iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: XII Month of publication: December 2025

DOI: https://doi.org/10.22214/ijraset.2025.76674

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A Review on IoT-Based Agricultural Robots: Seed Sowing, Fertilizer Spraying, and Grass Cutting Automation for Precision Farming

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Abstract: The imperative for global food security, driven by a projected population of 9.8 billion by 2050, conflicts with escalating labor costs and inherent inefficiencies in traditional agricultural practices. This review critically assesses the role of IoT-based agricultural robotics in advancing Smart Agriculture (SA) and Precision Farming (PA). We synthesize the state-of-the-art across three specialized domains—precision seed sowing, Variable Rate Technology (VRT) chemical spraying, and autonomous mechanical weed control—to establish the necessity and design principles of multifunctional robotic platforms, exemplified by systems like Krushi Yantra. Thematic analysis reveals that, for resource-constrained smallholders, the economy of scope provided by multi-tasking robots offers a superior solution over the economy of scale offered by specialized machinery. However, widespread adoption is limited by high acquisition costs, the rural connectivity gap (hindering real-time autonomy), and technical trade-offs required for cost-effective sensor fusion. Future research directions must prioritize hybrid 5G/WiFi6 communication infrastructures, sustainable hardware (solar power, lightweight chassis), and the integration of enhanced generalized AI to ensure robust, equitable, and environmentally conscious autonomy in modern agriculture.

I. INTRODUCTION: THE IMPERATIVE FOR AGRICULTURAL AUTOMATION

A. Global Food Security and the Crisis of Agricultural Labor

The agricultural sector faces immense pressure to meet the rising food demand projected by a global population expected to reach 9.8 billion by 2050[1]. Traditionally, farming relies heavily on manual labor, historical knowledge, and intuition, often resulting in generalized fertilization plans and fixed irrigation schedules. This approach frequently leads to the overuse of resources, increased production costs, and environmental degradation[1].

This inefficiency is compounded by a deepening crisis in the agricultural labor supply. Labor costs continue to mount, driven by regulatory changes like minimum wage and overtime, while the supply of potential farm employees shrinks due to demographic factors and immigration enforcement[3] The high costs and difficulty associated with securing labor have made the integration of labor-saving technology increasingly economically viable. The annualized savings derived from reduced reliance on manual labor act as a critical economic catalyst, often justifying the adoption of capital-intensive robotic systems despite their high up-front acquisition costs[3].

B. Defining Smart Agriculture and the Transition to Agriculture 4.0

The response to these challenges lies in the transition to Smart Agriculture (SA) and Precision Farming (PA). PA is defined as a paradigm that shifts away from managing entire fields based on theoretical average conditions—the "one size fits all" approach—to recognizing and responding to spatial and temporal variability within the field[1]. This site-specific management optimizes resource utilization.

The progression toward Agriculture 4.0 is characterized by the integration of technologies such as IoT, Artificial Intelligence (AI), Machine Learning (ML), and robotics, which collectively deliver enhanced efficiency, sustainability, and productivity[2]. IoT-based devices are fundamental, offering transformative capabilities including live tracking, pest control, irrigation management, and sophisticated soil analysis[8].

C. Scope and Contribution of the Review

This review provides a critical, thematic assessment of the current state-of-the-art in specialized IoT-based robots designed for three core agricultural tasks: seed sowing, fertilizer spraying, and grass cutting/weeding. The review synthesizes these specialized domains to justify the efficacy and design principles of multifunctional robotic platforms.

For small and mid-sized specialty crop producers, financial economy is not achieved through high volume (scale), but rather through the ability of a machine to perform diverse tasks (scope)[3]. Multifunctional robots, such as the proposed Krushi Yantra (or A.G.R.I. Yantra), represent an optimal solution by combining tasks like drilling, fertilizing, seed sowing, and watering into a single system[8] This approach strategically addresses the chronic issues of limited working capital and escalating labor costs faced by resource-constrained farmers[2]. By embedding multiple functionalities into a single chassis, the multifunctional design becomes an economic strategy aimed at widening technological accessibility beyond the domains typically serviced by large, scale-optimized industrial equipment.

II. FOUNDATIONAL CONCEPTS: IOT, SENSORS, AND AUTONOMOUS PLATFORMS

A. The Architecture of Smart Agri-Robotic Systems

The general architecture of autonomous agricultural robots mirrors that of complex robotic systems, comprising four main interacting components: a mobile platform, mechanical actuators (for execution), a vision system (for perception), and a control system (for decision-making)[10]. The operational intelligence is embedded within the IoT ecosystem, which includes sensors for environmental data collection, actuators for physical tasks, and an integrated embedded system containing a processor, memory, communication modules, and power management[12].

