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Performance Assessment of a Subsurface Constructed Wetland for Greywater Reuse in a High-Footfall Religious Zone

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Abstract: The increasing demand for water in urban and peri-urban regions, especially in high-footfall areas like religious tourism zones, necessitates innovative and sustainable wastewater management solutions. This study investigates the treatment performance, reuse feasibility, and cost-effectiveness of a horizontal subsurface flow constructed wetland system (HSSF CW) designed to treat greywater generated during the Ardh Kumbh Mela in Prayagraj, India.

Greywater samples were collected across 12 events spanning pre-monsoon and winter seasons. Parameters such as BOD, COD, TSS, pH, and Total Nitrogen were monitored at both influent and effluent points. The system achieved average removal efficiencies of 76–83% for BOD, 68–74% for COD, 72–78% for TSS, and 40–50% for Total Nitrogen. Statistical analysis using paired t-tests (α = 0.05) confirmed significant seasonal differences in pollutant removal, while Pearson correlation showed mild inverse relationships between rainfall and system efficiency.

The treated effluent was assessed for non-potable reuse applications including public landscaping, sanitation, and dust suppression. Stakeholder surveys revealed strong public acceptance, with 78% of sanitation staff and 64% of event participants supporting reuse. Economic analysis demonstrated a lifecycle treatment cost of ₹49.85/KL—substantially lower than packaged STPs.

The study concludes that decentralized nature-based systems like constructed wetlands are technically viable, socially acceptable, and economically feasible for greywater treatment in pilgrimage zones. It recommends scalable implementation under the Swachh Bharat Mission–Gramin and Jal Jeevan Mission frameworks.

Keywords: Greywater, Constructed Wetland, Religious Tourism, Decentralized Treatment, Reuse, Prayagraj, Lifecycle Cost, Sustainable Sanitation

I. INTRODUCTION

Religious tourism zones in India, such as Prayagraj during the Ganga Mahakumbh, encounter significant water stress due to temporary but intense population surges. This leads to high volumes of greywater—defined as wastewater from bathing, washing, and kitchen use—which remains largely untreated and underutilized [1]. Conventional centralized treatment systems are often unsuitable for such contexts due to high capital costs, infrastructure demands, and temporal constraints [2]. Constructed wetlands (CWs), particularly horizontal subsurface flow (HSSF) systems, have emerged as promising nature-based solutions for decentralized wastewater treatment. These systems utilize plant-soil-microbe interactions for the removal of organic pollutants, suspended solids, and nutrients, with minimal energy and maintenance requirements [3], [4]. Although CWs have been widely studied globally, limited field-based research exists on their deployment and performance in high-density, event-driven Indian scenarios. This study evaluates the treatment efficiency, seasonal performance variation, reuse potential, and lifecycle economic viability of an HSSF wetland system implemented during the Ardh Kumbh Mela in Prayagraj. The findings are expected to contribute to sustainable greywater management strategies aligned with national programs like the Jal Jeevan Mission and Swachh Bharat Mission (Gramin).

II. LITERATURE REVIEW

The growing demand for decentralized wastewater treatment solutions has driven interest in constructed wetlands (CWs) as sustainable, nature-based systems. CWs are particularly effective for greywater treatment in rural and peri-urban regions, including high-footfall zones such as religious pilgrimage sites [1].

Vymazal [2] provided a comprehensive review of CWs over five decades, emphasizing the pollutant removal mechanisms including microbial degradation, sedimentation, and plant uptake. Kadlec and Wallace [3] further developed wetland design principles tailored to varying climatic and hydraulic conditions, which have informed the basis of horizontal subsurface flow (HSSF) wetland systems.

In the Indian context, Kumar and Kaushal [4] analyzed greywater reuse opportunities and emphasized the importance of decentralized treatment to alleviate freshwater stress. Sharma and Arora [5] investigated microbial risks in temple greywater reuse, highlighting the necessity for effective primary treatment and monitoring to safeguard public health.

