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Advancements in Energy-Harvesting Techniques for Agricultural Applications: A Review

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Abstract: Over time, there has been rapid advancement in wireless sensor network (WSN) technologies. These networks have proven to be efficient tools in enhancing agricultural productivity. One significant development in WSNs is the integration of energy harvesting capabilities, allowing them to extract energy from the surrounding environment and utilize it to power wireless Internet of Things (IoT) devices. Energy harvesting involves converting ambient energy from various sources such as solar power, wind, and mechanical vibrations into usable power for devices. This review focuses on exploring the different techniques of energy harvesting for WSNs that can be effectively employed in agricultural monitoring systems. Additionally, it addresses the power consumption issues prevalent in agriculture and aims to identify the most effective strategies for resolving these problems.
Keywords: Energy-Harvesting, Solar energy, Wireless-power transfer, Airflow energy, Vibration energy, Microbial fuel cell energy.

I. INTRODUCTION

Energy-harvesting techniques have witnessed significant progress, particularly in the realm of agriculture. These techniques enable the extraction of energy from the environment, providing a sustainable power source for various agricultural applications. This review explores the latest advancements in energy-harvesting technologies tailored for agricultural purposes. The limited battery capacity of sensor nodes presents a significant constraint in their operation.

Previous research has introduced several energy-efficient schemes to address the power consumption challenge associated with sensor nodes. An alternative approach to mitigate the limited lifespan of these nodes is the utilization of energy-harvesting techniques. These techniques have been developed to enable sensor nodes to extract various forms of energy, such as solar power, wireless power transfer (WPT), mechanical vibrations, kinetic energy, and wind energy, from their surrounding environments (Adu-Manu *et al.*, 2018, Sudevalayam *et al.*, 2011) as shown in Fig. 1. Rechargeable sensor nodes, in comparison to traditional ones, can operate continuously for an extended period.

Ambient energy can be directly converted into electrical energy to power the sensor nodes or stored for future use. In the realm of agricultural applications, energy harvesting proves to be valuable in prolonging the lifespan of sensor nodes. Table 1 showcases the energy-harvesting techniques employed in previous research on precision agriculture, including their respective categories, wireless protocols, output energy/power, agricultural applications, and limitations. Energy-harvesting mechanisms can be combined with batteries in sensor nodes to enhance their performance.

For instance, a sensor node utilizing solar energy can effectively charge its batteries during daylight hours when sufficient sunlight is available. Conversely, during night time when sunlight is unavailable, power reduction techniques like sleep mode (i.e., duty cycle) can be employed to conserve energy.

Furthermore, when the sensor node's batteries have low residual energy, the node can enter restricted sleep periods (i.e., low duty cycle) and reduce transmission power (Bouazzi *et al.*, 2021, Nintanavongsa *et al.*, 2013). Implementing a maximum power point tracking system is another reliable technique for long-term battery charging, minimizing the charge-discharge cycle of the battery (Mazunga F. & Nechibvute A. 2021, Anisi *et al.*, 2017).

