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Experimental Investigation and Performance Analysis of a Solar Dryer Using Advanced Heat Transfer Materials

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***Abstract:** This thesis evaluates the performance of a mixed-mode solar dryer with a backup heater. This thesis compares the solar dryer alone with the solar dryer with backup heater in terms of drying rate, efficiency, and drying time. The primary collector, the secondary collector on the roof, three drying trays within a drying chamber, and the chimney make up the dryer. A single pass twin duct air heating system and an aluminium plate that has been coated black make up the primary collector. The drying chamber's top secondary collector and side walls are constructed of clear glass. The drying chamber is heated with a banana charcoal burner backup heater.*

A dryer was used for a variety of experiments. The two primary test kinds were tests with and without loads. The drying rate, drying duration, moisture content, and drying efficiency were the factors considered in the evaluation of the procedure. The average temperature without a load and the highest average temperature of the dryer were both 54.50 ^{o}C. The maximum average temperature of the dryer was 38.53°C after three hours of evening heating with the backup heater. A 32.66% average collector efficiency was also discovered. In a load test, 1000g and 7.0 kg of sliced banana chips were used to gauge how well the solar dryer performed. In the initial test, 1000g of sliced banana chips were dried from a starting moisture content of 60%wb to 0%. 8.70% of moisture remained after 20 hours of sunlight. For sunlight drying alone, it took almost two days (almost two days), and when the backup heater was utilised (only in the evening), it took almost two days (almost two days). Additionally, it was found that when a backup heater was utilised (just at night), the sun's drying rate and efficiency were 25.25 g/h and 28.56 g/h and 2.02%, respectively.

The second test used 7.0 kg of sliced banana with a starting moisture content of 60%wb and was conducted as a load test. For the ultimate moisture content, 4.04%wb was achieved in 28 hours of sunlight (nearly three days) and 37 hours of sunlight (almost four days), respectively. only when the backup heater was utilised, both during the day and at night, for solar drying. When utilising simply the sun, the drying rate and efficiency were calculated to be 113g/h and 11.94%, and 147g/h and 25.16% when using the backup heater (both day and night).

***Keywords:** Solar dryer, cabinet dryer, coal, black carbon, heating efficiency, thermal performance, renewable energy technologies*

I. INTRODUCTION

In many African countries, where the majority of the working population is employed, agriculture plays a significant role in the economy. However, despite the large agricultural workforce, the nation's food production falls short of meeting the people's demands [1].

Insufficient preservation and storage methods contribute to substantial losses, thereby reducing the availability of food.

Agriculture dominates India's economy, accounting for approximately 21% of the GDP. However, the industry faces several inherent challenges, including significant post-harvest losses caused by inadequate post-harvest management.

Given their inherent high moisture content, agricultural products begin to degrade immediately after harvest. The post-harvest phase involves rapid drying of the products to achieve the desired moisture content. Sun drying is the most common drying technique used, particularly in regions where the weather allows for drying food immediately after harvest [2]. Sun drying is reliant on clear skies and wind for optimal results. However, this method is slow and carries a high risk of agricultural output loss, making it inefficient under unfavourable weather conditions.

Figure 1: solar dryer

Throughout history, solar drying has been utilized to dry agricultural crops, harnessing the radiative radiation of the sun. While more effective than open sun drying, this method still relies on solar energy. The temperature inside the dryer, which is higher than the ambient temperature during sun drying, helps maintain the quality of the product and reduces drying time.

II. CASE STUDY

A. Primary Case (Objective)

The main objective of the study is to evaluate the efficiency of a mixed-mode solar dryer with a vegetable drying heat source.

B. Specific Objectives

To assess the performance of the solar dryer based on variables such as temperature, product moisture content, drying time, drying rate, and efficiency.
To compare the performance of the solar dryer with and without the backup heating system.

