SUSTAINABLE SMART FACTORIES: DIGITALIZATION'S IMPACT ON CARBON EMISSION REDUCTION

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Dedication

I dedicate this research to my mother, who embodies the essence of nature nurturing, resilient, and ever giving. Just as a mother selflessly cares for her children, nature sustains and protects all life on Earth. The unconditional love and affection of a mother closely resemble the harmony and balance found in the natural world. This profound connection has been my greatest source of inspiration in undertaking this research.

Witnessing my mother's unwavering strength and compassion has shaped my perspective on responsibility and care values that extend beyond personal relationships to our collective duty toward the environment. Her influence has instilled in me a deep commitment to preserving and protecting nature, ensuring that future generations inherit a world that is thriving and sustainable.

With this research, I aim to contribute to environmental sustainability by leveraging digital transformation technologies to reduce carbon footprints in manufacturing. It is my humble effort to merge technology with environmental consciousness, just as my mother seamlessly blends love with wisdom. This work is a tribute to her and to all those who believe in nurturing both people and the planet.

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Lastly, I acknowledge the influence of the broader society, whose complex layers and dynamics have shaped my thinking about leadership. The lessons I've learned from my interactions within this diverse milieu have greatly influenced the person and leader I am today.

Thank you all for being a part of this fulfilling journey.

ABSTRACT

SUSTAINABLE SMART FACTORIES: DIGITALIZATION’S IMPACT ON CARBON EMISSION REDUCTION

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2025

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In the era of rapid digitalization, the industrial sector is progressively embracing smart factory technologies to enhance efficiency, productivity, and competitiveness. At the same time, sustainability and carbon footprint reduction have emerged as critical imperatives, driving industries to adopt environmentally responsible practices. This research investigates the role of digital transformation technologies in the development

of smart factories and their influence on carbon footprint reduction. It explores the intricate relationship between digitalization and sustainability, offering a strategic framework for integrating these essential elements while navigating the complexities of disruptive technologies.

This study employs a mixed methods research approach, incorporating qualitative and quantitative methodologies, including an extensive literature review, expert interviews, and survey based data collection. By analyzing empirical data, the research provides insights into the adoption and implementation of digital transformation technologies, assessing their effectiveness in reducing carbon footprints at various levels of industrial operations. The study identifies key digital innovations such as the Internet of Things, artificial intelligence, machine learning, digital twins, virtual reality/ augmented reality and blockchain and evaluates their impact on sustainability driven manufacturing processes.

Findings from this research highlight the extent to which these technologies contribute to a carbon conscious industrial culture, enabling factories to optimize energy consumption, reduce waste, and enhance resource efficiency. The study further explores the challenges industries face in implementing digital solutions, including technological integration barriers, high initial investment costs, and workforce adaptability. It also discusses the role of policy frameworks and industry standards in accelerating the transition toward smart and sustainable factories.

Additionally, this research provides strategic recommendations for industry practitioners, policymakers, and future researchers, addressing key implementation challenges associated with digital transformation technologies. It outlines best practices for overcoming obstacles, measuring carbon footprint reductions, and achieving long term sustainability goals. The findings contribute to a deeper understanding of how industries can leverage digitalization to balance technological advancements with environmental responsibility, ultimately shaping a future where smart factories drive both economic growth and sustainable development.

By presenting a roadmap for harmonizing digitalization and sustainability in industrial operations, this study offers valuable insights into the evolving landscape of smart factories and their role in reducing the environmental impact of manufacturing.

