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Valorization of Fruit and Vegetable Market Waste via Batch Anaerobic Digestion: Reactor Performance and Scope for Future Optimization

Venkatesh K.R[1], Ahamed Hilal A.R[2]
[1]Department of Civil Engineering, University College of Engineering-Tindivanam, Tamil Nadu, India – 604307
[2]Department of Civil Engineering, Annamalai University, Tamil Nadu, India – 608002

Abstract: In India, nearly 5.6 million tonnes of fruit and vegetable waste are generated annually, much of which ends up in landfills, causing odor, environmental degradation, and greenhouse gas emissions. This study investigates anaerobic digestion as a sustainable and cost-effective technique for converting such biodegradable market waste into biogas, a renewable energy source. A novel 20-liter batch anaerobic reactor was custom-fabricated and operated under mesophilic conditions (35°C) for 41 days using unsegregated market-derived fruit and vegetable waste, with cow dung as inoculum. Key parameters—including pH, chemical oxygen demand, total suspended solids, volatile suspended solids, and alkalinity—were monitored throughout the operation, and biogas production was measured using the water displacement method. A maximum removal of 70 percent chemical oxygen demand and a biogas yield of 19.13 milliliters per liter were achieved. Although the study duration was limited by the academic calendar, the system maintained stable performance despite acidic pH and high solids. The reactor's low cost and simplicity highlight its potential for decentralized waste-to-energy solutions, especially when integrated with artificial intelligence-based real-time monitoring in future systems.
Keywords: Anaerobic Digestion; Biogas Production; Fruit and Vegetable Waste; Batch Reactor; Organic Waste Valorization; Sustainable Energy

I. INTRODUCTION

India stands second in the production of fruits and vegetables in the world. It contributes about 10% and 14% of the global fruit and vegetable production respectively [1]. Vegetable wastes are created during harvesting, transportation, storage, marketing, and processing. Due to their high moisture content and biodegradable nature, they deteriorate easily and produce a foul smell, becoming a source of environmental pollution.

According to the Food and Agricultural Organization (FAO), the estimated fruit and vegetable waste percentages for each commodity group in each step of the food supply chain are 15%, 9%, 25%, 10%, and 7% in agricultural production, post-harvest handling and storage, processing and packaging, distribution, and consumption respectively in South and South-East Asia [2].The Indian Agricultural Research Data Book (2004) estimated the production of fruits and vegetables in India at 150 million tonnes, with total waste generation at 50 million tonnes per annum—i.e., 30% of the total production. Given their high organic content, these wastes are more effectively treated using biological methods such as anaerobic digestion rather than incineration or composting. Anaerobic digestion is the biological degradation of organic and sometimes inorganic substances by a complex microbial ecosystem in the absence of oxygen. Methane production via anaerobic digestion involves four distinct metabolic stages. First, particulate organic matter undergoes hydrolysis by extracellular enzymes, converting polymers into monomers. Then, acidogenic bacteria convert these products into organic acids, alcohols, hydrogen, and carbon dioxide. Next, acetogenic bacteria transform these into acetic acid, hydrogen, and carbon dioxide. Finally, methanogenic bacteria produce methane from the acetogenic products [3], [4].

The primary advantage of anaerobic digestion is the generation of biogas, which can be used for steam heating, cooking, and electricity generation [5], [6]. The effluent produced after digestion can be used as a bio-fertilizer or soil conditioner [7]. Vegetable wastes generated in large quantities in markets are typically disposed of in municipal landfills or dumping sites [8]. Bioconversion processes are better suited for such wastes with moisture content above 50% than thermo-conversion processes [9]. Due to their high biodegradability and 75–90% moisture content, vegetable wastes serve as excellent substrates for bio-energy recovery through anaerobic digestion [10].

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A key limitation of anaerobic digestion for vegetable wastes is rapid acidification due to low pH and the production of volatile fatty acids, which reduce the methanogenic activity of the reactor [11]. Preliminary treatment is often required to minimize the organic loading rate. Hence, aerobic processes are not preferred for vegetable waste. The rate-limiting step in such digestion is typically methanogenesis, rather than hydrolysis, since methanogenic bacteria have a slow mass doubling time of 3–4 days in anaerobic systems.

