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Effect of Green Inhibitors on the Corrosion Rate of Mild Steel and Stainless Steel 304

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Abstract: Corrosion is an inevitable process that affects metals in everyday life, requiring constant efforts to manage due to its technical, economic, and aesthetic significance. It refers to the degradation of metal surfaces caused by reactions with environmental elements. The damage caused by corrosion can be severe, leading to structural failure of metal components, increased repair and replacement costs, product losses, and even safety hazards, as well as environmental pollution.

One effective method of mitigating corrosion is the use of inhibitors. These are chemical agents added in small amounts to reduce the corrosion rate. With growing awareness of environmental and health concerns, the focus has shifted towards developing eco-friendly, non-toxic corrosion inhibitors derived from natural sources.

In this study, the inhibition of corrosion on mild steel and stainless steel in corrosive environments such as hydrochloric acid was explored using green inhibitors. These inhibitors were extracted from natural sources like Cinnamomum verum (cinnamon) and Aloe barbadensis (aloe vera) in the form of oils and gel. The study was conducted at room temperature using the weight loss measurement technique to assess the effectiveness of these inhibitors.

Keywords: Corrosion control, green inhibitors, corrosion rate, inhibitor efficiency, eco-friendly inhibitors.

I. INTRODUCTION

Corrosion is a widespread and inevitable process that occurs when metals deteriorate due to chemical reactions with their environment. This natural phenomenon is a significant issue, especially in industries where metal structures are commonly used, as it leads to severe economic and safety-related consequences. The degradation of metals due to corrosion can cause structural failures, leading to costly repairs, replacements, and, in some cases, catastrophic events.

Traditionally, various methods have been employed to prevent or reduce corrosion, including protective coatings, cathodic protection, and the use of corrosion inhibitors. Among these methods, corrosion inhibitors are one of the most effective and widely used solutions. They are chemical compounds that, when added in small concentrations, significantly reduce the corrosion rate. However, many conventional inhibitors are often toxic, environmentally harmful, and hazardous to human health.

As a result, the search for green, eco-friendly corrosion inhibitors has gained momentum. Green inhibitors, derived from natural substances, are biodegradable, non-toxic, and renewable. Extracts from plants like **Cinnamomum verum** (cinnamon) and **Aloe barbadensis** (aloe vera) have shown promise as corrosion inhibitors due to their organic constituents, such as alkaloids, flavonoids, and phenolic compounds, which can effectively adsorb onto metal surfaces, forming a protective layer.

This study focuses on the use of cinnamon and aloe vera extracts as green inhibitors to reduce the corrosion rate of mild steel and stainless steel in hydrochloric acid. By investigating the effectiveness of these natural inhibitors, the study aims to contribute to the development of sustainable and environmentally friendly solutions for corrosion prevention in industrial applications.

II. LITERATURE REVIEW

Corrosion is a pervasive problem in numerous industries, particularly in sectors reliant on metals and alloys for manufacturing and infrastructure. The degradation of metals through chemical and electrochemical reactions with environmental elements causes significant damage, resulting in high maintenance costs, safety concerns, and environmental pollution. Therefore, researchers and engineers continuously seek effective methods for corrosion prevention. Among the various approaches, the use of corrosion inhibitors has emerged as one of the most cost-effective and efficient solutions. However, the toxicity and environmental hazards of synthetic inhibitors have led to a growing interest in green inhibitors, which are biodegradable, renewable, and environmentally friendly.

A. Corrosion Inhibition and the Role of Green Inhibitors

Corrosion inhibitors are substances added in small concentrations to mitigate or prevent the corrosion of metals exposed to aggressive environments. According to Gopiraman (2023), inhibitors act by adsorbing onto the metal surface, creating a protective barrier that blocks corrosive agents from interacting with the metal. Green inhibitors, a subset of corrosion inhibitors, are derived from natural products, primarily plant extracts, and have gained attention due to their eco-friendly properties.

