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Engineering Solutions for the Detection and Remediation of Emerging Microplastic Pollutants in Agricultural Soils and Water Supplies: A Systematic Review

Ali Bulama Gambo[1], Lawan Shettima Ali[2], Bulama Abubakar[3], Usman Babagana[4], Ibrahim Umar Sheikh[5], Ali Mohammad Kole[6], Mohammed Goni[7]
[1, 3, 5, 6]Department of Civil Engineering, FE & IT Integral University, 226026 Lucknow, India
[2]Department of Agricultural Engineering, Federal Polytechnic Mongono
[4]Department of Electrical Engineering, FE & IT Integral University, 226026 Lucknow, India
[7]Integral Institute of Agricultural Science & Technology (IIAST) Integral University, Lucknow

Abstract: Microplastic pollution of agricultural ecosystem is an increasing environmental crisis that has long-term impacts on soil health, water quality, food safety, and human health. This update review is a synthesis of existing information on the use of engineering solutions to detect and mitigate the effects of microplastic pollution in the soil and irrigation water bodies used in agriculture. This studyreviews the sources, distribution, and ecological effect of microplastics in agricultural systems, especially in the detection processes and remediation toolsand analyzing peer-reviewed articles that have been published in the most recent period (2015-2025). Among other methods, Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS), and novel AI-based strategies with up to 98.93% accuracy are the key detection methods. Some of the remediation methods include physical separation (membrane filtration with 78-99.9% removal efficiency), chemical methods (advanced oxidation processes), as well as biology (microbial degradation, phytoremediation, and enzyme-based systems). In our analysis we identify the most promising direction to be through integrated multi-barrier strategies that integrate detection, source control and remediation strategies. There are still critical gaps in knowledge related to nanoplastic detection, whether bioremediation will be effective in the long term, and analytical protocol standardization in the field. The review offers a broad guideline on how researchers, policymakers and agricultural practitioners can come up with evidence-based strategies to reduce the prevalence of microplastic contamination in agricultural systems.
Keywords: Microplastics; Agricultural soils; Water supply; Detection technologies; Remediation engineering; Environmental pollution.

I. INTRODUCTION

Microplastics, which are plastic debris between 1 mm and 5 mm, have become ubiquitous pollutants in both the terrestrial, freshwater, and marine ecosystems (GESAMP, 2016; Andrady, 2017). Although in the early stages of research mainly marine systems are examined, it is becoming evident that agricultural soils are one of the largest sources of microplastic pollution in the world (Nizzetto et al., 2016; Rillig et al., 2019). The amount of microplastics in agricultural areas is estimated to be four to twenty-three times higher compared to the marine environment because of the high land management activities and the persistent influx of plastics (van den Berg et al., 2020).

Plastic materials have gained a lot of relevance in the present-day agriculture since they are cheap, durable and multi-purpose. Nevertheless, excessive consumption of plastic materials has led to the formation of microplastics (MPs), Shorthorn plastic particles that are less than 5 mm long and continue to live in the environment long. Although the issue of marine microplastic pollution has been given a lot of focus, recent findings have shown that terrestrial environments (especially agricultural soils) have become major sinks of microplastics with sometimes higher levels than found in water(Masciarelli, et al 2025).

Various ways of exposure of agricultural soils to microplastics are by plastic mulch degradation, plastic greenhouse film, drip irrigation pipe, sewage sludge, compost, and using waste water whether treated or untreated(Chen et al 2025). These particles change the physical structure of the soil, influence water retention, perturb the microbial communities and modify nutrient cycling.

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In addition, microplastics have the ability to adsorb agrochemicals, heavy metals, and pathogens and serve as vectors that increase environmental and human health hazards.

As an engineer, microplastic pollution should be tackled through integrated solutions that can work in the areas of detection, monitoring, transport analysis, and remediation(Magalhães, et al 2025). The present review is devoted to engineering innovations that will help identify and eliminate microplastics in agricultural soils and water supplies, with a focus on new developments (2020-2025) and the applicability of the field.

