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Finding Approaches Enabling more Use of Sustainable Energy through Pellet Production

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Abstract: A growing number of people throughout the world are interested in finding new raw materials that may be used to make energy pellets. Before these raw materials are taken into consideration for its use in energy pellet production, they undergo a number of analytical evaluations and quality tests. Utilizing various resources from food waste agriculture, forestry and even extra materials from agri-food production to make energy pellets has grown in popularity these days.
The practicality of using raw materials for pellet manufacture such as pea trash, birch sawdust, chamomile waste, and soybean residue is explicitly examined in this study. This investigation's main goal is to produce thermal energy from these pellets while making sure they adhere to the necessary requirements.
The results obtained through this study show that the raw biomass residual materials can be beneficial for the production of make high-quality energy pellets. The specific strength characteristics of the pellets and their usefulness for producing thermal energy are significantly influenced by the composition of these raw ingredients.
Keywords: Pellets, Pellet production, Biomass, Energy production

I. INTRODUCTION

The significant increase in global wood pellet imports and exports in recent years has raised concerns about its adverse impact on the supply of raw materials in the forest products industry and on forest biodiversity. These difficulties have spurred pellet producers to investigate alternative raw material sources, including diverse energy crops, residues obtained by forest and agriculture, and some different forms of biomass products [1].

To ensure the sustainability of these alternative raw materials for pellet production, several key factors need to be considered, including logistical feasibility and meeting quality standards. Sustainable supply chains, the definition of optimal pellet-able characteristics, adherence to relevant industry standards, and fulfilling the requirements of end-users are all essential aspects. It's important to note that biomass availability is inherently unpredictable and can be highly variable, which may pose challenges in meeting supply and fuel demands when biomass is utilized as an energy source or fuel feedstock [2].

Using biomass as a substitute source of energy has significant socioeconomic as well as environmental benefits. Biomass offers a carbon-neutral raw resource for energy generation despite its limited availability. However, biofuels have relatively low bulk densities, with herbaceous biomass having a density of 80 to 150 kg/m3 and woody biomass having a density of 150 to 200 kg/m3 [4]. These qualities restrict their application to regions close to their source, and their changing moisture content and loose nature present difficulties, impeding their effective use of energy [5].

Large amounts of agricultural wastes are produced in many developing nations, but they are frequently used inefficiently, causing significant environmental degradation. In addition to sawdust, which is a prominent milling residue, these residues also include Groundnut shells, cotton stalks, mustard stalks, bagasse, jute sticks, coir pith, coffee husk and rice husk.

These leftovers from agro-processing or from wood processes are frequently considered as garbage, making them the most economical sources of biomass. A considerable effort has been made over the years to encourage the use of these wastes in various heating systems [7]. However, the majority of biomass leftovers are technically they are unsuitable for their use due to their concern in combustion and handling because they are less dense and have a higher moisture content than fossil fuels [8].

Nonetheless, the process of biomass densification has been employed to overcome these challenges. Densification involves compressing the raw materials in order to produce much denser fuels having consistent properties and sizes. This method enhances handling characteristics of biomass, volumetric calorific values are increased, and cost reduction in transport, collection, and storage [9]. Among the various techniques available, pelletizing has become the most widely adopted [10].