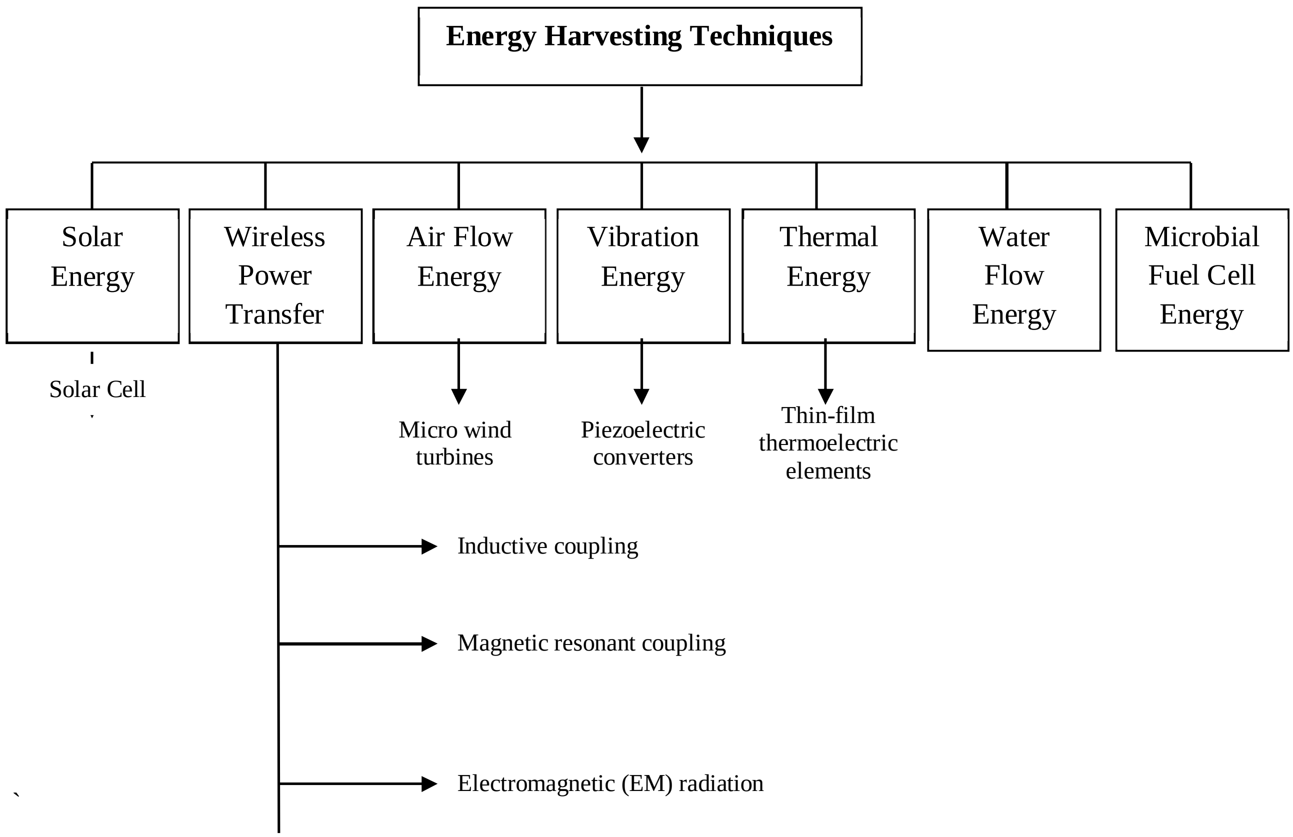

Figure 1. Energy-harvesting techniques in agriculture based on wireless sensor networks

Table 1. Energy-harvesting techniques for previous research works used in agricultural applications

Energy Harvesting Techniques		Reference Example	Wireless Protocol/ Device	Harvesting Energy/Power / Power Saving	Sensors/Actuators	Applications	Limitations
Solar Energy	Solar cell	Zou *et al.*, 2016	ZigBee (CC2530)	500 mW	Shadow detection, temperature, and humidity/shadow tracking to save energy	Trees in the agriculture field	Solar cell system is generally irregular and extensively influenced by the weather changes
WPT	Inductive coupling	Mittleider *et al.*, 2016	Zigbee	2.4 W	Vibration, pressure soil moisture, and temperature	Agriculture fields	Strong coupled magnetic resonance are required
	Magnetic resonant coupling	Simic *et al.*, 2015	N/A	1315 J	Agricultural environments sensors/water processing system	Agriculture areas	Exhausting the UAV battery
	Electromagnetic wave	Chen *et al.*, 2016	Zigbee	N/A	Temperature, Strain, humidity, and displacement	Agriculture fields	Harvested energy is inadequate to replenish an ad hoc network with multi-hop

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Air Flow Energy Wind Turbine	Nayak *et al.*, 2015	Zigbee	70–100 mW	Ambient temperature, rain fall, and soil moisture/irrigation system	Vineyard	Wind power is inefficient when the wind intensity is not constant and irregular
Vibration Energy Piezoelectric convertors	Müller *et al.*, 2010	ZigBee (CC2420 and CC2500) and CC1100	200 µW	Ambient vibration sensor	Agricultural machinery	Transmission errors due to Interferences from similar neighboring WSN and third-party system
	Bertacchini and Larcher, 2016	IEEE 802.15.4 (CC2500)	14%	MEMS inertial	Agricultural machinery	N/A
	Scorcioni *et al.*, 2011	IEEE 802.15.4	724 µW@2.0g	Vibration sensor	Agricultural machinery	Duty-cycle of the end device must be modified according to the total power collected by the piezoelectric convertor
Thermal Energy Thermo electrical elements	Philipp *et al.*, 2012	ZigBee (CC2530 embeded in HaLOEWEn platform	N/A	Temperature and soil moisture/irrigation control system	Precision irrigation	Harvested energy is comparatively low based on thermoelectric element
Water Flow Energy	Morais *et al.*, 2008	ZigBee	16–19 mW	Soil moisture, air temperature, relative humidity, soil temperature, and solar radiation/irrigation control system	Precision Agriculture	The amount of energy harvested is not enough alone to supply the ZigBee router node
Microbial Fuel Cell Energy	Sartori and Brunelli, 2016	LoRa	296 µW	Capacitive phreatimeter/irrigation system	Precision agriculture	The amount of microbial fuel cell power is not enough to power the LoRa wireless protocol and microcontroller directly