Several types of reactors are used for bio-energy recovery from solid wastes and wastewater, including batch reactors, single-stage, and two-stage systems. In batch reactors, waste is fed once, and all degradation stages occur sequentially. More retention time is required for complete conversion in such reactors. In one-stage systems, all reactions occur in a single vessel. These are preferred for full-scale anaerobic digestion due to their simple design and lower investment costs. In two-stage systems, separate reactors are used for acidogenesis and methanogenesis.

The objective of the current study is to evaluate the performance of a laboratory-scale anaerobic batch reactor using market-derived fruit and vegetable waste, mixed with cow dung as inoculum, under mesophilic conditions. The study focuses on analyzing key physicochemical parameters, monitoring biogas yield, and assessing COD removal efficiency over a 42-day operational period, which represents the reactor's start-up phase.

II. MATERIALS AND METHODS

This section outlines the materials used and the experimental procedures followed in conducting the anaerobic digestion study. It includes details of the waste substrate, inoculum selection, analytical methods for key parameters, and the design and operation of the batch anaerobic reactor.

A. *Food Waste*

Fruit and vegetable waste from a nearby market was collected. The fruits and vegetables selected were those with high moisture content, as such materials are known to stimulate biogas yield more effectively due to easier microbial degradation [12],[13].

B. *Seed Sludge*

Seed sludge is typically used to enhance the biodegradation process by providing active microbial cultures. In many bioremediation processes, sewage sludge and cow dung are used as seed sludge [14]. In this study, fresh cow dung was used as the inoculum due to its high microbial activity and buffering capacity.

C. *Analytical Methods*

The following physicochemical parameters were measured:

- pH- Using a calibrated digital pH meter.
- Total Solids (TS), Total Dissolved Solids (TDS) and Volatile Suspended Solids (VSS): Measured using gravimetric methods.
- Chemical Oxygen Demand (COD) and Alkalinity: Estimated using standard procedures recommended by IS 9234 – 1979, IS 10158 – 1982, and the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2017, 23rd Edition) [15].

D. *Reactor Set-Up*

A laboratory-scale anaerobic batch reactor was designed and fabricated using a 20-liter plastic container (commonly used for water storage). The reactor was provided with proper inlet, outlet, and gas collection arrangements. Biogas production was measured daily using the water displacement method. The displaced volume of water was considered equal to the volume of biogas produced. The reactor was maintained at mesophilic temperature conditions (35°C) using a water bath. The components of the reactor are shown in Figure 1.

Fig 1. Batch Scale Reactor Components

Initially, biogas was collected using a balloon flatter arrangement to estimate gas accumulation. However, this method proved unreliable due to leakage and back pressure, leading to underestimation. To improve accuracy and ensure repeatable measurements, the water displacement method was adopted. This technique provides a direct volume-to-volume estimation, making it more suitable for small-scale batch experiments where gas pressure and composition may vary. The displaced water volume was recorded daily and considered equal to the biogas generated, as supported in earlier laboratory-scale studies [4], [6].

E. Experimental Set-Up

Figure 2 illustrates the experimental setup of the anaerobic batch reactor. Approximately 3 kg of fruit and vegetable waste was chopped into small fragments and loaded into the reactor. Then, 4 kg of cow dung was diluted with 10 liters of water and added as seed sludge. The total liquid level was adjusted to 12 liters, (25 cm diameter and 25 cm height) leaving an 8-liter headspace for gas accumulation.

The inlet and outlet were sealed airtight to prevent oxygen entry. A gas collection tube was attached to the top port and connected to a balloon flatter to measure biogas production. The flatter was weighed before and after gas collection to determine the net gas volume. The system was checked for air leakage before operation.

After setup, the reactor was left undisturbed for a week to initiate digestion. Thereafter, samples were collected from the inlet and outlet on Days 0, 14, 28, and 41 for testing. Air weight and biogas volume were also recorded periodically.

