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Sustainable Manufacturing in India: Evaluating Green Technologies, Energy-Efficient Systems, and Strategic Enablers in Industry 4.0/5.0 Contexts

Jabbar Ahmad[1], Sanjeev Sarswat[2]
Vivekananda College of Technology and Management, Aligarh

Abstract: The increasing pressure of the need of environmentally friendly and resource-friendly industrial processes, has boosted the sustainable manufacturing as a strategic necessity, especially in the emerging economies such as India. The paper presents the multi-dimensional nature of the adoption of sustainability within Indian manufacturing, in particular, small and medium enterprises (SMEs). With the mixed-methods research design, the study combines survey information of more than 100 firms, interviews with experts, the estimation of green technology, organizational enablers, and policy mechanism using simulation modeling with RETScreens and MATLAB, and structural equation modeling (PLS-SEM) to evaluate the influence of green technologies, organizational enablers, and policy mechanisms.

The findings indicate a middle ground of adoption as far as green manufacturing processes like energy systems, waste heat recovery, and closed-loop water reuse are concerned. However, adoption is not equally distributed across the sectors because of the limitation of capital, absence of technical competencies, and fractured laws. Companies that have incorporated the use of Industry 4.0 technologies including the IoT, AI, and blockchain have shown better sustainability results, particularly when coupled with endogenous forces such as the dedication of top management, cross-functional education, and awareness of cultures regarding sharing knowledge. The importance of favorable policies and government incentives is also mentioned in the study but the current mechanisms are usually found to be insufficient to cover the needs of SMEs. Fuzzy set analysis and life cycle analysis (LCA) validate that effective adoption of sustainability is the product of synergistic technologies, organizational capacity and institutional support. The study gives a verified sustainability evaluation tool that can be used by companies to compare performance and strategize on interventions. The findings offer policy-makers, executives in the manufacturing sector, and scientific communities interested in scaling sustainable manufacturing with a view to scaling it in an inclusive and systematic manner.

Keywords: sustainable manufacturing, SMEs, Industry 4.0, green technologies, India, policy, organizational enablers, simulation modeling.

I. INTRODUCTION

The high rates of industrialization experienced in the last few decades have played a major role in enhancing the growth of the economy as well as causing a terrible environmental degradation. The industrial sectors consume more than 30 percent of the world energy, and about 20 percent of global carbon dioxide emissions are produced in the industry (International Energy Agency, 2023). With an increasing alarm around the issue of the environment, a green revolution of the industrial structure has become an international concern. In this regard, sustainable manufacturing has come out as a response mechanism of great concern to balance industrial development and environmental management.

Sustainable manufacturing can be described as the production of manufactured goods in economically viable processes to reduce adverse effects on the environment, energy and natural resources conservation, and employee and community safety (Dangelico & Pujari, 2019). The practice is not only in line with the triple bottom line in sustainability which is people, planet and profit but also in its inbuilt ecological responsibility, economic performance, and social equity. Moreover, it is in line with the United Nations Sustainable Development Goals (SDGs), that is, SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

As one of the most rapidly developing economies, India has a rather peculiar problem: on the one hand, the country has to maintain industrial development; on the other, it needs to reduce environmental and resource stress.

Despite the efforts of the national programs like Make in India, Zero Effect Zero Defect (ZED), and the National Action Plan on Climate Change (NAPCC), which are aimed at advancing sustainability in the manufacturing industry, implementation on a large scale is limited. The structural bottlenecks, including the high initial investment, the absence of technical expertise, the scattered policy resources, and insufficient infrastructure, are still slowing things down, especially for small and medium businesses (SMEs) that make up more than 90% of the industrial establishments in India (Awasthi et al., 2020; Sharma et al., 2020).

Green technologies are the core of the new manufacturing practice and they involve renewable energy systems, waste heat recovery, water recycling, and pollution control devices. The tools minimize the ecological imprint of production processes and maximize efficiency and production costs. At the same time, the use of sustainable materials, including biodegradable polymers, recycled alloys, and natural fiber composites, help to continue the cycle of resources and optimize the lifecycle of products (Zhang et al., 2019).

The same can be said about the incorporation of digital technologies into the framework of Industry 4.0. The Internet of Things (IoT), Artificial Intelligence (AI), Cyber-Physical Systems (CPS), and blockchain technologies make it possible to monitor the production process in real-time, make predictions, and manage energy more intelligently, thus increasing the adaptability and sustainability of production (Raut et al., 2020). At the same time, it is followed by the rise of Industry 5.0 that is all about people centered innovation and ethical AI, and the development of resilient, inclusive, and socially responsible manufacturing ecosystems (Nahavandi, 2019).

Even with the availability of technology, sustainable manufacturing in India is not even and occasional. Specifically, SMEs do not view sustainability initiatives as long-term investments but as a cost-center because they lack immediate returns and proper implementation of policies. Additionally, knowledge management practices and organizational learning are weak, leading to an inconsistent implementation of green activities and loss of the chance to modify the establishment on a system-wide level (Alam et al., 2023).

The present paper proposes an evidence-based integrated concept, which will align green technologies, energy-efficient systems, sustainable materials, and digital tools with organizational enablers and supports of policies. It is not just aimed to assess current practices as well as barriers but to find the possible ways of improvement in sustainability performance, especially in the resource-limited and digitally immature environments like SMEs in India.

The study is based on mixed-method research, which will involve structured surveys, semi-structured interviews, and simulation modeling using such tools as RETScreen, MATLAB/Simulink, and SimaPro. Partial Least Squares Structural Equation Modeling (PLS-SEM) and Fuzzy Set Qualitative Comparative Analysis (fsQCA) are used to conduct quantitative analysis whereas qualitative insights are used to bring contextual perspective to organizational readiness and policy gaps.

The intention of the present paper is to contribute to the body of knowledge and the industrial practice in the following ways:

(a) providing a systems-oriented view of sustainable manufacturing,

(b) empirically validating a comprehensive sustainability assessment framework, and

c) making strategic recommendations on how to embrace technology, policy reform and capacity building.