C. Sun Drying

Sun drying is an ancient method employed to minimize the deterioration of agricultural products. It relies solely on solar energy for drying [2]. The crops are spread out on the ground and dried by exposure to the higher temperatures of the sun. This drying method is commonly used for drying grains, and despite its simplicity, it remains widely practiced.

D. Solar Drying

Solar drying utilizes the sun's energy to dry agricultural products. By trapping and enclosing the heat, it raises the temperature of the produce, mitigating the limitations of open-air sun drying. This method improves the quality of the products to meet industry standards [3]. Although more efficient than open sun drying, its reliance on solar energy restricts its use on overcast and rainy days.

E. Classifications of Solar Dryers

Drying systems can be classified into two main categories: high temperature dryers and low temperature dryers. These categories can be further divided based on the heating source into fossil fuel dryers (for high temperature dryers) and solar energy dryers (for low temperature dryers). Additionally, solar dryers can also be categorized based on the airflow as:

1) Active solar dryer (solar dryer with forced convection)
2) Passive solar dryer (solar dryer with natural convection)

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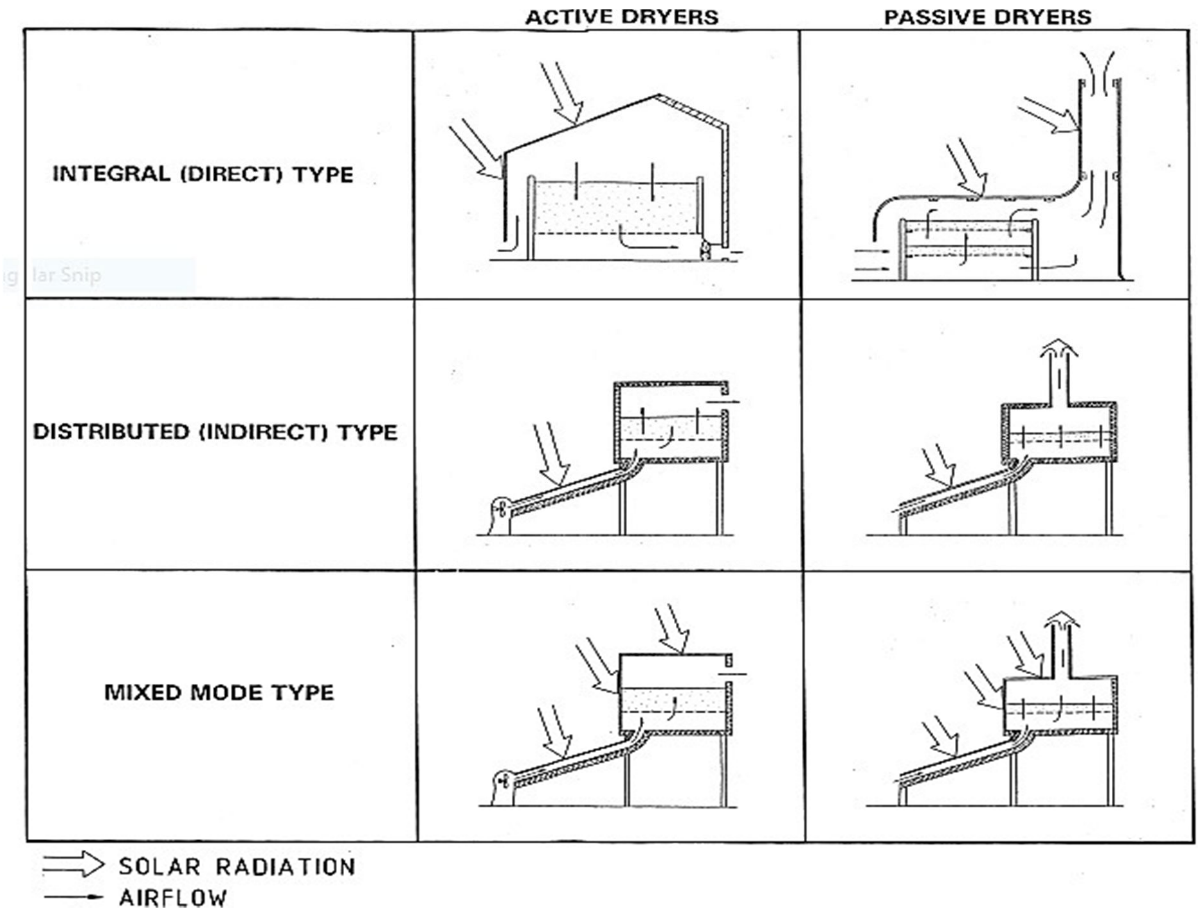

