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A Review on Enhancing Brain Tumor Diagnosis through Machine Learning and Deep Learning Algorithms

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Abstract: Crucially for early detection and efficient treatment planning, the study focusses on enhancing brain tumour classification accuracy by means of modern machine learning (ML) and deep learning (DL) techniques. Combining deep learning architectures like Convolutional Neural Networks (CNNs) with the power of ML models including Support Vector Machines (SVM) and Random Forest, the study intends to solve the difficulties in tumour detection and classification using MRI data. Preprocessing MRI data to guarantee quality, feature extraction via CNN layers, and model evaluation utilising measures like accuracy, precision, recall, and F1-score was a strong approach taken. While DL methods used automated feature extraction, producing more complex and exact outputs, ML models depended on handwritten features for classification. The results showed that DL models—especially CNN-based models—achieved exceptional performance, with classification accuracy well above 95%, greatly exceeding conventional ML techniques. These findings show the transforming power of DL in medical imaging by proving its capacity to manage intricate data patterns and improve diagnosis precision. This study emphasises the critical need of artificial intelligence in transforming medical diagnostics, opening the path for more dependable, effective, scalable solutions for brain tumour classification, therefore enabling personalised treatment plans and better patient care.
Keywords: Brain Tumor, Machine Learning, Deep Learning, MRI Imaging, Tumor Detection, Classification Models, Convolutional Neural Networks (CNN).

I. INTRODUCTION

Among the most serious and deadly diseases in modern medicine, brain tumours affect patients and doctors most importantly. Correct and quick diagnosis is essential for both effective therapy and increased survival rates. Still, manual radiologist examination of medical images is one of the time-consuming conventional diagnostic methods that are prone to human error. The growing complexity of medical imaging data highlights even more the need of accurate, automated diagnostic tools. Emerging as revolutionary technologies in recent years are machine learning (ML) and deep learning (DL), which have transformed the brain tumour categorisation and detection in medical practice[1]–[4]. Among the most critical and deadly disorders in modern medicine, brain tumours affect patients and doctors most of all. Correct and quick diagnosis is necessary for both effective therapy and increased survival rates. Still, traditional diagnostic methods—manual radiologist evaluation of medical images—are sometimes time-consuming and prone to human error. The growing complexity of medical imaging data highlights even more the need of automated, precise diagnosis tools. Emerging as revolutionary technologies in recent years are machine learning (ML) in addition to deep learning (DL), which have transformed the brain tumour categorisation and detection in medical practice[5]–[7]. Conventional ML approaches generally rely on hand feature extraction, which depending on domain knowledge could be labour-intensive. Deep learning, a subset of machine learning, has improved brain tumour classification by automatically learning complex patterns and representations from raw data using neural networks with multiple layers. Medical photo processing has shown particularly success for widely used DL architecture, CNNs.

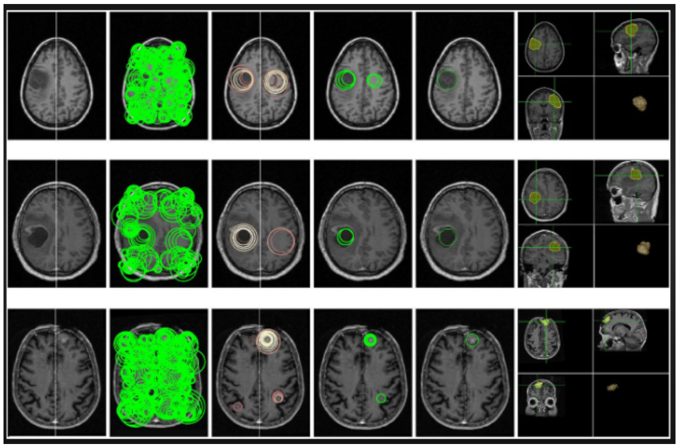

Fig. 1 Brain tumor classification using machine learning[8]