In brief, the research aims at filling the gap between theoretical and practical pursuits that can be of assistance to the stakeholders who are interested in ensuring a sustainable industrial future of India and other developing nations.

II. LITERATURE REVIEW

A. Green Technologies and Cleaner Production Systems

Sustainable manufacturing revolves around green technologies and tools that achieve a reduction in the impact on the environment and an increase in resource utilization. These are renewable energy systems, waste heat recovery systems, closed-loop water systems and pollution control apparatus. They are supposed to enable cleaner production processes on the entire production life cycle, starting with the extraction of the raw materials to its disposal (Swaminathan et al., 2024).

Examples of systems that are becoming common in material processing using semiconductor laser diodes include the ones that increase precision and minimize thermal wastage. Measurements performed on such technologies show that it is possible to reduce material losses and energy consumption. According to Vujanovic et al. (2019), the replacement of fossil fuels with renewable sources of energy, including solar and biomass, is not only carbon-friendly, but it is also more energy-secure and cost-effective in the long run. According to the United Nations Environment Programme (UNEP), cleaner production is an ongoing use of an integrated environmental approach to processes and products to minimize hazards to human beings and the environment. Moktadir et al. (2018) revealed that the compatibility of cleaner production and eco-efficiency and process redesigning increase sustainability especially when integrated into the supply chain.

The practice of green technologies has not been uniform, even though the benefits have been established and accepted. This is particularly the case among the small and medium enterprises (SMEs). It is constrained by the expensive capital, technologic knowledge, and communal green infrastructure. According to the suggestion of Omowole et al. (2024), these gaps could be filled with the help of the implementation of the public-private partnerships and the government-supported green tech hubs.

B. Energy-Efficient Systems in Manufacturing

Operation cost and environmental load in manufacturing is in the form of energy consumption. The International Energy Agency (2023) indicates that the industrial sector consumes more than 30 percent of the world energy. Therefore, the systems that are energy efficient play a crucial role in the realization of sustainability objectives.

The technological solutions involve high efficiency motors, variable frequency drive (VFD), real time energy management systems and demand side energy management. The innovations are not only energy-saving but also increase the reliability of the operations. AI and IoT are Industry 4.0 technologies that have made smart energy forecasting and optimization a reality, a factor that has led to more responsive energy systems (Kamble et al., 2020).

Waste heat recovery is a particularly impactful measure. According to Vujanovic et al. (2019), with the reuse of excess thermal energy, it is possible to increase the energy efficiency of metal and chemical industries by as much as 30%. On the same note, the viability of the introduction of renewable energy and the heat recovery mechanism in mid-sized industrial installations is confirmed by RETScreen-based tests as economically viable in the long term.

The virtual representation of physical processes, known as digital twins, are becoming more common to simulate and optimize the use of energy before it is put into real practice. Zhang et al. (2021) demonstrated how the digital simulations minimize the trial-and-error method of system design, enabling faults to be detected pre-emptively and energy to be saved.

Nevertheless, significant barriers persist. The mass adoption is not encouraged by the cost of installation, lack of skilled labor and incentives in policies. According to Alam et al. (2023), the institutional reforms that can have a positive impact on the outcomes of energy-efficient measures include capacity building, performance-based incentives, and third-party audits.

C. Smart Sustainable Forces 4.0 and 5.0

With cyber-physical systems and the IoT coupled with AI the manufacturing industry has become Industry 4.0 and all about real-time data analytics, automation, and decentralized decision-making. It is relevant to sustainability because it ensures the optimization of resources, minimization of wastes, and adaptive production systems (Kamble et al., 2018).

Predictive maintenance will be possible with the help of IoT sensors and AI algorithms that will reduce the number of times when equipment does not work, energy is wasted, and unexpected stops are made. Raut et al. (2020) emphasized that AI-based analytics can detect inefficiency in energy consumption and suggest the remedial measures without affecting the operations.

Even though blockchain technology is still at its early phase, it is a potentially good technology to use in the supply chain as far as transparency and traceability are concerned. Sustainable procurement and adherence to environmental regulations should be achieved through blockchain by tracing the origin of materials and assuring de facto ethical sourcing (Bag et al., 2021).

Industry 5.0 is the next step in these technological changes as it reintroduces humanistic and ethical aspects into the production process. It focuses on human and machine teamwork, strength, inclusion and accountability to the environment. Nahavandi (2019) states that Industry 5.0 will allow producing a personalized production without a loss of environmental quality applying such technologies as 3D printing and collaborative robotics.

Narkhede et al. (2023) suggested such benefits of Industry 5.0 as an increase in the strength of the circular manufacturing due to the possibility of modular design, disassembly, and reuse. However, to realize the potential of such technologies, it is necessary to deal with the problem of cybersecurity, the shortage of competencies, and the disintegrated digital infrastructure.

D. Sustainable Materials and Circular Resource Use

Material selection significantly influences the environmental footprint of manufacturing. Virgin metals, petrochemical plastics and synthetic composites are the traditional materials which are resource-consuming and in most cases not recyclable. Replacing the non-sustainable materials, bio-based polymers, recycled alloys and natural fiber composite materials have been trendy answers to these issues. Other alternatives to everyday plastics that are more environmentally friendly are bio-based polymers like polylactic acid (PLA) that can be converted to corn-based plastics or sugarcane-based plastics. They are finding more application in the packaging, medical equipment, and automobile interiors (Kumar et al., 2021). Their carbon footprints during the life cycle are much lower as compared to petroleum-based counterparts.

The circularity of the resource concerns the recycled metals like aluminum and steel. According to Singh et al. (2022), recycled aluminum consumes even less than half of the energy needed to create the first production, which makes it economically and environmentally appealing. The closed-loop recycling systems also increase the efficiency and savings of materials.
NFCs are the combination of either jute or hemp or flax with the biodegradable matrices, lightweight and strong and renewable. Moktadir et al. (2018) proved that NFCs were good alternatives to the use of glass fiber composites in automobiles and consumer products.
The Ellen MacArthur Foundation has come up with quantitative measures (Material Circularity Indicators or MCI) to quantify the reuse and recycling potential of material. Nonetheless, the factors of cost, processability, and performance variability still hinder the use of sustainable materials in mass production.