B. Sensor Technologies for Precision Input Management

Smart sensors are critical instruments in modern agriculture, providing the real-time data necessary for optimizing parameters like soil health and crop growth[7].The capability for true site-specific precision hinges upon the integration of various sensor categories [12]:

- Location Sensors: Global Navigation Satellite Systems (GNSS), particularly those enabled with Real-Time Kinematic (RTK) positioning, provide centimeter-level accuracy, which is essential for precise field mapping, navigation, and sowing[13].
- Optical Sensors: These devices capture spectral reflectance data, utilized for vegetation index analysis, such as the Normalized Difference Vegetation Index (NDVI). This analysis is routinely employed to assess crop health, chlorophyll levels, and drought stress, allowing farmers to detect spatial variations in crop performance[15].
- Electrochemical Sensors: These are crucial for rapid, non-destructive quantification of spatially variable soil nutrients and nutrient levels[13].
- Mechanical and Dielectric Sensors: These provide ground-level information regarding soil compaction and moisture content[13].

The effective combination and processing of these diverse inputs (sensor fusion) are non-negotiable for achieving genuine Variable Rate Technology (VRT), transforming agricultural robots from simple automated machines into sophisticated precision instruments[6].

C. Communication Infrastructure: The Bottleneck in Rural Deployment

Reliable, high-fidelity communication is essential for real-time data transmission and remote control, yet it constitutes a major hurdle for deployment in remote agricultural areas[15]. The communication architecture typically involves a blend of technologies classified by transmission distance [13]: short-range (Bluetooth, UWB), medium-range (Wi-Fi, ZigBee), and long-range Low-Power Wide-Area (LPWA) options such as LoRa and NB-IoT[12]. A significant limitation is the rural connectivity gap. Many farming regions, particularly in developing areas, suffer from weak mobile network coverage, limited access to broadband internet, and high data latency, which directly restricts the ability to deploy IoT devices effectively and perform necessary real-time monitoring and cloud-based analytics[17]. If this communication link is inadequate, the flow of real-time sensor data is compromised, forcing autonomous systems to operate at a lower level of functional autonomy than intended, thereby undermining the full benefits of precision agriculture. This technical requirement—simultaneously demanding short-range, high-data-rate links for vision processing and long-range, low-data-rate links for environmental sensing—inherently complicates the design and raises the cost of building an ostensibly "cost-effective" multifunctional platform like Krushi Yantra.

III. THEMATIC REVIEW OF SPECIALIZED AGRICULTURAL ROBOTIC APPLICATIONS

A. Automation of Seed Sowing: Mechanisms for Precision Planting

Robotic seed sowing systems aim to achieve optimal growth and yield by ensuring seeds are placed at precise depths and spacing[19]. Existing multifunctional prototypes, such as early Agrobots, have demonstrated the ability to perform tasks including drilling, fertilizing, seed sowing, and watering in a single integrated pass[8].

The mechanical core of these systems involves specialized seed dispensing mechanisms, often driven by solenoid actuators or servo motors, which enable accurate seed dispensing and precise hole-digging tasks[20]. Control over movement and operation sequencing relies on embedded coding systems or microcontrollers (e.g., Arduino or ESP32) that execute tasks at specified time intervals[8]. By automating this process, seed-sowing robots have been shown to boost planting productivity with extraordinary efficiency and accuracy compared to labor-intensive manual or conventional methods[20].

B. Precision Fertilizer and Chemical Spraying: Variable Rate Technology (VRT) in Robotics

Precision spraying relies on Variable Rate Technology (VRT) to move beyond the traditional uniform application of inputs[6] VRT utilizes geo-spatial and sensor-based data to apply nutrients or chemicals in variable rates, fitting the local, site-specific requirements within the field[6]. This selective application minimizes resource wastage, reduces production costs, and decreases environmental pollution[6].