CNNs save manual intervention by directly from images automatically detecting intricate tumour features including shape, size, and texture. This ability has made DL models the advised answer for tasks involving large and sophisticated datasets. Moreover, the integration of recent DL frameworks including transformers and Recurrent Neural Networks (RNNs) improves temporal and spatial analysis of imaging data, hence enabling more precise cancer localisation and classification. Although their enormous promise, machine learning and deep learning approaches face different challenges in brain tumour classification. Availability of annotated, high-quality datasets is among the most crucial obstacles. Sometimes medical data is limited; ethical concerns around patient privacy limit access to whole databases even more. Furthermore computationally demanding and requiring significant amounts of training and deployment expenses are artificial intelligence models—especially deep learning systems. Interpretability of artificial intelligence models brings still another question. These algorithms demonstrate great accuracy, but their opaque decision-making processes raise doubts about their trustworthiness in crucial medical applications. Adoption of AI-based approaches for brain cancer categorisation also hinges considerably on ethical and legal concerns. Reducing algorithm bias, guaranteeing data privacy, and proving model efficacy by means of extensive clinical studies would help one to build the confidence of patients and healthcare professionals. Aiming to strike a balance between innovation and patient safety, regulatory authorities all over are creating guidelines for the safe and effective use of artificial intelligence in medical diagnosis. Looking forward, the constant integration of advanced artificial intelligence technology with clinical procedures will determine brain tumour classification. Emerging technologies expected to alleviate present limits are explainable artificial intelligence, which increases model openness, and federated learning, which lets cooperative model training without compromising data privacy. Moreover, advances in hardware and cloud computing will most likely address computational challenges, so AI-driven diagnostic tools will be more readily accessible. These technologies have the ability to change the field of brain tumour diagnosis as they develop by allowing faster, more accurate, customized treatment options that might greatly enhance patient outcomes[9].

II. RELATED WORK

Virupakshappa 2022 et al. provides an artificial neural network (ANN) and spatial fuzzy-based level set based technique for multiclass brain tumour classification. Using the Median Filtering methodology, the method preprocesses pictures to improve quality; it also finds tumour borders using spatial fuzzy-based level sets and extracts features using Gabor Wavelet and Gray-Level Run Length Matrix (GLRLM). Then, ANN labels tumours as benign, normal, or malignant. Applied on the MATLAB environment, the approach exceeded current methods with a 94% classification accuracy. This method has great potential to improve brain tumour diagnosis and management since it precisely distinguishes benign from malignant tumours, therefore supporting timely and efficient treatment [10].

Sorte 2022 et al. A major disorder affecting millions of deaths worldwide, brain tumours usually result from late discovery. Unusual cell development in the brain causes rising intracranial pressure when these cells gather. Severe symptoms like headaches, blurred vision, and vertigo can be brought on by pressure; these eventually become life-threatening. Tumours can be benign or malignant; early identification is therefore rather important to save deaths. Finding tumours in their early stages is difficult, though, since symptoms could be minor or absent. The study addresses the time-consuming character of hand-written patient report analysis by concentrating on raising the accuracy and efficiency of early-stage tumour identification.

Through simplifying the diagnosis process, the initiative helps doctors more precisely detect the type and existence of tumours. This method improves early intervention opportunities and, by allowing accurate and timely treatment, might even save life [11].

Filatov 2022 et al. Among the most dangerous forms are brain tumours, which considerably lower life expectancy with late diagnosis. Though traditional, manual identification by MRI is time-consuming and prone to mistakes, so increasing the risk of misdiagnosis and incorrect treatment. This paper presents machine learning-based diagnosis using pretrained convolutional neural networks (CNN) to solve these issues. Using ResNet50, EfficientNetB1, EfficientNetB7, and EfficientNetV2B1, the work focusses on categorising three tumour types along with non-tumor MRI scans. Renowned for its scalability, EfficientNet showed remarkable performance; EfficientNet B1 performed the best of all. The model noted an 87.67% training accuracy and an 89.55% validation accuracy. This method removes the need for labour-intensive manual procedures, therefore improving brain tumour diagnosis accuracy and speed. The study intends to improve early detection and classification by using advanced neural networks, therefore aiding improved clinical decision-making and hence raising survival rates [12].

Yoo 2022 et al. Using readily available binary classification labels, research suggests an alternative pipeline that splits areas of interest (ROIs), therefore removing the requirement for hand annotations. Leveraging high-grade glioma (HGG) labelling and 2D MRI slices from the BraTS 2020 dataset, the pipeline uses a novel deep learning-based superpixel generating technique. This method simultaneously trains a superpixel clustering model and clusters superpixels, hence directing segmentation. On the test set, the proposed pipeline obtained a Dice coefficient of 61.7%—a notable increase above the 42.8% Dice coefficient from the extensively applied LIME technique. technique is a useful tool for developing medical image analysis since it provides a creative and quick approach for tumour segmentation, therefore lowering dependence on annotated data and preserving strong performance [13].