Figure 2: Typical Solar Energy Dryer Designs

F. Experimental Techniques and Dryer Assessment Preparing the Materials

The local market in provided fresh banana corms. With a stainless-steel knife, the corms were cleaned, peeled, and cut into discs that were between 3 and 4 mm thick. Before being cut into slices, the peeled corms were submerged in water for a while. Extra water was drained using tissue paper. Ejiofor (2010) said that the slice thickness should fall between 2 and 5 millimetres, hence the thickness of the banana chips used for the test fell within that range. By drying the banana in the oven, the banana's original moisture content was identified. From February through April, the exam was conducted. At various times during the experiment, the temperature, relative humidity, beginning and ultimate masses of the banana, and the wind speed, were all measured [3].

G. Instruments for Gathering Data

During the dryer's examination, many data like weight, temperature, wind speed, humidity, and sun insolation were evaluated. Prior to being put in the dryer utilising an electronic balance, the banana's original weight was determined [4]. Every two hours throughout the drying process, the weight was determined.

Every hour, the drying chamber and the collector's relative humidity were measured and recorded use the TGP-4500 and TY-4500 temperature and humidity data loggers from tiny-tag. These devices were calibrated for this purpose. The data was then retrieved by connecting the device to a computer.

A solar power metre was used to measure the solar radiation that struck the solar collector. SOLAR 100. Readings were obtained every 30 minutes starting at 8:00 am and ending at nightfall.

The TPI-575C1 wind vane anemometer was used to gauge the wind's velocity as it entered the drying chamber through the solar collector. Readings were obtained every 30 minutes starting at 8:00 am and ending at nightfall. Using the drying rates and efficiencies, the data was then transformed to an hourly basis and utilised to assess the dryer's performance.

III. EVALUATION OF THE SOLAR DRYER'S PERFORMANCE

A. Collector Efficiency

The dryer's thermal performance is gauged by the collector efficiency. It is described as the percentage of the collector's usable heat gain . According to Forson et al.'s (2007) Hottel-Wilier-Bliss equation, the solar air collector's steady state efficiency is provided as follows:

$$\eta c = Qg / ITAc$$

Were,

$$Qg = max\, Cpx\, (To - Ti)$$

Qg = Useful heat energy gained by air (kJ)

ma = Mass flow rate (kg/s)

Cp = Specific heat capacity of dry air (KJ/kgK)

$(To - Ti)$ = Average change in temperature (K)

Ac = area of the primary collector (m2)

IT = Average solar insolation (W/m2)

B. Drying Efficiency

The ratio of energy used to heat the sample and evaporate its moisture to the total energy spent is known as drying efficiency. This gauges the dryer's general efficacy.

$$\eta = MwL / ITATtd$$

Where;

Mw = Mass of moisture removed by dryer (kg)

AT = total area of collectors (m2)

IT = Average solar insolation (W/m2)

L = Latent heat of evaporation of water (kJ/kg)

td = Overall drying time, (seconds)

- For a dryer assisted with the biomass heater;

$$\eta = MwL / ITATtd + (McCV)$$

Where;

Mc = Mass of biomass (kg)

CV = calorific value of biomass (kJ/kg)

C. Average Drying Rate

The mass of moisture extracted by the dryer, Mw, and drying time are used to calculate the average drying rate, Mr, as shown in the following equation.

$$Mdr = Mw/td$$

Were,

Mdr = Average rate (kg/h)

