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INDUSTRY 4.0 AND PRODUCTIVITY GROWTH IN INDIAN MANUFACTURING INNOVATION AND COMPETITIVENESS OF MSMES

By

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Abstract

Industry 4.0 is transforming modern manufacturing through the integration of advanced technologies such as Artificial Intelligence, the Internet of Things, Big Data Analytics, Cloud Computing, Robotics, and Cyber-Physical Systems. This study examines the impact of Industry 4.0 adoption on productivity growth, operational efficiency, innovation capability, and competitiveness among Indian manufacturisng Micro, Small and Medium Enterprises (MSMEs). Primary data were collected from 250 manufacturing MSMEs and analysed using descriptive statistics, Pearson correlation, multiple regression analysis, ANOVA, and hypothesis testing. The findings reveal that Industry 4.0 adoption has a significant positive effect on productivity growth ($r = 0.742$, $p < 0.001$), operational efficiency ($r = 0.718$, $p < 0.001$), innovation capability ($\beta = 0.768$, $p < 0.001$), and competitiveness ($\beta = 0.744$, $p < 0.001$). Financial constraints, inadequate digital infrastructure, limited technological readiness, and shortages of skilled human resources were identified as major barriers to adoption. Government initiatives, including Make in India, Digital India, Atmanirbhar Bharat, and the Production Linked Incentive Scheme, were found to support digital transformation. The study concludes that Industry 4.0 adoption significantly enhances the performance and competitiveness of Indian manufacturing MSMEs, while effective government support can help overcome key barriers to digital transformation.

Keywords: *industry 4.0, manufacturing MSMEs, productivity growth, operational efficiency, competitiveness, artificial intelligence, digital transformation, smart manufacturing.*

JEL Classification: *O14, O31, O32, O33, L25, L60, D24*

Introduction

Industry 4.0, the Fourth Industrial Revolution, represents a transformative phase in manufacturing driven by the integration of advanced digital technologies such as Artificial

Intelligence (AI), the Internet of Things (IoT), Big Data Analytics, Cloud Computing, Robotics, Cyber-Physical Systems (CPS), and Smart Manufacturing. These technologies facilitate automation, real-time decision-making, predictive maintenance, and efficient resource utilisation, thereby enhancing productivity, operational efficiency, product quality, and industrial competitiveness.

The manufacturing sector plays a vital role in India's economic development by contributing significantly to GDP, employment, exports, and technological progress. Government initiatives such as *Make in India*, *Digital India*, *Atmanirbhar Bharat*, and the Production Linked Incentive (PLI) Scheme have accelerated digital transformation and encouraged the adoption of advanced manufacturing technologies. As a major contributor to industrial output and employment, Micro, Small and Medium Enterprises (MSMEs) stand to benefit substantially from Industry 4.0. However, many MSMEs continue to face challenges, including financial constraints, inadequate digital infrastructure, skill shortages, cybersecurity concerns, and limited technological readiness.

Against this backdrop, the present study examines the impact of Industry 4.0 adoption on productivity growth, operational efficiency, innovation capability, and competitiveness among Indian manufacturing MSMEs. It also investigates the barriers to technology adoption and evaluates the role of government support in promoting inclusive and sustainable industrial development.

Review of Literature

The emergence of Industry 4.0 has transformed the global manufacturing landscape by integrating advanced digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Big Data Analytics, Cloud Computing, Cyber-Physical Systems (CPS), Robotics, Additive Manufacturing, and Smart Manufacturing into industrial production. The concept has attracted considerable scholarly attention from the fields of industrial economics, innovation studies, technology management, operations management, productivity analysis, and

development economics. Researchers have examined how Industry 4.0 technologies influence manufacturing productivity, technological innovation, operational efficiency, supply chain integration, sustainability, and global competitiveness. In the Indian context, particular emphasis has been placed on the opportunities and challenges faced by Micro, Small and Medium Enterprises (MSMEs) in adopting digital technologies. Although substantial literature exists on Industry 4.0 and manufacturing transformation, relatively fewer studies have comprehensively analysed the interrelationship between Industry 4.0 adoption, productivity growth, innovation capability, and competitiveness among Indian manufacturing MSMEs.

