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Resource Efficiency and Sustainability Trade-offs in Hydroponic and Controlled Environment Agriculture: A Comparative Review

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Abstract: Rapid urbanization, climate variability, and the progressive reduction of arable land are placing increasing pressure on conventional soil-based agriculture. Controlled Environment Agriculture (CEA), particularly hydroponic cultivation systems, has emerged as a promising alternative due to its capacity for precise environmental control, higher land productivity, and improved water-use efficiency. This paper presents a comparative literature review of hydroponic and conventional agricultural systems with a specific focus on land, water, and energy performance metrics. In addition, the role of automation, intelligent control systems, and advanced lighting technologies in enhancing system stability and resource optimization is critically examined. The synthesis of empirical and analytical studies indicates that hydroponic systems consistently outperform conventional farming in terms of land use efficiency and water conservation, particularly in urban and water-scarce regions. However, these advantages are accompanied by significantly higher energy requirements, primarily driven by artificial lighting, climate control, and infrastructure demands. The findings suggest that the sustainability of hydroponic agriculture is highly conditional and dependent on system-level optimization and integration with low-carbon energy sources.
Keywords: Hydroponics, Deep Water Culture, Automation, Geoponics, Bioponics, Aeroponics, Sustainability, Vertical farming.

I. INTRODUCTION

Due to rapid growth in population and increasing urbanization, the demand for food continues to rise and will likely be a major bottleneck to sustain global population in various regions. At the same time, the availability of arable land is steadily declining as cities expand and climate change alters traditional farming conditions. The predicted population for 2050 ranges from 9.5 billion to 10 billion [1] and this number keeps on growing. With huge chunk of rural population migrating to urban cities for better lifestyle and income opportunities, this leaves a hole to fill in for production of crops [2]. Yet to consider the depletion of suitable land area for agriculture which overall reduces the possible work area for production of crops [2].

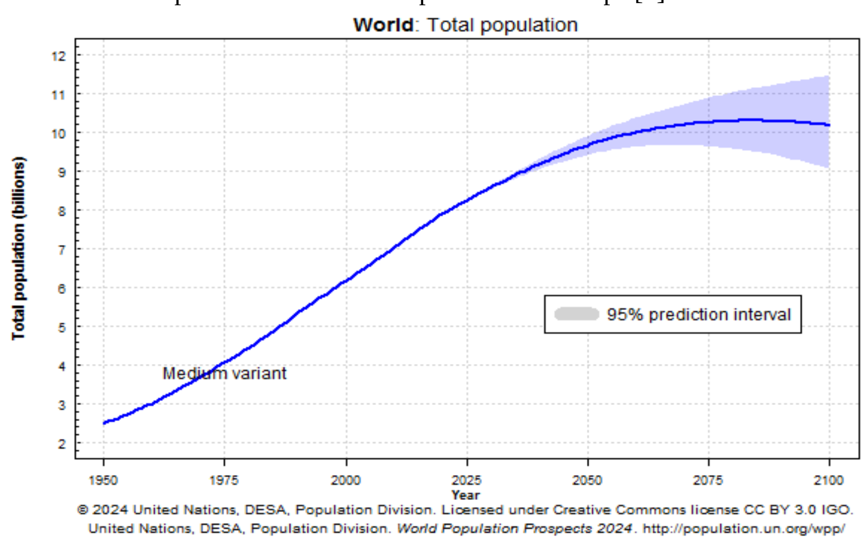

Figure 1.1 Global Population

Conventional soil-based agriculture is highly dependent on favourable weather patterns, soil fertility, and large land areas, making it increasingly difficult to sustain food production in urban and semi-urban regions. Recently in September 2025, a major flood affected 20 lakhs of people and shocking "more than 5.8 lakh farmers from 6,300-odd villages registered damage to almost 30 lakh acres". This flood caused widespread destruction across 22 districts in Haryana and it is just one example.[1]

To overcome these major events, some alternatives than traditional agriculture needs some light to be shed upon. Some practices like Permaculture and Agroforestry have been proposed to promote ecological balance between nature and our society. While these approaches offer long-term environmental benefits, their implementation often requires significant land area and extended time periods, limiting their feasibility in densely populated urban environments.