The concept of green inhibitors aligns with the principles of sustainable development, as these inhibitors are typically non-toxic, biodegradable, and sourced from renewable materials. Gopiraman explains that plant extracts, in particular, are attractive as green inhibitors because they contain a variety of organic compounds such as alkaloids, tannins, flavonoids, and polyphenols. These compounds are capable of adsorbing onto metal surfaces, forming a film that protects against corrosion. Green inhibitors are broadly classified into two categories: organic green inhibitors and inorganic green inhibitors. Organic inhibitors typically consist of plant-derived materials, while inorganic inhibitors may include elements like phosphates or silicates.

B. Adsorption Mechanisms of Green Inhibitors

Green inhibitors function primarily through adsorption mechanisms, which involve the adherence of inhibitor molecules onto the metal surface, preventing corrosive substances from making direct contact with the metal. The type of adsorption, whether physical or chemical, depends on several factors, including the nature of the metal, the corrosive medium, and the chemical structure of the inhibitor.

At room temperature, most green inhibitors adsorb onto metal surfaces via physical adsorption (physisorption), which involves electrostatic interactions between the inhibitor molecules and the metal surface. However, as temperature increases, chemisorption becomes the dominant mechanism. Chemisorption involves the formation of chemical bonds between the inhibitor and the metal, resulting in a more permanent protective layer. Gopiraman (2023) highlights that the effectiveness of green inhibitors can fluctuate over time, especially during prolonged exposure to corrosive environments. The ability of an inhibitor to maintain its protective qualities over an extended period is crucial for its practical application. In most cases, the efficiency of the inhibitor decreases with time as the protective film begins to degrade, especially in cases where physisorption is the primary mechanism of action.

C. Cinnamon Oil as a Green Corrosion Inhibitor

Numerous studies have investigated the potential of plant extracts as corrosion inhibitors. Bouraoui et al. (2023) explored the efficacy of cinnamon oil as a green inhibitor for stainless steel (SS304L) in hydrochloric acid (HCl) solutions. The authors conducted electrochemical and surface analysis to assess the corrosion inhibition efficiency of cinnamon oil. Their results indicated that the addition of 1% cinnamon oil led to a corrosion efficiency of 84% in 1.0 M HCl solution. Moreover, in a less aggressive medium (0.1 M HCl), the inhibition efficiency ranged from 86.6% to 96.0%, depending on the concentration of cinnamon oil.

The protective mechanism of cinnamon oil is attributed to its high content of essential oils, particularly cinnamaldehyde and eugenol, which are known to adsorb onto the metal surface. Scanning electron microscopy (SEM) confirmed the formation of a protective film on the stainless-steel surface, suggesting that cinnamon oil effectively blocks the active corrosion sites. This study demonstrates that cinnamon oil has considerable potential as a green inhibitor, particularly in acidic environments where metal dissolution is a concern. However, it also emphasizes the need for further investigation into the long-term stability and adsorption mechanisms of plant-based inhibitors in different corrosive media.

D. Aloe Vera Gel as a Corrosion Inhibitor

Harish Kumar et al. (2022) examined the anti-corrosion properties of Aloe vera leaf gel for mild steel in 5.0 M HCl using various techniques, including weight loss measurements and electrochemical impedance spectroscopy (EIS). Aloe vera, a plant known for its medicinal properties, contains a rich mixture of organic molecules such as polysaccharides, amino acids, and enzymes, which contribute to its effectiveness as a corrosion inhibitor.

The study found that the corrosion inhibition efficiency of Aloe vera increased with the concentration of the gel. At a concentration of 4 g/L, Aloe vera exhibited a 97% corrosion inhibition efficiency in 5 M HCl solution, making it a highly effective inhibitor for mild steel in acidic environments. The activation parameters obtained from electrochemical experiments indicated that Aloe vera adsorbs onto the metal surface via both physisorption and chemisorption, forming a stable protective layer that prevents metal dissolution. SEM analysis confirmed the formation of a protective film on the mild steel surface, consistent with the high inhibition efficiency observed.