A. Solar Energy

Solar energy derived from photovoltaic systems has found valuable applications in agriculture-based wireless sensor networks (WSNs) (Fasla & Anil 2021, Akhtar *et al.*, 2015). The use of solar cells presents an effective solution (Zhang *et al.*, 2017) to ensure the longevity and sustainability of agricultural monitoring systems. Numerous studies have employed solar cell energy to provide long-term power to sensor nodes in agriculture applications. For instance, Gutierrez et al. (2014) developed an irrigation system based on the ZigBee wireless protocol. The system aimed to optimize water usage for agricultural crops by placing temperature and soil moisture sensors within the plant roots. These sensors transmitted data to a web application via a gateway. The system employed solar cell panels and rechargeable batteries to power the WSN. Notably, water savings of up to 90% were achieved compared to conventional irrigation methods, making it suitable for geographically isolated regions with limited water sources. Zou et al. (2016) focused on enhancing the battery lifetime of a WSN by leveraging harvested energy, specifically solar cells, and employing shadow detection techniques.

This approach allowed sensor nodes to adjust their scheduling to optimize power production and battery levels. Routing and clustering mechanisms were utilized to optimize data transmission, and a Bayesian network provided warning reports of potential bottlenecks. Experimental results demonstrated the effectiveness of these techniques in enabling continuous and efficient network operations. Sah *et al.,* 2023 proposed a modified PROfile energy (Pro-energy) prediction technique to control unnecessary errors in solar-based harvesting systems related to the sensing devices, which estimates the most similar profile-based energy observation in previous time slots.

Their proposed method uses prior energy measurements to show future energy status in the respective time slots. Experimental observations on various performance matrices validate that the modified Pro-energy prediction technique exhibits more promising and superior performance than existing EMWA, weather-conditioned moving average (WCMA), and Pro-energy methods. Ravi et al. (2016) developed a micro-irrigation system powered by a small solar cell.

They conducted a life cycle assessment, comparing the proposed system with traditional methods such as aloevera cultivation. The evaluation highlighted the economic viability of the solar-powered system for rural areas, emphasizing its potential for agricultural electrification and economic growth. Roblin (2016) presented an irrigation system that relied on solar cells for regions with abundant sunlight. This system replaced traditional electricity grid or diesel generator-based pumps with solar-powered ones. The study showcased the advantages of solar-powered irrigation systems, including uninterrupted availability and reduced operating costs compared to other energy resources. Kumar et al. (2015) proposed a similar irrigation system that utilized photovoltaic panels to power a water pump.

This system improved water usage efficiency by converting continuous water flow into controlled drips. The integration of energy harvesting techniques with packet transmission control was suggested by Kwon et al. (2015). Their prediction technique enhanced WSN performance by adjusting packet transmissions based on estimated energy levels, resulting in improved throughput and power consumption. Hou et al. (2010) implemented a solar cell-powered WSN in a greenhouse for humidity and temperature control. The system employed low-power microcontrollers and transceivers to minimize power consumption. In another study by Alippi et al. (2012), a solar cell served as a battery charger for a WSN-based ZigBee wireless transceiver, enabling monitoring of vineyards' humidity, temperature, rain level, and leaf wetness. These studies demonstrate the effective utilization of solar energy and solar cell technologies in agricultural WSNs, enabling efficient monitoring and control of agricultural parameters while minimizing power consumption.