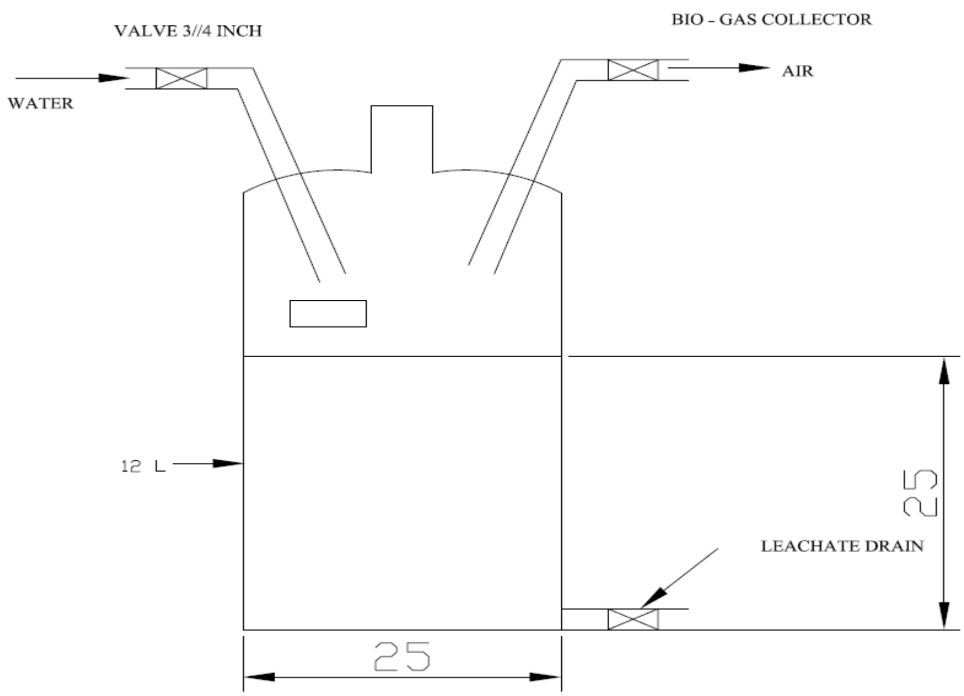

Fig 2. Experimental Setup of the Anaerobic Batch Reactor

III. RESULTS AND DISCUSSION

This section presents and discusses the key findings of the experimental study. Data related to reactor performance—including physicochemical changes, biogas yield, and solids behavior—are analyzed to evaluate the efficiency and stability of the digestion process.

A. Characterization of Seed Sludge

The seed sludge collected from the Biogas Plant of the Faculty of Agriculture, Annamalai University, was rich in organic matter and microbial biomass. It had total suspended solids (TSS) content of 70,100 mg/L and a volatile suspended solids (VSS) value of 28,000 mg/L, resulting in a VSS/TSS ratio of 0.4(Table 1). This ratio is widely recognized as an indicator of the biological activity in sludge and confirms the presence of a healthy microbial population capable of initiating anaerobic degradation [16]. This made it a suitable and cost-effective inoculum for biogas production.

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TABLE 1
CHARACTERISTICS OF SEED SLUDGE

TSS mg/L	VSS mg/L	TSS/VSS
70100	28000	0.4

B. Characterization of Fruit and Vegetable Waste

Table 2 presents the physicochemical characteristics of the reactor over 41 days. The pH values remained acidic, while alkalinity gradually increased—indicating the buffering capacity of the cow dung-based inoculum. COD values fluctuated based on the organic loading but decreased consistently in the effluent. TSS and VSS concentrations increased due to biomass growth. Biogas production began after 14 days, peaking on Day 41. These data collectively support the observation that fruit and vegetable waste has high biodegradability, consistent with studies on high-moisture substrates used for anaerobic digestion [17], [18].

