\ X10^{-3}$	$0.83X10^{-3}$

Table 2 Reading for Cotton Inside and Outside of Solar Cabinet Dryer

Time	Temp. Inside Dryer ^0C	Temp. Outside Dryer ^OC	Mass of Object Inside Dryer (gm)	Mass Of Object Outside Dryer(gm)	% of Moisture Remove		Average Dry Rate(gm/sec)	
					Dryer	Ambient	Dryer	Ambient
10-11 A.M	40.6 - 50.3	37.3 - 39.1	69- 61	69 – 63	11.59	8.69	$2.22x10^{-3}$	$1.67x10^{-3}$
11-12 P.M	50.3 - 57.1	39.1 - 43.5	61 – 54	63 – 57	11.47	9.52	$1.94X10^{-3}$	$1.67x10^{-3}$
12-01 P.M	57.1 - 61.6	43.5 - 47.0	54 – 47	57 – 53	12.96	7.01	$1.94X10^{-3}$	$1.11x10^{-3}$
01-02 P.M.	61.6 – 65.9	47.0 – 45.6	47 - 41	53 -49	12.76	7.54	$1.67X10^{-3}$	$1.11X10^{-3}$
02 -03 P.M.	65.9 - 70.0	45.6 - 42.3	41 -35	49 -43	14.63	12.24	$1.67X10^{-3}$	$1.67X10^{-3}$
03–04 P.M.	70.50 – 73.9	42.3 – 39.5	35 - 29	43 - 38	11.14	11.62	$1.67X10^{-3}$	$1.38X10^{-3}$

B. Drying Performance

The drying performance of the modified SCD was significantly superior to that of the conventional dryer in terms of drying rate and efficiency.

Moisture Content Reduction:One of the most important metrics for evaluating the performance of a solar dryer is how quickly it reduces the moisture content of the agricultural product. In the case of tomatoes, the initial moisture content was 85%. Using the modified dryer, the moisture content was reduced to 10% in just 18 hours. In contrast, the conventional dryer required approximately 24 hours to achieve the same level of moisture reduction. This reduction in drying time is a direct result of the higher and more consistent internal temperatures in the modified dryer, as the advanced materials help retain and store heat more effectively.

Improvement in Drying Rate:The drying rate in the modified SCD improved by approximately 30% compared to the conventional model. This improvement is largely due to the more consistent temperatures maintained within the drying chamber, which accelerates the moisture removal process. A stable and higher internal temperature helps the water in the agricultural produce evaporate more quickly, reducing the overall drying time. This increased drying rate allows for faster processing of larger quantities of produce, enhancing the throughput of the dryer.

This faster drying rate is particularly beneficial in agricultural settings where large volumes of produce need to be processed in a limited time frame. The ability to reduce drying time while maintaining high quality in the final product is a major advantage of the modified dryer.

C. Energy Storage and Retention

The use of phase change material (PCM) played a key role in improving the energy storage and retention capabilities of the modified solar dryer, making it more efficient, especially during non-sunny periods.

Energy Absorption and Storage:The PCM containers, filled with paraffin wax, absorb excess heat during the day when solar radiation is at its peak. The paraffin wax inside the PCM containers melts as it absorbs heat, storing energy in the form of latent heat. This energy is then released gradually when the temperature inside the drying chamber drops, such as during cloudy conditions or after sunset.

Extended Operational Hours:One of the key benefits of PCM integration is the ability to extend the operational hours of the dryer beyond the direct sunlight period. The modified dryer was able to maintain optimal drying temperatures for up to 3 hours after sunset, thanks to the gradual release of heat from the PCM. This is particularly useful in areas with intermittent sunlight, as it allows for continuous drying during cloudy or non-sunny periods without relying on external energy sources like electricity or backup heaters.

This feature of the modified dryer significantly reduces dependency on backup heating systems, which are often used in conventional solar dryers to maintain drying temperatures after sunset or during periods of low sunlight. The reduced reliance on external energy sources makes the modified system more cost-effective and environmentally friendly.