Mw = Mass of moisture dryer (kg)

td = Overall drying time (h)

D. Moisture Content

The amount of water in the produce is its moisture content. There are two methods for calculating the moisture content of produce: on a wet basis and on a dry basis.

$$Mwb = (mi - mf)\, x100/mi$$

- On dry basis, moisture

$$Mdb = (mi - mf)\, x\, 100/mf$$

Were,
Mwb= moisture content on wet (%)
Mdb= moisture content on dry (%)
mi = Initial mass of the product (kg)
mf = Final mass of the product (kg)

E. Moisture Gain or Loss

This is the % change in moisture during the course of the night. Further moisture loss is indicated by a negative number, whilst moisture gain is shown by a positive value. It is calculable as

$$Mn = Msr – Mss/MI$$

Where;
Msr = Mass at sunrise (kg)
Mss = Mass at sunset (kg)
MI = Initial mass of sample (kg)

IV. EXPERIMENTATION TECHNIQUES

The experiment was conducted at SRCEM College, located in Banmore, Gwalior, India. Banmore is a town situated in the Gwalior district of Madhya Pradesh. The study took place between February and April 2022. During the test, eight specific locations within the dryer were equipped with small tag recorders. Among these loggers, four were installed at different positions: one at the collector inlet to measure air temperature and relative humidity, one in the middle of the collector for the same measurements, and one above and below the collector exit to assess the corresponding air temperature and relative humidity. These measurements were taken as the air exited the collector and entered the dryer [5].

Additionally, three data loggers were placed in the drying room, with one positioned above each tray to measure the air's temperature and humidity. Another logger was placed at the chimney air vent outlet to analyse the temperature and relative humidity of the air leaving the drying room. Furthermore, a logger was suspended beneath a tree to monitor the temperature and relative humidity of the surrounding air. The data recorders were programmed to log information once per hour. Measurements of wind speed and solar insolation incident on the collector were taken using a wind vane anemometer (TPI-575C1) and a solar power meter (SOLAR-100). Readings were recorded every 30 minutes from 8:30 am to 6:30 pm.

Figure 3: Arrangements of banana slices on tray

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A. Parts of the Dryer

The mixed-mode solar dryer was made up of four components:

- The drying room
- The principal gatherer
- The Fireplace
- The Roof is a secondary collector

Figure 4: Isometric view of the mixed-mode solar dryer

When comparing the dryer with and without the backup heater, three distinct tests were conducted.

B. No Load Tests

The No load test was carried out to determine the collector's potential temperature rise relative to ambient temperature. Additionally, this test enabled researchers to determine the drying chamber's maximum allowable temperature increase over ambient. Additionally, a backup heater was operated from 18:30 to 21:30 hours after dusk. The feedstock was 310g of charcoal.
which was incremented every hour. Throughout the month of February, there were two tests run. During the test, temperatures, solar radiation, and wind speed were measured and utilized to determine the collector's efficiency.

C. Solar Drying Test

The solar drying test was followed by two further experiments. 1000g of sliced banana were used for the first test. Over each tray, 310g of the sliced banana were spread out in a single layer. Additionally noted were the dryer's assessment criteria. 7.0 kg of sliced banana were employed for the second test's evaluation of the dryer. The sliced banana weighed around 3.0 kilograms each tray. According to several tests, banana with a thickness of no more than 8 mm and a volume of 5 to 18 kg/m2 may be dried in a single batch with an average sun irradiation of between 310and 510 W/m2.
The original moisture content of the banana was measured by oven drying, and an average value of 60%wb was obtained. Based on the established starting moisture content, the decrease in weight of the banana slices was measured and utilized to assess the moisture loss of the slices during the drying process. Wet basis calculations were used to determine the moisture content at each point throughout the drying process. Banana slices were dried continuously until there was no discernible loss of weight or moisture. Based on the drying rate and drying efficiency, the dryer's performance was calculated, and results from various tests were compared [6].