E. Knowledge Management and Organizational Readiness

Technological interventions alone are insufficient for sustainable manufacturing. To be successful in implementation, it is imperative that an organization is ready particularly through knowledge management (KM). KM refers to standardized practices of knowledge capture, sharing and knowledge application in order to improve decisions and innovativeness.
According to Alam et al. (2023), a stronger KM practice increased the success of companies in implementing green technologies. The knowledge management that is most significant is codification (manuals, SOPs), personalization (mentorship, consultations with experts), and knowledge-sharing platforms. These are employed to curb redundancy, to know what has been wrong in the past, and to keep on improving.
Organizational culture is equally significant. The process of empowerment, participatory leadership, and sustainability-related training are the aspects that can create an environment in which green initiatives will flourish. Kamble et al. (2020) underlined that the successful transitions can be eased by transformational leadership and inter-departmental sustainability teams.
Such knowledge transfer and innovation is also bolstered by inter-organizational partnerships, between businesses, educational facilities, and government agencies. To SMEs that do not have their own R&D capability, these networks can be a critical source of information on sustainability, and to obtain technological support (Omowole et al., 2024).
Although KM is significant, it faces the following barriers, which are information silos, change resistance and poor IT infrastructure. In order to get the best out of the Industry 4.0 and 5.0, companies need to devise integrated KM frameworks that will resonate with their digital transformation strategies.

F. Barriers to Sustainable Manufacturing in Developing Economies

The barriers that developing economies have to deal with are structural and systemic when it comes to the adoption of sustainable manufacturing processes. The obstacles to investing in green technology are high capital need at the start, finance, and awareness, especially in the SMEs (Awasthi et al., 2020).
Skill shortages further complicate implementation. Most of the SMEs lack employees who are familiar with sustainability planning, energy, or environmental compliance modeling. Talent gaps in sustainability-intensive activities cannot also be filled because there are no training programs and academic-industry relations (Omowole et al., 2024).
Policy fragmentation and regulatory uncertainty exacerbate the situation. Overlapping jurisdictions and inconsistent enforcement discourage proactive compliance. Understanding the role of environmental regulation, Kamble et al. (2020) noted that most manufacturers see it as a burden, not as the innovation opportunity.
Lack of infrastructures, including poor electric power reliability, poor internet connection and disjointed supply chains impede the implementation of digital technologies needed to achieve sustainability. According to Raut et al. (2020), the tools such as IoT-based monitoring or blockchain-based traceability are rather theoretical in these regions without the digital backbone.
Cultural inertia also plays a role. Resistance to change in most of the traditional manufacturing companies is attributed to legacy systems, absence of incentives and the low customer demand of green products. It is an upgrade of short-termism and a reduction of pace of sustainability transitions (Bag et al., 2021).

G. Research Gaps and Conceptual Synthesis

Although literature is being developed on the topic of green technologies, energy-efficient systems and the organizational enablers, research which has been able to integrate these three aspects into a more detailed and empirically-based system is extremely scarce. The majority of the available models apply to large businesses established in advanced economies, whereas they have little application in the SME sector in India (Moktadir et al., 2018).

In addition, there is the lack of insights, which is region-specific with regard to infrastructure, policy, and social-cultural dynamic. Kamble et al. (2020) noted the importance of the adaptive models of sustainability to the local limitations, availability of resources, and governance as well.

Methodologically, the studies on the application of the quantitative approaches of modeling (e.g., PLS-SEM, fsQCA) and simulation (e.g., MATLAB, RETScreen, SimaPro) to the testing of the sustainability interventions are yet to be carried out. This gap is an area that brings much importance in improving the predictive and operational relevance of the research findings.

Finally, despite the industry 4.0 being a well-covered area, there is little to no research on the potential of human-centered, ethical, and inclusive innovation (Industry 5.0) when it comes to the concept of sustainable manufacturing (Narkhede et al., 2023).

III. RESEARCH METHODOLOGY

A. Research Design

This research will apply a mixed-methods research design that incorporates both the qualitative and quantitative research design in order to ensure that a detailed insight is obtained regarding sustainable manufacturing practices in the Indian industrial scenario. The methodological decision is determined by the fact that the concept of sustainability is multidimensional and comprises technological, organizational, economical, and policy-related aspects. It is a perfect fit to have a mixed-methods framework in this kind of research, because it will provide the generalizability and statistical rigor of quantitative research and the depth of the context of qualitative data. The research design would comprise exploratory, descriptive and causal research as a combination of which it will be a sound study of existence and effects of sustainable manufacturing practices.

This was done using the exploratory phase to determine some of the major drivers and barriers of sustainability in Indian manufacturing. Preliminary literature review and expert advice were also undertaken during this phase and formed the basis of variable selection and data collection instruments. The descriptive stage consisted of the systematic survey of the key manufacturing industries to trace the extent of the current green technologies, sustainable materials, and energy-efficient systems adoption. Lastly, the causal phase attempted to determine the relationships between technological, organizational and policy enablers through statistical models of relationships. Also, modeling with simulation based modeling using tools such as RETScreen, MATLAB, and SimaPro gave empirical verification of sustainability results using various scenarios.

The study is cross-sectional in that the time orientation of the study captures the data of the respondents and the firms at one time. Although this restricts the possibility to trace long-term trends, it has the practical and feasible approach to gather the data in the vast number of firms in the framework of time and resources. Interviews and surveys incorporated retrospective questions that were used to measure historical patterns of adoption and outcomes of organizational learning.

B. Research Objectives and Methodological Mapping

Depending on the type of variables, every research objective required methodological response. The study of green technologies and the recent sustainability experience in the industry was done with help of structured surveys aimed at companies of various industries including automotive industries, textile industries, and light-engineering industries. The surveys provided quantitative data about the kind of green technologies applied, their related performance measures, and the organization features.

The study employed secondary data analysis and a case study approach to attempt to analyze how sustainable manufacturing can be achieved with the help of emerging digital technologies, including IoT, AI, and blockchain. The analysis was conducted to determine the level of energy optimization and sustainability effects of selected companies that had adopted Industry 4.0/5.0 tools. Internal data regarding the utilisation of energy and processes efficiency was provided where possible.

