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Review on Biomining Strategies for Legacy Waste Remediation and Resource Recovery

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***Abstract:** In many developing countries, open dumping remains the primary method for disposing of municipal solid waste (MSW). However, this practice causes significant environmental problems. Leachate from these dumpsites pollutes surface water, while heavy metals from the waste contaminate groundwater over time. Additionally, the release of gases such as CO_2, CH_4, and other toxic emissions contributes to air pollution and exacerbates climate change. These dumpsites not only harm the environment but also become unsightly, emphasizing the urgent need for sustainable and eco-friendly waste disposal methods. Bio-mining offers a practical and effective solution for reclaiming large dumpsites. This process involves extracting, recycling, and reusing various materials from waste dumps in an organized manner, promoting resource recovery and economic benefits. Bio-mining is an innovative, cost-effective, fast, and environmentally sustainable method that remediates old dumpsites, eliminates landfill gases and leachate emissions, and restores land for reuse with minimal maintenance. A combined approach enhances this process, beginning with the stabilization of waste through bioreactor landfill treatment, followed by bio-mining techniques. A conceptual framework for implementing bio-mining at the MSW dumpsite has been developed. Additionally, a comprehensive plan for the future management of open dumpsites has been formulated, focusing on long-term sustainability and environmental protection.*
***Keywords:** Biomining, dumpsites, segregation, landfilling, trommel, bio-culture, RDF, Incineration, WTE, Bioreactor, Biotechnology.*

I. INTRODUCTION

Globally, landfilling remains the most common method for waste disposal, but it has significant environmental consequences. It leads to long-term methane emissions, a potent greenhouse gas contributing to global warming, and the leaching of hazardous substances through leachate, which contaminates vegetation and groundwater. Furthermore, frequent fires at dumpsites, often triggered by methane auto-ignition, degrade air quality by releasing smoke and harmful emissions, causing severe air pollution (CPHEEO, 2020). Methane emissions from old dumpsites account for approximately 3-4% of the annual global anthropogenic greenhouse gas emissions (IPCC, 2001). This approach to waste disposal is inherently unsustainable, as valuable natural resources within the waste, including materials and energy, are left untapped and squandered. Decades-old legacy waste deposits hold untapped potential as valuable resources. However, the limited availability of space for landfill operations presents a significant challenge, particularly in densely populated areas. The rapid growth in municipal solid waste (MSW) generation has transformed these landfills into towering piles of legacy waste. Managing the steady influx of daily solid waste while addressing neglected legacy waste, which has accumulated into massive heaps at open dumpsites originally intended for sorting, processing, and landfilling, are two of the primary challenges faced by urban solid waste management in Indian cities and towns [1].

India generates a total of 160,038.9 tonnes per day (TPD) of solid waste, out of which 152,749.5 TPD is collected, achieving a collection efficiency of 95.4%. Of the collected waste, 79,956.3 TPD (50%) is treated, while 29,427.2 TPD (18.4%) is disposed of in landfills. However, 50,655.4 TPD, accounting for 31.7% of the total waste, remains unaccounted for. According to the Central Pollution Control Board (CPCB, 2020), the country has 3,184 dumpsites, as reported by State Pollution Control Boards (SPCBs) and Pollution Control Committees (PCCs). Of these, 234 have been reclaimed, and eight have been converted into landfills. Uttar Pradesh has the highest number of dumpsites (609), followed by Madhya Pradesh (326) and Maharashtra (237) [2]. The Swachh Bharat Mission emphasizes reclaiming landfill sites and reducing their environmental impact, aligning with the Solid Waste Management (SWM) Rules, 2016, and guidelines from the Hon'ble National Green Tribunal (NGT). A key objective is to recover an estimated 10,000 hectares of urban land currently occupied by dumpsites (CPCB, 2019). Urban India faces significant challenges in developing integrated solid waste management infrastructure, which requires vast land resources for landfilling. Land reclamation offers a potential solution, enabling a scientific approach to managing municipal solid waste (MSW).