D. Solar drying in the hybrid mode test (backup heater used only in the evening)

A backup heater was utilized from 8:30 to 18:30 in the evening in addition to the solar dryer during the day. For the test, 900g of sliced cocoyam were utilized. This test included a number of the same parameters that were assessed in the previous test. To guarantee that the drying process proceeded over the night, this was done. Between 8:30 and 18:30, 310g of charcoal was put into the backup heater at hourly intervals [7].

E. Solar Drying In The Hybrid Mode Test (Backup Heater Used During The Daytime And In The Evening)

Additionally, two tests were run as part of this hybrid test. The drying chamber received heat both during the day and at night from the backup [8]. The test mass consisted of 7.0 kg of sliced banana. The backup heater received around 310g of charcoal every two hours throughout the day and every hour from 8:30 to 18:30.

F. No Load Tests

Using only the solar dryer during the day and the backup heater solely in the evening between 16:30 and 18:30 for two days.

Table No.1 Solar Dryer During the Day with aluminum plate and The Backup Heater

Day	Time (hrs)	Sunshinehours	Mass Tray1 (g)	M_w LossTray1 (g)	% M_w LossTray1 (g)	Total % MCTray1
Day 1	8:30	0	310.0	0.0	0.00	62.00
	10:30	2	283.0	27.0	8.70	53.30
	12:30	4	219.0	64.0	20.64	32.66
	14:30	6	178.0	41.0	13.22	19.44
	16:30	8	166.5	11.5	3.70	15.74
	18:30	10	164.5	2.0	0.64	15.10
Day 2	8:30	0	170.0	-5.5	-1.77	16.87
	10:30	2	163.0	7.0	2.25	14.62
	12:30	4	160.0	3.0	0.96	13.66
	14:30	6	157.0	3.0	0.96	12.70
	16:30	8	155.0	2.0	0.64	12.06
	18:30	10	154.0	0.0	0.00	12.06

which rose in the morning, peaked in the afternoon when insolation was at its maximum, and then began to drizzle in the evening, a backup heater was used to maintain the dryer's temperature above both the collector's temperature and the ambient temperature.

At 12:30, The collector reached a maximum temperature of 62.0°C while the ambient temperature was 32.66°C. The dryer's maximum temperature at tray 1 was found to be 52.33°C with an ambient temperature of 33.95°C. Having an average maximum temperature of 38^0C, the dryer's maximum average temperature was 50.80 ^{0}C. This caused the dryer to become roughly 16.82 ^{0}C hotter than the surrounding air.

When the backup heater was on at tray 2 of the dryer in the evening, the temperature was discovered to be 40.25°C, whereas the outside temperature was measured at 30.97°C at 18:30. The highest temperature on average for a dryer was 34.79°C and a maximum ambient temperature of 32.34°C on average; hence, the dryer's temperature was rose 5.85°C above ambient when the backup heater was engaged.

Table 2 Solar Dryer During the Day with black carbon material coated aluminum plate and Backup Heater

Day	Time (hrs)	Sunshine hours	Mass Tray2 (g)	M_w Loss Tray2 (g)	% M_w Loss Tray2 (g)	Total % MC Tray2
Day 1	8:30	0	297	0.0	0.00	59.40
	10:30	2	239	21.0	7.07	52.33
	12:30	4	198	41.0	13.80	38.53
	14:30	6	147.5	50.5	17.01	21.52
	16:30	8	126	21.5	7.23	14.29
	18:30	10	119	7.0	2.35	11.94
Day 2	8:30	0	113	6.0	2.02	9.92
	10:30	2	108	5.0	1.68	8.24
	12:30	4	104	4.0	1.34	6.9
	14:30	6	102	2.0	0.67	6.21
	16:30	8	101	1.0	0.33	5.88
	18:30	10	101	0.0	0.00	5.88