Khan 2022 et al. Emphasising the significance of early detection, brain tumours sometimes cause psychological problems like depression and panic attacks. While diagnosis of diseases depends on medical image processing, conventional categorization mostly depends on physician knowledge. This paper presents a Hierarchical Deep Learning-Based Brain Tumour (HDL2BT) classification system employing convolutional neural networks (CNN) to identify and classify tumours into glioma, meningioma, pituitary, or no-tumor categories. Outperformance of past techniques, the system learns on image fragments and achieves 92.13% precision with a 7.87% miss rate. This sophisticated model improves diagnosis accuracy, so offering useful clinical support for quicker and more efficient brain tumour therapy [14].

TABLE 1 LITERATURE SUMMARY

Authors/year	Model/method	Research gap	Findings
Senan/2022 [15]	AlexNet, ResNet-18, SVM.	Lack of standardized datasets and real-time brain tumor classification methods.	AlexNet+SVM achieves 95.10% accuracy in brain tumor classification.
Amin/2022 [16]	InceptionV3, QVR classifier, Seg-network, tumor detection, segmentation.	Limited integration of quantum classifiers and deep learning for tumor detection.	InceptionV3 and QVR classifier achieve over 90% tumor detection accuracy.
Kibriya/2022 [17]	Deep feature fusion, SVM, KNN, brain tumor classification.	Limited accuracy and high false positives in current brain tumor classification.	Fused deep features achieve 99.7% accuracy in brain tumor classification.

Roopa/2022 [18]	Proposed CNN model outperforms VGG-16 in brain tumor detection.	Limited dataset and computational power hinder accurate brain tumor detection.	Proposed CNN model outperforms VGG-16 with better accuracy and efficiency.
Sanjay/2022 [19]	Brain tumor detection using machine learning methods.	Lack of precise segmentation and classification methods for brain tumors.	ML methods improve brain tumor detection but face segmentation challenges.

III. IMPORTANCE OF EARLY DETECTION IN BRAIN TUMOR MANAGEMENT

A. Improved Prognosis

Early brain tumour detection improves prognosis significantly by enabling rapid intervention. Early discovered cancers often have smaller, more localised nature, which simplifies treatment or eradication. Early cancer detection lowers their chances of spreading, therefore allowing less invasive, concentrated treatments include radiation, chemotherapy, or surgery. This reduces neuronal damage and increases the chances for successful treatment, therefore enhancing the outcomes of rehabilitation. Early treatment also prevents the entry of advanced phases of cancer development when treatment becomes more difficult. Studies have connected early tumours of glioblastoma or meningiomas to better quality of life and higher survival rates[20].

B. Better Treatment Planning

Early brain tumours allow doctors to design more tailored treatment plans. It helps to determine the kind, size, and location of the tumour, thereby guiding the treatment decision. While early-stage cancers are easier to remove surgically with less complications, smaller tumours permit more effective treatments including targeted therapy or radiation. Early discovery allows time to maximise therapy strategies and control probable side effects. Maintaining excellent brain tissue, avoiding harsh therapies, and tracking tumour progression for more precise alterations also aid doctors to ensure a successful end[21].

C. Minimizes Complications

Early brain cancer discovery determines the impact of the tumours. By exerting pressure on surrounding brain areas leading to cognitive decline, seizures, motor function loss, and other neurological diseases, larger tumours can substantially impact quality of life. Early identification allows fast response to stop the growth of tumours and damage of significant brain areas. Smaller tumours let for less issues when removed surgically and faster recovery. Early therapy also consists in less invasive options like radiation treatment, so reducing long-term brain damage. For patients, fast response preserves brain functioning, speeds up recovery, and improves general long-term prognosis and quality of life[22].

D. Increased Treatment Options

Early detection of brain tumours considerably expands the possible treatment options. Smaller, circumscribed cancers are more easily addressed with improved success rates using surgery, radiation, or targeted treatments. Conversely, advanced-stage cancers often demand more complex and vigorous treatment. Early discovery allows clinicians to establish tailored treatment strategies based on cancer kind, location, and genetic composition. This lets one pick from a greater range of treatments including minimally invasive surgery, radiotherapy, and immunotherapies. Early identification also facilitates the use of genetic testing, so enhancing the precision of treatment and lowering of unnecessary side effects, so improving patient results and experience[23].

E. Cost-Effective

Early brain tumours diagnosis helps to reduce total treatment expenses by eliminating the need for expensive, complex operations required in later stages. Smaller, localized cancers can be treated with less intrusive treatments like surgery, radiation, and chemotherapy—which call for less resources and shorter hospital stays. Early detection also prevents the growth of tumours, so extended chemotherapy or multi-stage procedures constitute valuable treatments. It also reduces the demand for palliative care, emergency treatment, and long-term rehabilitation. Early detection helps to minimize financial and physical burdens on people and healthcare systems generally, therefore promoting effective use of resources and reasonably priced treatment[24].