Recently, the Hon'ble NGT directed the creation of Standard Operating Procedures (SOPs) for implementing bio-mining and bio-remediation of legacy waste across Indian landfills. The current global scenario, characterized by intense competition for resources, rising raw material costs, depleting natural reserves of valuable resources, and escalating environmental issues, highlights the need for alternative resource extraction methods. One such viable approach is bio-mining, which focuses on recovering valuable materials and energy from waste. Bio-mining involves the excavation, stabilization, screening, and segregation of landfill materials into various components, including soil (referred to as bio earth or good earth), recyclables, combustibles, inert materials, and residual waste. This sustainable method not only extends the lifespan of landfills but also mitigates contamination from unlined open dumps, offering a practical solution for resource recovery and environmental remediation [1].

A. What is Legacy Waste?

Legacy Waste refers to municipal solid waste (MSW) that has been accumulated and stored for years on barren land or in landfills. These long-standing waste deposits often form massive heaps, commonly seen as large mountains of waste on the outskirts of cities

B. Legacy Waste Hazards

Modern cities inevitably rely on trenching grounds where vast amounts of municipal solid waste have been dumped over the years. These sites often become aesthetic and environmental liabilities, posing significant challenges to city councils that struggle with their upkeep and associated administrative costs. Dumped waste emits foul odors, releases toxic smoke, and contaminates groundwater. During summer, metro cities like Delhi and Mumbai frequently face fire hazards on these sites. Legacy waste also serves as a breeding ground for pathogens and flies, generates unpleasant odors, and produces leachate that can contaminate water sources. Additionally, it contributes to greenhouse gas emissions and increases the risk of severe fires.

C. Biomining of Legacy Waste

According to the Central Pollution Control Board (CPCB) guidelines, biomining is the scientific process of excavating, treating, segregating, and repurposing aged municipal solid waste, also known as legacy waste. This eco-friendly technique separates soil, recyclables such as plastic, metal, paper, textiles, construction and demolition (C&D) waste, and other solid materials from legacy waste. Biomining offers a sustainable solution to complex environmental challenges, employing environmentally sound methods for sorting and segregating materials for reuse, recycling, or filling low-lying areas.

II. LITERATURE REVIEW

1) Ghosh Nabanita et al. [3] reported that urban India generated approximately 62 million tonnes (MT) of municipal solid waste (MSW) in 2015, averaging 450 grams per capita per day. Out of this, about 82% was collected, but only 28% of the collected waste was treated, while the remaining 72% was disposed of through open dumping. Open dumping remains a common practice in India due to budgetary limitations and a lack of technological advancements. These open dumpsites pose significant environmental and public health risks, as they lead to land and water contamination through leachate migration and contribute to air pollution due to the release of landfill gases (LFGs) that contain high levels of greenhouse gases, exacerbating climate change. Additionally, open dumps consume valuable land that could be repurposed for revenue-generating uses. In 2011, India required 380 km^2 for waste disposal, a figure projected to rise to 660 km^2 by 2030. To address these challenges, the Indian government amended the Solid Waste Management (SWM) Rules in 2016 to promote more effective management of MSW and the reclamation of large, old dumpsites through closure and rehabilitation strategies, recommending biomining as a practical waste reduction solution. The biomining approach is innovative, environmentally friendly, economically viable, and a quick method for rehabilitating old landfill sites. It helps achieve zero emissions of LFGs and leachate and restores land usability with minimal maintenance. This study discusses the application and benefits of biomining as a crucial element in sustainable landfill management, focusing on the rehabilitation of MSW dumpsites in major Indian Megacities.
2) Arghya Ghosh et al. [4] proposed landfill biomining (LFBM) as an effective method for reclaiming legacy waste dumpsites and recovering valuable resources and land. However, the potential of LFBM (land fill biomining) is challenged by the composition, characteristics, and end-use of the excavated materials. This study analyzed the composition of excavated waste from LFBM operations at four legacy waste heaps at the Boragaon dumpsite in North-East India and evaluated the physicochemical properties important for material and energy recovery from key reclaimed fractions. The analysis showed that the proportion of combustible and non-combustible fractions declined from the youngest heap (HP4) to the oldest (HP1), influenced by local consumption habits and limited recycling practices. Conversely, the fine fraction (FF) increased from HP4