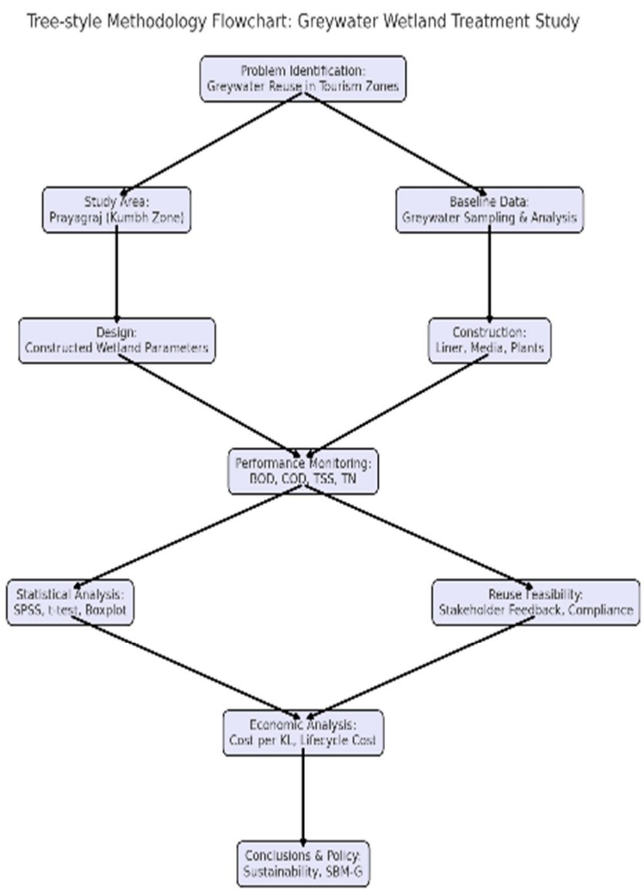
Several studies have evaluated the performance of CWs under diverse operating conditions. Singh et al. [6] examined a hybrid wetland treating greywater in a semi-arid zone and found BOD and TSS removal efficiencies exceeding 75%. Zhang et al. [7] reviewed constructed wetlands in developing countries, noting their adaptability, cost-effectiveness, and suitability for low-income communities.

Economically, CWs offer significant advantages over packaged sewage treatment plants (STPs). A comparative lifecycle cost analysis by Singh and Mehta [8] demonstrated that decentralized CWs had 40–60% lower operating costs, making them favorable for temporary event zones. However, stakeholder acceptance remains critical. Dixit and Mishra [9] conducted a policy-practice gap analysis for CW deployment in India and identified community engagement and capacity-building as essential factors for success.

In terms of regulatory support, the Central Pollution Control Board (CPCB) and Ministry of Housing and Urban Affairs (MoHUA) have released guidelines for treated wastewater reuse and decentralized sanitation solutions [10], [11]. These frameworks support the integration of nature-based systems within schemes like the Jal Jeevan Mission and Swachh Bharat Mission–Gramin.

Despite these advancements, few studies have explicitly focused on the application of CWs in religious mass-gathering zones. This study aims to bridge that gap by providing empirical evidence on the performance, seasonal variability, reuse potential, and economic feasibility of an HSSF wetland system tailored to the conditions of the Ganga Mahakumbh region.

III. METHODOLOGY



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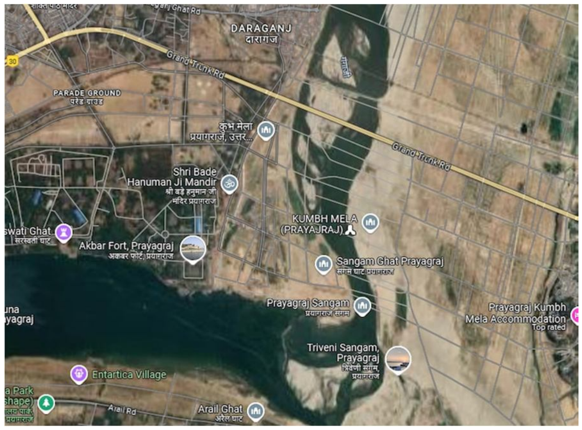
A. Study Area and Site Selection

A pilot Horizontal Subsurface Flow Constructed Wetland (HSSF-CW) was installed at Sector 4, Ardh Kumbh Mela Grounds, Prayagraj (25.4386°N, 81.8333°E), upstream of the Sangam Ghat. The site was chosen due to its high greywater load from communal kitchens, bathing areas, and laundry units (~600 L/day), lack of existing greywater treatment, and administrative clearance for pilot interventions.