On the second test day, the temperature trend started to decline in the evening after rising in the morning and reaching a peak value in the afternoon at the peak of insolation. The temperature in the dryer was nevertheless maintained higher than both the ambient and collector temperatures using a backup heater. Between the hours of 8:30 and 18:30, 310g of charcoal was burned as feedstock in the stove once, maintaining the dryer's temperature higher than the ambient air.
Within two hours of backup heat supply the dryer reached a maximum temperature of 36.96 C at tray 2 at an ambient temperature throughout the evening. of 31.8 C at 18:30. A temperature rise of 6.21 Cover ambient was discovered in the dryer, which had an average maximum temperature of 59.80 C and a maximum ambient temperature of 52.33 C.
Additionally, a 24-hour period with an average dryer temperature of 50.50 C and an ambient temperature of 41.72 C resulted in a temperature increase in the dryer of roughly 6.9 C.

A. Solar drying + backup heater (day and evening)

In this test, the sun dryer and backup heater were employed to dry banana slices from April 15 to April 23, 2022. The backup heater was fueled with approximately 310g of charcoal to maintain a consistent temperature in the dryer. Charcoal was added every 2 hours during the day, starting from 8:30, and every 1 hour from 18:30 onwards. During the experiment, 7.0 kg of banana slices with an average initial moisture content of 62%wb were dried to an average final moisture content of 4.64%wb in a little over 3 days, utilizing 28 hours of sunlight. This indicates an average moisture content reduction of 32.66% wb throughout that time. With the assistance of the backup heater, the dryer achieved an average moisture content of 5.85% to 6.21% wb in 2-4 days, starting from an initial moisture content of 62.66% wb on average, with the lowest moisture content value observed when the backup heater was employed.
By the end of the second day of drying, after 20 hours of sunlight, the combination of the dryer and backup heater had reduced the moisture content to 9.48% wb. However, the drying process continued into the third day without significant changes in the weight of the banana slices. Furthermore, when the backup heater was used to continue the drying process in the evening until the third day, there was an average moisture loss of 16% and 3.18% during the evenings of day 1 and day 2, respectively.

V. CONCLUSION

Performance assessment of a mixed mode solar dryer with a backup heater involved conducting no load and load tests. The backup heater, fueled by a charcoal burner, ensured continuous drying even at night and on cloudy days. In the absence of load, the dryer and ambient temperatures on days 1 and 2 were 38.53 °C and 19.44 °C, and 52.33 °C and 32.66 °C, respectively, indicating an elevated temperature conducive to drying. Based on the loading density of the product, banana chips with an average initial moisture content of 62.0% wb were dried to an average moisture content of 3.70% to 8.70% wb in 2-4 days, with the backup heater achieving the lowest moisture content value.

The performance of the dryer was evaluated in terms of efficiency and drying rate. The collectors demonstrated efficiency ranging from 23.78% to 27.17%, with maximum efficiency observed under high solar insolation. Test 1 and Test 2 revealed drying efficiencies of 5.85% and 9.48% for sun drying alone, and 10.24% and 13.50% when the backup heater was used both during the day and at night. The drying rates were 25.25 g/h and 28.56 g/h for Test 1, and 113 g/h and 147 g/h for Test 2, with the backup heater contributing to the higher values. The addition of the backup heater resulted in drying rate increases of 11.94% and 25.16% for Test 1 and Test 2, respectively.

The test indicated that the loading density of the product influences the dryer's performance, with higher densities leading to increased drying rates and efficiencies. Consequently, the sun dryer has the capability to efficiently dry crops with high moisture contents for safe storage. Incorporating a backup heater further enhances the dryer's performance in terms of speed and efficiency.

VI. FUTURE SCOPE

To further enhance the performance of the solar dryer, the following measures can be implemented:

1) Proper sealing should be ensured between the drying chamber and the primary collector to prevent heat loss to the surrounding air.
2) Lengthening the metal tube when utilizing the backup heater would promote even heating and improve heat transmission across the trays.
3) Raising the distance from the ground to the air intake vent would facilitate smooth airflow through natural convection.
4) Careful sealing of the spaces surrounding the dryer's ceiling would minimize heat loss from the chamber.