Throughout 1998, 0.76 million tons of municipal solid waste were produced daily throughout Asia, with annual growth rates of 2-3% in poor countries and 3.2-4.5% in industrialized ones [11] (2006). Throughout the 1990s, Asia served as the location for a various regional and national projects involving solid waste management. The World Bank's Metropolitan Environmental Improvement Program has made significant contributions to improving solid waste management in major Asian cities such as Beijing, Mumbai, Colombo, Jakarta, Metro Manila, and later, Kathmandu. Between 1994 and 1998, communities in the Philippines, Thailand, and Indonesia received assistance from the South-East Asia Local Solid Waste Improvement Project, an aid initiative supported by the Canadian International Development Agency (CIDA). This assistance covered a range of issues related to solid waste management, including the establishment of recyclable "waste banks," the identification of suitable landfill sites, the coordination of waste collectors and recycling businesses, and the provision of training in hazardous waste management. Highly populated regions like Singapore, Japan, Thailand, Malaysia, South Korea, Indonesia, China, and the Philippines are under pressure to improve their solid waste management systems. They are striving to better control their waste streams and transition from mere disposal to the recovery of materials and energy. It is noteworthy that San Antonio will become the first U.S. city to utilize human feces for commercial methane gas production. This innovative approach represents a significant step in utilizing sewage as a potential source of power. Using the gas collection method instead of incineration has the potential to yield more energy from waste. An illustrative case study conducted by Woch et al. (2015) focused on a specific forest division in Poland. The study aimed to assess whether woody waste biomass from forests could serve as a renewable energy source. The findings indicated that the energy generated could potentially supply a substantial population's needs. According to a June 2013 report from "Ecoprog GmbH," there are approximately 2,200 waste-to-energy plants worldwide, capable of processing over 255 million tons of waste annually. Particularly in China, Europe, Japan, Australia, and the USA, commercial waste-to-energy technology have been employed.

Energy from solid waste in India [12]: India has a significant potential for producing electricity from solid waste. Municipal solid waste (MSW) can be divided up and collected, used again, or recycled for a fair price. To make a living, the informal sector currently collects certain resources from the streets and rubbish bins. But a large amount of organic and recyclable waste winds up in landfills untreated. Over 81% of MSW is regularly dumped in open landfills without any sort of treatment. According to a 2014 Planning Commission report, the nation can profitably use about 65% of its waste to produce energy and/or compost through planned efforts to reduce, reuse, recover, recycle, and remanufacture (5Rs) waste. The remaining 10 to 15% of waste can be reduced to under 20% by using the right technologies to support the recycling sector. Bio methanation, pyrolysis, and incineration are among the technological possibilities. As a result, selecting waste-to-energy technology offers a variety of waste-management options. In contrast to pyrolysis and incineration, methanation is the most efficient technique. Incinerators are attacked mostly for the dangerous air they emit and the air pollution their ash causes. Anaerobic digestion [13], which is a component of bio-methanation, produces methane by employing bacteria in confined spaces to break down organic waste. The availability of high-quality organic waste is a requirement for bio-methanation. In order to ensure that organic waste is properly separated from inorganic trash before its usage as a raw material in the bio-methanation process, waste pickers must be involved. Sludge is produced as a by-product of this process, which can then be utilized to create compost. Other methods are being developed in the area as a result of ongoing research, such as the methodology presented by Brar et al. (2014) for power generation utilizing methanol fuel cells as well as the socioeconomic and environmental impact a biogas plant could have in a small community. [14] Nikita Singh Narsi Visharad, by Sanjay Sharma, 2022: This study paper primarily focuses on a review of the creation fuel pellets derived from municipal solid waste using smart machines from mixed municipal solid waste. This project's primary goal was to assess the RDF (Refuse Derived Fuel) energy potential that could be obtained by using the dry waste that was recovered. To treat the waste and perform additional calculations and calorific value analyses, a dross machine was employed. Shahab Sokhansanj, C. Jim Lim, Fahimeh Yazdan Panah, and Hamid Rezaei, 2022: The major topic of this research study of Refuse-Derived Fuel with Variable Plastic, study, Organic, and Wood Compositions for pelletization. The various compositions listed above were used for palletization, and analysis was then done to determine which composition would produce fuel at the highest efficiency.

II. MATERIALS AND METHODS

A. Raw Materials

Coffee husk residue, nut shell residue, yard trash residue (including grass clippings and leaves), and rice mill residue are included. Table 1 shows additives and raw materials used along with their ratios. It's vital to note that both the basic materials and the additives underwent fragmentation before the pellet manufacturing process began. Samples weighing 100 grammes (with an accuracy of 1 gramme) were sieved so that particle size of the raw material can be measured. The mesh sizes of sieves included were 0.25, 0.5, 1.4, 1, 2.0, 2.8, 3.15 mm. All of this was considered after thorough study from PN-EN-ISO 17827-2:2016-07 guidelines [16].