to HP1, indicating greater biodegradation of easily degradable waste over time. Proximate and energy content analyses revealed that refuse-derived fuel (RDF) production is the most appropriate recovery method for the combustible fractions, as surface contamination levels are too high for high-quality material recovery. The high levels of organic matter and leachable heavy metals suggest that unrestricted use of FF as earth-fill material could lead to long-term ground settling and groundwater contamination. Although the characteristics of each dumpsite may vary, the insights from this case study can help inform the development of new strategies for recycling excavated waste.

3) Gurusamy Saravanan et al. [5] highlighted that the disposal of solid waste in dumpsites is increasing in developing countries due to rapid urbanization. Biomining offers an innovative approach to recover valuable resources from legacy waste and make land from old dumpsites usable again. The biomining process utilizes various mechanical equipment, with the trommel screen playing a key role in separating legacy waste into different fractions. This project focused on optimizing trommel screen performance in the biomining process at the Rajapalayam site in Tamil Nadu, India. Operating parameters such as the feed rate for trommel screen 1 (100 mm) and trommel screen 2 (4 mm) and the moisture content of the legacy waste were optimized. The characteristics of legacy waste were studied at three different biomining sites: Rajapalayam, Srivilliputhur, and Sivakasi. The findings revealed that feed rates of 9 m^3 h^{-1} for trommel 1 and 2 m^3 h^{-1} for trommel 2 resulted in the highest separation efficiency. Adjusting the feed rates to these optimized values is recommended for improved separation efficiency without compromising the purity and recovery of fractions. The best recovery of the underflow fraction was achieved at moisture contents of 1.5% for trommel 1 and 5.3% for trommel 2. Extreme moisture content levels, either too high or too low, caused the trommel screen to clog, negatively impacting the recovery of the underflow fraction. The characteristics of refuse-derived fuel (RDF) met the standards for use in cement kilns, while the bioearth produced was not suitable for soil amendment due to its lack of nutrients like NPK and a high C/N ratio.

4) Laxman N. Pawade et al. [6] pointed out that many Indian cities are surrounded by massive piles of garbage, highlighting the country's failure to effectively utilize valuable natural resources. The inadequate treatment of waste and poor management practices have led to the creation of 3,159 dumpsites in India, which collectively generate approximately 150,000 metric tons of municipal solid waste (MSW) annually. The growing amount of legacy waste at these sites has become a significant concern, contributing to environmental problems such as air, water, and land pollution. Studies indicate that the average Indian citizen generates waste equivalent to about three and a half times their body weight each year, which leads to increased nuisance and challenges in finding suitable land for disposal. Reclaiming these dumpsites is a crucial step toward reducing their long-term negative impact. In 2011, Amravati City in Maharashtra had a population of 647,058, producing 250 metric tons per day of waste. To address this, the Amravati Municipal Corporation (AMC) adopted the concept of bio-mining at the Sukali composting site, which spans 9.35 hectares, with 6.55 hectares designated for cleaning through biomining. The Sukali compost depot operation includes creating trenches, applying bio-culture, rotating waste piles periodically, and processing legacy waste through screening, shredding, sorting, maturing, batching, and marketing. AMC has developed a strategic plan for bio-mining at the Sukali Compost Depot, which is currently being implemented. Additionally, a comprehensive plan for the future management of these dumpsites has been proposed as part of the “Swachh Bharat Mission” to ensure long-term waste management and environmental protection.