The tools used to assess the life cycle of the material (LCA) were used to assess the sustainable materials and compare them to conventional inputs. The simulation of material environmental impacts, recyclability, and carbon footprint were done using SimaPro and OpenLCA with its standard databases and available published literature. This was supported with firm level information on how they practiced substitution of materials and trends of procurement.

Both empirical survey data and simulations modeling supported the analysis of energy-efficient systems and their effect on the reduction of emissions. Through the use of RETScreen, renewable energy integration, recovery of waste heat, and smart grid controls were expected to save energy and reduce greenhouse gases emissions. Such simulations were based on real life data gathered at manufacturing sites. The qualitative semi-structured interviews were used to investigate the barriers and enablers of sustainability, particularly with reference to SMEs. The use of interviews with policy experts, plant managers, and sustainability officers revealed the perceptions, experiences, and institutional issues that are difficult to determine by conducting surveys. Thematic coding and triangulation of the above insights with quantitative data were then done.

The research came to a conclusion with the creation and validation of a framework of sustainability assessment to harmonise the various types of data gathered. The statistical test on the causal relationship between significant items in this model was carried out by PLS-SEM (Partial Least Squares Structural Equation Modeling). Simultaneously, Fuzzy Set Qualitative Comparative Analysis (fsQCA) was used to find groups of conditions that can all be expected to result in high performance in sustainability.

C. Data Collection Strategy

They were structured surveys and semi-structured interviews as the primary data were obtained. The manufacturing companies in five industrial clusters in India were sent the questionnaires electronically. The items of the questionnaire were the Likert-type questions, categorical variables, and performance indicators to the green technology adoption, energy management, and organizational culture. To achieve internal consistency, a pilot sample of 15 respondents to pre-test the instrument and make adjustments in the instrument in accordance with the responses provided by the pilot sample.

The key informants who were reached through purposive sampling were interviewed semi-structurally and numbered 12. They involved senior engineers, production heads, sustainability consultants and government officials who were part of industry associations. The interviews were face to face or video linked and never recorded until they consented. NVivo software was used to code thematically the transcriptions, and some common themes as well as some unusual insights could be recognized.

Several sources of secondary data were used to collect the data i.e. government databases, industrial sustainability reports, journal articles, and international technical manuals are some of the reputable sources. The other sources included the Ministry of MSME, Bureau of Energy Efficiency, UNIDO case reports, and peer-reviewed articles published after 2015. These are the secondary data points which were used to supplement survey results, create simulation models and a policy context.

Triangulation of sources and methods was used to validate and make the data reliable. As an example, the results of the interviews about the technology adoption were cross-verified with the survey results and governmental records. The simulation output was scaled to the real firm level data on energy when available. There were ethical standards observed during the research such as the informed consent, anonymity and the secured storage of information.

D. Sampling and Population

The analysis was mainly carried out on small and medium enterprises (SMEs) in the energy-intensive manufacturing industries including automotive components, textiles, chemicals and light engineering industries. These industries were chosen due to the fact that they are resource demanding and the Indian industrial scenario has large proportion of them. SMEs were selected because they constituted a major contribution to the GDP and employment, and were underrepresented in the sustainability research.

The selection of survey participants was conducted through purposive sampling where a set of conditions was pre-determined to include a past history of green initiatives, ISO 14001 certified, or involved in government-driven programmes such as the Perform, Achieve and Trade (PAT) or Zero Effect Zero Defect (ZED). Interviews were carried out using a snowball sampling method in order to access expert respondents who have specialized knowledge.

The survey has achieved a final sample size of 127 companies that has a very broad range in relation to scale, technology as well as geographical divisions. The sample size was larger than the minimum needed to analyze PLS-SEM since it suggests a minimum of 10 observations per path that has to be estimated. After 12 interviews, the qualitative sample was found to be saturated according to the best practices in both grounded theory and thematic analysis.

E. Analytical Tools and Validation

Quantitative data were analyzed with the help of SPSS to conduct the descriptive statistics and SmartPLS to develop structural models. The PLS-SEM approach made it possible to test formative and reflective constructs, where latent variables could be examined, including the organizational readiness and the knowledge management. Standard indices were used to measure the model fit by the consideration of the Average Variance Extracted (AVE), the Composite Reliability and the R-squared values.

Qualitative data were analyzed using thematic coding techniques. Analysis of transcripts of interviews was done separately and the emergent codes were classified into superordinate themes consisting of policy, digital skill gaps, and institutional inertia. Quantitative results were interpreted based on these findings and they were also used to improve the conceptual framework.

The simulation modelling of energy systems was MATLAB simulation and renewable energy integration simulation modelling was done using RETScreen. The SimaPro was used in carrying out life cycle analysis and this gave detailed environmental performance measures of various combinations of materials and processes. The instruments gave the research an experimental nature where projections and scenario studies complemented the empirical data.

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The complexity of the causal relationships and configurational roads to sustainability were investigated with the help of Fuzzy Set Qualitative Comparative Analysis (fsQCA). The solution resulted in the discovery that different sets of enabling conditions such as leadership commitment and digital maturity could result in high performance, even though not all the technological readiness is ideal.

The validation was done through triangulation of multiple levels, expert opinion and statistical validity verification. This has made sure that the proposed framework was not just theoretically based but also empirical and practically applicable.