II. METHODOLOGY

The methodology was based on systematic reviewProcessas shown in Fig. 1. It started with the identification where peer-reviewed papers were obtained through Scopus, Web of Science, and ScienceDirect, Google Scholar, and IEEE Xplorecovering publications from 2015 to 2025. with the help of predetermined keywords concerning microplastics, agricultural soils, water systems, detection technologies, and engineering remediation. This was succeeded by screening where by duplicate records and obviously irrelevant studies were eliminated through title and abstract assessment. During the eligibility phase, full-text articles were evaluated based on inclusion and exclusion criteria, which were engineering relevance, application to soil or freshwater, and methodological strength. Lastly, all the studies that qualified were qualitatively synthesized and compared. Each of the stages, decision paths, are visually represented in the clean flowchart that corresponds to this methodology (Figure 1) to guarantee transparency, reproducibility, and adherence to review standards in journals.

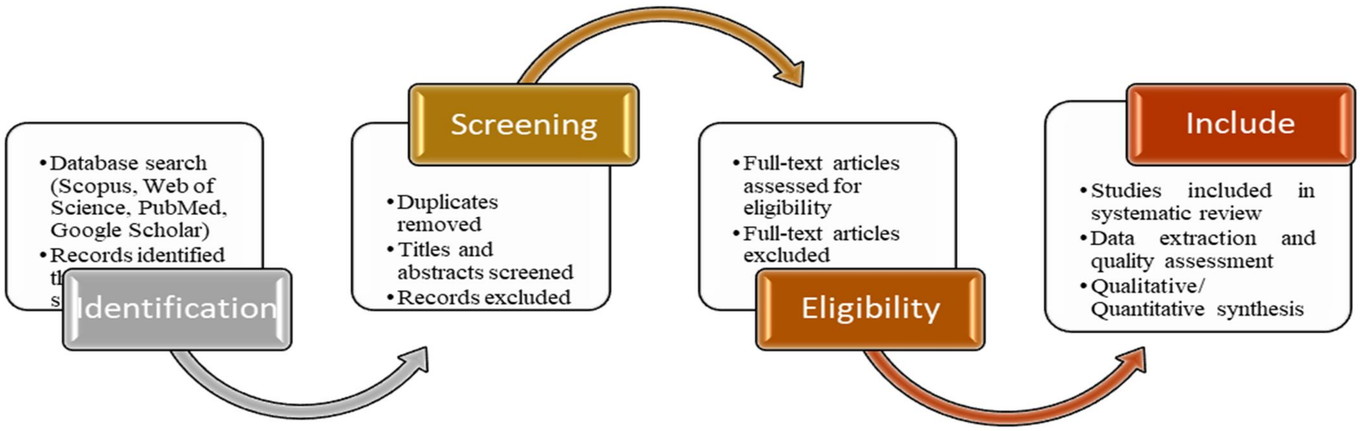

Figure 1. Flowchart Systematic review methodology.

III. BEHAVIOR AND CHARACTERIZATION OF MICROPLASTICS IN AGRICULTURE

A. *Sources and Pathways*

Microplastics get into farm soils via numerous anthropogenic sources and with different amounts and type of polymer. One of the most prominent sources of sewage sludge is its application, which has a range between 1,000 and 150,000 particles per kilogram of dry sludge depending on the efficacy of wastewater treatments and the populations of sources (Corradini et al., 2019; Lares et al., 2018). Agricultural plastic mulches that are popular in terms of temperature control and weed management break down in the presence of ultraviolet rays and mechanical forces, emitting microplastic particles into soil matrices (Huang et al., 2020; Qi et al., 2018).

Microplastics are brought by irrigation water, especially when they are obtained via treated wastewater or surface water and deposited in agricultural soils on a multiple-planting-season basis (Mintenig et al., 2017; Piehl et al., 2018). Atmospheric deposition is the least examined source of microplastic fibers and fragments, which deposit on the crop surfaces and soil (Allen et al., 2019). The municipal organic waste can also be used to produce compost that later has microplastic contaminants in the form of food packaging and other plastic materials in the waste stream (Weithmann et al., 2018).

B. *Types of Polymers and Physicochemical properties.*

The most common types of polymer found in agricultural soils are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) (Beriot et al., 2021; Liu et al., 2018; Rillig et al., 2017).