Advanced robotic sprayers integrate sophisticated sensor fusion systems, combining data from RGB cameras, LiDAR, and GPS, often analyzed by AI[6]. This intelligence allows the robot to detect specific targets, such as tree canopy height, leaf density, or weeds, and precisely control individual spray nozzles[6]. For instance, AI-enabled smart sprayers use machine learning to distinguish a target (e.g., a crop) from a non-target (e.g., a pole) and shut off all nozzles when no object is detected, maximizing accuracy and minimizing chemical drift[6]. This high level of sophistication, which requires complex sensor fusion and dedicated AI processing, establishes a significant technological benchmark. A cost-effective multifunctional robot attempting to match this performance would face a challenge, potentially requiring a trade-off between affordability and the environmental and economic benefits afforded by true site-specific precision.

C. Robotic Grass Cutting and Mechanical Weed Control

Autonomous weed cutters and robotic lawn mowers (RLM) are effectively deployed for maintenance, primarily managing weeds in orchards and dedicated areas, with typical working capacities[5]. Navigation relies on positioning systems like GPS[5].

Weed detection is governed by advanced computer vision systems that utilize deep learning models, such as TinyML and the YOLO (You Only Look Once) algorithm, for object recognition and analysis[16]. This technological integration saves significant manual effort and reduces the necessity for broad-spectrum pesticide use, thereby mitigating environmental pollution[15]. Furthermore, the successful implementation of deep learning for accurate weed recognition implies that the necessary vision intelligence can be shared across multiple tasks. If a single onboard camera system can be trained to recognize targets for weeding, soil conditions for sowing, and nutrient deficiencies for spraying.

IV. SYNTHESIS OF MULTI FUNCTIONALITY: THE CASE OF THE KRUSHI YANTRA PLATFORM

A. The Economic Rationale for Multi-Tasking Robots

For smallholder farmers and producers of specialty crops, efficiency is derived from versatility. Since large, specialized machines optimized for **scale** (high volume of a single task) are financially impractical for smaller operations, the market demands machines with wide **scope** (performing many different tasks)[3]. Multifunctional robots, by condensing several critical field operations (e.g., tillage, planting, monitoring, maintenance) into a single chassis, offer a superior economic solution to counter labor shortages and limited capital[8].

B. Functional Design and Working Principles of Krushi Yantra (A.G.R.I. Yantra)

Krushi Yantra (or A.G.R.I. Yantra) is designed specifically as a cost-effective automated apparatus targeting low-income farmers[2]. Its core objective is to automate repetitive, laborious agricultural tasks, including ploughing, seed sowing, monitoring, and potentially harvesting[9]. The integrated working principle involves a sequential approach using a single mobile platform: field preparation (ploughing and soil data collection), followed by precise seed sowing, and subsequent crop monitoring. The entire process is maneuverable via remote application control[9].

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

The synergy required for combining the three featured functions is managed through component sharing: the mobile base and navigation system are common, allowing for rapid transition between tasks.

C. System Architecture and Operational Flow

The high-level integration of the core functions—seed sowing, fertilizer application, and grass cutting/weeding—is managed by a central microcontroller and orchestrated through an IoT interface. The present invention discloses a **sequential operational control method** for a multifunctional agricultural robotic system, herein referred to as *Krushi Yantra*, capable of performing multiple agricultural operations including **ploughing, seed sowing, fertilizer application, and grass cutting/weeding**.

In accordance with an embodiment of the invention, the operation is initiated through a **remote IoT-enabled user interface**, such as a mobile application, by which a user selects one or more desired agricultural tasks. The selected commands are transmitted to a **central microcontroller**, which functions as the primary control unit for coordinating and executing all system operations.Upon receipt of the task selection, the control unit determines whether **field preparation or ploughing** is required. If field preparation is selected, the microcontroller actuates a ploughing mechanism.