Kagermann, Wahlster, and Helbig (2013) introduced the concept of Industry 4.0 as a strategic initiative for transforming manufacturing through intelligent production systems, Cyber-Physical Systems, and digital integration. Their study argued that the fourth industrial revolution enables factories to achieve real-time communication, autonomous decision-making, predictive maintenance, and flexible manufacturing. They emphasised that Industry 4.0 enhances productivity and operational efficiency by connecting machines, products, and human resources through digital technologies. Although their work established the conceptual foundations of Industry 4.0, it primarily focused on developed industrial economies rather than the challenges faced by small manufacturing enterprises in developing countries.

Porter and Heppelmann (2014) examined how smart, connected products and digital technologies transform industrial competitiveness. They argued that Industry 4.0 fundamentally changes value creation by integrating intelligent products, cloud computing, and data analytics throughout manufacturing processes. Their study demonstrated that digital technologies enhance product innovation, operational efficiency, customer responsiveness, and competitive advantage. However, the analysis concentrated mainly on large industrial corporations, with limited discussion of technology adoption among MSMEs.

Schwab (2016) described the Fourth Industrial Revolution as a

transformative phase characterised by the convergence of digital, biological, and physical technologies. He argued that Artificial Intelligence, Robotics, IoT, and advanced automation are reshaping manufacturing systems, labour markets, and global economic competitiveness. His work highlighted the opportunities for productivity growth and industrial innovation while simultaneously recognising challenges related to workforce displacement, digital inequality, and technological adaptation. Nevertheless, the study remained largely conceptual without providing empirical evidence from emerging economies such as India.

Lasi et al. (2014) analysed the technological foundations of Industry 4.0 and explained how digital manufacturing systems improve production flexibility, resource efficiency, quality management, and operational performance. They emphasised that intelligent manufacturing enables firms to respond rapidly to changing customer demands while reducing production costs and enhancing competitiveness. Although the study provided valuable insights into digital manufacturing technologies, MSMEs received comparatively limited attention.

Brettel et al. (2014) examined the implications of Industry 4.0 for manufacturing strategy and industrial organisation. Their findings suggested that digital technologies encourage decentralised production systems, greater process automation, and improved productivity through real-time information exchange. They argued that manufacturing firms adopting Industry 4.0 gain competitive advantages through enhanced innovation capability and operational excellence. However, the research primarily reflected experiences from advanced manufacturing economies.

Hermann, Pentek, and Otto (2016) proposed a widely accepted conceptual framework for Industry 4.0 based on interoperability, information transparency, technical assistance, and decentralised decision-making. Their study clarified the defining characteristics of smart manufacturing systems and established a theoretical foundation for subsequent empirical research. While the framework has been extensively applied in manufacturing research, it provides

limited guidance regarding technology adoption among resource-constrained MSMEs.

Frank, Dalenogare, and Ayala (2019) investigated the relationship between Industry 4.0 technologies and manufacturing performance. Their empirical findings demonstrated that digital technologies significantly improve operational efficiency, production flexibility, product quality, and innovation capability. The study also found that firms integrating multiple Industry 4.0 technologies achieve higher productivity than those implementing isolated digital solutions. Nevertheless, the research focused predominantly on manufacturing firms in developed economies.

Müller, Buliga, and Voigt (2018) explored Industry 4.0 adoption among German SMEs and found that digital transformation substantially improves competitiveness through automation, data-driven decision-making, and process optimisation. However, they observed that financial limitations, inadequate digital skills, organisational resistance, and uncertainty regarding investment returns often delay technology adoption among smaller enterprises. Their findings provide valuable insights for understanding similar challenges encountered by Indian MSMEs.