LIST OF TABLES

Table 4.1: Participants Experience Details 49

Table 4.2: Participants Job Roles 52

Table 4.3: Participants Country of Operations 53

Table 4.4: Carbon footprint monitoring with respect digital maturity 74

Table 4.5: Digital maturity vs Sustainability goals 82

LIST OF FIGURES

Figure 2.1: The theoretical framework for the effect of digital economy on carbon emission intensity. 22
Figure 4.3: Participants Geography 53
Figure 4.4: Digital Maturity vs Motive 54
Figure 4.5: Participants familiarity on Digital Transformation & Sustainability 55
Figure 4.6: ESG team familiarity on Digital Technologies 55
Figure 4.7: Digital Twins adoption 56
Figure 4.8: META AR & VR adoption in Industries 57
Figure 4.9: Cloud Usage 58
Figure 4.10: IOT Usage 58
Figure 4.11: Robotic and automation Adoption 59
Figure 4.12 :AI & ML usage 60
Figure 4.13: Big Data Usage 61
Figure 4.14: Blockchain Adoption 62
Figure 4.15: Sustainability initiative status in Industries 64
Figure 4.16: Circular economy initiatives 65
Figure 4.17: Technology use in circular economy activities 65
Figure 4.18: Carbon Footprint Monitoring using Digital tools 66
Figure 4.19: Application of Digital Twins vs Operational Areas 67
Figure 4.20: Meta Technologies adoption 68
Figure 4.21: Cloud Technologies usage in operations 69
Figure 4.22: IOT application in operations 70
Figure 4.23: SMART Grid Application in operations 71
Figure 4.24: Robotic automation and 3D printing usage in operations 71
Figure 4.25: AI/ML usage in operations 72
Figure 4.26: Digital Technologies usage operations for carbon footprint reduction 73

Figure 4.27: Digital technologies effect in reducing factory's carbon emissions 75
Figure 4.28: Carbon Footprint Reduction rate using digital technologies 76
Figure 4.29: Skill gap in digital technologies **77**
Figure 4.30: Main barriers to adopting digital solutions for carbon footprint reduction 78
Figure 4.31: Measuring carbon emissions 79
Figure 4.32: Legay system Digitization challenges 80
Figure 4.33: Regulatory Challenges 81
Figure 4.34: ROI Challenges 81
Figure 4.35: Interest on collaborations 84
Figure 4.36: KPI's for tracking carbon emissions reduction through digital technologies 85
Figure 4.37: Technologies vs areas for carbon footprint reduction 87
Figure 4.38: Future invest plans in digital technologies to reduce carbon footprint 89
Figure 5.1: Assessment procedure of the Carbon Footprints 95
Figure 5.2: Boundaries for calculation of Carbon Footprint