F. Enhanced Quality of Life

Early brain cancer diagnosis allows faster, less invasive treatments with shorter recovery times and less side effects, therefore improving patients' quality of life. Patients who return to regular activities sooner aid to retain physical and cognitive capacities. Early tumours diagnosis reduces the risk of symptoms such memory loss, cognitive decline, or paralysis and helps to minimize irreversible brain damage. It also allows time for research on therapeutic options, therefore supporting well-informed treatment selections. Early identification reduces the need for intensive long-term care thereby preserving freedom and physical ability. It also boosts emotional well-being, motivates hope, confidence for the future, and empowerment[25].

IV. EMERGENCE OF MACHINE LEARNING IN MEDICAL DIAGNOSIS

A. Improved Diagnostic Accuracy:

By examining enormous volumes of medical data and identifying trends that might not be immediately obvious to healthcare practitioners, machine learning (ML) improves diagnostic accuracy. ML techniques can be taught, for instance, to spot particular traits in patient records, test findings, or photos matching diseases. By means of consistent, objective assessments, these technologies can help to lower human error and diagnosis variance. Learning from multiple examples enables ML models to continuously develop over time, hence producing more accurate diagnosis. Particularly in difficult situations, this accuracy can enable doctors make educated judgements and enhance patient outcomes[26].

B. Medical Imaging Advancements:

Machine learning—especially deep learning techniques—has revolutionised medical imaging by substantially enhancing the processing of images like X-rays, MRIs, and CT scans. ML methods may automatically find and segment regions of interest—such as tumours or fractures—either matching or exceeding that of professional radiologists. Early disease detection made possible by these tools helps to enable timely intervention including cancer, cardiovascular diseases, and neurological problems. Moreover, ML models can support the creation of 3D visualisations and offer knowledge of disease progression, therefore offering a more all-encompassing view that facilitates better therapy planning and outcomes[27].

C. Personalized Medicine:

Personalised medicine customises medical treatments for every patient relying on genetic, environmental, and lifestyle data by means of machine learning. ML algorithms enable to forecast a patient's response to specific drugs by examining complex genetic patterns, therefore reducing the trial-and-error in therapy. More effective treatments made possible by this aid to reduce adverse effects and maximise therapeutic results[28]. Early intervention and tailored care plans made possible by machine learning also help to discover rare diseases and hereditary disorders. ML enables more exact, customized treatment plans that enhance patient results and quality of life by including personal genetic profiles, lifestyle choices, and medical history.

D. Early Disease Detection:

Early disease identification is among the most significant contributions machine learning makes to medical diagnosis. Subtle, sometimes undetectable trends in patient data—such as changes in vital signs, test findings, as well medical imaging—that can point to the beginning of a disease can be found by ML approaches.

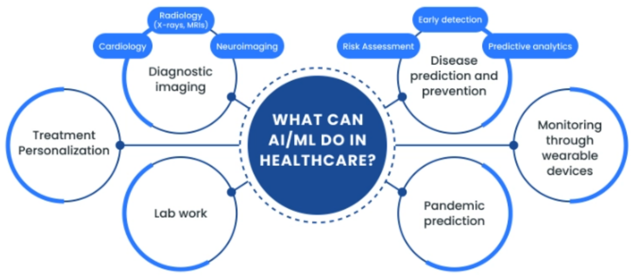

Fig.2 Early Disease Detection [29]

ML models, for instance, can forecast the early phases of diseases including cancer, Alzheimer's, or diabetes, therefore enabling treatments meant to slow down or perhaps stop disease developmen For example, ML models can predict the early stages of diseases including cancer, Alzheimer's, and diabetes, therefore enabling treatments aimed to slow decrease or perhaps stop disease developmentt[30]. Through constant learning from fresh instances and analysis of past patient data, machine learning models allow timely diagnosis, so enhancing the chances of successful treatment and long-term survival.