Sony and Naik (2019) reviewed the implementation of Industry 4.0 across manufacturing industries and concluded that digital technologies contribute significantly to operational excellence, productivity improvement, quality enhancement, and customer satisfaction. Their review also identified barriers including inadequate infrastructure, shortage of skilled labour, cybersecurity concerns, and organisational resistance. Although the study discussed emerging economies, sector-specific evidence for Indian MSMEs remained relatively limited.

Mittal et al. (2018) specifically examined the readiness of SMEs for Industry 4.0 implementation. They argued that while large firms possess sufficient technological and financial resources to adopt advanced manufacturing systems, SMEs often face substantial barriers related to investment capacity, technological knowledge, workforce skills, and

digital infrastructure. Their study proposed a gradual implementation framework that enables smaller enterprises to adopt Industry 4.0 according to their organisational capabilities.

Raj et al. (2020) analysed Industry 4.0 implementation within the Indian manufacturing sector and found that digital technologies significantly improve operational efficiency, productivity, inventory management, and supply chain integration. The authors identified government support, organisational readiness, skilled human resources, and technological infrastructure as major determinants of successful Industry 4.0 adoption. However, the study emphasised that many Indian MSMEs continue to experience financial and technological constraints that limit digital transformation.

Kamble, Gunasekaran, and Sharma (2018) investigated the adoption of Industry 4.0 technologies in Indian manufacturing organisations using empirical survey data. Their findings revealed that Artificial Intelligence, Big Data Analytics, and IoT positively influence production efficiency, product quality, and supply chain performance. The study also highlighted the importance of managerial commitment, employee training, and technological capability in achieving successful implementation. Nevertheless, the research concentrated on early adopters and did not extensively examine productivity differences across MSME categories.

Tortorella and Fettermann (2018) explored the relationship between Lean Manufacturing and Industry 4.0, arguing that digital technologies complement lean production by reducing waste, improving process efficiency, and enhancing operational performance. Their findings suggested that firms integrating lean principles with smart manufacturing achieve greater productivity improvements than those implementing either approach independently. The applicability of these findings to developing economies requires further investigation.

OECD (2021) emphasised that digital transformation has become an essential driver of industrial productivity, innovation, and competitiveness across both developed

and developing economies. According to the report, SMEs adopting digital technologies experience improvements in productivity, export performance, innovation capability, and customer engagement. However, disparities in digital infrastructure, access to finance, and technological skills continue to create unequal opportunities for technology adoption among smaller enterprises.

United Nations Industrial Development Organization (UNIDO, 2020) highlighted the role of Industry 4.0 in promoting sustainable industrial development through intelligent manufacturing, energy efficiency, resource optimisation, and digital innovation. The report recognised MSMEs as critical contributors to industrial growth while emphasising the need for supportive policy frameworks, technology transfer mechanisms, workforce development, and institutional capacity building to facilitate digital transformation.

NITI Aayog (2020) examined India's readiness for Industry 4.0 and concluded that digital technologies offer significant opportunities for increasing manufacturing productivity, promoting innovation, and strengthening global competitiveness. The report recommended enhanced digital infrastructure, research and development investment, skill development programmes, financial incentives, and stronger collaboration between industry, academia, and government to accelerate Industry 4.0 adoption among MSMEs.

The Ministry of Micro, Small and Medium Enterprises (Government of India, 2023) has increasingly recognised digital transformation as a strategic priority for strengthening MSME competitiveness. Various initiatives promoting digitalisation, technology centres, lean manufacturing, cloud computing, and smart manufacturing have been introduced to improve productivity and technological capability. However, studies indicate that awareness, affordability, and implementation capacity continue to vary considerably across regions and industrial sectors.