TABLE OF CONTENTS

LIST OF TABLES 9

LIST OF FIGURES 10

CHAPTER I: INTRODUCTION 14

1.1 INTRODUCTION 14

1.2 RESEARCH PROBLEM 16

1.3 PURPOSE OF RESEARCH 17

1.4 SIGNIFICANCE OF THE STUDY 17

1.5 RESEARCH PURPOSE AND QUESTIONS 20

CHAPTER II: REVIEW OF LITERATURE 21

2.1 THEORETICAL FRAMEWORK 21

2.4 SUMMARY 26

CHAPTER III: METHODOLOGY 30

3.1 OVERVIEW OF THE RESEARCH PROBLEM 30

3.2 OPERATIONALIZATION OF THEORETICAL CONSTRUCTS 31

3.3 RESEARCH PURPOSE AND QUESTIONS 34

3.4 RESEARCH DESIGN 34

3.5 POPULATION AND SAMPLE 36

3.6 INSTRUMENTATION 37

3.8 DATA COLLECTION PROCEDURES 39

3.9 DATA ANALYSIS 43

3.10 RESEARCH DESIGN LIMITATIONS 44

3.11 CONCLUSION 45

CHAPTER IV: RESULTS 48

4.1 SURVEY RESPONSE SUMMERY 48

4.1.1. SURVEY PARTICIPANT DEMOGRAPHICS & INSIGHTS 48

4.1.2 PERCEPTIONS AND AWARENESS: SUSTAINABILITY & DIGITAL TRANSFORMATION IN INDUSTRY 54

4.1.3 EXISTING SUSTAINABILITY PRACTICES AND DIGITAL TECHNOLOGIES IN INDUSTRIAL USE 64
4.1.4 CHALLENGES AND BARRIERS TO IMPLEMENTING SUSTAINABILITY PRACTICES AND DIGITAL TECHNOLOGIES 77
4.1.5 VISION AND STRATEGIES FOR DIGITAL TECHNOLOGIES IN SUSTAINABILITY AND CARBON REDUCTION 84
4.2 INTERVIEW RESULTS 90
4.5 CONCLUSION 93
CHAPTER V: DISCUSSION 95
5.1 DISCUSSION OF RESULTS 95
5.3 DISCUSSION OF RESEARCH QUESTION TWO 103
CHAPTER VI: SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS 106
6.1 SUMMARY 106
6.2 IMPLICATIONS 110
6.3 RECOMMENDATIONS FOR FUTURE RESEARCH 112
6.4 CONCLUSION 114
APPENDIX A SURVEY COVER LETTER 117
APPENDIX B INFORMED CONSENT 119
APPENDIX C INTERVIEW GUIDE 124
APPENDIX D SURVEY QUSETIONS 125
REFERENCES 155

CHAPTER I: INTRODUCTION

1.1 Introduction

Sustainability is of paramount importance to factories in our current era of human civilization (Mitchell, 2017). Carbon emissions are one of the key factors in the sustainability goals for industries. The amount of damage done in the past few decades with respect to carbon emissions is huge (Paris Agreement: Sustainable Development Knowledge Platform, 2015). Globally nations have come together and agreed to reduce the carbon footprint. These greenhouse gas emissions need to be controlled to reduce global warming. To control greenhouse gas emissions, it’s important to track these emissions and measure their contribution to climate change. Global warming and environmental pollution pose significant concerns for nations and individuals worldwide(Maamoun, 2019). The urgency to address climate change has prompted many countries to adopt a vision of sustainable development. In 1987, the United Nations Brundtland Commission defined sustainability as *"meeting the needs of the present without compromising the ability of future generations to meet their own needs."*(Commission, 2005). Sustainability encompasses three key dimensions: social, economic, and environmental (Commission, 2005).

While sustainability traditionally focuses on core concepts such as natural resource consumption, resilience, supply chain management, environmental management systems, waste management, water and energy conservation, and the broader biophysical environment, it also extends to encompass vital social aspects. These include human rights, child labor prevention, ensuring safe working conditions, promoting health, and preventing discrimination. The scope of sustainability is continually expanding, involving every individual in a global mission to ensure a viable and thriving future for generations to come.

On the other hand, the Industrial Revolution 4.0 is driving the transformation of factories into SMART facilities by fostering a culture of digital manufacturing(Ma et al., 2022). Manufacturing units and factories are actively pursuing digitalization throughout the entire process, from concept to delivery. It is evident that SMART factories are not only digitally enabled but also creating digitally operated environments. Industry 4.0 goes beyond making factories SMART; it also aims to make consumers smarter through business transformation(Shi et al., 2020).

This research project aims to provide an overview of how SMART factories can reduce their carbon footprint by adopting latest technologies. In December 2015, 195 countries adopted the Paris Agreement at the Paris Climate Change Conference, committing to limiting global warming to below 2 degrees Celsius and striving to stay below 1.5 degrees Celsius('Paris Agreement .:. Sustainable Development Knowledge Platform', n.d.). Factories in many countries are significant contributors to environmental pollution, making them key players in sustainability efforts(Paris Agreement: Sustainable Development Knowledge Platform, 2015). To achieve the goals of the Paris Agreement it is important to involve factories and manufacturing units which play a vital role in environmental change. The factories have already started their digital transformation journey and started becoming smart factories. A combined effort of digital manufacturing and reduction of carbon footprint and environmental management system can give better results for both factories and sustainability goals. Bringing clear and measurable methods and approaches for carbon footprint reduction with digital manufacturing is very essential, which will be a win-win situation for the world and manufacturing units.

1.2 Research Problem

Research on carbon footprint reduction in manufacturing units using digital transformation technologies is essential for environmental sustainability, economic viability, regulatory compliance, technological advancement, and social responsibility. It provides a comprehensive approach to tackling one of the most pressing global challenges of our time. Manufacturing units are major contributors to global carbon emissions, playing a significant role in the environmental footprint of industrial activities (Wang and Wang, 2023). As the demand for sustainable manufacturing practices increases, there is a pressing need for innovative solutions to reduce the carbon footprint within this sector (Sovacool et al., 2021). Digital transformation technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, and Blockchain, offer promising avenues for enhancing efficiency and sustainability. However, the potential and practical application of these technologies in achieving substantial carbon footprint reduction in manufacturing units are not fully understood.