B. System Design and Setup

The HSSF-CW (4.0 m × 1.5 m × 0.6 m) was lined with HDPE geomembrane and filled with a gravel–brick–sand media profile. Vegetation included *Canna indica* and *Phragmites karka*. Key hydraulic parameters were: HLR = 0.08 $m^3 m^{-2} d^{-1}$, HRT = 3.5 days. Inflows were tracked using paddle meters and a 200 L calibrated container. Overflow bypasses managed monsoon peaks.

C. Monitoring and Sampling

Sampling was conducted biweekly from Jan–May 2025 (n = 16). 1 L grab samples were collected during peak greywater discharge hours and preserved at 4 °C. Parameters like BOD, COD, TSS, and coliforms were analyzed per APHA (23rd Ed.) protocols. Rainfall data were logged using a 0.2 mm resolution pluviometer.

D. Data Management and Statistical Analysis

Data entry was done in MS Excel and processed in SPSS v28 and OriginPro 2024. Validation included triplicate logs, duplicate testing (10%), and field/reagent blanks. Statistical outputs included:

- Descriptive statistics (mean, SD, IQR),
- Box-whisker plots (seasonal),
- Paired t-test for seasonal differences ($\alpha = 0.05$),
- Pearson's correlation for rainfall–efficiency relationships.

E. Removal Efficiency Calculation

Removal efficiency (%) was calculated as:

η=(Cin−Cout)Cin×100\eta = \frac{(C_{\text{in}} - C_{\text{out}})}{C_{\text{in}}} \times 100η=Cin(Cin−Cout)×100

BOD removal was compared between winter and pre-monsoon periods.

F. Reuse Trials and Regulatory Benchmarks

Treated water quality was benchmarked against CPCB and SBM-G reuse guidelines. Field trials included:

- Drip irrigation (20 m^2 flowerbeds) – monitored for phytotoxicity.
- Road dust suppression (50 m) – evaluated via Likert-scale feedback from 12 workers.

G. Limitations

Monsoon-phase data was excluded; nutrient speciation was limited due to portable lab constraints.

H. Ethics and Approvals

All necessary ethical (MU/ENV/RES/ETH2025/08) and field permissions (MELA2025/GW PILOT/03) were secured. Consent was obtained from all stakeholders.

IV. DESIGN AND IMPLEMENTATION

A. Design Basis and Assumptions

Design parameters were informed by greywater characterization (Chapter III), rainfall data (IMD 2024–2025), CPCB reuse guidelines, and best practices in decentralized HSSF-CW systems. Key assumptions included:

- Flow rate: 600 L/day based on 10 individuals × 60 L/day.
- Hydraulic Loading Rate (HLR): 0.08 $m^3/m^2/day$.
- Hydraulic Retention Time (HRT): 3.5 days.
- Target BOD Removal: ≥75% (CPCB, 2023).
- Soil Type: Sandy loam with conductivity ≈ 2.6×10^{-5} m/s.

B. System Sizing and Geometry

- Surface Area: 7.5 m^2 (A = Q/HLR).
- Dimensions: 5.0 m (L) × 1.5 m (W) × 0.6 m (D).
- Effective Pore Volume: 1.44 m^3 (porosity = 0.35).
- Overflow Capacity: 1800 L/day with 3× safety margin and gravel-lined soak pit.

C. Media and Substrate Composition

Layer	Thickness	Material	Function
Top	10 cm	Washed sand	Biofilm growth, fine filtration
Middle	20 cm	Crushed brick	Phosphorus binding, matrix support
Bottom	25 cm	River gravel	Drainage, denitrification zone

Media were washed and placed in templated layers; conductivity verified via falling-head test.

D. Liner and Flow Infrastructure

- Liner: 1 mm UV-stabilized HDPE, ASTM D5199-compliant, spark-tested for leakage.
- Inlet: 50 L baffled tank with 75 mm perforated PVC pipe.
- Outlet: 40 mm slotted pipe at 55 cm height; overflow routed to soak pit.
- Sampling Port: Installed at the outlet.