E. The Role of Plant Extracts in Corrosion Inhibition

Rani and Basu (2023) emphasize the importance of plant extracts in corrosion inhibition, particularly in light of environmental concerns associated with synthetic inhibitors. Plant-based inhibitors are biodegradable, non-toxic, and readily available, making them an attractive alternative to conventional corrosion control methods. The use of plant extracts as corrosion inhibitors has been studied extensively, with researchers focusing on the role of various organic compounds such as tannins, alkaloids, and flavonoids in corrosion protection.

Plant extracts function as mixed-type inhibitors, meaning they can simultaneously reduce both anodic and cathodic reactions during the corrosion process. This dual functionality is attributed to the presence of multiple active compounds in plant extracts, which can adsorb onto the metal surface and block both oxidation and reduction sites. Furthermore, the presence of heteroatoms such as nitrogen, oxygen, and sulfur in plant-derived compounds enhances their ability to interact with metal surfaces, promoting strong adsorption and effective inhibition.

Despite the promising results obtained from studies on plant-based inhibitors, Rani and Basu (2023) highlight the need for further research to fully understand the adsorption mechanisms and the active components responsible for corrosion inhibition. The development of computational models, combined with experimental data, could provide valuable insights into the molecular interactions between plant-based inhibitors and metal surfaces, facilitating the design of more efficient and sustainable corrosion inhibitors.

F. Challenges and Future Directions in Green Corrosion Inhibitor Research

While green inhibitors have shown considerable promise, several challenges remain in their development and application. One of the primary challenges is the variability in the chemical composition of plant extracts, which can lead to inconsistent results in corrosion inhibition studies. The concentration of active compounds in plant extracts can vary depending on factors such as the plant species, geographical location, and extraction method used. This variability makes it difficult to standardize green inhibitors for industrial applications.

Another challenge is the need for long-term studies to assess the stability and durability of green inhibitors in harsh environments. While many plant extracts have demonstrated high inhibition efficiencies in laboratory settings, their performance in real-world conditions, such as fluctuating temperatures, varying pH levels, and prolonged exposure to corrosive agents, remains largely unexplored.

Additionally, the adsorption mechanisms of plant-based inhibitors are not fully understood, particularly with regard to the interactions between different compounds within the extract and their collective effect on metal surfaces.

Future research should focus on addressing these challenges by developing standardized extraction methods for plant-based inhibitors and conducting long-term studies in diverse environments. Computational modeling could also play a crucial role in identifying the most effective plant compounds for corrosion inhibition and optimizing their molecular structures for enhanced performance. Furthermore, the integration of plant-based inhibitors with other corrosion control methods, such as coatings and cathodic protection, could lead to more comprehensive and sustainable corrosion prevention strategies.

III. MATERIALS AND METHODS

A. Materials Required

- Mild steel and stainless steel 304 samples
- Inhibitors: Cinnamomum verum (cinnamon oil), Aloe barbadensis miller gel
- Corrosive medium: 1.5M Hydrochloric Acid (HCl)
- Distilled water
- Beakers
- Weighing scale

1) Metal Preparation

Mild steel samples with dimensions of 28×18×20 mm (5 samples) and stainless steel 304 samples measuring 23×29×10 mm (5 samples) were selected. These samples were initially ground using a belt grinder, followed by polishing with emery papers graded 1/0, 2/0, 3/0, and 4/0 before corrosion testing.

2) Preparation of Aloe barbadensis miller Gel

Fresh Aloe barbadensis miller leaves were harvested, cleaned with double-distilled water, and peeled to extract the inner gel. The gel was blended using a grinder, with the addition of warm double-distilled water to form a consistent paste. This mixture was then used at varying concentrations in 1.5M HCl.