This research is crucial for developing sustainable industrial practices that align with carbon reduction goals for manufacturing units. The findings will contribute to the broader discourse on sustainable development and offer a pathway for industries to transition towards greener and more efficient operations.

1.3 Purpose of Research

The primary aim of this research is to understand the various factors contributing to carbon footprint generation in heavy manufacturing industries. Additionally, the research seeks to explore the different digital transformation technologies available and currently applied in the manufacturing sector. By investigating these technologies, this study aims to evaluate their potential to significantly reduce the carbon footprint of manufacturing units.

- To understand the source of carbon footprints in the manufacturing sectors
- To understand the latest digital transformation technologies adopted in the manufacturing sector

To identify the scientific relationship between digitization impact on the carbon footprint reduction goals of the smart factories

The results of this study will be valuable to the manufacturing industry and digital transformation professionals. It will aid in developing better practices and tools for applying these technologies and measuring their impact on carbon footprint reduction, thereby contributing to overall sustainability efforts.

1.4 Significance of the Study

This research is significant as it explores the intersection of digital transformation and sustainability in industrial operations, providing valuable insights into how smart factory technologies contribute to carbon footprint reduction. As industries worldwide face mounting pressure to adopt environmentally responsible practices, this study offers a strategic analysis of how digitalization can enhance sustainability without compromising productivity or economic growth.

Available Digital Transformation Technologies

By evaluating key digital transformation technologies—such as the Internet of Things (IoT), artificial intelligence (AI), digital twins, metaverse applications, and blockchain—this research highlights their potential in optimizing energy consumption, minimizing waste, and improving overall resource efficiency. It also examines the challenges industries encounter in adopting these technologies, including high initial costs, integration complexities, data security concerns, and workforce adaptability issues.

Role Players in Building Smart Factories and Challenges

The study provides practical insights for industry leaders, policymakers, and researchers by outlining best practices for implementing digital solutions while ensuring measurable carbon footprint reduction. It also emphasizes the role of policy frameworks, corporate leadership, and industry regulations in fostering smart, sustainable factories. Furthermore, it discusses collaboration between governments, businesses, and technology providers in overcoming adoption barriers and driving large scale digital sustainability initiatives.

Current Challenges in Carbon Footprint Reduction and Vision with Digital Transformation

This research identifies critical obstacles industries face in reducing their carbon footprint, such as energy intensive production processes, outdated infrastructure, and the lack of standardized measurement frameworks. By demonstrating how digital transformation can serve as a catalyst for sustainability, the study provides a roadmap for industries to integrate technological advancements with ecological responsibility.

Ultimately, this research contributes to the global sustainability agenda by offering strategic guidance on leveraging digitalization for long term environmental and economic benefits, helping industries transition toward a smarter, greener future.

1.5 Research Purpose and Questions

The primary pupose of this research is to systematically analyze the key factors contributing to carbon footprint generation within heavy manufacturing industries. Furthermore, this study aims to explore the spectrum of digital transformation technologies currently available and implemented in the manufacturing sector. By critically examining these technologies, the research seeks to assess their effectiveness in mitigating carbon emissions and enhancing sustainability within industrial operations. Through this evaluation, the study endeavors to provide empirical insights into the role of digitalization in promoting environmentally responsible manufacturing practices while maintaining operational efficiency and competitiveness.

Research Questions

1. What are the critical areas in factories for carbon footprint generation?
2. What digital transformation technologies implemented in the manufacturing unit reduced the carbon footprints and how did you measure it?
3. How is the carbon credit calculation dependent on the critical carbon footprint generated in factories?

The collected data will be consolidated and Use data analytics tools to compare pre and post implementation metrics and assess the impact of digital transformation on carbon footprint reduction. Analysis will be conducted on the collected data to identify patterns, correlations, and causal relationships.

From this research, a comprehensive framework will be developed for implementing digital transformation technologies to achieve carbon footprint reduction in manufacturing units. This framework will integrate insights gained from the literature review, case studies, surveys, and data analysis. It will provide a step by step guide outlining best practices, tools, and strategies tailored for manufacturing units.