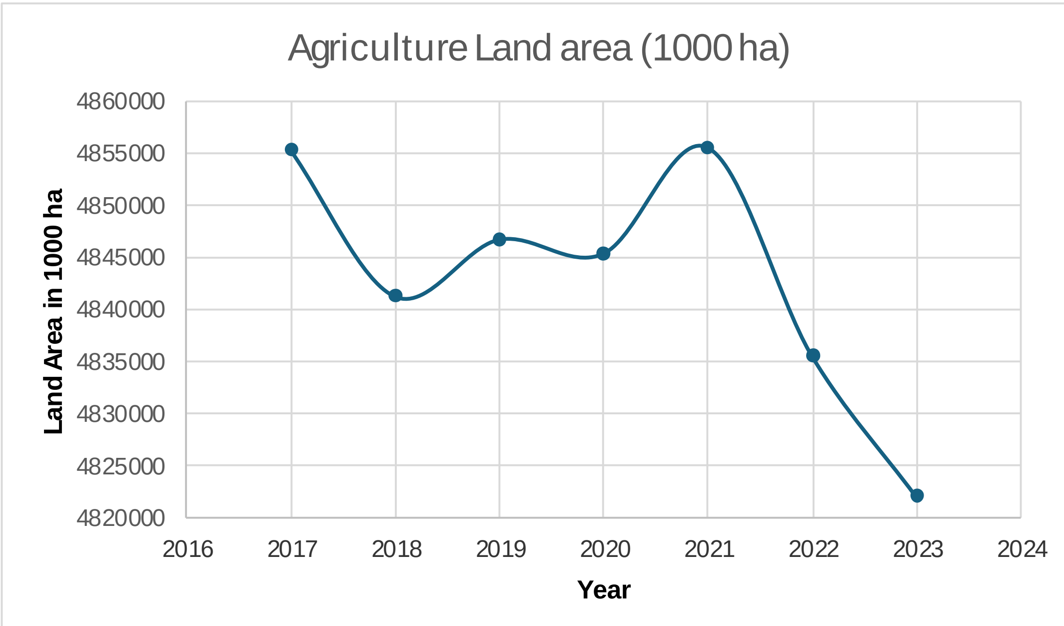

Figure 1.2 available Agriculture land area of the World

Controlled environment agriculture has emerged as a promising solution to overcome these limitations [3][11]. Among its various forms, hydroponics has gained considerable attention due to its ability to grow plants without soil by supplying nutrients directly through water. Hydroponic systems enable precise control over growing conditions, resulting in improved crop yield and reduced resource wastage [4][6]. Furthermore, the integration of automation technologies into hydroponic systems allows continuous monitoring and regulation of critical parameters such as nutrient concentration, temperature, humidity, and light intensity [11][13][14]. This paper aims to present a theoretical review of automated hydroponic systems and analyse their potential as a sustainable solution for urban and individual-level food production. The study focuses on understanding system components, automation techniques, and comparative performance based on previously published research.

II. LITERATURE REVIEW

The literature selection for this paper was conducted to identify relevant studies on hydroponics and around automation in hydroponics. The studies included were published between 2000 and 2025.

Kheir Al-Kodmany [3] Author examined vertical farming as a response to food insecurity, urban population growth, land scarcity, and climate change. By synthesizing interdisciplinary research and real-world projects, it shows that low-rise and rooftop vertical farms using hydroponics, aeroponics, and aquaponics are already viable, delivering high yields with reduced water, land, and transport costs.

Dionysios Touliatos, Ian C. Dodd, Martin McAinsh [4] this paper addresses the problem of land scarcity and declining agricultural land availability, especially under rapid urbanization. Vertical farming has been proposed as a solution, but prior studies often lacked fair, controlled comparisons between vertical and horizontal systems. The authors specifically investigate whether vertical column–based farming systems (VFS) genuinely outperform conventional horizontal hydroponic systems (HHS) when planting density, root zone volume, nutrient supply and environmental conditions are held constant.

Guilherme Lages Barbosa et al [5] This paper performs a direct, quantitative comparison between hydroponic lettuce production, and conventional soil-based lettuce farming. The comparison is done using three core sustainability metrics: Land use, Water use and Energy use. The study uses lettuce production in Yuma, Arizona as a real-world case study.

Gruda, N et al [6] This paper reviews soilless cultivation systems (hydroponics, substrate culture, aeroponics) with a specific focus on how they improve water use efficiency (WUE), enhance product quality (nutritional value, uniformity, safety) and reduce environmental pressure compared to soil-based agriculture.