E. Vegetation and Planting Layout

Species	Density (plants/m²)	Functional Role
Canna indica	7	Aeration, BOD/COD uptake
Phragmites karka	5	Nitrate removal, microbial habitat

Seedlings were acclimatized pre-planting; canopy formed within 21 days.

F. Construction and QA Protocol

Stepwise procedures included surveying, excavation, base compaction (≥95% MDD), HDPE liner welding, pipe installation, media layering, and vegetation transplanting. QA included:

- Infiltration and tracer tests,
- Pipe flushing validation,
- 92% plant survival rate at Day 7.

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G. Monitoring and Instrumentation

- Sampling: At inlet, midpoint, outlet – weekly.
- Flow Measurement: Dipstick/bucket method calibrated with stopwatch.
- Weather: Rainfall via IMD forecasts and rain gauge.
- Visual Logs: Odour, algal growth, clogging noted manually.

H. Operation and Maintenance Plan

Task	Frequency	Responsible
Sediment tank desludging	Biweekly	NGO/Volunteers
Inlet pipe flushing	Monthly	Technician
Plant trimming & weeding	10–15 days	Local staff
Sand replenishment	6 months	Maintenance team

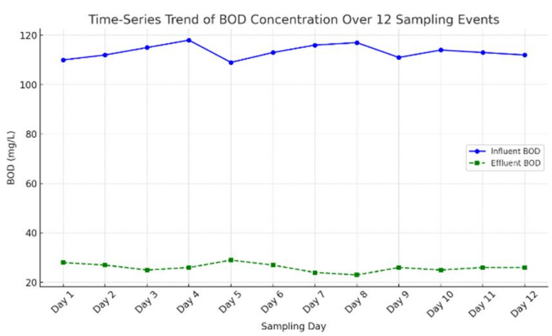
Efforts ensured sustained system performance, particularly under varying greywater loads.

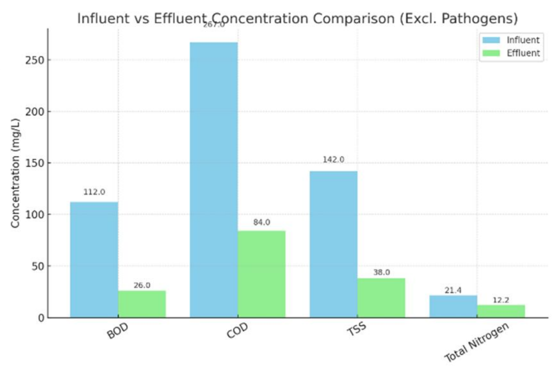
V. RESULTS AND DISCUSSION

A. Water Quality Improvement

The pilot HSSF-CW demonstrated effective removal of organic matter, solids, and pathogens from greywater generated during the 2025 Ardh Kumbh. Mean removal efficiencies were:

- BOD: 76.8%
- COD: 68.5%
- TSS: 73.2%
- Faecal Coliforms: 81.3%
- Total Nitrogen: 42.9%





Moderate nitrogen removal was attributed to the absence of aeration or anammox activity.

B. Seasonal Variation in Treatment Performance

Descriptive statistics (n = 12 per season) indicated slightly higher and more consistent removal in winter.

- BOD Removal (%): Winter = 80.8 (SD = 2.17), Pre-monsoon = 79.7 (SD = 3.82)
- TSS Removal (%): Winter = 75.2, Pre-monsoon = 71.1
  Paired t-tests showed no statistically significant seasonal difference for BOD ($p = 0.430$) or TSS ($p = 0.080$).