CHAPTER II:

REVIEW OF LITERATURE

2.1 Theoretical Framework

The theoretical framework for this research is built upon established theories and models related to sustainability, digital transformation, and industrial efficiency. It integrates key concepts from environmental sustainability theories, technology adoption models, and industrial digitalization frameworks to analyze the impact of digital transformation on carbon footprint reduction in heavy manufacturing industries. While previous research has provided valuable insights into the individual effects of digitalization and sustainability practices, a comprehensive understanding of their combined impact remains elusive. This knowledge gap highlights the need for further research that explicitly examines the combined impact of both on manufacturing units.

There is a growing need to understand how digitization of the factories can contribute to sustainability and reduction of carbon footprints. This research aim to shed light on the potential synergies and benefits that arise when organizations integrate digital transformation and sustainability practices.

The major contribution to this research involves the following subjects.

Carbon footprints and their calculation methodology in manufacturing units.

The term “carbon footprint” is very popular in recent times. The globally accepted definition of the term "carbon footprint” is still awaited, but the notion print does exist. The definition of the carbon footprint given by (Wiedmann and Minx, 2007) is mostly recognized and it states that “the carbon footprint is a measure of the total amount of carbon dioxide emissions directly and indirectly caused by an activity or accumulated over the life stages of a product. There are scientific methodologies and formulae derived to calculate the carbon footprint.

We need to identify the baseline of carbon emissions in the factory and quantify them. The source of carbon emissions and its measurement is a key factor in calculation of the contribution to greenhouse gas emissions. Examining these methods and their variables for various particulars and parameters and establishing the relation of the carbon footprint calculation to carbon credit calculations is an important activity.

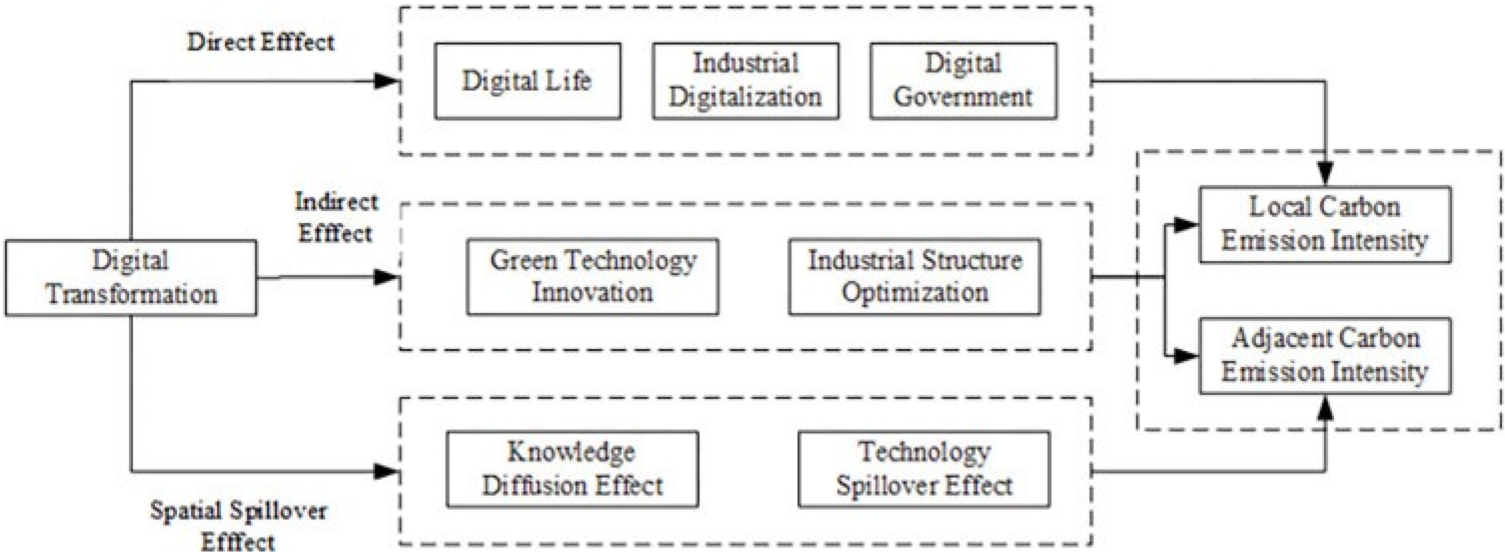

Figure 2.1 The theoretical framework for the effect of digital economy on carbon emission intensity.