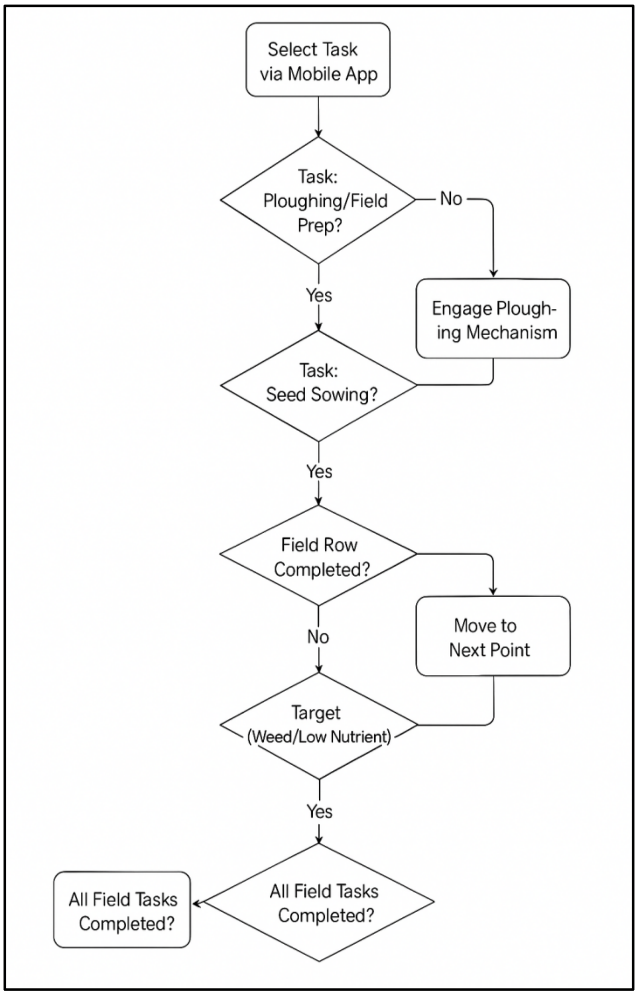

Figure 4.3.2: Sequential Operational Flowchart for the Krushi Yantra Multifunctional Agricultural Robot

D. Hardware and Software Integration for Combined Tasks

The cost-effectiveness mandate of Krushi Yantra dictates a reliance on widely available, economical hardware components.

Hardware Components: The central coordinating unit is typically a microcontroller (e.g., Arduino or ESP32), which manages actuation and sensor data[2]. Movement relies on DC motors, while precision tasks like seed metering and hole creation are handled by servo motors or solenoid actuators[20]. Sensory input includes ultrasonic sensors for path planning and field boundary detection, soil sensors for environmental monitoring, and an embedded camera (e.g., ESP32 Cam) for image analysis and assessment[20].

Software and IoT Integration: The system facilitates remote operations and data oversight through an IoT-based control system, often communicating via a mobile application using a Wi-Fi interface[9]. This real-time sensor data is critical for optimizing resource delivery[20].

The successful deployment of Krushi Yantra fundamentally requires robust functional modularity, meaning that the seed sowing, fertilizer spraying, and grass cutting end-effectors must be quickly and easily swapped or reconfigured. If this transition is complex or time-consuming, the operational time savings generated by combining tasks are diminished, eroding the robot's value proposition. Furthermore, the constraint of building a low-cost system necessitates using less powerful COTS components, meaning complex AI processing must be managed remotely or simplified drastically, placing significant dependency on reliable communication infrastructure.

V. COMPARATIVE PERFORMANCE AND CRITICAL ANALYSIS

A. Performance Comparison: Krushi Yantra vs. Single-Function Systems

The true value proposition of a multifunctional platform is not technical superiority in any single task, but rather economic leverage achieved through high asset utilization.

- Cost and Accessibility: Specialized robotic systems have high upfront costs, which represent a significant entry barrier[17]. Krushi Yantra's cost-effective structure 2 mitigates this by allowing a single investment to cover diverse seasonal needs, maximizing the return on capital investment for small farms.
- Efficiency and Functionality: Specialized robots are generally optimized for speed and volume (high scale) in their one specific task (e.g., high planting output per hour)[8]. Krushi Yantra, conversely, offers high scope efficiency, measured by the overall operational time and labor cost saved through the combination and execution of multiple field preparation and maintenance tasks in sequence. Qualitatively, these platforms significantly reduce manual labor and improve yield predictability[3]. For example, the consolidation of annual field operations is hypothetically projected to reduce overall seasonal labor costs[3].
- Autonomy: While specialized VRT sprayers achieve high autonomy through real-time, sensor-driven decision-making [6], multifunctional prototypes often operate with medium autonomy, relying on remote monitoring and control via a mobile application to guide operations[9].

B. Technical Limitations of Current Multifunctional Designs

All agricultural robots face significant technical hurdles in achieving robustness across variable and complex farm environments, requiring outstanding adaptability and precise obstacle avoidance capabilities.10 A persistent industry challenge is the lack of uniform standards across precision agriculture technologies, which continues to hamper data sharing and interoperability between different robotic components, systems, and sensors.5 Moreover, the dedication to achieving cost-effectiveness forces multifunctional systems to compromise on the high-end sensor fusion and processing power required for advanced VRT or real-time deep learning detection systems.