TABLE 2
VARIATION OF PHYSICOCHEMICAL PARAMETERS, COD REMOVAL, AND BIOGAS PRODUCTION DURING ANAEROBIC DIGESTION AT DIFFERENT TIME INTERVALS

Parameter	Day 0 (Influent)	Day 0 (Effluent)	Day 14 (Influent)	Day 14 (Effluent)	Day 28 (Influent)	Day 28 (Effluent)	Day 41 (Influent)	Day 41 (Effluent)
pH	4.02	4.09	4.28	4.40	4.22	4.28	4.21	4.26
COD	4320	3880	9600	4000	9800	3800	11330	3400
COD Removal	—	10%	—	58%	—	61.2%	—	70%
Alkalinity	360	380	460	480	490	520	540	620
Biogas	—	—	—	13.90	—	17.11	—	19.13
TSS	23255	27400	31150	33100	36425	38800	41100	42300
VSS	8400	9500	9840	10570	9985	11680	11250	12540

Note: All values except pH and biogas are in mg/L. COD Removal (%) and Biogas production (mL/L) are reported only for effluent.

C. Effect on pH, COD Removal, and Biogas Production

To assess the overall reactor performance and microbial activity, critical indicators such as pH variation, chemical oxygen demand (COD) removal, and biogas generation were closely monitored. These parameters reflect the biochemical progression of anaerobic digestion and provide insight into the operational dynamics of the system.

1) pH Variation

The pH of the digester ranged from 4.02 to 4.26, remaining consistently acidic throughout the digestion cycle (Figure 3). This was due to the accumulation of volatile fatty acids (VFAs) during hydrolysis and acidogenesis, especially in the initial phase. Although ideal pH for methanogenesis ranges between 6.5 and 7.5, cow dung used as inoculum provided substantial buffering capacity that prevented further acidification [16], [19]. Notably, several studies have reported that methanogenic bacteria can remain active under slightly acidic conditions, particularly in batch systems with high-strength organic loads [18], [20]. The marginal rise in pH over time indicates a transition from acidogenesis to methanogenesis, supported by the consumption of VFAs by methanogens [21]. This microbial adaptation has also been observed in reactors treating market and food waste with similar acidic profiles [10].

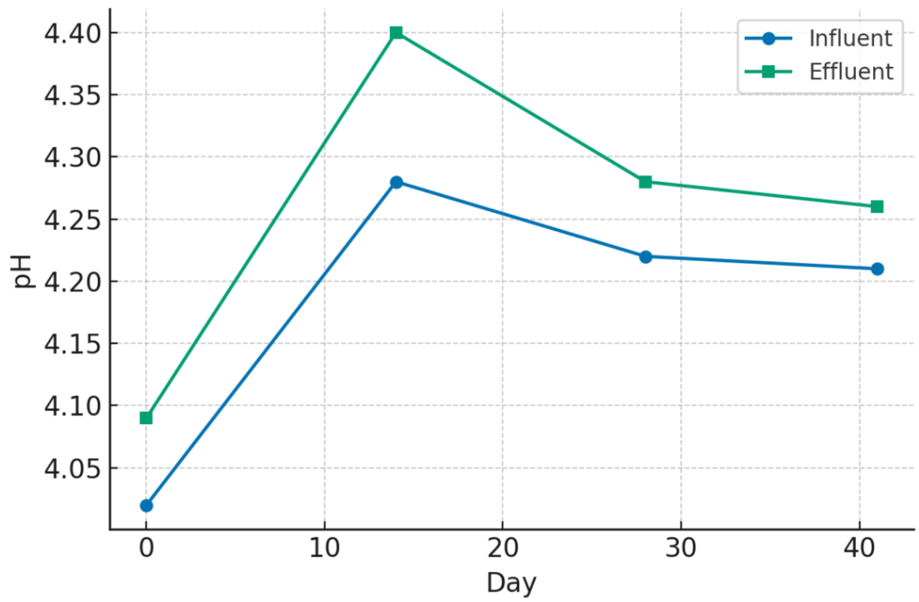

Fig 3 pH Variation During Digestion Cycle

2) COD Removal Efficiency

As shown in Figure 4, COD removal increased progressively from 10% on Day 0 to 70% by Day 41. This indicates effective microbial degradation of soluble organic compounds present in the feedstock. The initially low removal efficiency was likely due to the accumulation of intermediate acids, which temporarily inhibited methanogens. However, as the microbial consortia acclimatized, COD removal improved sharply, reflecting efficient conversion of carbohydrates and proteins into methane and carbon dioxide [17], [18]. Similar removal patterns have been reported for batch digesters treating fruit and vegetable wastes, where peak performance was achieved beyond the third week [20], [21]. The relatively high COD values also validate the need for long retention times, typical of batch anaerobic systems [5].