C. Graamans et al [7] This paper evaluates soilless crop production systems (hydroponics, substrate culture, greenhouse cultivation) from a sustainability and land-use perspective, with a strong emphasis on soil conservation.

Elly Nederhoff, Cecilia Stanghellini [8] This paper examines how water use efficiency (WUE) of tomato production can be dramatically improved by moving from open-field agriculture, greenhouse cultivation and closed and semi-closed hydroponic greenhouse systems.

B. Sanyé-Mengual et al [9] This life cycle assessment evaluates the environmental impacts of urban hydroponic tomato production in Lyon, France. Despite reduced transport distances and high water-use efficiency, the system exhibited higher greenhouse gas emissions per kilogram of tomatoes than conventional open-field production due to energy-intensive greenhouse operation and infrastructure impacts.

Rui de Sousa et al [10] This review examines global food system challenges and evaluates home hydroponics as a complementary solution for improving food security and environmental sustainability in urban areas. It highlights hydroponics' advantages in water efficiency, reduced land use, shorter supply chains, and improved food quality, while emphasizing that sustainability is strongly dependent on low-carbon energy sources. The paper identifies technological complexity, energy demand, and accessibility as key barriers, concluding that home hydroponics—when integrated with renewable energy, automation, and building design—can enhance urban resilience but should complement rather than replace conventional agriculture.

Redmond Ramin Shamshiri et al [11] This review examines the technological evolution of greenhouses into advanced controlled environment agriculture systems and their transition toward plant factories and urban vertical farming. It highlights advances in automation, sensor networks, IoT, artificial intelligence, microclimate control, and energy optimization that enable reliable year-round food production in cities.

Celina Gómez, Luigi Gennaro Izzo [12] This review examines how light-emitting diode (LED) technology can increase crop production efficiency in controlled environment agriculture by enabling precise control of light spectrum, intensity, and timing. It shows that while red and blue light drive photosynthesis, green and far-red wavelengths improve whole-canopy photosynthesis and plant morphology, and that dynamic, targeted, and intracanopy LED lighting strategies can substantially reduce energy consumption.

Konstantinos Tatas et al [13] This study presents iPONICS, a low-cost IoT-based monitoring and control system designed specifically for hydroponic greenhouses. Using a wireless sensor network, solar-powered operation, and a fuzzy logic controller, the system monitors key hydroponic parameters (pH, EC, DO, temperature, humidity) and dynamically controls irrigation.

Alejandro Isabel Luna Maldonado et al [14] This chapter reviews the integration of automation, IoT, artificial intelligence, and robotics in hydroponic systems, presenting real-world implementations ranging from microcontroller-based real-time control and fuzzy logic pH regulation to neural network prediction, expert systems, and robotic plant manipulation. The reviewed systems demonstrate improved precision, reduced labor, higher reliability, and scalability of hydroponics, concluding that intelligent automation is fundamental for the future expansion of controlled environment agriculture.

III.OVERVIEW OF HYDROPONICS

All Hydroponics is a technique that uses nutrient-enriched water solutions to produce plants without the need for soil. Plant roots can grow more quickly and effectively in these systems because they are immediately exposed to nutrients, oxygen, and water. Aeroponic systems, Deep Water Culture (DWC), and Nutrient Film Technique (NFT) are common forms of hydroponic systems. A fertilizer reservoir, water pumps, growing channels or containers, artificial lighting, and plant support structures make up a standard hydroponic setup. Maintaining ideal environmental conditions is essential since plants are totally dependent on the given nutritional solution. Plant health and yield are directly impacted by factors including temperature, humidity, electrical conductivity (EC), and pH level.

Hydroponics eliminates reliance on soil quality and drastically lowers water consumption when compared to conventional gardening. Because of these benefits, hydroponic systems are especially well suited for urban settings with limited water and space.

A. Land Use Efficiency

One of the most consistently reported advantages of hydroponic systems is their superior land use efficiency. Experimental comparisons between vertical and horizontal hydroponic systems demonstrate dramatic increases in yield per unit floor area when vertical stacking is employed. For example, vertical farming configurations have been shown to achieve more than tenfold increases in yield per square meter compared to conventional horizontal hydroponic systems, primarily due to higher planting densities rather than increased individual plant mass.