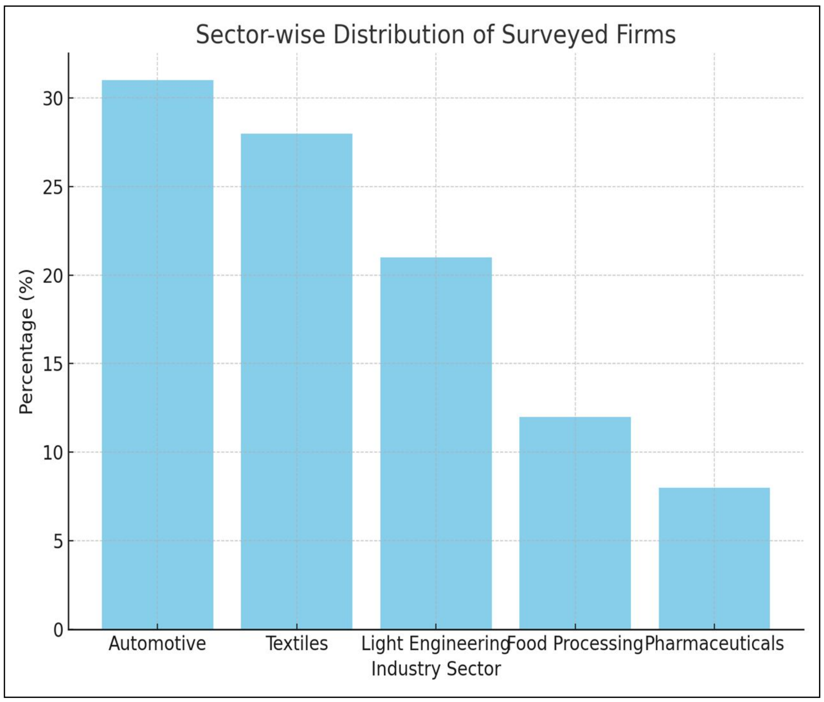
IV. RESULTS AND DISCUSSION

A. *Overview of Respondent Firms*

The survey was done on 127 manufacturing companies in five Indian industrial areas. This sample comprised micro (12%), small (40%), medium (35%) and large (13%) firms with automotive components (31%), textiles and garments (28%), light engineering (21%), food processing (12%) and pharmaceuticals (8%) representation in the sector. The respondents included operational managers and sustainability officers, as well as engineers at plant level.

Its geographic distribution revealed that there was a clustering of sustainable adoption activities in the states of Maharashtra, Tamil Nadu and Gujarat with the northern states falling behind. Policy nudges and pressure on SMEs by customers increased their awareness of sustainability practices even though they had limited capital.

Figure 4.1: Sector-wise distribution of surveyed firms (n=127), showing strong representation from automotive and textile sectors.



B. *Adoption of Green Technologies and Practices*

Survey findings indicated that 68 percent of the firms had adopted some type of green technology. Solar PV installations (42 per cent), waste heat recovery systems (37 per cent) and closed-loop water recycling (29 per cent) were the most prevalent. Only 18 percent of them had entirely engaged clean production techniques through the value chain.

Thematic interview details revealed that the existing companies that had previously implemented green technologies did so to meet ISO 14001 or governmental plans such as PAT. The companies that integrated green technologies with real-time viewing devices demonstrated the decline of the energy bill by 12-18 percentage, and the operational efficiency was improved by 15 percent.

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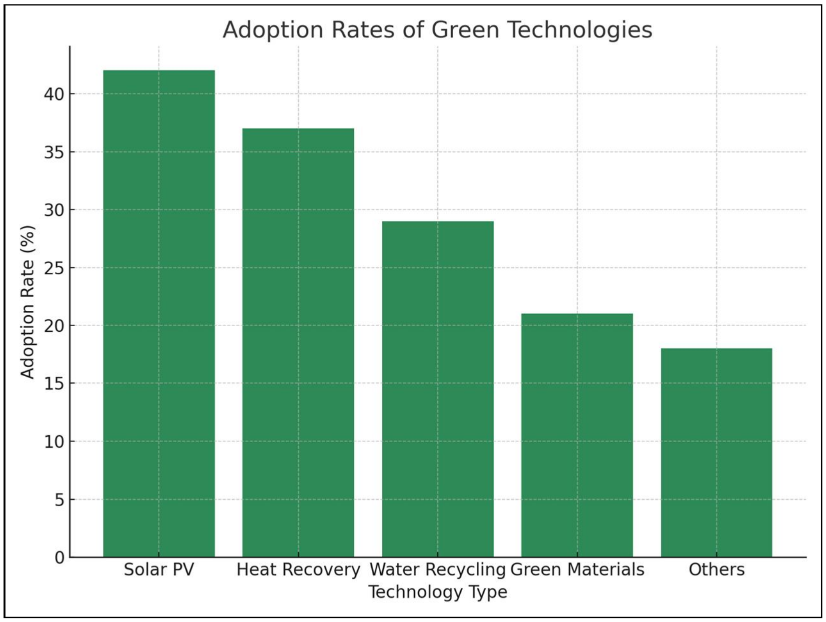
Figure 4.2: Adoption rates of green technologies among surveyed firms. Solar PV and heat recovery systems were most common.

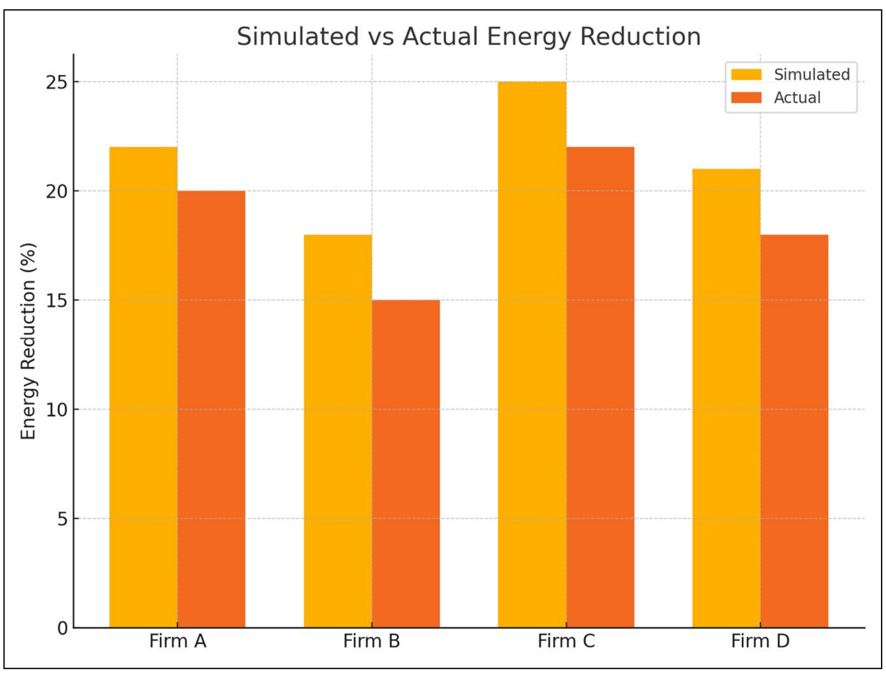


C. Energy Efficiency Outcomes and RETScreen Simulation

The simulations of 22 firms selected on the basis of renewable energy and heat recovery integration were carried out using RETScreen, with a comparison of pre- and post-integration energy profile. The findings showed that a possible decrease in annual energy consumption was 22.6 percent and a 19.4 percent reduction in carbon emissions. The solar PV (3.2 years) and the highest ROI-modeling interventions were the solar PV.