Digital transformation of urban infrastructure has a spatial spillover effect and affects nearby cities’ carbon emissions.(Song et al., 2024)

The relation between carbon credits and sustainability and their impact on manufacturing units.

Manufacturing industries prioritize ambitious sustainability goals, striving to reduce their environmental impact through energy efficiency, waste reduction, and digital transformation while aligning with global regulations and corporate responsibility initiatives. In 1987, the United Nations Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." (Carbon credit: Understanding the concept, its evolution and implications, ET EnergyWorld, no date).Sustainability has many factors to be considered as whole indexing and measurement. Carbon footprints and green house gas emissions are one of the key factors in sustainable industrial models. The socio and economic impact of these carbon footprints is an important and vital relation in sustainability. A meaningful relation of these carbon credits and sustainability indexes very important dimension for the manufacturing sector in addressing the sustainability goals.

Various sectors, departments and process of manufacturing units contributing carbon credits and sustainability.

Manufacturing industries are widespread across various sectors. The industries' process varies with respect to the products they manufacture. Grossly most of the manufacturing industries include general departments like utilities, logistics, production, and a few others. Every product has a life cycle from the womb to tomb. The process of manufacturing of these products' various raw materials consumption, production processes, waste management, supply chain and service models in general. (Gao et al., 2014a)

The amount of greenhouse gas emissions and the carbon footprints generated by these various departments at different stages of the production process plays the key role in calculating the carbon footprint. The total carbon footprint generated by these departments and the emphasis to reduce the greenhouse gas emissions to be measured and monitored by the manufacturing unit and document it. This documentation will be the basis for carbon credit calculation and sustainability indexing. Identification of the departments and their direct contributions to the carbon credits is crucial and this can help the factories management in addressing sustainability goals by identifying perpetrator in the process.

Digital transformation technologies are implemented in the manufacturing units making them smart factories.

Industry 4.0 revolution has been making a swift change to the way manufacturing units work. The paradigm shift created by the digital transformation in the manufacturing units is very important in understanding the way future production works. The "Smart Factory" trend has been already picked up by various manufacturers globally. The manufacturers and the stakeholders have started strategically investing in this sector. The factories are continuously striving to become smart by adopting the latest technologies and parallelly building the capacity to handle them too. The advantages of being smart in manufacturing has equal level of risks.

The latest technologies used in the process of manufacturing and their impact on reduction of greenhouse gas emissions.

Smart factories adopt many of the latest technologies in the process of digital transformation. Industrial Internet of things, Artificial Intelligence, machine learning, robotics and many other technologies are implemented by the manufacturers in the factories to make them smart and highly productive. Technology is not limited to the ones mentioned earlier and the innovation and research in factory automations are erasing all the boundaries of limitation. Augmented and Virtual reality with the help of meta technologies has been remarkably contributing in building and operating the digital twins of the factories. The continuous improvement in the industries are aligned with the digital transformation goals by the manufacturers.

Metrics for measuring the impact of greenhouse gas emissions and digital technologies used for building smart factories.

The digital technologies help the manufacturers to measure and track the results of the system with a fine accuracy. The application of the industry 4.0 technologies created a platform for the factories to effectively understand the functioning of the system and track the performance.

The application of these digital technologies in the factory may directly or indirectly impact the greenhouse gas emissions. The impact of these technologies can be understood by studying the post change in the carbon footprint of the factory.

2.4 Summary

Existing research primarily focuses either on digital transformation technologies or sustainability goals, with limited studies exploring their combined impact. Manufacturing industries face significant challenges in achieving sustainability objectives while simultaneously undergoing digital transformation. A deeper investigation is required to understand how digital adoption influences carbon footprint reduction and sustainability outcomes.