B. Wireless Power Transfer

Recent advancements in wireless power transfer (WPT) hold the potential to greatly extend the lifespan of Wireless Sensor Networks (WSNs), allowing them to operate continuously. WPT techniques enable the transmission of electromagnetic energy between devices without the need for physical contact. This capability has the potential to overcome the power supply limitations of WSNs. As a result, researchers have explored the use of mobile nodes capable of delivering power to deployed sensor nodes (Lai and Hsiang 2019, Mittleider *et al.,* 2016; Chen *et al.,* 2016). However, WPT technology presents challenges in terms of energy cooperation among neighbouring nodes in WSNs. To address this, future research aims to enable sensor nodes to harvest energy from the environment and transfer it to other nodes in the network, creating a self-sustaining network (Gurakan *et al.,* 2016). Recent studies have focused on multi-hop energy transfer (Kaushik *et al.,* 2013; Xie *et al.,* 2013), which has paved the way for new energy cooperative schemes and WPT charging protocols. WPT can be categorized into three main subcategories: electromagnetic (EM) radiation, magnetic resonator coupling, and inductive coupling, as depicted in Figure 2. Wireless charging in WSNs can be achieved through EM radiation and magnetic resonant coupling. EM signals, however, suffer from attenuation over distance and may pose health risks due to active radiation. On the other hand, magnetic resonant coupling proves to be efficient within several meters and can meet the power requirements of WSNs in agricultural settings. Numerous studies have utilized WPT to charge sensor nodes in various applications and fields. Overall, recent developments in WPT offer promising solutions for enhancing the longevity and sustainability of WSNs. By leveraging energy harvesting and cooperative techniques, WSNs can operate continuously and efficiently in various applications, including agriculture.

C. Air Flow Energy

Utilizing wind energy is an additional method for harvesting energy that can be employed to supply power to sensor nodes in agricultural applications. In the study conducted by Nayak *et al.,* 2014, an adaptive routing protocol, wind energy harvesting, and sleep scheduling were investigated to reduce the power consumption of ZigBee transceivers and prolong the lifespan of the Wireless Sensor Network (WSN).

D. Vibration Energy

Piezoelectric-based vibration energy can be effectively utilized to charge the battery of sensor nodes, thereby extending their operational lifespan. In a study conducted by Müller et al. (2010), various Wireless Sensor Network (WSN) protocols based on ZigBee (CC2420 and CC2500) and CC1100 were analyzed for their suitability in agricultural applications. To achieve real-time capability, low latency, and deterministic behavior in the context of agricultural machinery, a fully synchronous protocol with a time-slot architecture was proposed. The main objective of their application was to monitor the back door position and filling level of a forage wagon using a ZigBee (CC2420) RF transceiver. Clock synchronization among all nodes was implemented to ensure precise power on/off timings for each sensor node. Additionally, an energy-harvesting unit based on a piezoelectric material was designed, providing an average power output of 200 µW to the sensor nodes. With this setup, the sensor node was able to transmit a data payload of nine bytes in just 40 ms.

E. Water flow Energy

Morais et al. (2008) developed a multi-energy sources platform specifically designed for precision agricultural applications. The researchers investigated the viability of water flow, wind speed, and solar radiation as potential energy sources to fulfill the requirements of a ZigBee router node in a Wireless Sensor Network (WSN). They presented several powered solutions for WSNs based on these energy sources.

In terms of water flow energy, the authors focused on utilizing the water flow in the pipes of crop irrigation systems to generate energy for the ZigBee router node. This approach can be implemented in various agricultural settings such as greenhouses, aquaculture, and hydroponic systems, where water recirculation through pipes is continuous. Similar to larger hydroelectric generation utilities, a turbine connected to a small direct current (DC) generator can be driven by the water flow in the pipes, which originates from the main water source.

The experimental results demonstrated that when the three energy sources (water flow, wind, and solar) were combined, they were able to generate 58 mAh of energy, surpassing the energy requirement of the ZigBee router node, which was 39 mAh. Specifically, the design focused on harnessing water flow energy from irrigation system pipes to generate power for the ZigBee router node. This innovative concept can be applied in diverse agricultural settings, such as greenhouses, aquaculture, and hydroponic systems, where water recirculation in pipes remains constant. Similar to conventional hydroelectric generation setups, the water flow from the main source can be utilized to drive a turbine connected to a small direct current (DC) generator.

F. Microbial Fuel Cell Energy

Microbial fuel cells are another type of energy harvesting technique that extracts energy from an energy-neutral system. Sartori and Brunelli (2016) proposed the use of microbial fuel cells to power an underground freshwater monitoring system. This system was designed to monitor water levels in the phreatic zone, artesian wells, and tanks. It consisted of a low-cost phreatimeter sensor, a low-power microcontroller (MSP430FR5739), and a low-power LoRa wireless protocol. However, the energy extraction from the microbial fuel cell, which amounted to 296 µW, was insufficient to directly power the active mode of the LoRa wireless protocol and microcontroller.