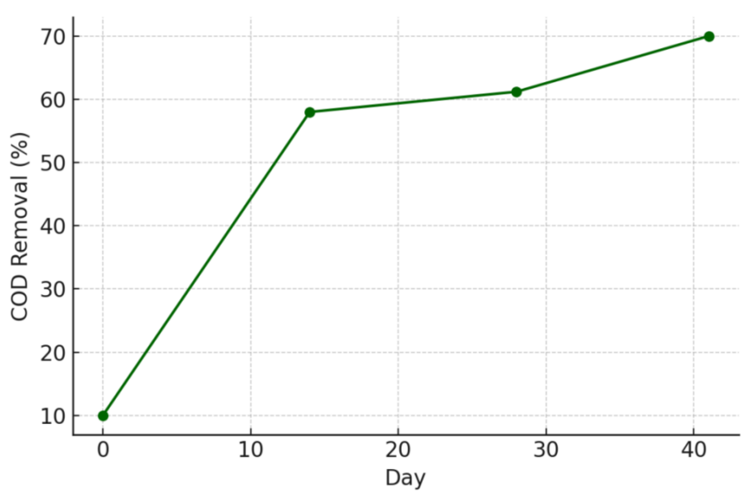

Fig 4 COD Removal (%) vs. Time

3) Biogas Generation

Biogas production was initiated after 14 days and increased gradually, reaching 19.13 mL/L by Day 41. The close alignment between COD removal and biogas yield (Figure 5) confirms the successful methanogenic activity in the reactor. The fruit and vegetable waste substrate, rich in simple sugars and cellulose, provided a highly fermentable organic base for biogas production. This is consistent with earlier findings on organic waste digestion that emphasize the high biogas potential of substrates with moisture content >80% [10], [21].

The low initial yield was due to acid accumulation and microbial lag, while the increasing trend reflects microbial stabilization and active methanogenesis [19]. Notably, the biogas volume observed in this study is comparable to values reported in reactors with similar feedstock under mesophilic conditions [4], [6].

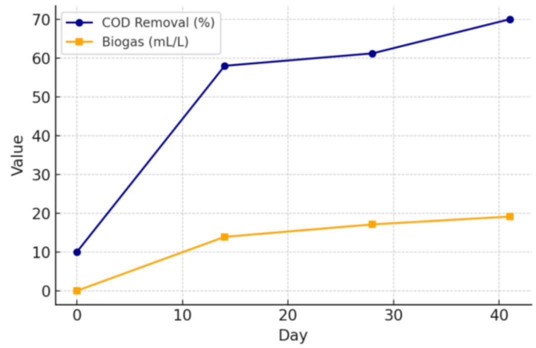

Fig 5 COD Removal and Biogas Yield vs. Time

4) TSS, VSS Trends and Need for Post-Treatment

As shown in Figure 6, both total suspended solids (TSS) and volatile suspended solids (VSS) increased steadily from Day 0 to Day 41. TSS values ranged from 23,255 mg/L to 42,300 mg/L, while VSS rose from 8,400 mg/L to 12,540 mg/L. These concentrations are typical for solid-rich substrates like undiluted fruit and vegetable waste, which contribute high particulate and organic matter loads to batch digesters. The observed increase can be attributed to biomass growth, floc formation, and accumulation of undigested fibrous solids over time. The continued increase reflects microbial activity and undigested solids accumulation [22].

The VSS/TSS ratio remained around 0.4, indicating a stable microbial population and effective substrate-to-biomass conversion. High TSS in effluent may also include undigested solids and microbial residues, reinforcing the need for post-treatment. Similar high solids loading has been observed in studies dealing with market waste digestion, where coarser fibrous content contributes to TSS elevation [11], [20]. This further supports the integration of Dissolved Air Flotation (DAF) or filtration-based systems in downstream treatment [23].