The use of smart meters and prediction of loads using machine learning has also led to optimization of demand side and the reduction of tariffs during peak hours within companies that have implemented these systems. Evidence of these findings was supported by survey results that showed that digitally mature companies were performing at least 20-25 percent better than their counterparts in terms of energy performance.

Figure 4.3: Comparison of energy reduction achieved via RETScreen simulations vs. reported actual performance among adopters.

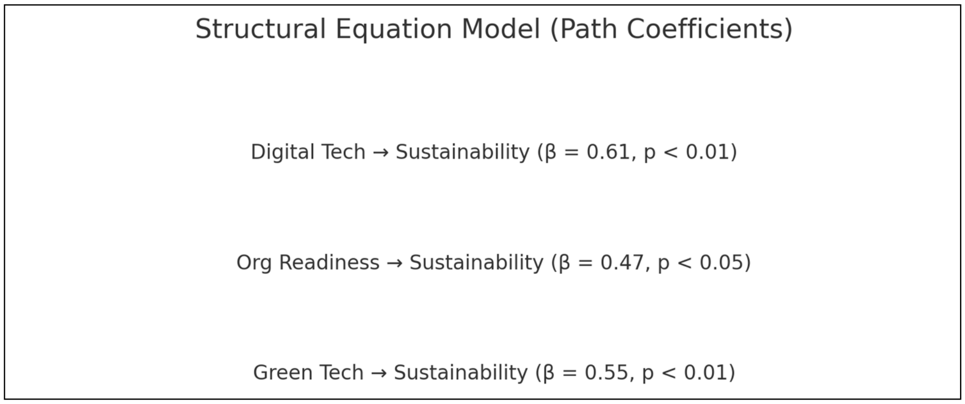


D. Smart Manufacturing and Industry 4.0 Impacts

Among industry 4.0 tools, 41% of the respondent firms were identified to have adopted it with IoT and AI being the most outstanding. These technologies were associated with predictive maintenance, real-time emissions, and processes controls. Only three pilot projects of large textile exporters used blockchain-based traceability.

As per the PLS-SEM modeling, the relationship between sustainability outcomes and the adoption of digital technologies was very strong in a positive direction (beta = 0.61, $p < 0.01$). To a great degree, this relationship was moderated by organizational preparedness, which was measured as a training and IT capability. Interviewees suggest that the lack of cybersecurity readiness and data manipulation expertise can be viewed as one of the most significant problems.

Figure 4.4: Structural equation model showing path relationships among green tech adoption, digital maturity, and sustainability performance.



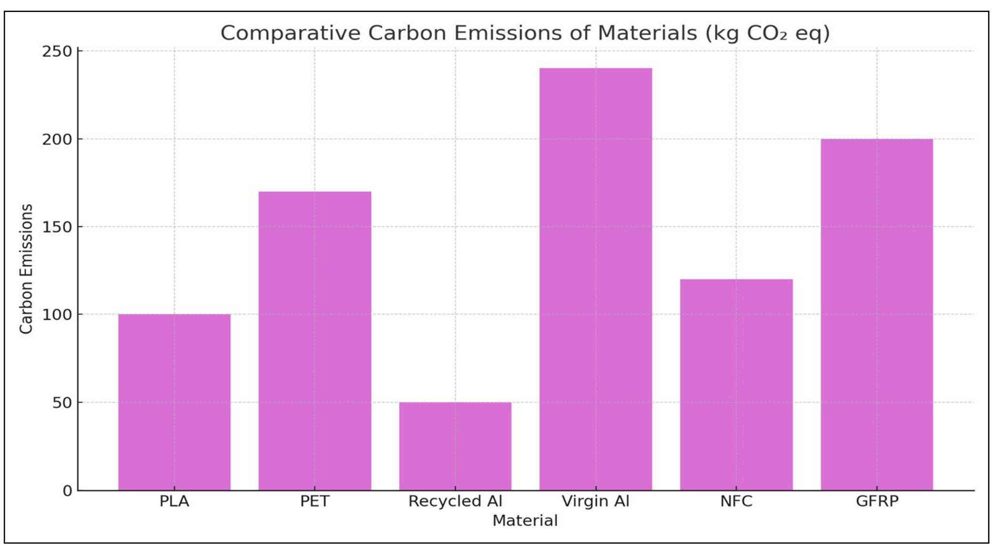
E. Life Cycle Assessment of Sustainable Materials

SimaPro was used to analyze the life cycle assessment of PLA biopolymer, recycled aluminum and natural fiber composite material against conventional material. The packaging made of PLA revealed 42 percent decrease in cradle-to-grave carbon emissions when contrasted with PET. Aluminum recycling saved 88 percent energy and 79 percent emissions compared to the virgin aluminum.

The natural fiber composites and in particular jute epoxy and hemp polypropylene composite were not very strong but exhibited high biodegradability. Its cost, presence of processing bottlenecks and unstable supply chains was the reason behind its low adoption.

Survey data also affirmed that 21 percent of firms had already switched to through sustainable materials, and the majority of them attributed this to the costs and performance uncertainties. But the preference of the customers and export markets were becoming increasingly enablers.

Figure 4.5: SimaPro-based life cycle assessment comparing conventional and sustainable materials.