To address this, a DC-to-DC boost converter was employed to raise the input voltage from a small value of 130 mV to 4.5 V. It should be noted that solar cells are commonly preferred in agricultural applications as they are easy to install, efficient in sunny conditions, and provide higher energy output compared to other energy harvesting techniques. Table 1 illustrates the energy supply capabilities of various harvesting techniques.

Solar panels, for instance, can provide 100 mW/cm^2, while radio frequency, thermal, vibration, wind, microbial fuel cell, magnetic resonant coupling WPT, and water flow techniques offer lower energy outputs of 0.001, 0.06, 0.8, 1.0, 0.296, 14, and 19 mWs, respectively (Morais *et al.*, 2008; Sartori *et al.*, 2016; Paradiso *et al.*, 2005; Seah *et al.*, 2013). In a practical example depicted in Figure 2 (Part A), the power consumption of the WSN components from Alippi et al. (2012) is considered. With power requirements of 35 mW for ZigBee (Chipcon CC2420), 0.27 mW for the temperature sensor, 3 mW for the humidity sensor, 0.27 mW for the rain gauge sensor, 5 mW for the leaf wetness sensor, and 24 mW for the ATmega128L microcontroller (Abbasi *et al.*, 2014), a single solar panel measuring 2×2 cm2 would be sufficient to power this WSN. However, as the power consumption of the WSN increases, the size of the solar panel would need to be adjusted accordingly.

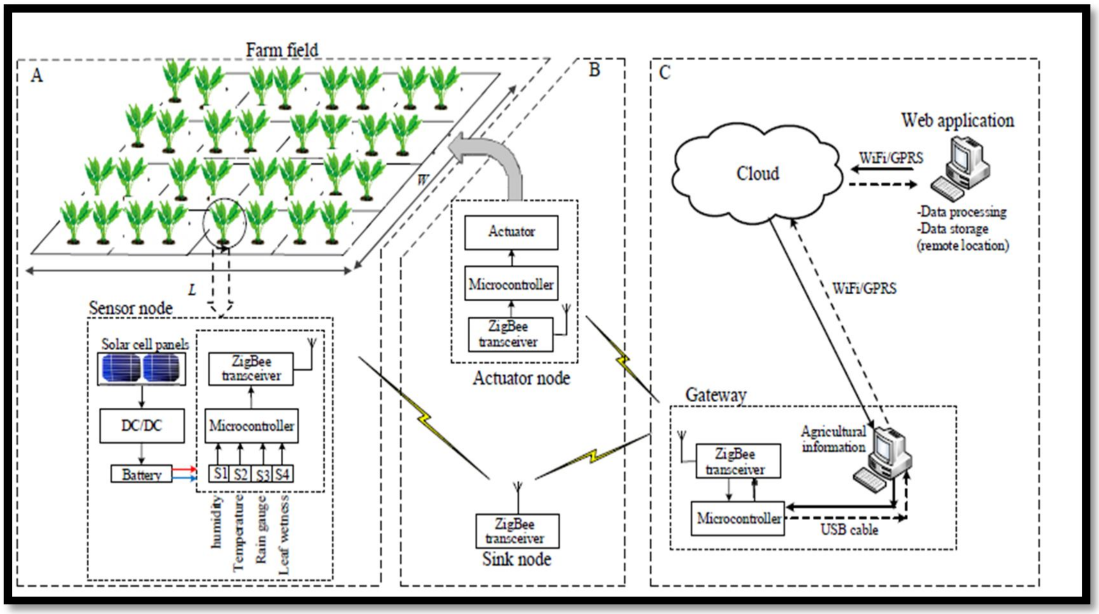

Figure 2. Example of farm field-based Internet of Things (IoT) and provided by a solar cell battery charger: (a) Agriculture sensor node with related sensor and solar cell, (b) Sink and actuator nodes, and (c) Gateway node and cloud computing (Source: Jawad *et al.*, 2017)

II. CONCLUSIONS

This paper presents a comprehensive review on energy-harvesting techniques in agriculture. The taxonomy presented in this review highlights various types of energy harvesting techniques suitable for the agricultural domain, including solar energy, wireless power transfer, airflow energy, vibration energy, water flow energy, and microbial fuel cell energy. Among these techniques, solar cells are preferred for most agricultural operations as they can serve as efficient battery chargers for wireless sensor networks (WSNs). Solar cells are easy to install, perform well in sunlight, and provide higher energy output compared to other energy-harvesting techniques. Specifically, solar panels can generate a power supply of 100 mW/cm^2, while vibration, wind, microbial fuel cell, magnetic resonant coupling wireless power transfer, and water flow techniques can provide power outputs of 0.8, 1.0, 0.296, 14, and 19 mWs, respectively. Furthermore, this review also investigates and compares previous research to identify the current challenges and issues associated with implementing WSNs in agricultural applications.