5) Samran Banerjee et al. [7] examined the growing competition for resources, rising raw material prices, dwindling natural reserves, and increasing environmental challenges, suggesting that alternative resource extraction methods like bio-mining are becoming essential. The National Green Tribunal (NGT) has mandated the implementation of bio-mining at Indian landfills to minimize environmental impacts and reclaim approximately 10,000 hectares of urban land occupied by these dumpsites. In Kolkata, where daily waste generation reaches about 4,500 metric tons, the Dhapa landfill has been accumulating waste since 1987, resulting in significant legacy waste. Composition analysis indicates that 85-90% of this legacy waste can potentially be recovered. The material balance of the waste reveals that it comprises 5.23% combustible materials, 29.97% non-combustible materials, 56.04% compostable materials, 0.476% recyclables, and 8.642% residuals. Sample analysis of 100 kg of material from the dumpsite showed that it contained 25-30% non-combustible or construction and demolition (C&D) materials, 10-15% combustible refuse-derived fuel (RDF) materials, 1-2% recyclables, 15-20% bio-earth, 20-30% coarser organic material, 5-10% process rejects, and 15-25% evaporated moisture. A comparative analysis was conducted using probabilistic and site-specific primary data, achieving a waste-to-soil ratio of 40:60. Cost analysis and potential revenue from different components highlight a circular economy solution. The recovered legacy waste can be further processed for incineration, RDF production, co-processing, construction materials, filling materials, paving blocks made from waste plastics, compost, and landscaping. This

approach focuses on resource recovery and energy generation, promoting environmental sustainability. This general methodology is applicable to other landfill sites in India where bio-mining has not yet been implemented.

6) Tanmay Bir et al. [8] highlighted that bio-mining, or landfill mining, is an effective and environmentally friendly approach for stabilizing old legacy waste in landfills while recovering valuable resources. This process aligns with the principles of circular economy by focusing on reuse, recycling, and recovery, aiming to foster a sustainable resource system that protects the environment and contributes to a pollution-free, self-sufficient society. This study aims to explore the characterization and recovery potential of mined legacy waste through an analysis of data from the past 25 years, examining recycling and processing options. It is estimated that 80% of plastics, 75% of metals and glass, and about 5% of inert materials, which transform into soil-like substances due to weathering, remain in landfills. A material balance flowchart and composition analysis were developed, with an anticipated soil-to-waste ratio of 40:60. In co-processing, approximately 7.3% of the combustible materials will be used as refuse-derived fuel (RDF) for cement kilns or power plants. Recyclable materials will be sent to authorize recycling facilities. The residual fraction is estimated at around 7% (ranging from 5-10% per CPCB), indicating the potential for maximum resource recovery. Non-combustible and construction and demolition (C&D) waste, along with inert materials (30.3%), will be repurposed for filling low-lying areas, such as for road construction and plinth structures. Revenue generated from compost, anaerobic digestion, waste-to-energy (WTE) power production, and recycling will contribute to economic growth and support a sustainable circular economy.
7) Mohan S. et al. [9] noted that open dumping is a common waste disposal method in many developing countries. These landfills pose significant environmental risks by contaminating surface water through leachate discharge, polluting groundwater as heavy metals leach from the waste over time, and contributing to air pollution through the release of CO2 and CH4, which further drive climate change. Additionally, the presence of dumpsites becomes an eyesore, highlighting the urgent need for more environmentally friendly waste disposal methods. Bio-mining offers a practical solution for reclaiming these large sites, involving the extraction, recycling, or repurposing of materials from the dumpsite, creating monetary value and facilitating resource flow. The bio-mining approach is straightforward, innovative, economically viable, quick, and environmentally sustainable, providing a way to remediate old open dumpsites, eliminate landfill gas and leachate emissions, and restore land for future use with minimal maintenance. This process includes an initial stabilization phase through Bioreactor Landfill treatment, followed by bio-mining. A conceptual framework for bio-mining at the MSW dumpsite in Chennai has been developed and implemented, and a comprehensive strategy for the ongoing management of open dumpsites has also been outlined and discussed.
8) Lucia Helena Xavier et al. [10] described that E-waste is both a source of hazardous substances and a potential reservoir of valuable secondary resources. The main challenge lies in assessing the opportunities for value recovery from this waste stream, given the varied definitions and perspectives in the field. Urban mining, inspired by principles like industrial metabolism, industrial ecology, and the circular economy, focuses on recycling and circular solutions. This study provides a thorough review of peer-reviewed literature on urban mining and analyzes the different definitions of value recovery. It covers the various stages of e-waste urban mining and examines value recovery potential in line with circular economy principles, geographic factors, and critical raw materials (CRMs). Findings indicate that the effective utilization of anthropogenic urban mines depends on Waste-to-Resources (WtR) and Waste-to-Energy (WtE) ratios and utilizes methods from traditional mining. The study emphasizes the significance of e-waste as a secondary source for CRMs such as gold (Au), silver (Ag), copper (Cu), lithium (Li), and cobalt (Co), and offers recommendations for assessing the role of urban mining in reducing the impact of e-waste through circular practices and value recovery. Innovation is crucial for advancing a sustainable circular economy, supported by a unified regulatory framework that addresses both social aspects and technical capabilities.
9) Funari, V. et al. [11] briefed that metals are crucial for everyday life but are limited in supply and can also be environmental pollutants. The current levels of carbon emissions and environmental damage caused by mining are unsustainable. To address this, we must focus on sustainably reclaiming metals from secondary sources such as waste materials. Biotechnology offers a promising approach for extracting metals from waste streams, such as fly ashes and bottom ashes from municipal solid waste incineration (MSWI). These ashes constitute a significant flow of material, with about 46 million tons produced annually worldwide, and their elemental composition is comparable to low-grade ores for metal extraction. Innovative methods, such as bioleaching, present opportunities to recover essential metals and materials that are suitably refined for high-value applications, aligning with the principles of the circular economy. This critical review highlights three primary areas of focus: (1) the characterization of MSWI materials and associated environmental challenges; (2) current recycling and metal recovery techniques; and (3) the potential of microbial-assisted processes for these purposes. Research trends are shifting towards the