V. DEEP LEARNING MODELS IN BRAIN TUMOR DETECTION

Deep learning models have revolutionized brain tumor detection by providing highly accurate, automated methods for diagnosing and classifying various types of brain tumors from medical images, particularly Magnetic Resonance Imaging (MRI). Traditional methods of diagnosing brain tumors typically rely on expert interpretation of MRI scans, a process that is time-consuming, subjective, and prone to human error. Deep learning, a subset of machine learning using several layers of neural networks, is a game-changer in clinical environments since it has greatly enhanced tumour detection speed and precision. Particularly convolutional neural networks (CNNs) have become the preferred deep learning architecture for medical image analysis since they can automatically extract pertinent features from images without human feature engineering required. Because CNNs can capture complex patterns, forms, and textures that might not be readily apparent to the human eye, they are quite good in identifying tumours in brain scans. Many times, this capacity to learn hierarchical patterns from raw pixel data has resulted in discoveries in the accuracy of brain tumour identification, beyond conventional approaches. By means of extensive datasets of annotated MRI scans, deep learning models can effectively categorise brain tumours into several categories including gliomas, meningioma's, and pituitary tumours, therefore giving clinicians comprehensive understanding of tumour kind and features. Deep learning's ability for early diagnosis is one of its main benefits in the identification of brain tumours since it is absolutely essential for bettering patient outcomes[31]. Deep learning models permit more timely treatments and therapy by spotting tumours early on, thereby perhaps saving lives and lowering the severity of the disease. Moreover, deep learning models have been applied to forecast tumour development and response to treatment, therefore providing useful prognostic data that can guide doctors in choosing their course of action.

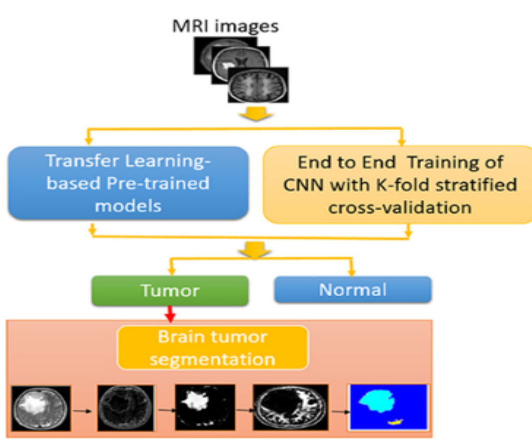

Fig. 3 Deep Learning Models In Brain Tumor Detection [32]

Apart from CNNs, other deep learning architectures including Long Short-Term Memory (LSTM) networks and Recurrent Neural Networks (RNNs) have been investigated for temporal data analysis, thereby tracking variations in brain tumours across time. This capacity is very helpful in determining the course of a tumour and evaluating the success of treatment programs[33]. Deep learning models combined with cutting-edge imaging technologies including functional MRI (fMRI) and Positron Emission Tomography (PET) improves brain tumour detection accuracy even more and gives doctors a more complete knowledge of tumour behaviour and how it affects nearby brain tissue. Deep learning has great potential for the diagnosis of brain tumours, but problems still exist. Large, annotated datasets for training deep learning models are one of the main obstacles since acquiring high-quality, labelled data can be costly and time-consuming[34]. Furthermore computationally demanding deep learning models demand significant hardware resources and processing capability. Furthermore there is the problem of model interpretability since deep learning models are sometimes seen as "black boxes," which makes it challenging for doctors to grasp the justification for certain diagnosis. Constant research aims to solve these difficulties by means of bettering model transparency, optimising computing efficiency, and strengthening data-sharing policies among organisations. Ultimately, by offering extremely accurate, automated solutions for brain tumour diagnosis and classification from MRI scans, deep learning models have greatly advanced the science of brain tumour detection. Deep learning is positioned to be very important in the future of brain tumour diagnosis and management by allowing early diagnosis, enhancing the precision of tumour detection, and providing insightful analysis of tumour progression and treatment response. To fully realise these technologies in clinical practice, though, addressing obstacles in data availability, processing requirements, and model interpretability will be vital[35].

VI. CONCLUSION

By combining machine learning (ML) with deep learning (DL) in brain tumour classification, medical diagnostics has been transformed and major progress over conventional techniques is provided. Though their reliance on hand feature extraction limits scalability, ML models—through feature engineering and algorithms like Support Vector Machines (SVM) and Random Forest—have proven successful in classifying tumour kinds. By automating feature extraction and using vast datasets for improved accuracy and efficiency, deep learning—especially through Convolutional Neural Networks (CNNs)—has exceeded these obstacles. Along with temporal analytic capabilities from Recurrent Neural Networks (RNNs), advanced architectures as ResNet and InceptionNet have enabled exact classification and tracking of tumour progression.