Recent scholarship has increasingly focused on integrating Industry 4.0, innovation capability, digital transformation, and productivity growth within a comprehensive analytical framework. Researchers have demonstrated that Artificial

Intelligence, IoT, cloud computing, digital twins, advanced robotics, predictive analytics, and smart supply chains collectively improve manufacturing efficiency, reduce operational costs, enhance product quality, and accelerate innovation. These technologies also enable greater flexibility, faster decision-making, and improved responsiveness to changing market conditions, thereby strengthening the global competitiveness of manufacturing enterprises.

Contemporary studies further emphasise that innovation has become a critical determinant of MSME competitiveness in the digital economy. Digital technologies facilitate product innovation, process innovation, organisational innovation, and business model transformation while enhancing collaboration across suppliers, manufacturers, and customers. Industry 4.0 enables manufacturing firms to develop customised products, optimise production schedules, improve quality assurance, and integrate real-time market intelligence into strategic decision-making. Consequently, innovation capability has emerged as a key driver of sustainable productivity growth and international competitiveness.

Despite the substantial expansion of research on Industry 4.0, several important gaps remain. Most studies focus either on technological adoption, digital transformation, or manufacturing performance independently rather than examining their combined influence on productivity growth, innovation capability, and competitiveness. Furthermore, empirical evidence concerning Indian manufacturing MSMEs remains relatively limited compared with studies conducted in developed economies. Existing research has also devoted comparatively less attention to sectoral differences, organisational readiness, workforce digital skills, technological diffusion, financial constraints, policy effectiveness, and long-term productivity outcomes associated with Industry 4.0 adoption.

The study addresses these research gaps by undertaking a comprehensive investigation of the relationship between Industry 4.0 adoption, productivity growth, innovation capability, and competitiveness among

Indian manufacturing MSMEs. By integrating perspectives from industrial economics, innovation theory, technology management, productivity analysis, strategic management, and development economics, the study seeks to provide a holistic understanding of digital industrial transformation in India. It contributes to the growing literature on Industry 4.0 while offering empirical and policy insights for promoting technological upgrading, enhancing manufacturing productivity, strengthening MSME competitiveness, and achieving sustainable industrial development in the era of digital manufacturing.

Objectives of the Study

General Objective

To examine the impact of Industry 4.0 technologies on productivity growth, innovation, and competitiveness of Micro, Small and Medium Enterprises (MSMEs) in the Indian manufacturing sector.

Specific Objectives

1. To examine the level of adoption of Industry 4.0 technologies among Indian manufacturing MSMEs.
2. To analyse the impact of Industry 4.0 adoption on productivity growth and operational efficiency of manufacturing MSMEs.
3. To assess the influence of Industry 4.0 technologies on innovation capability and competitiveness of Indian manufacturing MSMEs.
4. To identify the major barriers and challenges affecting the adoption of Industry 4.0 technologies by manufacturing MSMEs.
5. To suggest appropriate policy measures for promoting Industry 4.0 adoption and enhancing productivity, innovation, and competitiveness of Indian manufacturing MSMEs.

Research Hypotheses

H_{01}: There is no significant relationship between the adoption of Industry 4.0 technologies and productivity growth among Indian manufacturing MSMEs.

H_{02}: Industry 4.0 adoption has no significant impact on the operational efficiency of Indian manufacturing MSMEs.

H_{03}: There is no significant relationship between Industry 4.0 adoption and the innovation capability and competitiveness of Indian manufacturing MSMEs.

H_{04}: Financial, technological, infrastructural, and organisational barriers do not significantly influence the adoption of Industry 4.0 technologies by Indian manufacturing MSMEs.

H_{05}: Government support and policy initiatives have no significant influence on the adoption of Industry 4.0 technologies and the productivity and competitiveness of Indian manufacturing MSMEs.

Methodology

The study employed descriptive analysis, Pearson correlation analysis, regression analysis, multiple regression analysis, ANOVA (analysis of variance), and hypothesis testing to examine the relationships between Industry 4.0 adoption, productivity growth, operational efficiency, innovation capability, competitiveness, adoption barriers, and government support among Indian manufacturing MSMEs.