3) Preparation of Aloe barbadensis miller Solutions

Four different concentrations of Aloe vera gel were prepared in a series of volumetric flasks, with inhibitor concentrations of 0ml/60ml, 1ml/60ml, 5ml/60ml, 10ml/60ml, and 15ml/60ml in a 1.5M HCl solution.

Inhibitor (ml)	Solution (HCl + distilled water) (ml)
0	60
1	60
5	60
10	60
15	60

4) Preparation of Cinnamon Oil Solutions

Similarly, varying concentrations of cinnamon oil (0ml/60ml, 1ml/60ml, 5ml/60ml, 10ml/60ml, and 15ml/60ml) were prepared in four different volumetric flasks, using the same solution mixture.

Inhibitor (ml)	Solution (HCl + distilled water) (ml)
0	60
1	60
5	60
10	60
15	60

B. Method

The corrosion study was conducted using the weight-loss method, where the weight changes in the metal samples immersed in the corrosive medium were measured over time. This technique involves comparing the weight loss of mild steel and stainless steel 304 samples before and after exposure to the corrosive solution.

1) Procedure for Mild Steel Inhibition

Five pre-weighed mild steel samples were immersed in 100 ml beakers containing 60 ml of 1.5M HCl solution with different concentrations of Aloe vera gel (0ml, 1ml, 5ml, 10ml, 15ml). Each beaker held one mild steel sample suspended with the help of glass hooks. The samples were exposed for 7 days, after which they were removed, dried, and reweighed. The same procedure was repeated for stainless steel 304 samples, but using cinnamon oil as the inhibitor. The weight loss of each sample was recorded, and inhibition efficiency was calculated using the following formula:

Inhibitor efficiency (%) = (CRO−CR)/CRO(CRO - CR) / CRO(CRO−CR)/CRO * 100

Where:

CRO = Corrosion rate without inhibitor

CR = Corrosion rate with inhibitor

2) Metallography

- Samples were ground using a belt grinder, followed by polishing with emery papers graded 1/0, 2/0, 3/0, and 4/0 to prepare them for microstructural analysis.
- The polishing step ensures a flat, scratch-free surface with a mirror-like finish.
- After polishing, the samples were etched using specific etching agents: Nital (1-5 ml HNO_3 + 100 ml alcohol) for mild steel and Ferric Chloride solution (5g $FeCl_3$ + 50 ml HCl + 100 ml water) for stainless steel.
- The etching process generates contrast between microstructural features on the surface, allowing for better examination under a microscope.

3) Hardness Testing

- Place the lever in position "A" for the unloading phase.
- For stainless steel, use a diamond indenter with a 120° apex angle, while for mild steel, use a 10 mm ball indenter.
- Position the sample on the anvil and turn the handwheel until contact is made with the indenter, continuing until the small pointer reaches "4" (automatic zero setting).
- Apply a minor load of 10 kg to the sample to fix its position.
- Shift the lever from position "A" to "B," transitioning from unloading to loading, applying the full load of 150 kg for 15 seconds.
- Once the pointer stabilizes, return the lever to position "A" and record the hardness reading.
- Repeat these steps for both mild steel and stainless steel samples.

IV. RESULTS AND DISCUSSION

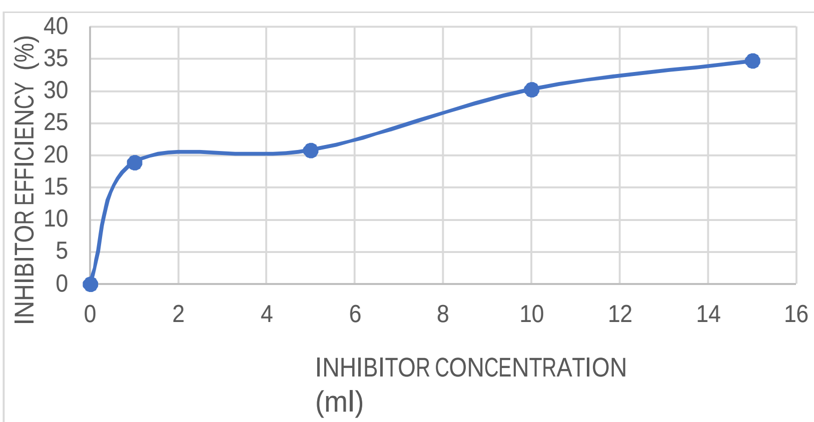
The inhibitory effect of Aloe barbadensis miller extract on the corrosion of mild steel in a hydrochloric acid solution is presented below:

- Density of Mild Steel: 7.85 g/cm³
- Cross-sectional Area: 0.7665 in²
- Time: 168 hours

Sample No.	Inhibitor Concentration (ml)	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Inhibitor Efficiency (%)
1	0	86.02	82.85	3.17	1674.59	--
2	1	87.61	85.04	2.57	1357.63	18.92
3	5	88.65	86.14	2.51	1325.94	20.82
4	10	85.30	83.09	2.21	1167.46	30.28
5	15	87.50	85.43	2.07	1093.50	34.70

Table 1: Corrosion rate, weight loss, and inhibitor efficiency for mild steel in 1.5 M HCl solution.

SCALE
X - AXISIS 1UNIT = 2 ml
Y – AXISIS 1 UNIT = 5 %



The graph below (Fig. 1) illustrates that the inhibitor efficiency increases as the concentration of Aloe vera gel increases, effectively reducing the corrosion rate of mild steel in 1.5 M HCl.

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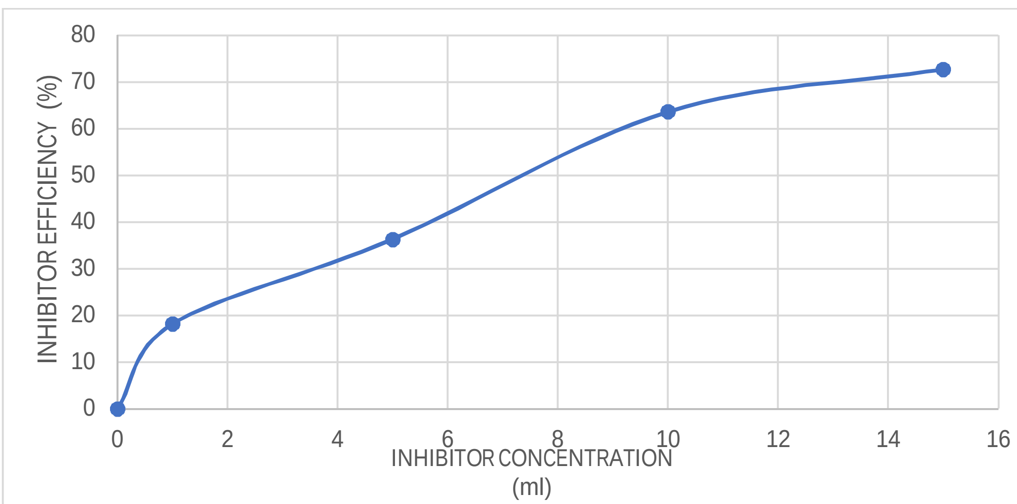
For the effect of cinnamon oil on the corrosion of stainless steel 304 in hydrochloric acid:

- Density of Stainless Steel 304: 7.93 g/cm³
- Cross-sectional Area: 1.0145 in²
- Time: 168 hours

Sample No.	Inhibitor Concentration (ml)	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Corrosion Rate (mpy)	Inhibitor Efficiency (%)
1	0	55.62	55.51	0.11	43.46	--
2	1	56.95	56.86	0.09	35.55	18.20
3	5	58.01	57.94	0.07	27.65	36.37
4	10	55.90	55.86	0.04	15.80	63.64
5	15	55.83	55.80	0.03	11.85	72.73

Table 2: Corrosion rate, weight loss, and inhibitor efficiency for stainless steel 304 in 1.5 M HCl solution.