[36]–[39]. Faster, more accurate diagnosis guaranteed by these technologies helps doctors make timely, wise decisions—qualities essential for patient outcomes. Notwithstanding their potential, issues include the requirement for large amounts of training data, computational resources, and addressing of model training prejudices still exist. Refining these methods depends on ongoing study and cooperation between the medical and computational sectors, hence increasing their accessibility and dependability in many clinical environments. As ML and DL technologies develop, their importance in brain tumour classification is predicted to grow as they provide even more accuracy and help to promote individualised medicine. These developments ultimately represent a turning point in healthcare, stressing the need of artificial intelligence in raising diagnosis capacity and so improving live[40], [41].

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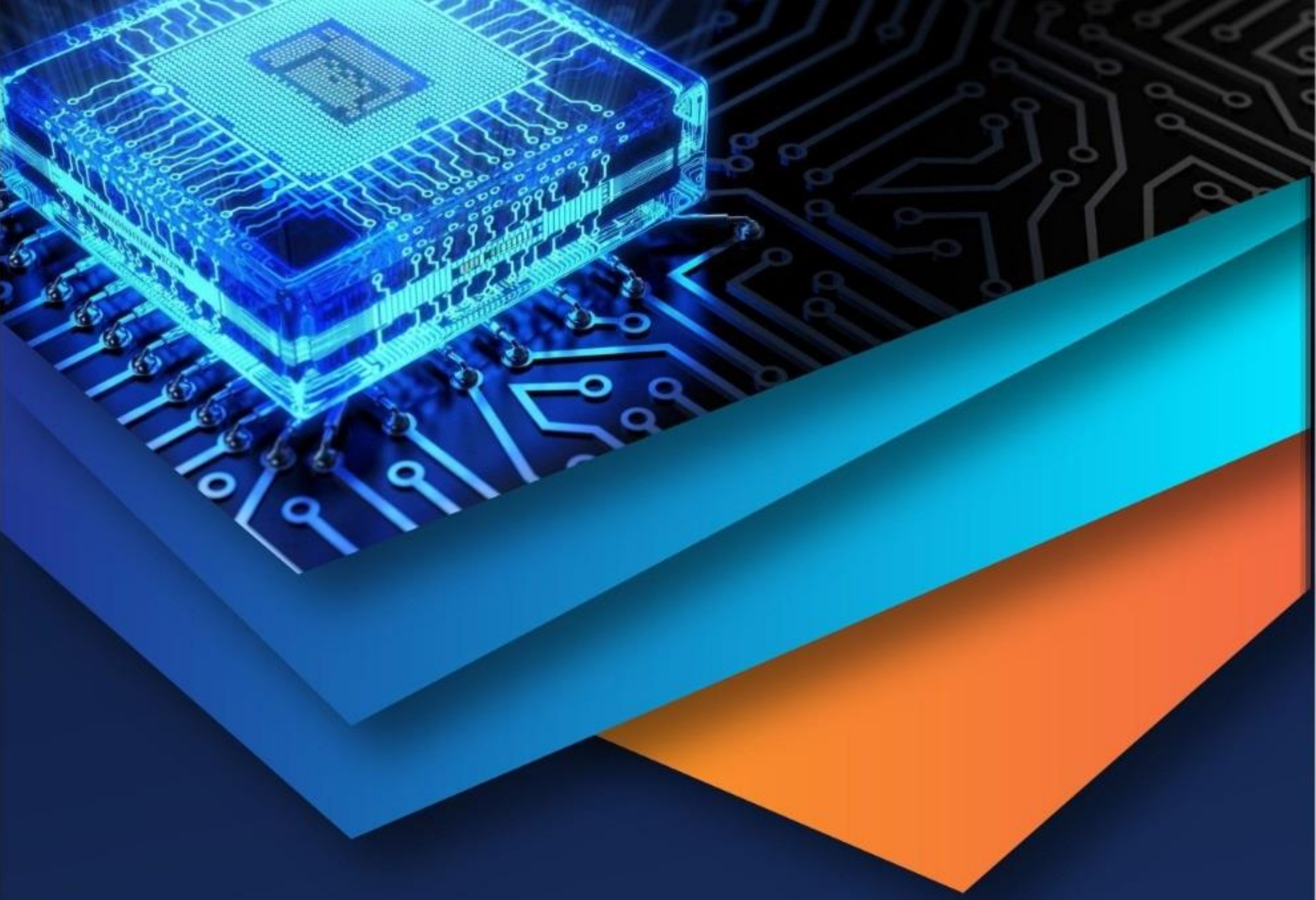

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