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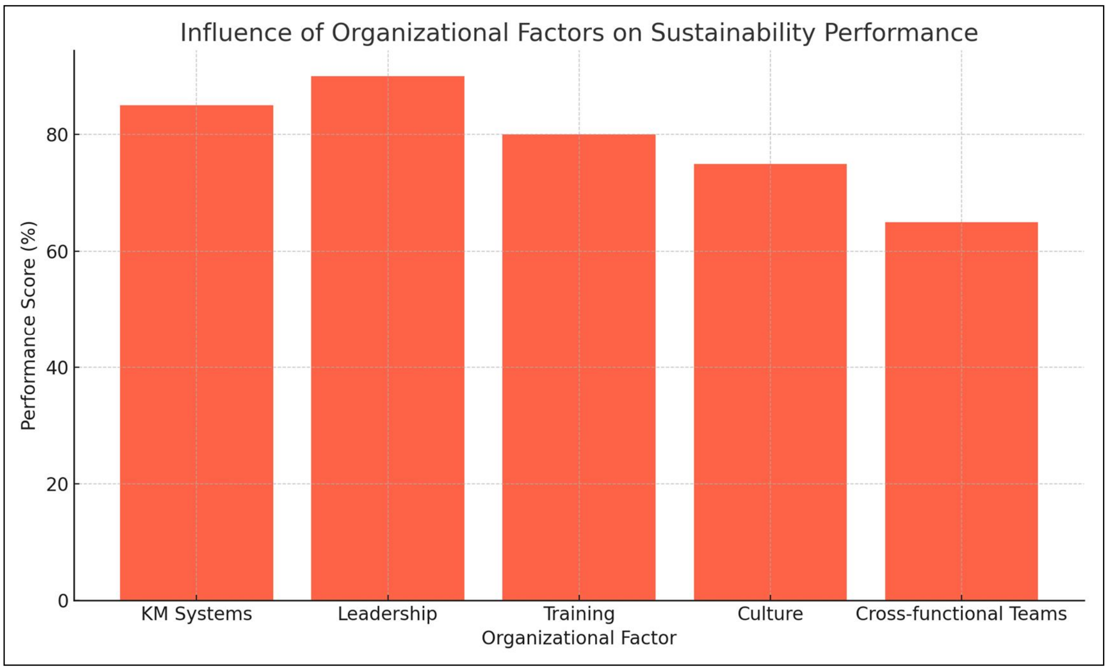
F. Organizational Enablers and Knowledge Management

As thematic analysis of the interview transcripts showed, the likelihood of attaining sustainability integration was much higher in a firm that has a well-developed knowledge-sharing platform and good leadership support. Best practices could be duplicated throughout units because the codification of the knowledge was done in manuals and repositories of cases.

Transformational leadership emerged as a key enabler. Companies that at the very top level were engaged in green activities had more training budget, employee motivation and stronger alignment of sustainability with business strategy. The PLS-SEM further established the fact that the relationship between green practice implementation and performance was highly dependent on the organizational culture (0.47 and $p < 0.05$).

The barriers to change that were mentioned the most were resistance to change, departmental silos and absence of cross-functional sustainability teams. Generally, SMEs were not inclined to have formal KM systems, but SMEs that were either collaborating with the academia or that were part of industrial networks tended to adopt better.

Figure 4.6: Composite scorecard showing correlation of organizational enablers (e.g., KM, leadership, training) with performance metrics.



G. Policy Perception and Regulatory Challenges

The companies that were surveyed had mixed perceptions about the sustainability policy environment in India. Although the programs such as PAT, and ZED were recognized to raise awareness, their practice was considered bureaucratic and non-consistent. SMEs reported that 34 percent of them had undergone any concrete advantage of being in policy programs.

Interviewees recalled that many of the regulations in various ministries overlapped and this sometimes led to confusion, and that the incentives to comply were in favor of bigger companies. Greater transparency in guidelines, subsidy of green technology and streamlining documentation procedures were all in demand.

Some participants proposed that there should be local sustainability cells that impart technical and financial advice to a specific sector. It was also proposed that partnership with research centers, innovation centers, state energy offices etc should be used to overcome the bottlenecks in implementing the changes.

H. fsQCA Findings: Configurations for Success

Fuzzy Set Qualitative Comparative Analysis (fsQCA) was used to investigate combinations of factors, which contributed to high performance levels in terms of sustainability. The analysis identified three dominant configurations:

1) High digital maturity + strong leadership + external funding
2) Green technology + knowledge sharing + supportive policy environment

Such setups confirm that there is no universally adequate factor. Instead, a great variety of situation-specific paths to the achievement of sustainability exist, particularly in heterogeneous SME contexts. This understanding renders such an idea of creating modular frameworks of sustainability instead of the one size fits all solution believable.

I. *Summary of Empirical Insights*

The results underscore the multidimensional nature of sustainable manufacturing. Although technological solutions like AI-based monitoring and solar PV are measurable in terms of positive effects, they rely on organizational culture, commitment of the leadership, and knowledge systems to succeed. The digital divide especially within SMEs is one of the major bottlenecks, as well as lack of uniformity in implementation of policies and infrastructural constraints.

Simulation tools and advanced analytics proved environmental and financial advantages but the real experience is still burdened by inertia due to the absence of integrated planning, skill gaps and aversion to cost. However, the pioneers demonstrate that digitalization, material innovation, and strategic leadership can be the great sustainability payoff.

V. CONCLUSION AND POLICY IMPLICATIONS

This paper provides an in-depth analysis of the sustainable manufacturing process, specifically in the Indian industrial scenario with emphasis on the interaction of green technologies, energy-efficient frameworks, and organization enablers within the scope of Industry 4.0 and 5.0. The study, using a mixed-methods design, which included structured surveys, in-depth interviews, simulation modeling, and structural equation modeling, determines the opportunities and constraints that define the adoption of sustainability in manufacturing firms, particularly the small and medium enterprises (SMEs).

The results show that even though a significant proportion of the firms have embarked on the use of green technologies like solar photovoltaic systems, waste heat recovery units and closed-loop water recycling systems, the extent of full-scale integration of these technologies is a limited phenomenon. The energy modeling conducted in RETScreen and MATLAB demonstrates that the significant decrease of energy consumption and emissions can be accomplished once these technologies are integrated with smart monitoring and predictive tools. However, they are normally constrained by capital constraints, lack of online infrastructure, and dissemination of knowledge, particularly amongst the SMEs.