A methodology in line with the PN-EN-ISO 18134-3:2015-11 standard [17] was used to measure the moisture preset in the finished pellets and in the raw materials. Consistent mass needs to be reached when moisture needs to be measured. In that case, the pellets were heated up until 105°C. The technique used for heating up these pellet samples involved using a drier. This drier used 'forced air circulation' to heat the samples to the required temperature These standardized procedures ensure that the moisture content and particle size distribution of the materials and pellets being analyzed are reliable and precise. [18].

TABLE I. SPECIFICATIONS OF THE MACHINE USED TO CREATE PELLETS

Raw material type	Raw material [%] Mass share	Additive Types	Additive percentage share	Designation of the pellet
Coffee husk	100	-	-	A1
Almond shells	100	-	-	A2
Coffee husk	50	Lignin	50	A3
Almond shells	50	Starch	50	A4
Coffee husk	50	Lignin, Starch	30, 20	A5
Almond shells	50	Lignin, Starch	30, 20	A6

B. Method Followed for Producing Pellets

1) Almond and coffee shells were both wet to an 18% moisture level. Here, it's crucial to emphasize that the additives weren't wet. The formula: -

$$m_w = \frac{d_2 - d_1}{100 - d_1} \times m_m \qquad (1)$$

yields the amount of water. Where m_w is the weight of water used to moisten the mixture in grammes, d_2 is the percentage of actual water needed in the mixture, d_1 is the percentage of water already present in the mixture, and m_m is the mass of the moistened mixture in grammes. [19].

2) Shredding: Dried waste is passed through the shredder. The shredder cuts the waste into small parts for better compression in the binding process.
3) Size Reduction: The shredded waste is then passed through the conical nozzle which reduces the size under pressure.
4) Densification: The mass of dry waste per meter cube is increased. In short density of the material is increased.
5) Palletisation: In the final stage, the pellets of desired shape and size are made with the help of different shapes of nozzles and a pressurizer.

TABLE II. Specifications of the machine used to create pellets

Specifications	Measurement units	Parameters
Rated power of the electric motor	kW	7.5
Electric motor supply voltage	V	400
Rotational speed of the motor	Rads/s	151.8
Rate of reduction	-	1.13
Shaft speed	Rads/s	11.6
Total rollers	-	2
Roller diameter	mm	100
Roller width	mm	50
Roller grooves dimensions (width x depth)	mm	3 x 3
Spacing between roller groove	mm	3
Die type	-	Flat
Diameter of die	mm	230
Die thickness	mm	28
Hole diameter in the die	mm	8
Hole quantity in the concerned dye	Pcs.	126
Feeding hopper capacity	dm^3	20
Pellet mill dimension (length x width x height)	mm	1300 x 650 x 1020
Pellet mill mass	kg	250

C. Approaches for Assessing the Resulting Product

A 7.5 kW electric motor-driven pelleting mill consisting of a stationary flat die and A rotating press rollers was used to consolidate the raw materials and their mixtures (as shown in Figure 1). Please see Table 2 for the pellet mill's precise technical specs. Notably, the l/d ratio (length to diameter) of pellets was 3.125.

1) Geometrical Properties

Geometric properties such as pellet diameter, pellet length, etc are an essential part when examining pellets produced with pellet mill having stationary die. All these examinations done followed guidelines laid out by PN-EN-ISO 17829:2016-02 standard [20]. Now for the measurement part of things the minimum mass of pellets selected was taken as 100 grammes. All these geometric properties were measured using a calliper. Again, to ensure that the accuracy of pellets was as low as 0.1 millimetres, entire test is repeated three times. The measurement of mass of the pellets was also done using laboratory-level measuring scales to for ensuring that precision of the pellets is up to the mark of 0.01 grams.

2) Ash Content and Calorific Value

Guidelines given in PN-EN-ISO 18125:2017-07 standard were followed to find the Calorific value (CV). This involved deploying the calorimetric method by using a Isoperibol calorimeter. Additionally, in accordance with the PN-EN-ISO 18122:2016-01 standard, the ash content was assessed by subjecting pellet samples to ashing at a concluding temperature of 550°C. This assessment also included testing through crushing and cutting.