The escalating concern over climate change has prompted industries worldwide to explore innovative strategies for reducing carbon emissions. Digital transformation has emerged as a pivotal approach, leveraging advanced technologies to enhance operational efficiency and minimize environmental impact. This literature review examines the role of digital transformation in carbon footprint reduction, focusing on key technologies, their applications, and the associated challenges.

The industrial sector is a significant contributor to global carbon emissions, accounting for approximately 20% of CO_2 emissions worldwide. As concerns about climate change intensify, there is a growing imperative for factories to adopt strategies that mitigate their environmental impact. Digital transformation has emerged as a pivotal approach, leveraging advanced technologies to enhance operational efficiency and reduce carbon footprints. This literature review explores the role of digital transformation in reducing carbon emissions within manufacturing environments, examining key technologies, their applications, and associated challenges.

Digital transformation involves integrating digital technologies into all areas of business operations, fundamentally changing how organizations operate and deliver value. This integration has significant potential for reducing carbon emissions by optimizing processes, improving energy efficiency, and enabling sustainable practices.

Studies have shown that digital technologies can indirectly reduce carbon emissions by promoting green technological innovation and reducing energy intensity. For instance, the implementation of digital solutions in manufacturing processes can lead to more efficient resource utilization and lower energy consumption, thereby decreasing overall emissions (Shen et al., 2023)

An integrated study of sustainability, carbon credits, and digital technologies in manufacturing can address the following key questions:

- ✓ What are the primary factors contributing to carbon footprints in manufacturing?
- ✓ What are the carbon offset goals and sustainability challenges faced by the manufacturing sector?
- ✓ How do digital transformation technologies impact various departments within manufacturing units?
- ✓ What measurable effects do these technologies have on carbon footprints and sustainability efforts?
- ✓ Which digital technologies contribute positively to sustainability objectives?
- ✓ How can the impact of digital transformation on carbon footprint reduction be effectively measured?

During research it has been observed that several digital technologies play a crucial role in reducing greenhouse gas emissions/

- **Internet of Things (IoT):** IoT devices enable real-time monitoring and management of energy usage, facilitating immediate adjustments to reduce waste. For example, smart sensors can detect inefficiencies in industrial equipment, allowing for timely maintenance and energy savings.

- **Artificial Intelligence (AI) and Machine Learning (ML):** AI and ML algorithms analyze vast datasets to optimize energy consumption patterns. In building management, AI can predict heating and cooling needs, adjusting systems proactively to conserve energy (Song et al., 2024)
- **Digital Twins:** These virtual replicas of physical assets allow for simulation and analysis of processes, identifying opportunities for efficiency improvements and emission reductions. In urban infrastructure, digital twins can model energy flows to optimize city-wide energy consumption (Guo et al., 2024)
- **Blockchain:** Blockchain technology ensures transparency and traceability in supply chains, promoting sustainable sourcing and reducing emissions associated with unethical practices. By providing immutable records, blockchain can verify the carbon footprint of products throughout their lifecycle.

In the manufacturing sector, this integration has the potential to significantly reduce carbon emissions by optimizing processes, improving energy efficiency, and fostering sustainable practices. Studies have demonstrated that digital transformation can lead to a notable decrease in carbon dioxide emissions. For instance, research focusing on Chinese manufacturing enterprises found that digital transformation significantly reduced carbon emission levels, primarily through enhanced energy efficiency and green technology innovation The integration of IoT and AI in manufacturing processes has been shown to significantly reduce carbon emissions. A study focusing on Chinese manufacturing enterprises found that digital transformation led to a notable decrease in carbon dioxide emissions, primarily through enhanced energy efficiency and green technology innovation (Guo et al., 2024)

This research aims to bridge the gap by systematically analyzing the role of digital transformation technologies in advancing sustainability within manufacturing industries. By leveraging data driven insights, automation, and process optimization, industries can make informed decisions that lead to reduced resource consumption and lower carbon footprints. Furthermore, the study seeks to highlight the benefits of emerging technologies in minimizing greenhouse gas emissions and promoting sustainable industrial practices.