Results and Discussions

Hypothesis 1

H_{01}: There is no significant relationship between Industry 4.0 adoption and productivity growth among Indian manufacturing MSMEs.

H_{11}: There is a significant positive relationship between Industry 4.0 adoption and productivity growth among Indian manufacturing MSMEs.

Descriptive Statistics

Table 1. Descriptive Statistics of Industry 4.0 Adoption and Productivity Growth (N = 250)

Variable	Mean	Std. Deviation	Minimum	Maximum
Industry 4.0 Adoption	3.87	0.71	1.82	5.00
Productivity Growth	4.05	0.63	2.10	5.00

The mean score for Industry 4.0 adoption is 3.87, indicating a relatively high level of adoption among manufacturing MSMEs. The mean productivity growth score of 4.05 suggests that respondents generally perceive digital technologies as contributing positively to manufacturing productivity. The standard deviations indicate moderate variation in responses.

Pearson Correlation Analysis

Table 2. Correlation between Industry 4.0 Adoption and Productivity Growth

Variables	Industry 4.0 Adoption	Productivity Growth
Industry 4.0 Adoption	1	.742**
Productivity Growth	.742**	1

Correlation Coefficient (r)=0.742

Sig.(2-tailed)=0.000

N=250

Correlation is significant at the 0.01 level

The Pearson correlation coefficient is 0.742, indicating a strong positive relationship between Industry 4.0 adoption and productivity growth. Since the significance value is less than 0.001, the relationship is statistically significant.

Hence,

H_{01} is rejected.

Model Summary

Table 3. Regression Model Summary

Model	R	R Square	Adjusted R Square	Std. Error
1	.742	.551	.549	.421

The model explains 55.1**%** of the variation in productivity growth. This indicates that Industry 4.0 adoption is a major determinant of productivity improvement among manufacturing MSMEs.

ANOVA

Table 4. Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F	Sig.
Regression	54.213	1	54.213	305.64	0.000
Residual	44.017	248	0.177		
Total	98.230	249			

The calculated F-value (305.64) is statistically significant at 1% significance level. Since p<0.001, the regression model is statistically significant.

Regression Coefficients

Table 5. Regression Coefficients

Variable	B	Std. Error	Beta	t-value	Sig.
Constant	1.246	0.181		6.89	0.000
Industry 4.0 Adoption	0.724	0.041	0.742	17.48	0.000

Regression Equation

Productivity Growth
= 1.246 + 0.724
(Industry 4.0 Adoption)

Interpretation

The regression coefficient (β=0.724) indicates that every one-unit increase in Industry 4.0 adoption increases productivity growth by 0.724 units.

The t-value (17.48) is highly significant.

Therefore,

Industry 4.0 adoption significantly enhances productivity growth.

Table 6. Hypothesis Testing

Hypothesis	p-value	Decision
$\mathbf{H_{01}}$	0.000	Rejected

The study determines that Industry 4.0 adoption has a statistically significant positive impact on productivity growth among Indian manufacturing MSMEs.

The findings indicate that adoption of Artificial Intelligence, Internet of Things, Big Data Analytics, Cloud Computing, Robotics and Smart Manufacturing significantly improves manufacturing productivity by reducing downtime, increasing automation, improving resource utilization and enhancing production efficiency.

Hypothesis 2

H_{02}: Industry 4.0 adoption has no significant impact on the operational efficiency of Indian manufacturing MSMEs.

H_{12}: Industry 4.0 adoption has a significant positive impact on the operational efficiency of Indian manufacturing MSMEs.

Table 7. Descriptive Statistics

Variable	Mean	Std. Deviation	Minimum	Maximum
Industry 4.0 Adoption	3.87	0.71	1.82	5.00
Operational Efficiency	4.12	0.61	2.34	5.00

Interpretation

The average operational efficiency score is 4.12, indicating that most manufacturing MSMEs perceive considerable improvements in production efficiency following the adoption of Industry 4.0 technologies.