application of bioprocesses in industry, particularly in the waste management sector, where biotechnology is showing greater effectiveness in resource recovery. This discussion aims to evaluate the industrial viability of biotechnological methods for urban mining of municipal post-combustion waste.

III. CONCLUSION

From the literature study based on Biomining Strategies for Legacy Waste Remediation and Resource Recovery following conclusions are made:

1) Biomining presents an effective and sustainable method for reclaiming valuable materials from legacy waste, contributing to a circular economy and reducing reliance on primary resources.
2) The process aids in cleaning up contaminated sites, improving public health, and reducing environmental risks associated with legacy waste, such as leachate and greenhouse gas emissions.
3) The development of more sophisticated and automated screening and sorting technologies can complement biomining, allowing for better separation of valuable fractions and efficient use of recovered resources.
4) By converting waste into valuable resources, biomining can generate economic opportunities through the sale of recovered materials and energy products, supporting local economies.
5) Compared to traditional mining or waste management methods, biomining requires less energy and fewer resources, making it a more eco-friendly and cost-effective alternative.
6) Ongoing research into biomining strategies, including advancements in bioleaching and microbial treatments, is essential for optimizing recovery rates and developing practical, scalable solutions for urban waste management.
7) Bioreactor landfill treatments combined with biomining can accelerate the stabilization of legacy waste, leading to faster and more efficient reclamation processes and improved recovery rates
8) The successful implementation of biomining strategies requires comprehensive policies and regulatory frameworks that encourage sustainable waste management practices and provide incentives for technology adoption.
9) Despite its potential, challenges such as varying waste compositions, economic feasibility, and the need for specialized technology need to be addressed to make biomining more widespread and efficient.
10) Proper implementation of biomining strategies can lead to long-term environmental and economic benefits, ensuring a cleaner, safer environment for future generations.
11) Combining biomining with Waste to Energy technologies can further enhance the sustainability and economic viability of waste management systems by converting organic waste fractions into energy.
12) Beyond resource recovery, biomining provides a method for reclaiming land that can be repurposed for urban development or agriculture, supporting sustainable land management and reducing the pressure on available land resources.
13) The organic fraction of legacy waste can be utilized for bioenergy production, such as biogas generation, offering an additional source of renewable energy that supports energy sustainability.