Similar findings have been reported in digesters treating market and organic waste. Tapia-Tussell et al. [4] recorded TSS levels exceeding 37,000 mg/L and VSS above 15,000 mg/L in fruit waste slurry digestion. Jankowski et al. [11] documented high solids concentrations (>40,000 mg/L) during anaerobic digestion of fruit and vegetable waste mixtures. Additionally, Tambone et al. [7] emphasized that reactors fed with municipal solid waste or vegetable residues commonly exhibit elevated TSS and VSS due to the heterogeneous nature of the substrates and microbial growth.

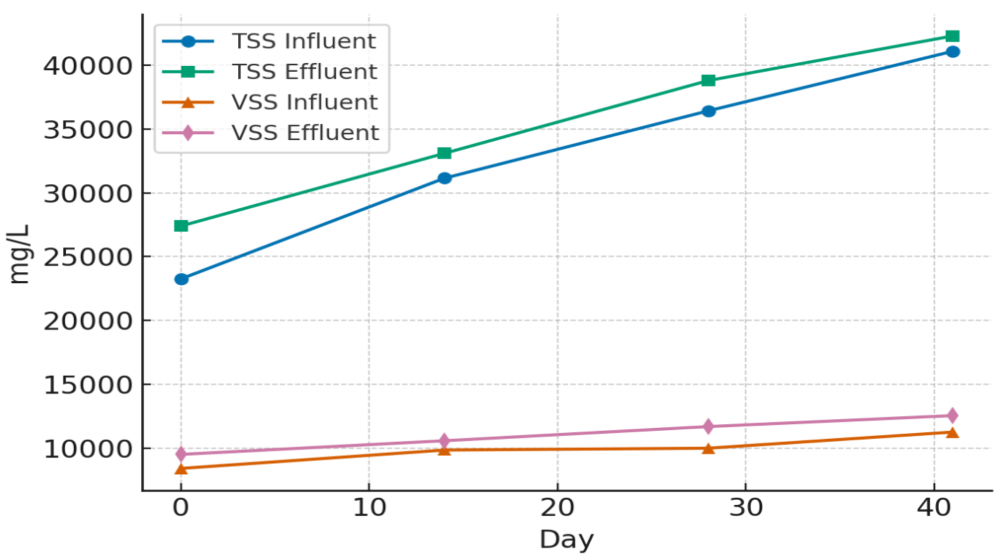

Fig 6 TSS and VSS Concentrations Over Time

Despite achieving a 70% reduction in chemical oxygen demand (COD) and noticeable biogas production, the final effluent characteristics from the anaerobic reactor—COD: 3400 mg/L and total suspended solids (TSS): 42300 mg/L exceeds the permissible limits set by the Central Pollution Control Board (CPCB), India, which are 250 mg/L for COD and 100 mg/L for TSS for discharge into inland surface waters [24].Therefore, anaerobic treatment alone is not sufficient for regulatory compliance. This hybrid approach—anaerobic digestion followed by advanced aerobic bioreactors and DAF systems—represents the current best practice for treating high-strength organic wastewaters such as fruit and vegetable waste leachates.[25],[26].

IV. CONCLUSION

This study confirms that anaerobic digestion is a feasible method for converting fruit and vegetable market waste into biogas using a low-cost batch reactor system. Over a 41-day digestion period, the system achieved a maximum COD removal efficiency of 70% and biogas yield of 19.13 mL/L. Parameters such as TSS, VSS, and pH remained within biologically functional ranges, despite the acidic environment. However, effluent COD and TSS exceeded CPCB standards, indicating the need for secondary aerobic treatment. Advanced technologies like MBR, SBR, and MBR—along with Dissolved Air Flotation (DAF)—are recommended to meet discharge norms.

Due to the course timeline, the reactor was terminated at the end of its initial operational period (42 days), representing the start-up phase. Future research should extend the operation to evaluate steady-state performance, optimize loading rates, and examine long-term gas production trends.