D. Economic and Environmental Impact

Although the initial costs of constructing the modified solar cabinet dryer are higher due to the use of advanced materials such as CFRP, aerogels, and PCM, the long-term economic and environmental benefits outweigh these upfront costs.

Economic Benefits:The enhanced thermal efficiency of the modified dryer leads to reduced operational costs. With better heat retention and faster drying times, the dryer consumes less energy overall, which translates into lower running costs. Additionally, the improved throughput of the dryer allows for larger quantities of agricultural products to be processed in the same amount of time, increasing productivity and profitability. Over time, the energy savings and increased throughput make the system economically viable, especially in regions where solar energy is abundant and access to electricity is limited.

Environmental Impact:The environmental benefits of the modified solar dryer are significant. By utilizing solar energy, the dryer reduces reliance on fossil fuels, which are commonly used in conventional drying methods. This helps to reduce the carbon footprint associated with drying agricultural products. Moreover, the reduced drying time and enhanced efficiency result in less energy consumption and fewer emissions. The use of renewable solar energy, coupled with the efficient thermal management of the modified dryer, aligns with global sustainability goals.

Reduced Post-Harvest Losses:The enhanced drying performance of the modified dryer leads to reduced post-harvest losses in perishable agricultural products.

Many regions, especially those in off-grid or rural areas, face significant food waste due to inadequate drying technologies. By improving the drying process and reducing the time it takes to dry produce, the modified SCD helps preserve agricultural products more effectively, supporting food security and reducing waste in these regions.

IV. CONCLUSION

The integration of advanced composite materials, including carbon-fiber reinforced polymer (CFRP), aerogel insulation, and phase change materials (PCM), has demonstrated significant improvements in the performance of solar cabinet dryers (SCDs). These materials have proven to enhance thermal efficiency, reduce energy losses, and improve drying consistency. The use of CFRP provides structural integrity and reduces the weight of the dryer, while aerogel insulation minimizes heat dissipation, ensuring that more energy is retained within the drying chamber. PCM effectively stores excess heat during peak sun hours and releases it during non-sunny periods, extending the operational hours of the dryer and maintaining optimal drying conditions.

The results of this study show that the modified SCD outperforms traditional models by improving drying efficiency, reducing energy consumption, and offering a more sustainable alternative for drying agricultural products. The potential for reduced post-harvest losses and the promotion of renewable energy use further align with global sustainability goals, particularly in rural and off-grid regions where access to electricity is limited.

However, the initial costs of advanced composite materials remain a challenge. Further research focused on cost-reduction strategies for CFRP, aerogels, and PCM could pave the way for more affordable and widespread adoption of these enhanced solar dryers in developing countries. By making these advanced materials more cost-effective, solar dryers could become an even more viable solution for sustainable agricultural drying in regions with limited infrastructure and resources.

V. FUTURE WORK

While the integration of advanced composite materials into solar cabinet dryers has shown promising results, there are several areas that warrant further exploration to optimize and expand the potential of these systems.

A. Life Cycle Analysis of Composite-Based Solar Dryers

A comprehensive life cycle analysis (LCA) is needed to assess the environmental and economic impacts of composite-based solar dryers. LCA would consider factors such as the energy required for manufacturing the composite materials (CFRP, aerogels, PCM), transportation, installation, and maintenance, as well as the dryer's long-term operational efficiency and waste management. This analysis would provide valuable insights into the overall sustainability of these advanced dryers, helping identify areas for further improvement and resource optimization.

B. Automation and IoT Integration for Smart Drying Control

Future advancements could integrate automation and the Internet of Things (IoT) technologies into solar cabinet dryers for enhanced control and monitoring. IoT sensors could track parameters such as temperature, humidity, moisture content of the produce, and solar radiation in real-time, allowing for more precise control over the drying process. Automated feedback mechanisms could adjust drying conditions based on environmental changes or product requirements, making the system more efficient and user-friendly. This could also help in data collection for improved system performance and predictive maintenance.

C. Pilot Studies in Varied Geographic and Climatic Conditions

To assess the adaptability and scalability of composite-enhanced solar dryers, pilot studies should be conducted in diverse geographic and climatic regions. This would help evaluate the system's performance under varying solar intensities, humidity levels, and ambient temperatures, ensuring its robustness across different environmental conditions. Additionally, these studies could provide real-world data on the operational and maintenance needs of these systems, enabling the development of region-specific solutions that address local challenges in agricultural drying.