Comprehensive comparative reviews further confirm this pattern across horticultural crops [4-6]. Yield improvements of over 150–200% have been reported for lettuce, tomato, spinach, and herbs when hydroponic systems replace soil-based cultivation. These gains are attributable to controlled nutrient delivery, year-round production cycles, and the elimination of soil-related constraints. From an urban planning perspective, vertical farming enables "zero-acreage farming," integrating food production into rooftops and building interiors. This decoupling of crop production from horizontal land requirements is frequently cited as a critical advantage in dense urban environments. However, land use efficiency alone does not equate to sustainability. Life cycle assessment (LCA) studies indicate that while hydroponic systems minimize physical land occupation, infrastructure materials and energy inputs may offset land-based benefits. Thus, land productivity gains must be evaluated in conjunction with broader environmental impacts.

Table I: Land Use Efficiency

Crops	Hydroponic Yield (kg/m^2)	Conventional Yield (kg/m^2)	Yield Increase (%)
Lettuce	25.6	8.2	212%
Tomato	45.3	15.7	188%
Strawberry	12.8	5.4	137%
Basil	18.2	6.9	164%
Spinach	21.4	7.6	182%

B. Water Use Efficiency

Water use efficiency (WUE) is another domain in which hydroponics demonstrates substantial performance advantages. Soilless systems reduce water consumption by recirculating nutrient solutions and minimizing evaporation losses. Review studies report reductions of up to 70–90% compared to conventional irrigation systems [6]. Quantitative comparisons in tomato production reveal that product water use (PWU) can decline from over 100 L/kg in open-field systems to as low as 4 L/kg in closed, high-technology hydroponic greenhouses. These improvements are driven by precise irrigation scheduling, reduced transpiration through environmental control, and recovery of condensed water vapor in closed systems. Similarly, cross-crop analyses indicate approximately 85% reductions in water use per kilogram of produce in hydroponic systems. These findings are particularly relevant for arid and semi-arid regions where water scarcity constrains agricultural productivity.

Nevertheless, water savings do not uniformly translate into overall environmental superiority. LCA analyses demonstrate that reductions in water consumption may contribute less to total environmental performance than energy-related emissions. Therefore, hydroponics should be viewed as highly water-efficient but not automatically environmentally optimal.

Table II: Water Consumption and Water Efficiency

Crops	Hydroponic Water Use (L/kg)	Conventional Water Use (L/kg)	Water Saving (%)
Lettuce	12.5	85.6	85.44%
Tomato	18.3	120.4	84.80%
Strawberry	22.7	150.8	84.96%
Basil	15.2	100.3	84.56%
Spinach	13.8	92.1	85.02%

C. Energy Consumption: The Central Trade-off

Across nearly all comparative studies, energy use emerges as the primary limitation of hydroponic sustainability. Model-based analyses comparing hydroponic and conventional lettuce production reveal approximately 80-fold higher energy consumption per kilogram of produce in hydroponic systems[5][9]. Energy demand is largely attributable to artificial lighting, heating, cooling, and environmental control. Similarly, multi-crop comparative reviews report energy increases of approximately 70–80% relative to soil-based systems. Even in urban rooftop systems designed to reduce transport emissions, greenhouse heating and electricity use dominate environmental impact categories. Importantly, reduced "food miles" alone do not compensate for elevated energy requirements. Studies indicate that local urban hydroponic systems can exhibit higher greenhouse gas emissions than conventional rural production if powered by carbon-intensive electricity. Thus, energy source and efficiency constitute the critical determinants of hydroponic sustainability. Without integration of low-carbon energy systems, hydroponic agriculture risks shifting environmental burdens rather than alleviating them.

Table III: Energy Requirement and Energy Efficiency

Crops	Hydroponic Energy Use (kWh/kg)	Conventional Energy Use (kWh/kg)	Energy Increase (%)
Lettuce	3.2	1.8	78%
Tomato	4.5	2.6	73%
Strawberry	5.8	3.4	71%
Basil	4.1	2.3	78%
Spinach	3.7	2.1	76%

IV. AUTOMATION IN HYDROPONIC SYSTEM

Automation is essential to raising hydroponic systems' dependability and efficiency. Sensors, controllers, and actuators are used in automated hydroponics to continuously monitor and modify environmental variables. Temperature, humidity, light intensity, water level, Full spectrum LEDs and nutrient concentration are all measured via sensors. These electronics add stability and reduces human errors, It reduces the constant monitoring process which is the major con of Hydroponics.