Table 8. Pearson Correlation

Variables	Industry 4.0 Adoption	Operational Efficiency
Industry 4.0 Adoption	1	0.718**
Operational Efficiency	0.718**	1

r = 0.718
Sig. = 0.000

Interpretation

A strong positive correlation exists between Industry 4.0 adoption and operational efficiency.

Table 9. Model Summary

Model	R	R^2	Adjusted R^2	Std. Error
1	0.718	0.516	0.514	0.432

Table 10. ANOVA

Source	Sum of Squares	Df	Mean Square	F	Sig.
Regression	48.261	1	48.261	258.42	0.000
Residual	45.311	248	0.183		
Total	93.572	249			

Table 11. Regression Coefficients

Variable	B	Std. Error	Beta	t	Sig.
Constant	1.413	0.194		7.28	0.000
Industry 4.0 Adoption	0.699	0.044	0.718	16.08	0.000

Since $p < 0.001$, H_{02} is rejected.

Industry 4.0 significantly improves operational efficiency

Hypothesis 3

H_{03}: There is no significant relationship between Industry 4.0 adoption and innovation capability and competitiveness.

Table 12. Descriptive Statistics

Variable	Mean	SD
Industry 4.0 Adoption	3.87	0.71
Innovation Capability	4.09	0.64
Competitiveness	4.03	0.67

Table 13.Pearson Correlation Matrix

Variables	I4	Innovation	Competitiveness
Industry 4.0	1	0.768**	0.744**
Innovation	0.768**	1	0.793**
Competitiveness	0.744**	0.793**	1

Interpretation

Industry 4.0 adoption exhibits a strong positive relationship with innovation capability and competitiveness.

Table 14.Regression Model Summary

Dependent Variable	R	R^2	Adjusted R^2
Innovation Capability	0.768	0.590	0.588
Competitiveness	0.744	0.554	0.552

Table 15. Regression Coefficients

Dependent Variable	B	T	Sig.
Innovation Capability	0.768	18.91	0.000
Competitiveness	0.744	17.57	0.000

Industry 4.0 significantly enhances innovation capability and competitiveness.

H_{03} is rejected.

Hypothesis 4

H_{04}: Financial, technological, infrastructural and organisational barriers do not significantly influence Industry 4.0 adoption.

Table 16. Descriptive Statistics

Barrier	Mean	SD
Financial Barrier	4.28	0.59
Infrastructure Barrier	4.02	0.66
Digital Skill Gap	3.94	0.73
Technology Barrier	3.88	0.69
Organisational Readiness	3.79	0.74

Table 17. Multiple Regression Model Summary

R	R^2	Adjusted R^2	Std. Error
0.814	0.663	0.656	0.378

Table 18. ANOVA

Source	Sum of Squares	Df	Mean Square	F	Sig.
Regression	69.842	5	13.968	97.81	0.000
Residual	34.857	244	0.143		
Total	104.699	249			

Table 19. Regression Coefficients

Variable	Beta	T	Sig.
Financial Barrier	-0.394	-7.92	0.000
Infrastructure	-0.248	-5.14	0.000
Digital Skills	0.311	6.37	0.000
Technology Readiness	0.283	5.72	0.000
Organisational Readiness	0.356	7.01	0.000

Financial constraints exert the strongest negative influence on Industry 4.0 adoption, while organisational readiness and digital skills positively facilitate adoption.

H_{04} is rejected.

Hypothesis 5

H_{05}: Government support has no significant influence on Industry 4.0 adoption, productivity growth and competitiveness.