It is also found in the study that companies, which make use of Industry 4.0 technology, including AI, IoT, and blockchain, have better sustainability results, especially in terms of energy optimization and emissions monitoring. But, these advantages are highly interfered with internal organisational variables like knowledge management practices, training of employees, and leadership commitment. Companies that had developed a good top-to-bottom sustainability vision and functional alignment always performed better than others in terms of the environment and operations.

Policy engagement emerged as a double-edged factor. Despite the awareness created by national programs like PAT and ZED, they are bureaucratic and do not provide sector specific services to the SMEs hence limiting their effectiveness to resource limited SMEs. The inconsistency of regulations and its fragmentation also fails to stimulate the investment into the sustainable transitions on the part of the private sector. Nonetheless, companies have indicated their readiness to abide by the standards of sustainability with the proper incentives, simplified process, and local assistance.

The sustainability framework that was achieved through the validation process in this study integrates technological aspects, organizational aspects, and policy aspects. It allows companies to benchmark their preparedness regarding sustainability, and measure their preparedness levels as well as design interventions strategically. Fuzzy set analysis also reveals that there exists no single route to attaining sustainability; instead, it is the outcome of various and situation-specific arrangements with technology, knowledge, and policy convergence.

What this means to policymakers is that sustainability policies in the future need to be more than merely technical requirements and instead, construct enabling ecosystems via financial incentives, capacity building, and a coherent regulatory structure. Sustainability cells that are technology-specific, industry-academia ties and distributed knowledge centres can be instrumental in further adoption. At the same time, sustainability cannot be seen as a source of compliance burden on the part of industry leaders, but rather a strategic lever in innovation, risk reduction, and long-term competitive positioning.

Overall, the paper has provided an empirically and holistic conceptualization of sustainable manufacturing in the emerging economies, which links the gap between theory and practice. It establishes a feasible roadmap that can be collectively assembled by industry, government and research agencies to develop an ecologically and economically viable manufacturing ecology.

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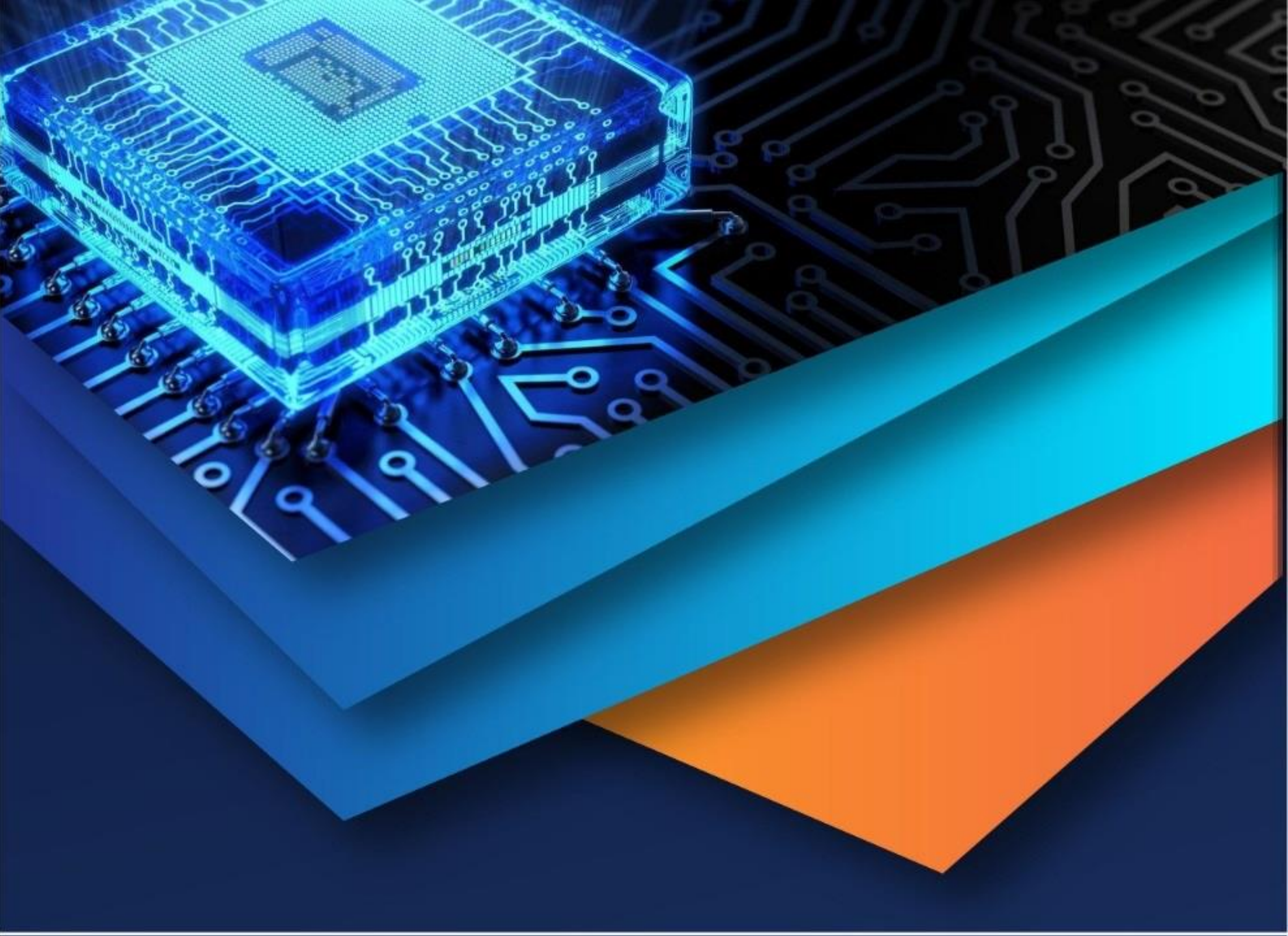

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