Pumps, lighting systems, ventilation units, and other components are automatically regulated by microcontrollers and control units that process sensor data. This minimizes human error and lessens the need for physical intervention. Additionally, automated systems have the ability to log data over time, which facilitates system optimization and performance analysis. Automation improves crop consistency and enables hydroponic systems to run with less oversight.

Automation in hydroponic systems is typically implemented through closed-loop control architectures [11][14] that integrate environmental and nutrient sensing, embedded control units, and electromechanical actuators. From referencing another paper [10]. Sensors continuously measure critical parameters such as pH, electrical conductivity (EC), nutrient solution temperature, ambient temperature, humidity, light intensity, dissolved oxygen, and carbon dioxide concentration. The acquired sensor data is processed by microcontrollers or programmable logic controllers operating under real-time constraints, enabling deterministic task execution and rapid response to parameter deviations. Actuators such as dosing pumps, solenoid valves, circulation pumps, LED grow lights, and ventilation systems are dynamically regulated to maintain optimal growth conditions. Advanced control strategies, including fuzzy logic controllers, are often employed for pH and nutrient regulation to achieve smoother control behaviour and avoid oscillations associated with conventional threshold-based methods. In addition, data-driven approaches such as neural-network models can be used to predict short-term variations in nutrient parameters, allowing proactive adjustments. The incorporation of network connectivity further enables remote monitoring, data logging, and supervisory control, improving system reliability, reducing manual intervention, and enhancing overall resource efficiency in controlled-environment hydroponic cultivation.

V. RESULTS AND DISCUSSION

A. Advantages of Hydroponics

Across the reviewed studies, a clear consensus emerges that hydroponic systems generally outperform conventional agriculture in terms of land and water use efficiency. By eliminating soil and delivering nutrients directly to plant roots, hydroponics significantly reduces water losses and enables higher yields per unit area.

However, energy demand remains the primary environmental bottleneck, particularly in systems relying on artificial lighting, climate control, and automation. As a result, the environmental superiority of hydroponics is highly conditional upon the integration of low-carbon energy sources. While technological advancements such as energy-efficient LEDs, automated monitoring, and predictive control systems [12][13] can substantially improve performance, they cannot eliminate the inherent energy intensity of controlled-environment agriculture. Therefore, sustainability assessments must adopt a comprehensive, system-level and life cycle perspective rather than focusing solely on water or yield metrics.

Hydroponic systems are most appropriate in water-scarce regions, high land-value urban contexts, controlled environments powered by renewable energy, and for high-value horticultural crop production where economic returns justify the technological inputs. Conversely, in regions with abundant arable land, low land pressure, and access to inexpensive but carbon-intensive electricity, conventional agricultural systems may remain environmentally preferable. Despite their advantages, hydroponic systems continue to face challenges, particularly high energy consumption. The development and wider adoption of closed-loop systems offer further improvements in water efficiency and nutrient recycling, strengthening their sustainability potential, though energy optimization remains a critical priority.

B. Challenges and Future Scope

Although multiple studies consistently identify energy consumption as the principal environmental bottleneck of hydroponic and vertical farming systems, existing research remains fragmented. Most studies isolate individual components—such as lighting efficiency, HVAC optimization, or renewable energy integration—without evaluating their combined system-level interactions.

Closed-loop hydroponic systems have demonstrated substantial reductions in water consumption through nutrient recirculation and condensation recovery. However, current literature primarily emphasizes water savings in controlled experimental settings rather than long-term operational resilience.

Comprehensive life cycle assessments integrating automation and renewable integration scenarios [9]. Standardized comparative metrics across crops and climatic contexts. Long-term durability studies of infrastructure materials. Economic viability analyses integrating energy volatility. Hybrid systems combining hydroponics with circular nutrient recovery (e.g., aquaponics, bioponics). Future research should prioritize integrated system modelling that jointly evaluates yield, water, energy, emissions, and economic performance.