All polymers have specific physicochemical characteristics which determine their environmental behavior, detection and remedial efficiency. Polyethylene is the most widespread type of plastic in the world, which manifests itself in agriculture through the form of fragments of mulch films and packaging materials (Steinmetz et al., 2016). It is hydrophobic with a low density (0.92-0.97 g/cm3), which impacts the transport behavior of soil-water systems.

The extent of weathering highly changes surface characteristics, which forms oxidized functional groups that change hydrophobicity, charged surface, and interaction with soil constituents and soil pollutants (Brandon et al., 2016). The additives added in the manufacturing, such as plasticizers, flame retardants, and colorants, can be leached by microplastics and bring new environmental issues in addition to the polymer matrix (Hahladakis et al., 2018).

C. Environmental Fate and Transport.

The transport of microplastic in agricultural soil is determined by the soil size, shape, density, and physicochemical properties (Huerta Lwanga et al., 2017). Vertical transport occurs more rapidly via preferential flow pathways using macropores, which may allow migration of microplastic to groundwater (O'Connor et al., 2019). Earthworms and other soil fauna bioturbate soil moving microplastics both vertically and horizontally (Boots et al., 2019), and root development and agricultural tillage activities have additional impacts on spatial distribution (Machado et al., 2018).

Microplastic dynamics in water systems change in correlation with the density of particles in comparison to the water, the characteristics of the surface that influences the aggregation of particles, and the dynamics of the flow (Kooi et al., 2018). A biofilm on microplastic surfaces changes the buoyancy and can be used in vertical transport in the water column (Rummel et al., 2017). Contact with natural organic matter and suspended sediments has an impact on aggregation and settling behaviour, which condition transport and bioavailability to aquatic organisms (Besseling et al., 2017).

Microplastics gain access into agro-environment systems via primary and secondary sources. Primary microplastics are the products of industrial raw materials and additives, and secondary microplastics are the products of larger plastic agricultural products being fragmented. Plastic mulch films are deemed to be the most important source, and the source of heavy load of microplastics in soils following their repeated use and mechanical degradation(Pandey, et al 2023)

Once on the soil, microplastics are moved down the soil by the process of tilling, irrigation, and bioturbation, and horizontally by the process of runoff and erosion. The fine particles may enter ground water, which will pollute sources of drinking water and irrigation. Necessary to the engineering of the positioning and design of remediation systems is to know these mechanisms of transport.

IV. MICROPLASTICS DETECTION TECHNOLOGIES

A. Methods of Preparation and Extraction of Samples.

The efficient extraction of microplastic in complex environmental matrices followed by analytical characterization is essential to effective detection of microplastic. In the case of soil samples, the most commonly used method is density separation, which is based on solutions with high densities of sodium chloride (NaCl), zinc chloride (ZnCl2), sodium polytungstate (SPT), or sodium iodide (NaI) to make microplastic particles suspended, and clustering the heavier soil minerals sink (Fuller and Gautam, 2016; Quinn et al., 2017). Density solution choice entails tradeoffs concerning the separation efficiency, cost, environmental risk, and operational sophistication (Hurley et al., 2018).In the case of water samples, it is possible to collect the microplastics by filtering them using membrane filters of a specified pore size (Karlsson et al., 2017). The elimination of organic matter by oxidative or enzymatic digestion is one of the essential stages of soil and water sample preparation (Cole et al., 2014; Hurley et al., 2018). Fenton reagent and enzyme cocktails are suitable tools to reduce biological material, but they do not impact regular types of polymers (Tagg et al., 2017).

B. Visual Identification and Microscopy

Visual Identification and Microscopy Tuberculosis can be identified by observing white spots on the x-ray X-rays and smears under the microscope.Both visual sorting and microscopy are the basic methods of primary microplastic determination, but both of them have serious drawbacks in terms of accuracy and efficiency (Hidalgo-Ruz et al., 2012). The most common studies are using visual identification alone with the error rates of between 20% and 70% and misidentification of natural materials as microplastics (Loder and Gerdts, 2015). By using advanced microscopy methods, such as scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDX), one can get detailed morphological and elemental data (Jung et al., 2018).