C. Scalability and Real-World Deployment

The prioritization of operational scope makes platforms like Krushi Yantra highly scalable for small to mid-sized farms and specialty crop systems where the prohibitive cost and singular focus of high-scale machinery render it impractical[3]. However, technical adoption is incomplete without supporting infrastructure. Ensuring the longevity and operational effectiveness of this complex, high-tech machinery requires the concurrent development of robust support systems, clear maintenance protocols, and comprehensive technical training for farmers[2].

VI. RESEARCH GAPS, CHALLENGES, AND FUTURE DIRECTIONS (CRITICAL ANALYSIS)

A. Major Debates in Agricultural Robotics: Affordability and Equity

A central debate in agricultural robotics concerns equitable access. The high upfront acquisition costs associated with advanced systems create a significant barrier for small and mid-sized farms globally, hindering technological adoption and exacerbating socioeconomic disparities[5] Furthermore, the increasing reliance on AI systems raises concerns regarding farm data sharing and ownership, which must be resolved to facilitate wider use of these sophisticated technologies[5].

While basic IoT and drone technology are becoming integrated into smallholder farming, robotics remains out of reach for many due to economics, infrastructure deficits, and a lack of specific technical awareness[9].

B. The Role of Advanced Connectivity: 5G, Edge Computing, and Autonomy

The advancement toward robust, functional autonomy in agri-robotics remains protracted[3] This slow rate of progress is directly attributable to the inherent variability of complex agricultural settings and, more critically, to the deficiencies of rural telecommunication infrastructure[2]. Achieving advanced autonomy mandates reliable, high-throughput, and low-latency network connectivity for critical operations such as real-time decision transmission, off-board AI processing (Edge Computing), firmware management, and remote operational assistance[18]. Consequently, the lack of sufficient rural connectivity presents a fundamental restriction on the deployment of sophisticated functional intelligence[11]. Fifth-generation telecommunications (5G) is systematically engineered to address this infrastructural gap, primarily by delivering three transformative technical advantages: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and Massive Machine-Type Communications (mMTC)[18]. These capabilities are essential for supporting data-intensive, real-time in-field activities [1], such as streaming high-resolution video to an off-board Mobile Edge Computer (MEC) for immediate weed detection and decision transmission[18]. Since reliance on public 4G often results in communication instability and high latency in sparse agricultural regions [18], the practical implementation necessitates hybrid network solutions[18] Empirical evaluations have demonstrated that the deployment of private 5G-SA (Stand-Alone) systems, when combined with high-speed private WiFi6 networks, can successfully meet the demanding communication requirements essential for the next generation of highlyautonomous agri-robots[18].

C. Next-Generation Intelligence and Sustainability Integration

Future research must prioritize the development of more robust, generalized intelligence. This such as Convolutional Neural Networks (CNNs) and reinforcement learning, to allow robots to execute complex, real-time field-level decisions[1]. Involves integrating deep learning techniques, Deep learning models have already shown their potential to enhance the accuracy of tasks like crop phenotyping by incorporating multimodal data fusion[15].
autonomous agri-robots[18].

D. Next-Generation Intelligence and Sustainability Integration

Future research must prioritize the development of more robust, generalized intelligence. This involves integrating deep learning techniques, such as Convolutional Neural Networks (CNNs) and reinforcement learning, to allow robots to execute complex, real-time field-level decisions[1]. Deep learning models have already shown their potential to enhance the accuracy of tasks like crop phenotyping by incorporating multimodal data fusion[15].
The technological drive toward high efficiency must also reconcile its ethical and environmental implications. Robots optimized for efficiency in specific parameters may inadvertently reinforce ecologically vulnerable monoculture systems, potentially counteracting sustainability efforts despite resource savings[19]. Environmental concerns also include:

- E-waste and Energy Consumption: The manufacturing, operation, and finite lifespan of complex electronic systems contribute to energy demand and e-waste generation[19].
- Soil Degradation: The weight and repeated movement of robotic platforms can lead to soil compaction, reducing fertility and water infiltration capacity[19].

To address these challenges, future development must integrate solar power [14], focus on lightweight chassis designs to mitigate compaction, and develop lightweight AI models optimized for robustness and energy efficiency[15]. Research is needed to ensure that AI models are trained for high crop diversity to prevent the optimization of technology from reinforcing ecologically unsustainable uniformity.