VI. CONCLUSION

The reviewed literature demonstrates that hydroponic and controlled environment agriculture systems provide substantial improvements in land and water efficiency compared to conventional soil-based farming. However, these gains are offset by increased energy requirements, making sustainability highly dependent on technological optimization and low-carbon energy integration. Hydroponics should thus be framed not as an inherently sustainable agricultural revolution, but as a conditional and context-dependent strategy whose environmental viability emerges only under carefully designed operational and energy frameworks. By solving issues with land scarcity, water use, and climate variability, automated hydroponic systems offer a viable strategy for sustainable urban agriculture. Automation improves system scalability, uniformity, and efficiency, making hydroponics appropriate for both urban and individual food production.

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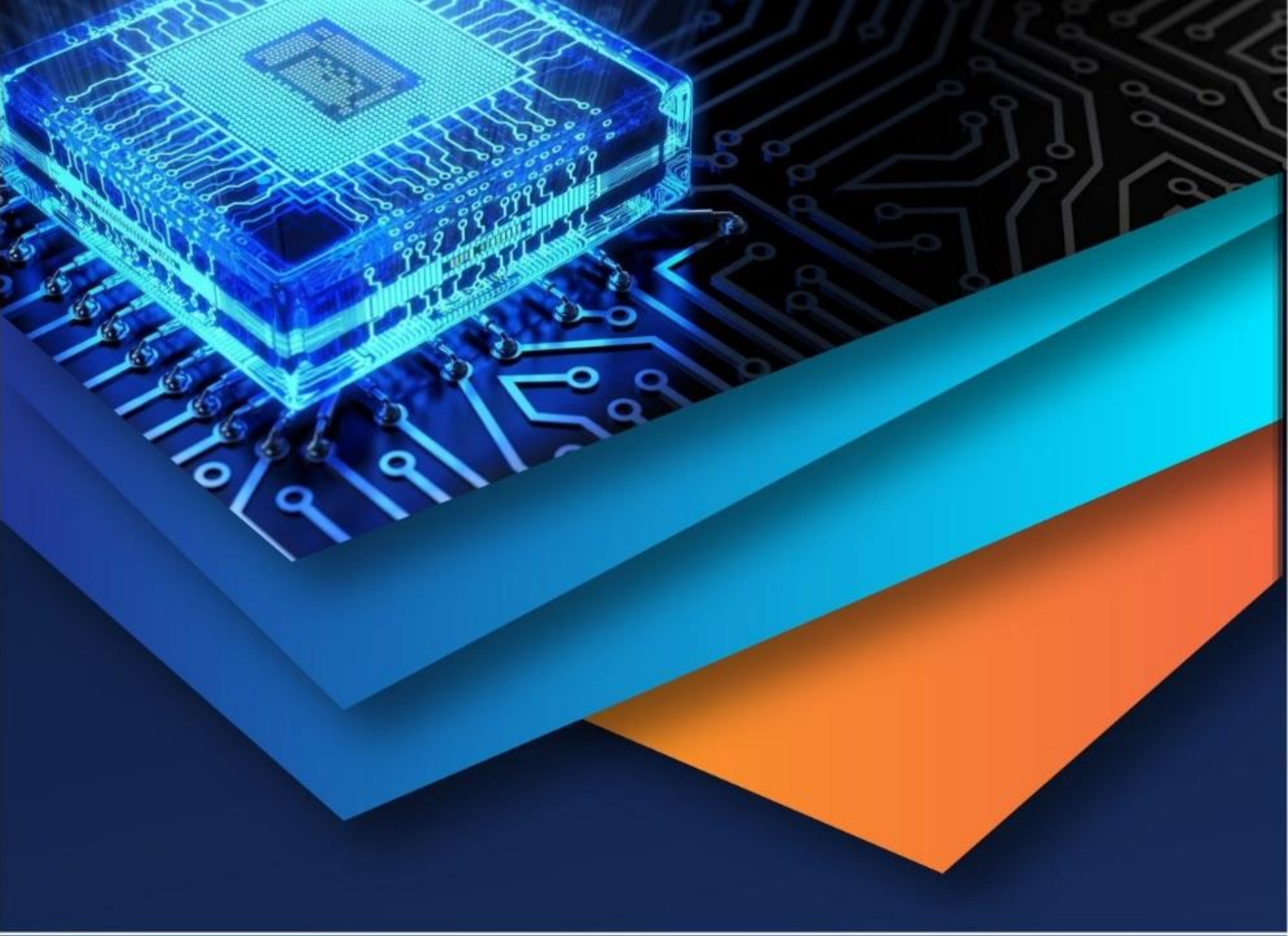

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