3) Crush Tests

In the crush test section, working platens were taken which were continuously rotating at high speed which the pellets were being placed in. The pellets involved in the process were size-specific having a total length of 100 millimeters. Studies done by [16 and 17] shows that these crush and cut tests can be used to show how much compressive strength the pellets are capable of withstanding simulates the stress placed on pellets during storage in bins or silos due to the weight of those stacked above them, as well as the crushing force they undergo in screw conveyors. The knife's blade angle was locked at 45°. These experiments allowed to plot some resulting curves which were then used for finding crush and cut force values. The specific density of the pellets was computed using measurements of length, mass, and diameter obtained from randomly selected samples. The computational process was conducted following the subsequent steps:

$$\rho_s = \frac{4 \times 10^6 \times m}{\pi \times d^2 \times l}$$

In this context, "ρ_s" represents the specific density of the pellets, and "m" signifies the mass of a randomly selected sample of pellets, d is the average diameter of that sample of pellets, and "l" is the total length of pellets in that sample [22].

4) Specific and Bulk Density

PN-EN-ISO 17828:2016-02 standard guidelines were followed for finding bulk density of samples tested, considering measurements of both their mass and volume [14]. To do this, the pellets had to be poured into a container with a 5 dm^3 capacity, any extra was removed with a slat, and finally the pellets had to be weighed on a lab scale in order to determine their bulk density.

5) Mechanical Strength

The assessment of pellet mechanical strength was done by following the PN-EN-ISO 17831-1:2016-02 standard guidelines. The sample's weight was exactly 500 grams, and the drum rotated at a constant speed of 40 revolutions per minute throughout the entire 10-minute duration of the test. Following strength testing, the sample pellets were sieved through a mesh size one millimetre smaller than the diameter of the pellets.

The following formula (3) was used to determine the pellets' mechanical strength:

$$S_U = \frac{m_f}{m_i} \times 100$$

where SU is the mechanical strength of the pellets, m_f is their mass following the strength test, and m_i is their mass initially [23].

III. RESULTS AND DISCUSSION

In this case, the level of fermentation determined the final product's characteristics. Table 3 gives an idea about how the size of the particle of the waste collected is distributed along with used raw materials in pellet manufacture. Almond shells exhibited the highest degree of fragmentation, with 18.32% of the material passing through a mesh with a square opening of 0.25 mm. In contrast, there was minimal fragmentation in the residue from rice mills, as 87.5% of the material remained retained on the sieve with a mesh size of 3.15 mm. After the incineration process, an assessment was conducted to determine the moisture content, CV, and ash content of each distinct raw material employed in pellet production. The data gathered are displayed in Table 4. Coffee husks and almond shells were altered to have a 20% moisture content in accordance with our defined approach. Notably, garden trash had the lowest calorific value, measuring 15976.89 kJ/kg, while residual from rice mills had the highest calorific value, measuring 20928.44 kJ/kg. Raw material moisture content had a big impact on calorific value, with rice mill residues having the lowest moisture percentage at 7.36%. The CV value is determined by type of raw material in usage as well as its density. Utilizing the results obtained in CV and ash content of the samples tested, we effectively produced six composite pellets as part of this study (as shown in Figures 2 and 3). Although these pellets had comparable calorific values, Table 5 shows that their ash contents differed. A2, A4, and A6 pellets in particular had minimal ash content—below 3%—while the rest produced more ash, but not more than 6.31%. Different amounts of additives that weren't pre-moistened caused the varied moisture content before the pelleting procedure.

TABLE III. RAW MATERIAL TYPE AND TYPE OF MESH IN THE SIEVE USED

Raw material Type	Sieve mesh size [mm]							
	3.15	2.8	2.0	1.4	1.0	0.5	0.25	0.0
Coffee husk	12.33	0.33	0.66	7.6	25.6	48.5	5.25	1.1
Almond shells	2.11	0.29	0.8	1.32	3.27	29.11	46.61	16.89
Yard waste	24.33	3.51	9.11	14.29	11.93	18.48	9.22	8.61
Leftovers from rice mills	85.55	3.33	5.52	3.89	0.91	0.79	0.22	0.17