C. Mechanical Engineering of Microplastic Detection technologies.

As indicated in the table 1, microplastic detection methods are different in the medium of application, principle of detection and performance of the analytical performance. Spectroscopic techniques (FTIR/u-FTIR and Raman) are popular in the analysis of soil and water because of the high polymer identification ability and the Py-GC/MS technique offers a precise quantitative data at the cost of sample destruction and high cost. Imaging methods and AI-based approaches are high throughput and fast but with high training requirements and calibration.

Table 1. Engineering-Based Detection Techniques for Microplastics in Agricultural Soils and Water

Technique	Medium	Detection Principle	Advantages	Limitations	References
FTIR / μ-FTIR	Soil & Water	Infrared spectral fingerprinting	High polymer specificity	Time-consuming, lab-based	Zhang et al., 2021; Primpke et al., 2020
Raman Spectroscopy	Soil & Water	Molecular vibration analysis	Detects smaller MPs (<1 μm)	Fluorescence interference	Li et al., 2022
Py-GC/MS	Soil & Sludge	Thermal decomposition	Quantitative polymer mass	Destructive, costly	Dierkes et al., 2021
Hyperspectral Imaging	Water	Spectral reflectance	Rapid, non-contact	Needs ML calibration	Zhang et al., 2023
Microfluidic Chips	Water	Size-based separation	Portable, low sample volume	Prototype scale	Wang et al., 2024
AI-assisted Microscopy	Soil & Water	CNN-based image recognition	High throughput	Training data needed	Yang et al., 2023

D. In-Situ Detection and Sensor technologies.

Another recent area of research is the development of the field-deployable sensors used in real-time to detect microplastic (Goncalves et al., 2020). Light scattering, absorption, or fluorescence optical sensing methods have the potential to engage in continuous monitoring (Bianco et al., 2020). Microfluidic sensors are based on the variation in electrical characteristics of plastic particles and aqueous mediums, which is used to generate an impedance signal (Shen et al., 2018). The use of hyperspectral imaging methods that combine spatial and spectral data is promising because it can be analyzed rapidly (Serranti et al., 2018).

V. MICROPLASTIC REMOVAL REMEDIATION TECHNOLOGIES

The table 2 presents key remediation measures that are used in the reduction of microplastic in soil, highlighting their mechanisms, applicability, and tradeoffs inherent in each. Physical methods, including soil washing, can be used to clean hotspots in high-contaminated soils, but can lead to massive soil disturbance. The amendment-based approaches, and specifically biochar use, aim at both the immobilization of the microplastics and at the same time enhancing the quality of the soil but there are still questions about the fate of the amendments in the long-term in the environment. Alternatives to landfill that are more environmentally benign and sustainable such as phytoremediation and microbial degradation have been proposed; but their application is often limited by low rates of remediation and inability to be effective under field conditions. Together, the table shows that a cradle-to-cradle remedial framework that is adapted to the specifics of the site must be employed in managing the issue of microplastic in the soil.

Table 2. Engineering Remediation Strategies for Agricultural Soils

Strategy	Mode of Action	Applicability	Advantages	Challenges	References
Soil Washing	Physical separation	Hotspots	Rapid removal	Soil disturbance	Tang et al., 2021
Biochar Amendment	Immobilization	Farmland	Low cost, soil health	Long-term fate	Yang et al., 2022
Phytoremediation	Root trapping	Cropland edges	Sustainable	Slow process	Boots et al., 2021
Microbial Degradation	Enzymatic breakdown	Controlled soils	True degradation	Limited field success	Ru et al., 2020

A. Traditional Filtration Systems.

The simplest engineering solution to removing microplastic in water is filtration (Ma et al., 2019). Sand filtration involves large microplastics (usually >50 mm) by straining, settling and adsorbing the filter media (Talvitie et al., 2017). The membrane filtration technologies are more efficient in removal capacity, and microfiltration (0.1-10 mm) can remove most microplastic particles, whereas ultrafiltration (0.01-0.1 mm) has a greater ability to pick up smaller particles (Sun et al., 2019). The fouling of membranes is a serious task (Enfrin et al., 2020; Talvitie et al., 2017).