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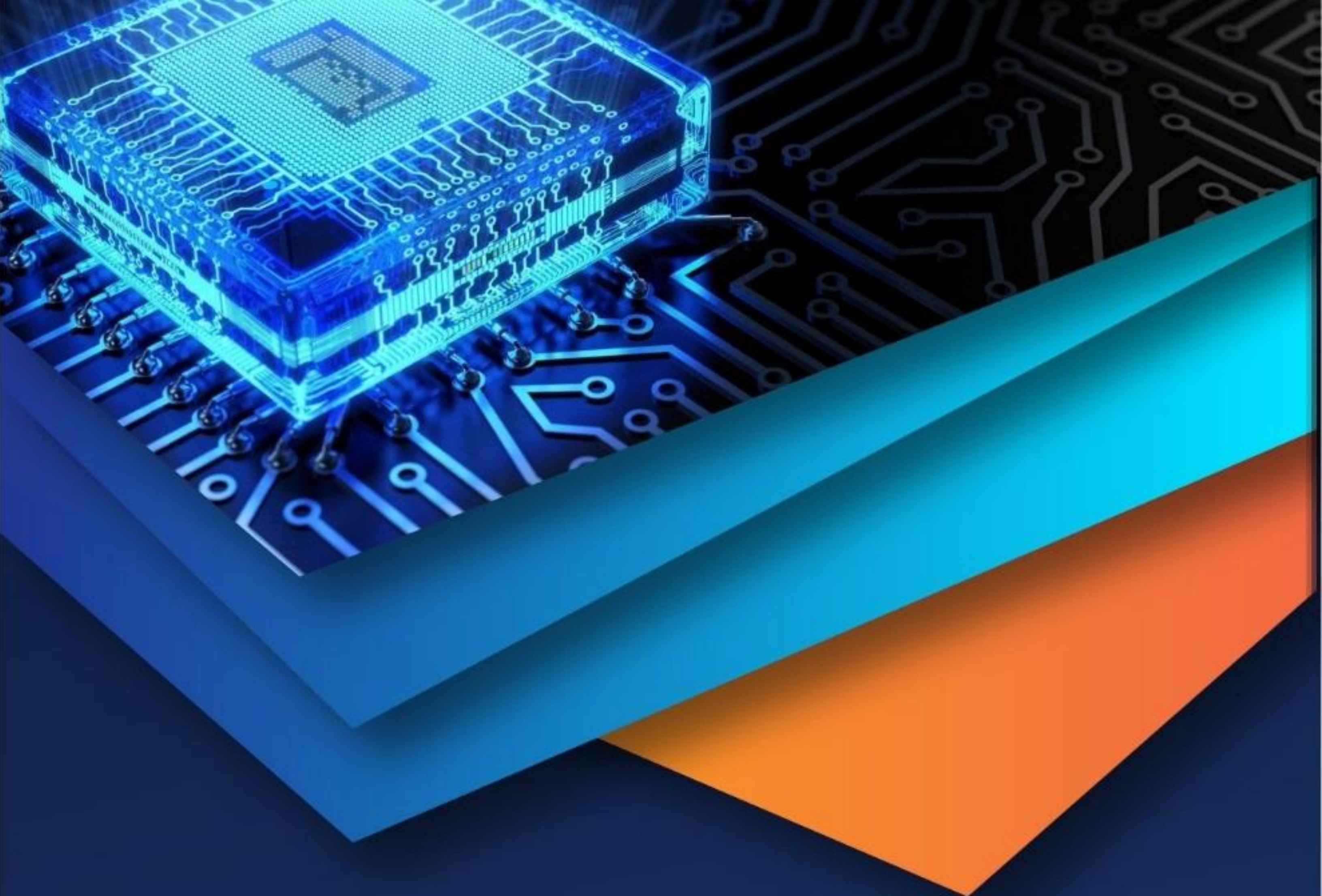

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