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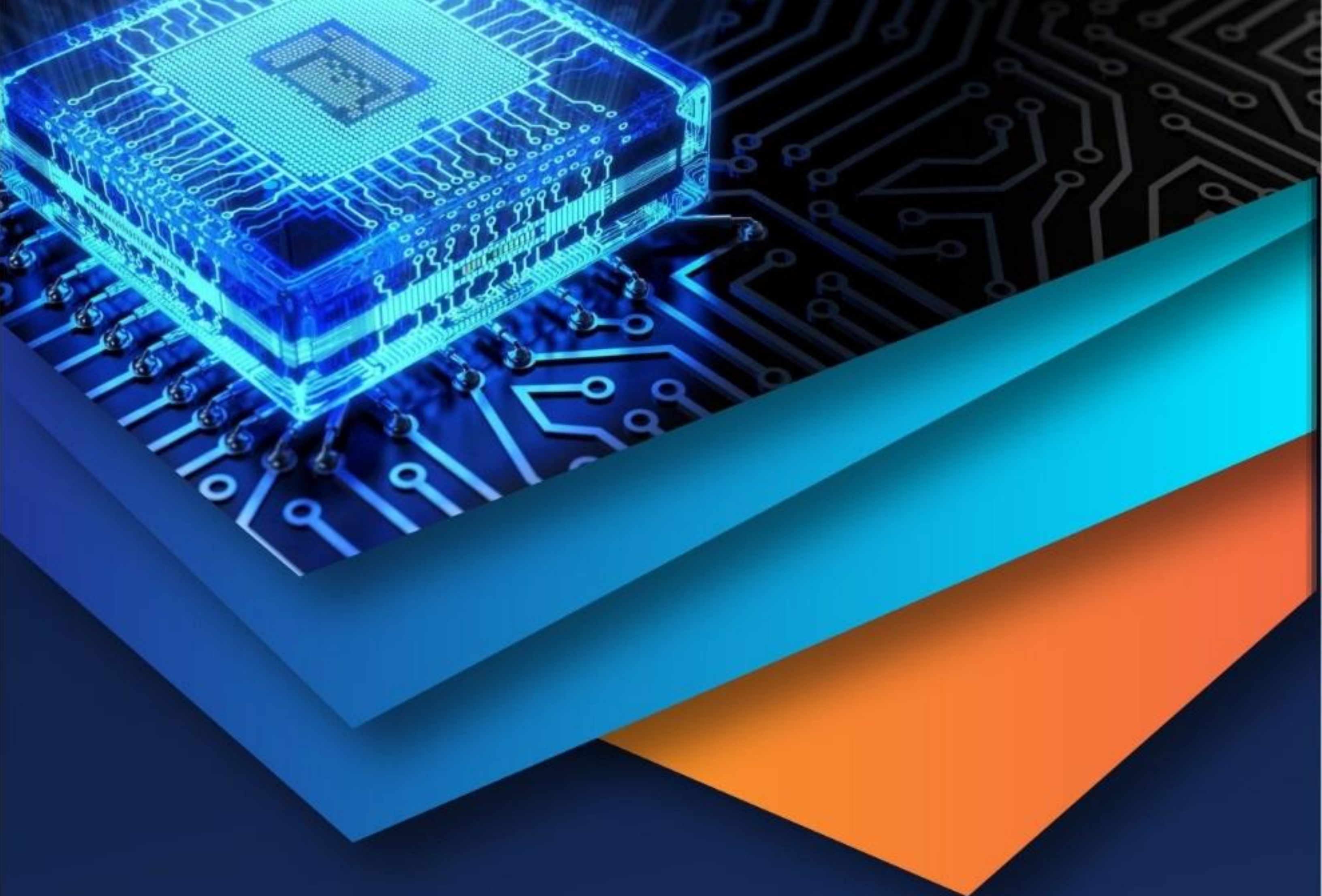

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