B. State of the Art Separations.

The principle of dissolved air flotation (DAF) takes advantage of the difference in density between water and microplastics by creating microscopic bubbles of air (Eerkes-Medrano et al., 2019; Rajala et al., 2020). The hydrocyclone technology employs centrifugal force to distinguish the particles in terms of density and size differences (Jiang, 2018). The electrokinetic separation methods utilize electric fields to utilize the differences in charge between the microplastic particles and aqueous media (Perren et al., 2018).

C. Processes Chemical and Electrochemical.

Coagulation and Flocculation Coagulation refers to the process in which water molecules clump together.<|human|>Coagulation and Flocculation Coagulation is the clumping of water molecules.The processes of coagulation and flocculation combine the small microplastic particles into bigger flocs that can be removed by either sedimentation or flotation (Ma et al., 2019). Particle suspensions are destabilized with coagulants such as aluminum sulfate, ferric chloride, and polyaluminum chloride (Skaf et al., 2020; Wang et al., 2020). Research indicates that microplastic removal efficiencies will reach up to 95% and above when conditions are optimized (Ma et al., 2019; Rajala et al., 2020). The generation of sludge is an important factor to be considered (Lv et al., 2019).

D. Electrocoagulation

In-site electrochemical oxidation of sacrificial anodes produces coagulant species in electrocoagulation (Akarsu et al., 2021; Perren et al., 2018). The benefits of this approach are that chemical handling is minimized and the sludge volumes are also minimized. Primary operating expenses include energy usage and replacement of electrodes (Akarsu et al., 2021).

E. Enhanced Oxidation Processes.

Prospective degradation of microplastics is provided by the advanced oxidation processes (AOPs) that produce highly reactive hydroxyl radicals (Enfrin et al., 2020; Tofa et al., 2019). Polymer chain scission can be triggered by processes such as UV/H_2O_2, Fenton and photo-Fenton reactions, ozonation and photocatalysis. Full mineralization takes long durations of treatment and high amounts of energy (Liu et al., 2021). Titanium dioxide-based photocatalytic methods can be used to degrade materials via solar energy (Tofa et al., 2019).

F. Physical Soil Treatment

The microplastics can be separated in soil using soil washing processes with the use of water and surfactants and rely on the difference in density and size (Okoffo et al., 2019; Zhang and Liu, 2018). Thermal processing in which the plastic polymers are subjected to controlled heating breaks down or volatilizes them, which is restricted by high energy demand and emissions issues (Horton et al., 2017). Severely contaminated soils might also require excavation and containment (Crossman et al., 2020).

G. In-Situ Remediation

On-site technologies that do not require excavation of soil are beneficial in agricultural practice (de Souza Machado et al., 2019). The application of plants in phytoremediation has not been very effective (Lozano et al., 2021). Physicochemical property altering soil amendments have the potential to decrease the mobility of microplastic (de Souza Machado et al., 2019). Microplastics have the potential to be concentrated by electrokinetic remediation (Kim et al., 2018).

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VI. ENGINEERING FRAMEWORK FOR MICROPLASTIC MANAGEMENT IN AGRO-ENVIRONMENTAL SYSTEMS

Figure 2 presents an engineering framework of managing microplastics in agro-environmental systems based on systems, organized in a sequential chain of actions of source to monitoring and policy feedback. The framework starts with the identification of the source which includes primary and secondary microplastic sources of agricultural plastics, wastewater sludge, and organic amendments (Li et al., 2020). The contaminants are further recycled in terms of space and time through transport mechanism, such as soil erosion, irrigation runoff, leaching, and bioturbation, which mediate their space and time dynamics in agro-ecosystems (Rillig et al., 2017; Horton et al., 2017).