The use of AI-enhanced monitoring systems is strongly encouraged to enable real-time process control, predictive analytics, and operational optimization in small-scale biogas systems for decentralized waste-to-energy applications.

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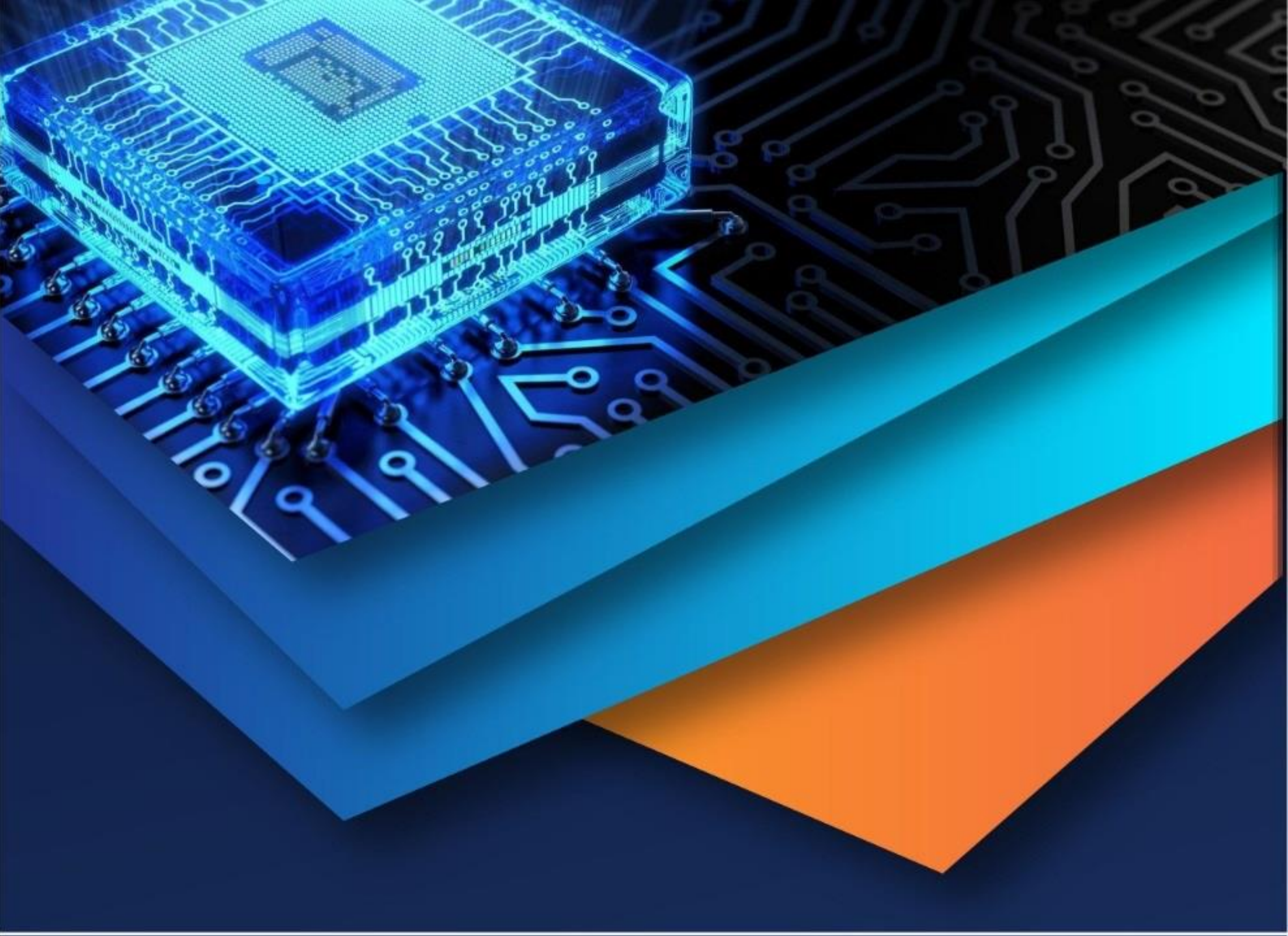

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