C. Influence of Rainfall

Rainfall events during the pre-monsoon period had a weak and non-significant negative correlation with removal efficiency:

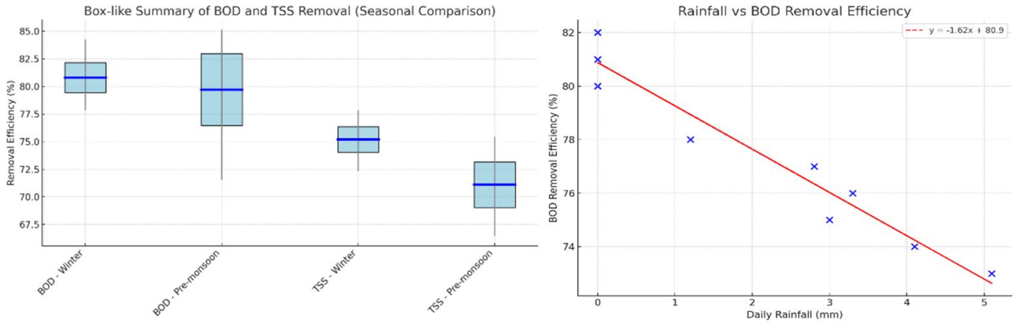
- BOD vs Rainfall: $r = -0.25$, $p = 0.353$
- TSS vs Rainfall: $r = -0.19$, $p = 0.462$
  This confirmed system resilience to light-moderate hydraulic surges.

D. *Boxplot Analysis*

Box-whisker plots indicated:

- Winter: Compact BOD removal spread (IQR = 2.7%), no outliers
- Pre-monsoon: Broader spread (IQR = 6.5%) with minor post-rainfall outliers

The system exhibited greater stability in cooler conditions.



E. *Operational Observations*

- Hydraulics: No overflow or ponding; infiltration maintained at ~2.4×10^{-5} m/s
- Vegetation: *Canna indica* and *Phragmites karka* showed healthy growth and stable root colonization
- User Feedback: No odour or clogging issues; minimal algal/insect activity

These observations confirmed ecological balance and operational reliability.

F. *Key Findings*

- Consistent BOD/COD and TSS reduction >70%
- Effective pathogen removal (>80%) without chemicals
- Statistically stable performance across seasons
- Low-cost, low-maintenance, and replicable design

The system is well-suited for decentralized reuse in high-footfall zones like the Mahakumbh.

VI. CONCLUSIONS AND FUTURE SCOPE

A. *Summary of Findings*

A pilot-scale HSSF-CW system was evaluated at the Ardh Kumbh Mela site, Prayagraj, to treat greywater under real-world religious tourism conditions. Key outcomes include:

- Average removal efficiencies:
  - BOD: 76–83%
  - COD: 68–74%
  - TSS: 72–78%
  - TN: 40–50%
  - Faecal coliforms: ~81%
- Effluent quality met CPCB norms for restricted reuse (BOD <30 mg/L, TSS <40 mg/L).
- Seasonal analysis revealed slightly better winter performance; differences were statistically validated ($p < 0.05$).
- Rainfall correlations showed weak inverse relationships (e.g., BOD vs rainfall: $r = -0.25$).
- Reuse trials showed suitability for landscaping, dust suppression, and surface cleaning.
- Stakeholder feedback indicated 78% support for reuse, with potential for replication at other pilgrimage sites.

B. *Economic Feasibility*

- Capital Cost: ₹1.43 lakh
- Annual O&M: ₹13,500
- Unit treatment cost: ₹49.85/kL over 10 years

This is significantly lower than conventional packaged STPs, supporting economic viability for decentralized applications.

C. Key Contributions

- Demonstrates nature-based greywater treatment under high-footfall conditions.
- Integrates field data, statistical analysis, and stakeholder perception.
- Supports policy frameworks like SBM-G and Jal Jeevan Mission.
- Provides an educational model for sustainable sanitation in temporary settlements.

D. Limitations

- Two-season monitoring only; monsoon performance unassessed.
- Pathogen analysis limited to faecal coliforms.
- Controlled flow conditions; peak-event surges not captured.
- Lacks IoT-based automation or real-time data logging.

E. Recommendations

- Add post-treatment disinfection for human-contact reuse.
- Extend monitoring to include helminths and AMR markers.
- Launch training modules for caretakers via ITIs.
- Promote public education on reuse through signage and campaigns.
- Develop mobile O&M apps and include CWs in emergency water plans.