SCALE
X - AXISIS 1UNIT = 2 ml
Y – AXISIS 1 UNIT = 10 %



The graph (Fig. 2) demonstrates a significant increase in inhibitor efficiency as the concentration of cinnamon oil increases, reducing the corrosion rate of stainless steel 304 in the corrosive medium.

A. Microstructures

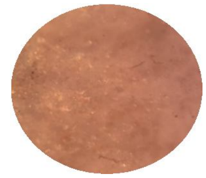
Before Corrosion

- The grain boundaries of both mild steel and stainless steel are clean and well-defined.
- Crystallographic mismatches between adjacent grains are noticeable.

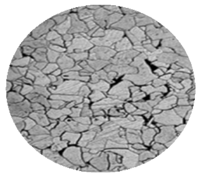
After Corrosion:

- The grain boundaries become more pronounced, showing signs of preferential corrosion.
- Corrosion products tend to accumulate along the boundaries, creating a rougher, more irregular surface.
- Voids or cavities may form along the grain boundaries due to material degradation.

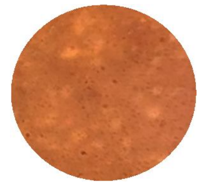
Before corrosion of stainless steel,100X



After corrosion of stainless steel,100X



Before corrosion of mild steel,100X



After corrosion of mild steel, 100X

Fig. 3: Microstructural images before and after corrosion of mild steel and stainless steel at 100X magnification.

B. Rockwell Hardness Test

The hardness results before and after corrosion are shown below:

S. No.	Material	Before (HRC)	0 ml (HRC)	1 ml (HRC)	5 ml (HRC)	10 ml (HRC)	15 ml (HRC)
1	Stainless Steel	33.8	31.8	32.0	32.5	33.0	33.6
2	Mild Steel	27.0	19.0	20.6	22.1	23.5	23.7

Table 4: Rockwell hardness values for stainless steel 304 and mild steel before and after corrosion.

The hardness values indicate that both mild steel and stainless steel experienced a reduction in hardness after corrosion, with higher concentrations of inhibitors showing some resistance to hardness loss.

V. DISCUSSION

The results demonstrated that Aloe barbadensis miller and cinnamon oil are effective green inhibitors for mild steel and stainless steel, respectively, in 1.5M HCl. Aloe vera showed a steady increase in inhibition efficiency, reaching 34.70% at 15 ml concentration, while cinnamon oil achieved up to 72.73% efficiency. Both inhibitors reduced the corrosion rates by forming protective layers on the metal surfaces. Microstructural analysis revealed grain boundary degradation due to corrosion, which was mitigated by the inhibitors. Hardness testing also showed less reduction in hardness when inhibitors were present, indicating their role in maintaining material integrity during corrosion.

VI. CONCLUSION

1) This study aimed to evaluate the effectiveness of Aloe barbadensis miller and cinnamon oil as environmentally friendly corrosion inhibitors.
2) The results confirmed that both compounds successfully reduced the corrosion of stainless steel and mild steel in 1.5 M HCl solutions, with their inhibition efficiency increasing alongside concentration and immersion time.
3) Aloe barbadensis miller proved to be a highly effective inhibitor for mild steel in acidic environments, offering a potential alternative to conventional inhibitors containing harmful chemicals.
4) Aloe vera gel functioned as a mixed-type inhibitor, protecting the metal surface from both anodic and cathodic reactions.
5) Corrosion resulted in rough and irregular grain boundaries, resembling intergranular corrosion, which could weaken the material over time.
6) The hardness of the materials decreased after corrosion, but the presence of inhibitors significantly slowed this reduction, helping maintain the mechanical properties of the metals.