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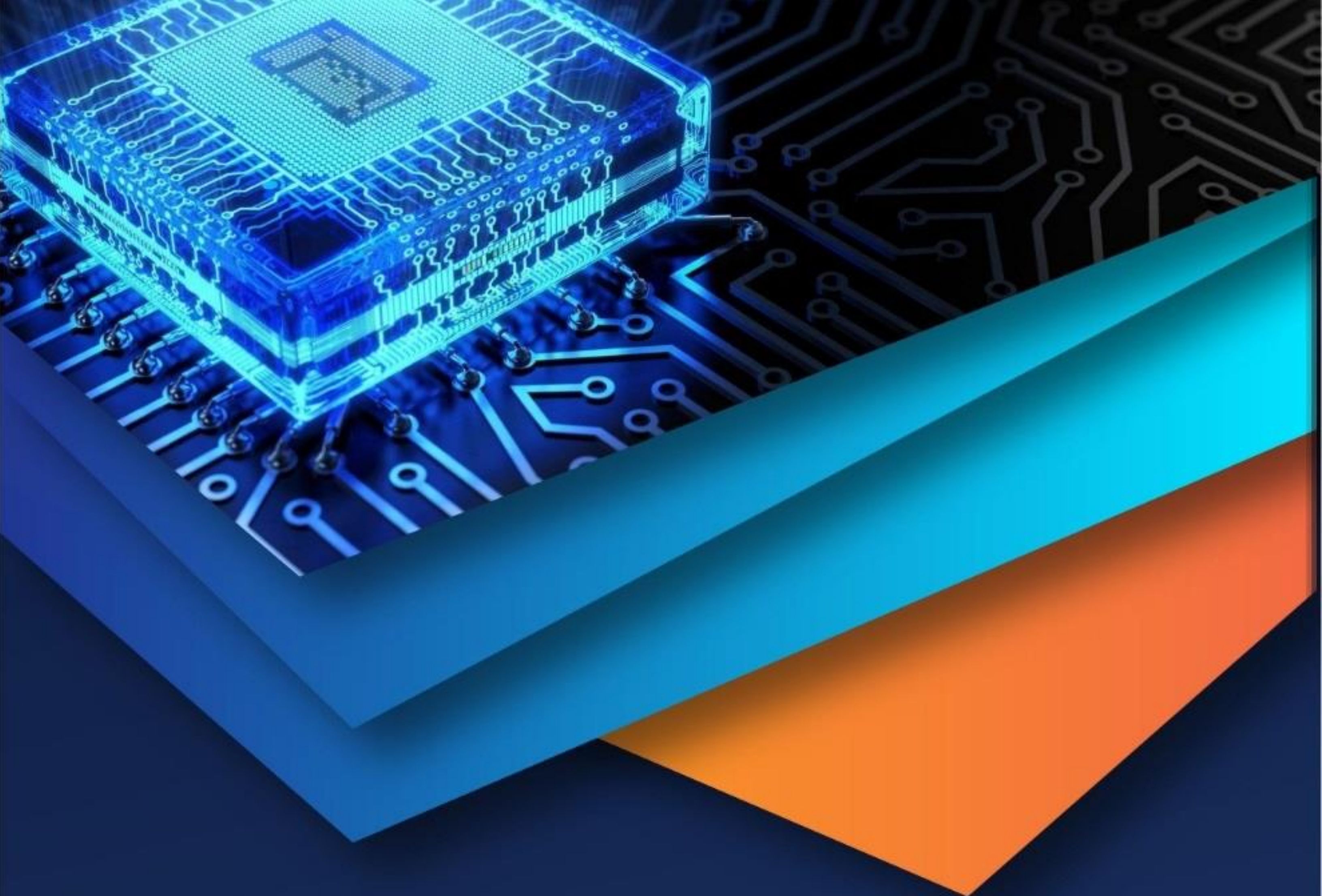

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