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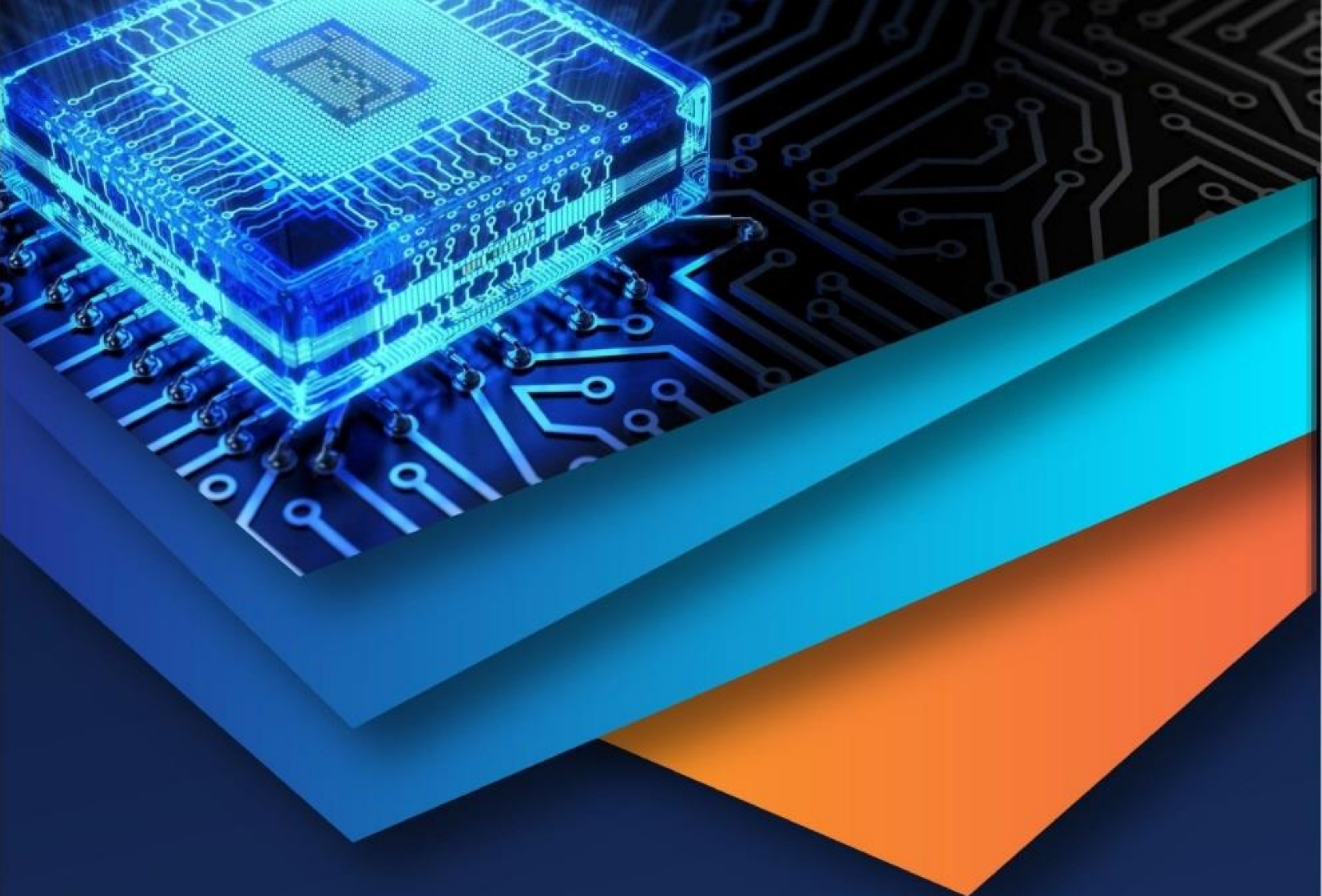

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