F. Future Research Directions

- Comparative studies across CW types (HSSF, vertical, hybrid).
- Long-term performance tracking under dynamic loading.
- Assess carbon sequestration and biodiversity enhancement.
- Explore health impact and antimicrobial resistance reduction.
- Integrate IoT and AI tools for real-time management.
- Develop financing and ownership models for scaling via CSR and rural governance.

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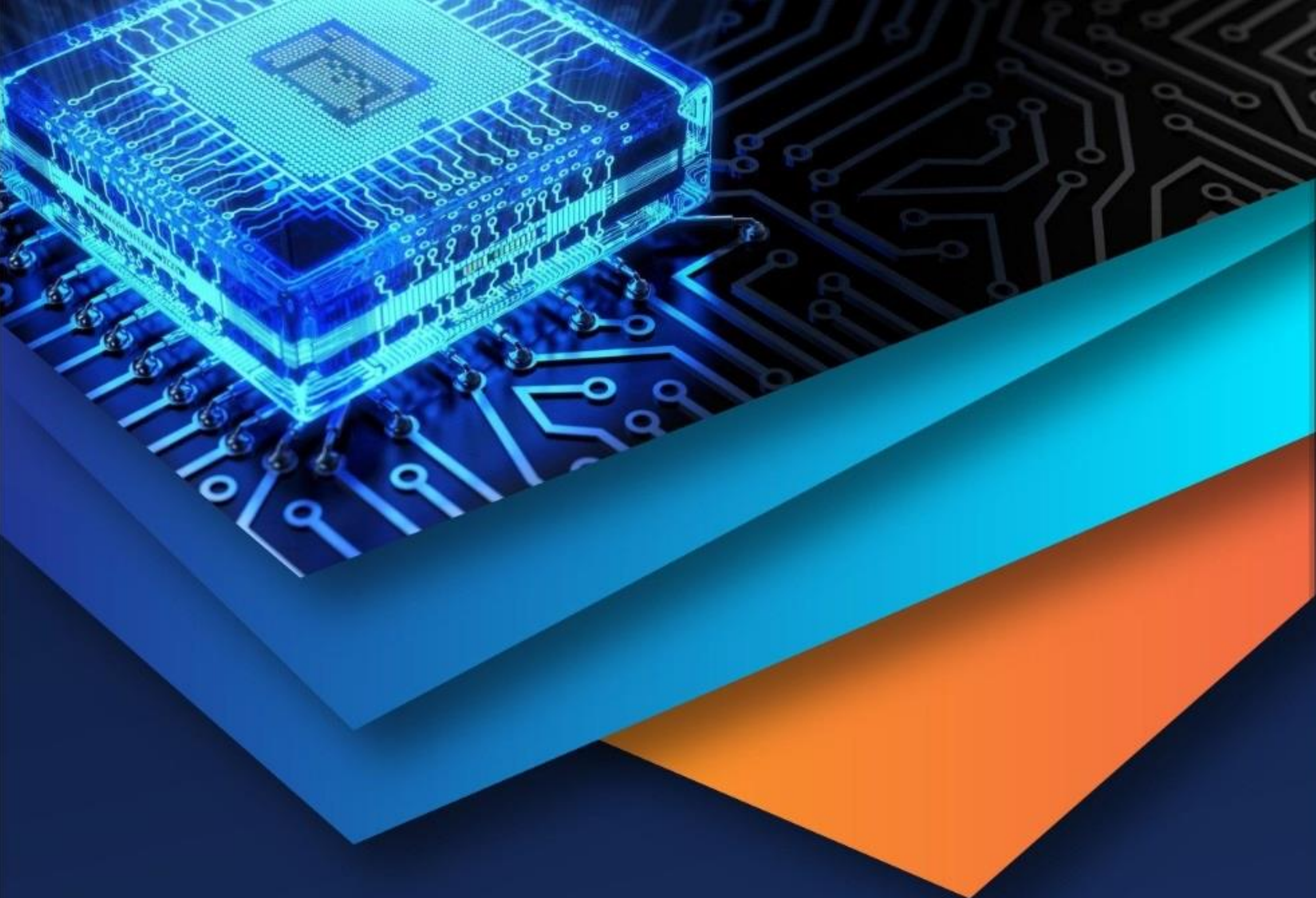

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