TABLE IV. RAW MATERIAL TYPE AND THEIR CHARACTERISTICS

Raw material used	Moisture content [%]	Calorific value [kJ/kg]	Ash content [%]
Coffee husks	15.76	17252.21	5.34
Almond shells	9.02	17664.12	1.66
Yard waste	10.12	15976.89	2.61
Leftovers from rice mills	7.49	20928.44	5.01

With one exception, all of the pellets in our sample had calorific values greater than 17 MJ/kg and an ash percentage under 6%. Possible explanations for this phenomenon include mineral contamination in coffee husks. The large energy content of leftovers from rice mills in the A5 and A6 mixtures are responsible for the increased energy content in our pellets. In contrast, the addition of residues from rice mills in the mixture was linked to the decreased energy value of A3 pellets.

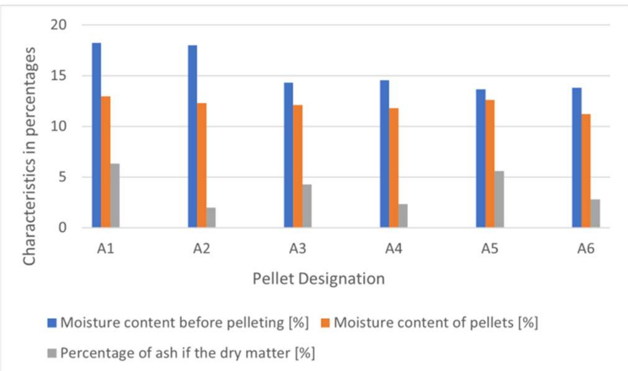

Fig. 1. Characteristics of resulting pellets

The geometric characteristics of the manufactured pellets is presented in Table 5 along with mechanical strength. Mechanical strength plays a pivotal role in pellet production, as pellets susceptible to breakage raise the potential for fire or explosion hazards during storage and transport. Additionally, they can result in increased dust emissions, potential obstructions in boiler feeding systems, and disintegration issues.

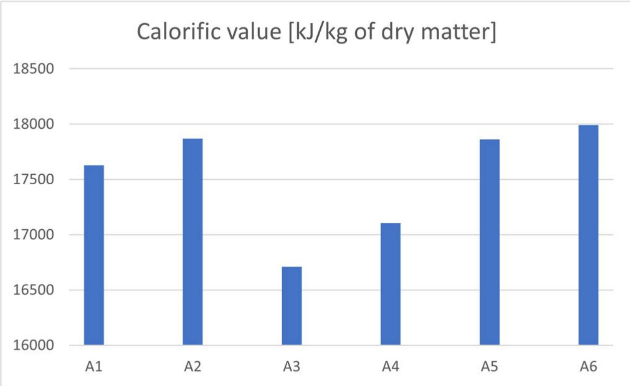

Fig. 2. Calorific values obtained of resulting pellets

Among all the pellets produced, those labelled as A4, crafted from a mixture of coffee husks and almond shells, displayed the highest level of mechanical strength, reaching 97.11%. Overall, all of the pellets were remarkably robust in terms of mechanical strength. However, it should be noted that the mechanical strength dropped significantly in the case of the mixture consisting of leftovers from rice mills and yard trash with coffee husks (pellet A5), measuring just above 90%.

The A4 mixture's pellets are characterized by their elevated specific density, denoting a significant degree of compaction, and they exhibit a low ash content of only 2.33%, both contribute to their excellent mechanical strength. The amount of ash in the mixture contributes to lessening the binding forces between the elements needed to create pellets. This phenomenon became clearer after the pellets made from the A5 combination were mixed with coffee husks, which had the greatest ash level (5.59%).

TABLE V. Geometric and mechanical characteristics of resulting pellets

Designation of pellet	Diameter [mm]	Length [mm]	Specific density [kg/m^3]	Bulk density [kg/m^3]	Mechanical strength [%]
A1	8.29	26.89	1032.98	487.21	95.71
A2	8.26	24.51	1147.03	506.33	96.54
A3	8.33	31.23	1130.31	606.91	95.07
A4	8.29	33.01	1153.22	584.87	97.11
A5	8.30	26.31	1128.33	566.98	90.33
A6	8.36	27.39	1078.19	545.21	94.61

A4 manufacture was favored by the information on calorific value along with mechanical strength, hardness, cutting force, and energy consumption throughout the pellet production process. The results, illustrated in Table 6, clearly reveal the substantial impact of the raw material composition on these characteristics.