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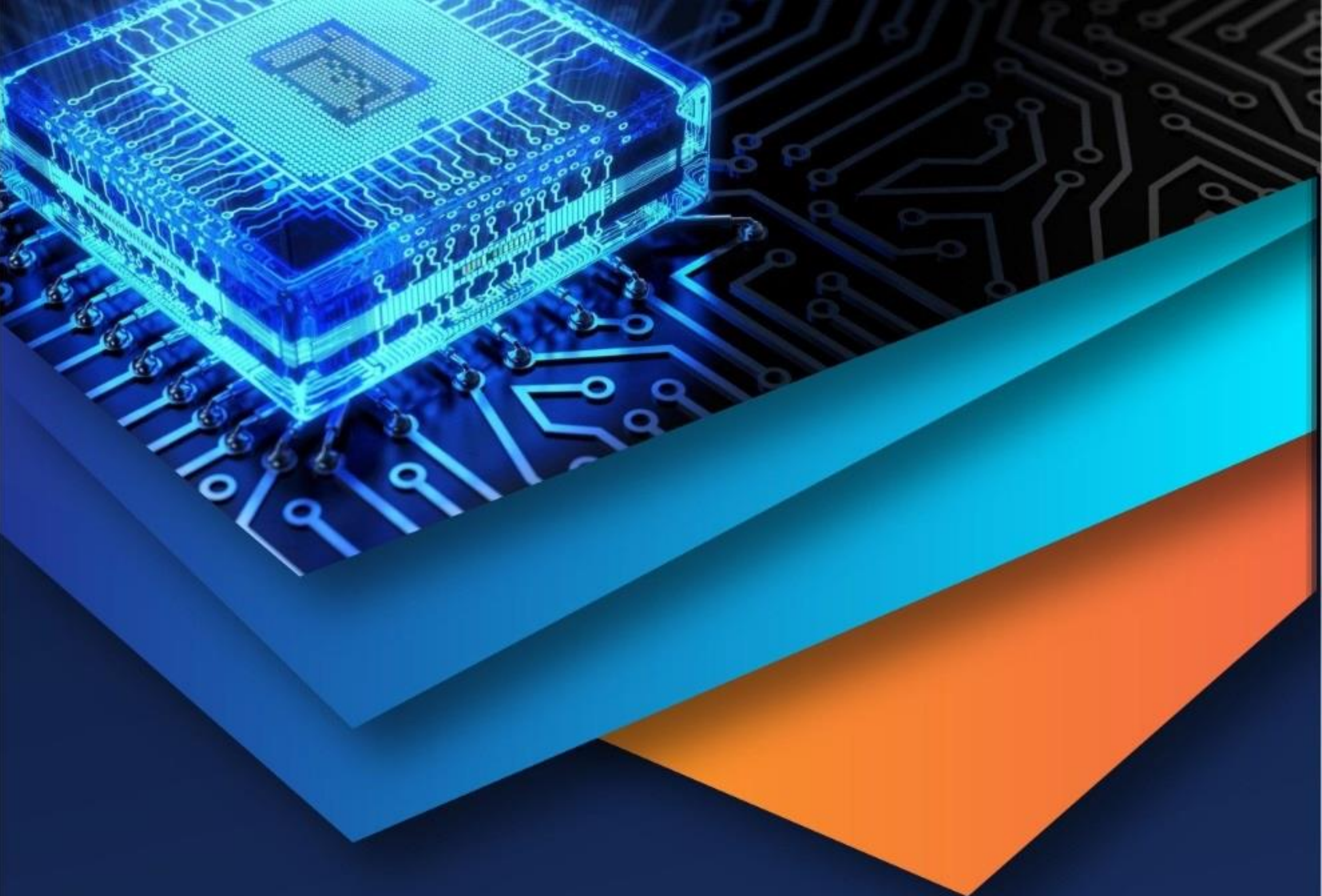

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