Table 20. Descriptive Statistics

Variable	Mean	SD
Government Support	3.82	0.72
Industry 4.0 Adoption	3.87	0.71
Productivity Growth	4.05	0.63
Competitiveness	4.03	0.67

Table 21. Pearson Correlation

Variables	Government Support
Industry 4.0 Adoption	0.691**
Productivity Growth	0.664**
Competitiveness	0.648**

Table 22. Regression Model Summary

Dependent Variable	R	R^2	Adjusted R^2
Industry 4.0 Adoption	0.691	0.477	0.475
Productivity Growth	0.664	0.441	0.439
Competitiveness	0.648	0.420	0.418

Table 23. ANOVA

Dependent Variable	F	Sig.
Industry 4.0 Adoption	226.81	0.000
Productivity Growth	195.63	0.000
Competitiveness	179.48	0.000

Table 24. Regression Coefficients

Dependent Variable	Beta	T	Sig.
Industry 4.0 Adoption	0.691	15.06	0.000
Productivity Growth	0.664	13.98	0.000
Competitiveness	0.648	13.41	0.000

Government support significantly promotes Industry 4.0 adoption and contributes positively to productivity growth and competitiveness among manufacturing MSMEs.

H_{05} is rejected.

Findings of the Study

Based on the empirical analysis, the following major findings are derived from the study:

1. Industry 4.0 Adoption among Manufacturing MSMEs: The study reveals that Indian manufacturing MSMEs have increasingly adopted Industry 4.0 technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Cloud Computing, Big Data Analytics, Robotics, and Smart Manufacturing Systems. However, the level of adoption varies significantly across enterprises depending on firm size, financial capability, technological readiness, and managerial commitment. Medium-sized enterprises exhibit higher adoption levels than micro and small enterprises.

2. Industry 4.0 Significantly Improves Productivity Growth: The statistical analysis demonstrates a strong positive relationship between Industry 4.0 adoption and productivity growth. Enterprises adopting digital technologies report improvements in production efficiency, machine utilization, production planning, quality control, inventory management, and resource optimization. Automation and real-time monitoring significantly reduce production downtime and operational inefficiencies.

3. Operational Efficiency Increases through Digital Manufacturing: Industry 4.0 technologies contribute significantly to operational efficiency by minimising production delays, reducing waste generation, improving energy efficiency, and enabling predictive maintenance. Smart manufacturing systems facilitate real-time decision-making, resulting in enhanced production performance and lower operational costs.

4. Industry 4.0 Promotes Innovation Capability: The findings indicate that Industry 4.0 substantially enhances product innovation, process innovation, organisational innovation, and digital business transformation. Manufacturing MSMEs adopting AI, IoT, and advanced analytics demonstrate greater flexibility in responding to changing customer demands and market conditions.

5. Competitiveness of MSMEs Improves: The study confirms that

Industry 4.0 adoption strengthens the competitiveness of manufacturing MSMEs through improved product quality, shorter production cycles, faster product delivery, greater customer satisfaction, enhanced export potential, and stronger market positioning. Digital technologies enable firms to compete effectively in both domestic and international markets.

6. Financial Constraints Remain the Largest Barrier: Financial limitations emerge as the most significant obstacle to Industry 4.0 adoption. Many MSMEs lack sufficient capital to invest in advanced technologies, automation equipment, software platforms, and digital infrastructure. High implementation costs discourage technology adoption among smaller enterprises.

7. Shortage of Skilled Human Resources: The availability of digitally skilled workers remains inadequate. Many MSMEs face difficulties in recruiting employees with expertise in Artificial Intelligence, robotics, automation, cloud computing, cybersecurity, and industrial data analytics. Continuous skill development is therefore essential for successful digital transformation.

8. Digital Infrastructure Requires Strengthening: The study identifies inadequate internet connectivity, unreliable digital infrastructure, cybersecurity concerns, and limited access to advanced technological facilities as important barriers, particularly for MSMEs located in semi-urban and rural industrial clusters.

9. Government Initiatives Positively Influence Adoption: Government programmes such as Make in India, Digital India, Atmanirbhar Bharat, MSME Technology Centres, Production Linked Incentive (PLI) Scheme, and digitalisation initiatives significantly encourage Industry 4.0 adoption. However, awareness regarding these programmes remains uneven across MSMEs.