Despite having a rather low starting moisture content (13.8%), A5 outperformed the other pellets in terms of effectiveness (106.7 kg/h) and energy expenditure (38.4 Wh/kg). It's crucial to remember that A5 has the lowest mechanical strength (90.23%).

A1 and A2 both used more than 100 Wh/kg of energy during the procedure; A1 was made from chamomile waste, whereas A2 was made solely from birch sawdust.

Without any additives, birch sawdust (A2) had a poorer pelleting efficiency (39.2 kg/h). The mixture of birch sawdust and pea waste (A4), in comparison, showed noticeably better pelleting efficiency, topping 45%. Incorporating soybean waste (A6) led to an additional 140% gain in efficiency and a 55% decrease in energy use.

TABLE VI. Effectiveness and energy consumed during pelleting process

Pellets designation	Measured effectiveness [kg/h]	Energy consumption [Wh/kg]
A1	83.2	108.5
A2	39.1	100.3
A3	91.1	44.2
A4	56.8	43.9
A5	106.9	38.1
A6	93.7	44.3

These findings underscore the influence of the chemical composition of raw materials on the palletization process. Specifically, a higher fat content in soybean waste enhances process efficiency and reduces energy consumption. It's essential to remember that the energy utilized in the palletization process is just one element of the overall cost of pellet production, which encompasses raw material expenses, equipment operation costs, labor expenses, and potential costs associated with the final drying of raw materials [24].

The results we obtained concerning the mechanical strength of pellets, as depicted in Figure 2, underscore the significant influence of pellet composition, as previously observed in another study [24]. Jiang et al.'s [25] research on the mechanical strength of wood biomass pellets yielded a variety of outcomes, which could be attributed to variations in lignin content in the raw material and fluctuations in pellet moisture levels.

A2 and A4, which are both based on almond shells, showed the best mechanical strength among our pellet compositions. On the other hand, A5, which was made from coffee husks with the addition of garden debris and scraps from rice mills, had the lowest mechanical strength at 122.88 N. The compressive strength of compost-based pellets in a prior study [16] fell within the range of 99 to 130 N, aligning with the outcomes of the current compression test. These dependencies are attributable to the unique makeup of the relevant raw components. Particles are forced into close contact under high pressure, which encourages inter-particle bonding. This procedure causes natural binding substances like starch, protein, and lignin to be removed from the particles, which helps to establish strong bridges between the particles.

Analyzing the pellets' cutting force revealed similar connections (Figure 3). A2 and A4 pellets made from birch sawdust had the highest cutting forces, respectively (161.28 N and 156.22 N). In contrast, A5 and A3 pellets had the lowest cutting forces (31.29 N and 56.04 N, respectively).

In Kraszkiewicz et al.'s study [20], they observed that pellets produced from a combination of rapeseed straw and press cake, with the addition of spelt hulls, exhibited the highest cutting force, registering at 136.6 N. Conversely, the pellets crafted from rapeseed straw and soybean hulls displayed the lowest cutting force, measuring just 42.2 N.

IV. CONCLUSION

The identification of raw materials capable of ensuring the longevity of these pellets is closely linked to the continuous search for waste materials suitable for producing pellets as a renewable energy source. Achieving this stability involves a meticulous balance in the composition of the raw materials utilized. The composition of these raw ingredients is of utmost importance when it comes to pellet production from biomass remnants.

The findings of our investigation unequivocally show that choosing the proper raw material composition has a major influence on a number of crucial factors. First, it has an impact on the end product's calorific value, which is essential for estimating its energy potential. Furthermore, it plays a critical role in assessing the levels of ash and heavy metals within the pellets, impacting their environmental suitability. Additionally, the composition of the raw materials dictates the physical attributes that influence the resilience of the pellets during storage and transportation, as well as the energy consumption during the pellet manufacturing process.