The detection phase combines sophisticated analytical and imaging methods, including FTIR, Raman spectroscopy, hyperspectral imaging, and AI-assisted microscopy, that allow determining and quantifying microplastics in soil and water matrices through the reliable detection mechanism (Pripke et al., 2020; Zhang et al., 2023). Detected outputs guide the risk assessment sub-module, where the exposure pathways, ecological effects and the possible human health hazards are assessed through modeling and decision support tools (Rillig et al., 2021). Depending on risks, optimization and remediation strategies such as soil washing, amendment-based immobilization, phytoremediation, and microbial degradation are chosen and optimized based on the site-specific factors (Boots et al., 2019; Yang et al., 2022; Ru et al., 2020). The framework supports monitoring and feedback of policies, which allows ongoing assessment of the remediation effectiveness and allows adaptive management based on regulation and sustainable farming.

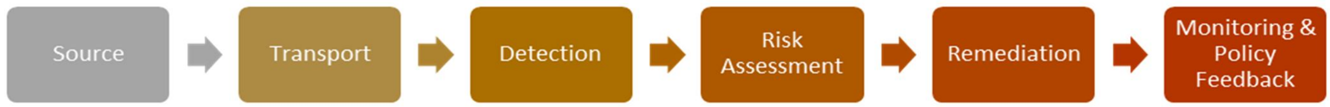

Figure 2. Engineering Framework for Microplastic Management in Agro-Environmental Systems

This framework integrates engineering detection technologies, soil-water transport modeling, remediation design, and long-term monitoring supported by regulatory feedback mechanisms.

VII. CRITICAL ANALYSIS AND COMPARATIVE EVALUATION.

A. *Comparison of the Method of Detection.*

Detection method effectiveness has to be measured under various performance dimensions (Koelmans et al., 2019). Spectroscopic methods are definitive polymer identification methods but have throughput and size limitation issues (Primpke et al., 2018). Visual methods are fast screening but will not be accepted with acceptable error rates unless the result was confirmed by spectroscopy (Loder & Gerdts, 2015). Pyrolytic methods can give quantitative values of a mass but cannot offer spatial information (Fischer & Scholz-Bottcher, 2017). There is no detection technique that covers all the requirements of the analysis (Koelmans et al., 2019).

B. *Remediation Technology Effectiveness.*

The performance of remediation technology in water and soil application differs significantly (Ma et al., 2021). Membrane filtration has maximum removal efficiency of water, but it encounters the challenge of fouling and costs (Enfrin et al., 2019). Coagulation-flocculation is less expensive and moderately efficient in the removal (Skaf et al., 2020). In soil remediation, there is no technology that is currently viable and cost effective to do the entire size range (Zhang & Liu, 2018). The biological methods are not fast enough to be used practically (Yuan et al., 2020). The most possible approach is prevention (Horton et al., 2017).

C. *Cost-Benefit Analysis*

Economic viability is one of the determinants of technology adoption (Olesen et al., 2019). In the case of water treatment, combining it with an existing infrastructure is cost-beneficial (Talvitie et al., 2017). Capital cost of membrane filtration is high but can be justified in high value applications (Ma et al., 2019). In the majority of cases, the cost of soil remediation is high and uneconomically viable only in extreme situations (Crossman et al., 2020).

VIII. CONCLUSION

Microplastics are currently ubiquitous pollutants of agro-environmental systems, and nowadays agricultural soils are identified as key sinks where they frequently occur in high levels compared to aquatic and marine systems.

Various forms of polymers are introduced in the soils through intensive agricultural activities, including the application of plastic mulches, irrigation systems, sewage sludge, compost and wastewater, and they persist in the soils interacting with soil structure, microorganisms and hydro-logical processes. These interactions affect the microplastic transport, accumulation and bioavailability, as well as contribute to increased susceptibility of microplastic to agrochemicals carried by microplastics, heavy metals and pathogens threatening ecosystem functioning, water quality and human health.

This review points out that microplastic pollution in both soil and water systems cannot be fully dealt with by a single detection or remediation technology. Recent in-situ sensor development and AI-based systems have potential future solutions to sustained monitoring, but established analytical methods can also give precise results as to source and concentration. Another limitation of the remediation strategies, though effective in water treatment, is its low level of application in soils because of its high cost, energy requirements, and long-term unpredictability of effectiveness. As a result, a systems-based approach, integrating the focus on source control, prevention, optimum detection, site-specific remediation, and ongoing monitoring with the assistance of the policy feedback is necessary. This can only be done through sustainable management of microplastics within the agricultural landscapes and also protecting soil health, water resources and food security.