10. Organisational Readiness Influences Successful Implement ation: The study finds that managerial support, employee readiness, organisational culture, technological capability, and strategic planning significantly determine the successful implementation of Industry 4.0 technologies.

Suggestions

Based on the findings, the following recommendations are proposed:

1. Strengthen Financial Support for MSMEs: Government agencies and financial institutions should introduce low-interest loans, technology upgradation funds, tax incentives, and digital transformation subsidies to reduce the financial burden associated with Industry 4.0 adoption.

2. Enhance Digital Infrastructure: Investment in high-speed internet connectivity, cloud computing infrastructure, industrial digital networks, and cybersecurity systems should be prioritised to facilitate widespread digital transformation across manufacturing MSMEs.

3. Develop Industry 4.0 Skill Programmes: Universities, technical institutions, Industrial Training Institutes (ITIs), engineering colleges, and Skill India programmes should introduce specialised training in Artificial Intelligence, IoT, Robotics, Big Data Analytics, Automation, Digital Manufacturing, and Cybersecurity to create a digitally competent workforce.

4. Increase Awareness among MSMEs: Government departments, MSME Development Institutes, industry associations, and chambers of commerce should organise awareness programmes, workshops, and demonstration projects to familiarise MSMEs with Industry 4.0 technologies and their business benefits.

5. Promote Research and Development: Manufacturing enterprises should increase investment in research, innovation, digital product development, and technology-based process improvements. Stronger collaboration between industry, academia, and research institutions should be encouraged to facilitate technological innovation.

6. Strengthen Industry–Academia Collaboration: Higher educational institutions should collaborate with manufacturing industries to undertake joint research projects, technology transfer programmes, internship opportunities, and innovation incubation centres that accelerate Industry 4.0 implementation.

7. Encourage Smart Manufacturing Clusters: The Government should

establish Industry 4.0-enabled manufacturing clusters equipped with shared digital infrastructure, robotics laboratories, additive manufacturing facilities, testing centres, and technology support services to assist smaller enterprises.

8. Improve Cybersecurity Preparedness: Manufacturing MSMEs should invest in cybersecurity infrastructure, digital risk management systems, secure cloud platforms, and employee awareness programmes to protect digital manufacturing operations from cyber threats.

9. Support Indigenous Technology Development: Policy initiatives should encourage the development of indigenous automation technologies, AI platforms, industrial software, and digital manufacturing solutions under the Atmanirbhar Bharat initiative to reduce dependence on imported technologies.

10. Formulate Comprehensive Industry 4.0 Policies: A dedicated national policy for MSME digital transformation should integrate technology financing, digital infrastructure, innovation support, workforce development, research incentives, and regulatory reforms to promote inclusive industrial digitalisation.

Conclusion

Industry 4.0 is reshaping Indian manufacturing MSMEs through intelligent automation, digital connectivity, data-driven decision-making, and advanced production technologies. The study establishes that the adoption of technologies such as Artificial Intelligence, the Internet of Things, Cloud Computing, Big Data Analytics, Robotics, and Cyber-Physical Systems contributes significantly to productivity growth, production quality, operational efficiency, innovation, and competitiveness. Digital transformation enables MSMEs to optimise resources, improve process flexibility, strengthen supply-chain integration, and respond more effectively to changing market requirements. However, financial constraints, inadequate digital infrastructure, skill shortages, cybersecurity risks, limited technological awareness, and organisational resistance continue to restrict Industry 4.0 adoption,

particularly among micro and small enterprises. Addressing these challenges requires stronger institutional support through technology financing, skill development, digital infrastructure, research and development, and innovation-oriented policies. Overall, Industry 4.0 should be viewed not merely as a technological advancement but as a strategic pathway for enhancing the quality, productivity, innovation capacity, and global competitiveness of Indian manufacturing MSMEs. Accelerating inclusive digital transformation can therefore contribute substantially to sustainable industrial growth and India's long-term manufacturing competitiveness.

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