VII. CONCLUSION

The rigorous review of IoT-based agricultural robotics confirms the existence of highly capable, specialized systems for precision seed sowing, VRT chemical spraying, and autonomous weed control. However, the overarching conclusion is that the pathway to widespread global adoption, particularly among resource-constrained success of this model is critically reliant upon the use of hybrid COTS hardware and robust, if simplified, software interfaces.
Multifunctional IoT-based agricultural robots offer transformative potential by bridging the technological chasm between high-end research
Keywords: Smart Agriculture, Agricultural Robot, IoT, Seed Sowing Robot, Fertilizer Spraying, Grass Cutting, Precision Farming, Krushi Yantra.

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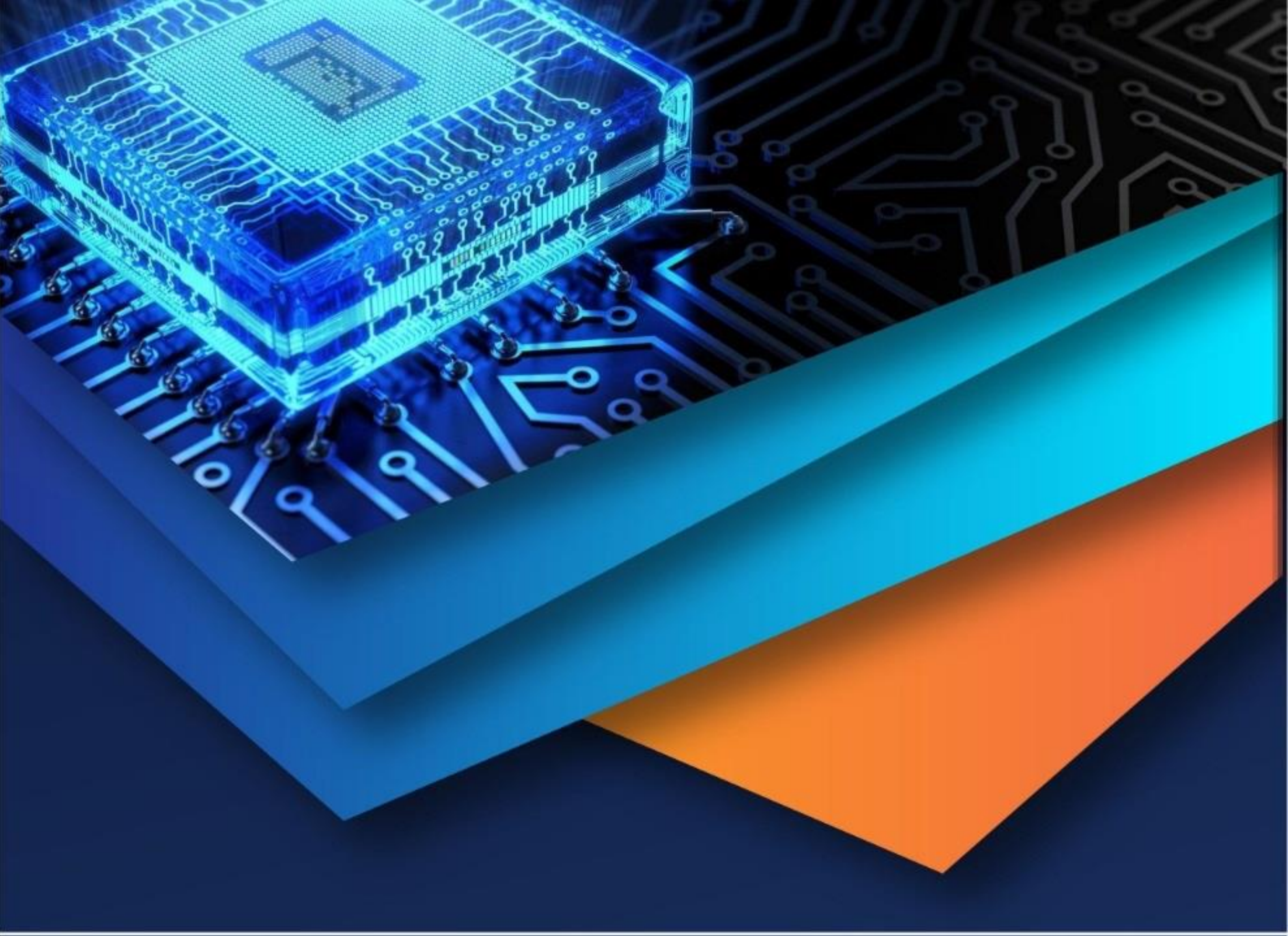

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