Through enhanced pellet production methods and materials, this line of research has significant promise for improving the use of renewable energy.

V. DECLARATION OF CONFLIC

The authors declare that there is no conflict of interest while submitting the manuscript.

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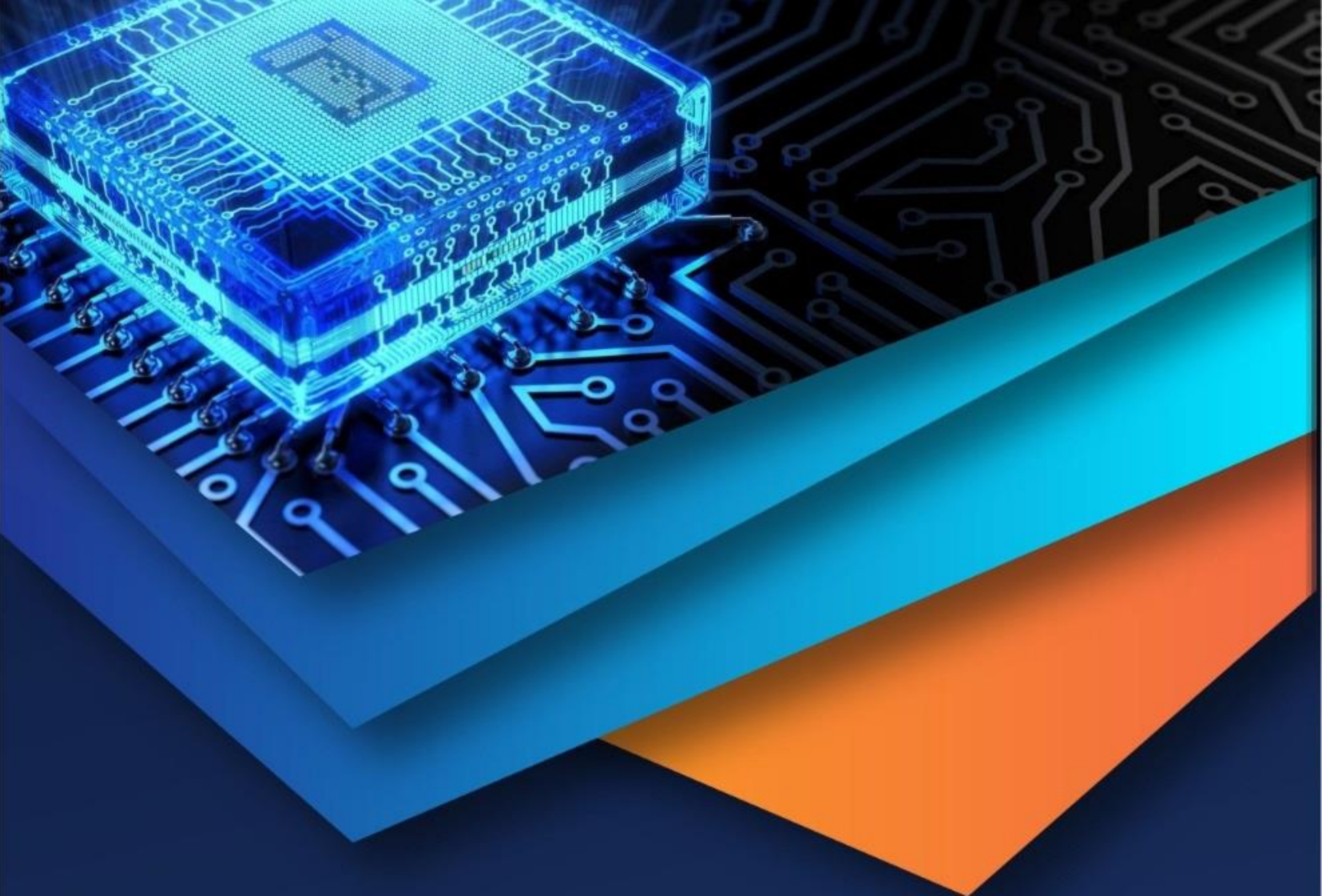

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