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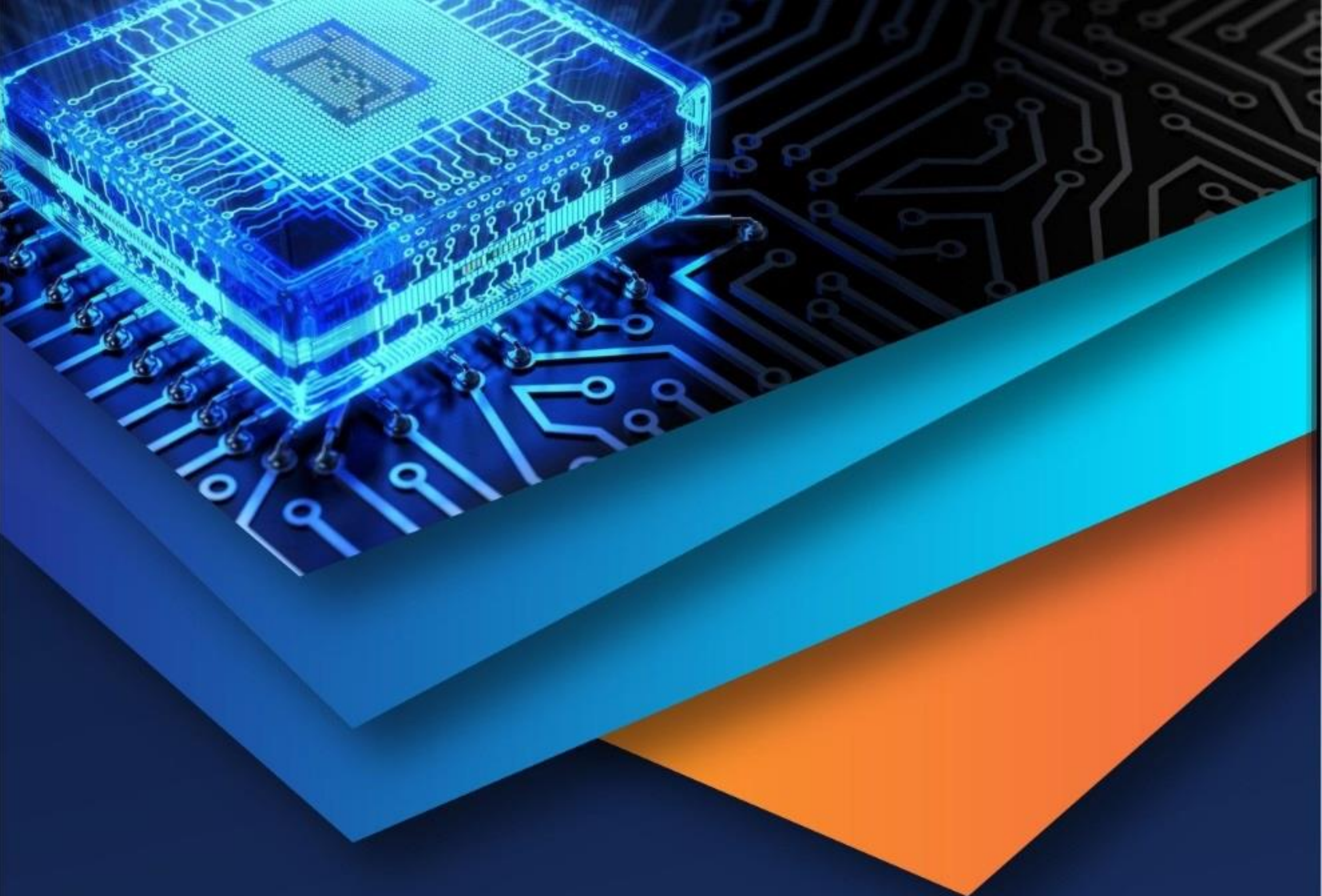

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