CHAPTER III:

METHODOLOGY

3.1 Overview of the Research Problem

The need to reduce carbon footprints in manufacturing units has become a critical issue in the context of environmental sustainability, economic viability, regulatory compliance, technological advancement, and social responsibility. Manufacturing industries are among the largest contributors to global carbon emissions, significantly impacting environmental sustainability (Wang et al., 2023). As industries face increasing pressure to adopt sustainable practices, there is an urgent need for innovative solutions to mitigate their environmental impact (Sovacool et al., 2021).

Digital transformation technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, and Blockchain, present promising opportunities for improving energy efficiency, optimizing resource utilization, and reducing greenhouse gas emissions. However, despite their potential, the practical applications and measurable impact of these technologies in achieving substantial carbon footprint reductions remain insufficiently explored.

This research addresses this gap by investigating how digital transformation technologies can drive sustainability in manufacturing industries. The study aims to provide empirical insights into their effectiveness, implementation challenges, and long term benefits. The findings will contribute to the broader discourse on sustainable industrial practices, offering a roadmap for industries to transition toward greener, more efficient, and technology driven operations.

3.2 Operationalization of Theoretical Constructs

Operationalization involves defining theoretical constructs in measurable terms for empirical analysis. This research examines how digital transformation technologies affect carbon footprint reduction in manufacturing industries. The theoretical constructs are based on sustainability frameworks, digital transformation theories, and industrial efficiency models. Below is the operationalization of the key constructs used in the study:

1. Carbon Footprint in Manufacturing

The total greenhouse gas (GHG) emissions (measured in CO_2 equivalent) generated by manufacturing operations, including energy consumption, material usage, and production processes, logistics, transport and other elements involved in the total production life cycle which will generate the carbon footprints. Operationalization:

- Indicators: CO_2 emissions (tons/year), energy consumption (kWh), waste generation (kg/year), recycling (tons/year), circular economy (kg/year), plastic usage reduction (tons/year)

- Measurement Tools: Carbon accounting software, Environmental Impact Assessments (EIA), Life Cycle Assessment (LCA) ESG software, IOT technology, Sensor detection models, Data Analysis models.

2. Digital Transformation Technologies

Advanced digital tools and systems used to optimize manufacturing operations, improve efficiency, and reduce environmental impact. *Operationalization:*

- Key Technologies:
  - META (AR/VR): Training and remote operating technologies for process and safety
  - Industrial Internet of Things (IoT): Real time monitoring of energy consumption, predictive maintenance.
  - Artificial Intelligence (AI): Smart process optimization, automated energy management.
  - Cloud Computing: Remote access of data and secured data storage services
  - Automation & Robotics: Process improvements and robotic operation to reduce risks which in volve manual work.
  - Big Data Analytics: Data driven decision making for energy efficiency.
  - Blockchain: Transparent carbon credit tracking, supply chain sustainability.
  - Digital Twins: Virtual simulations to optimize factory processes and resource usage.
- Measurement Tools: Technology adoption levels (survey based scoring), interviews, implementation case studies, industry reports.

3. Impact of Digital Transformation on Carbon Footprint Reduction

The extent to which digital technologies contribute to lowering emissions and improving sustainability in manufacturing.

Indicators:

Reduction in carbon footprint after digital adoption (% decrease in emissions).

Energy savings achieved through digital interventions. (% decrease in emissions)

Waste reduction efficiency. (% improvement in efficiency)

Measurement Tools: Comparative analysis (before vs. after digitalization), expert interviews, survey based assessments.

This operationalization framework ensures that theoretical constructs are systematically measured using quantitative (emission reduction data, technology adoption rates) and qualitative (expert interviews, case studies) methods. This research examines the key barriers to adopting digital technologies for sustainability in manufacturing, including high capital investment requirements, employee resistance to change, lack of technical expertise, and regulatory constraints. Understanding these challenges is crucial for developing effective implementation strategies. The study will utilize industry surveys, expert interviews, and survey reports to gather insights from key stakeholders, including industry leaders, policymakers, and technology adopters. By identifying these barriers, the research aims to provide actionable recommendations to facilitate smoother digital transformation, ensuring that manufacturing industries can effectively integrate advanced technologies to achieve sustainability and carbon footprint. By defining measurable indicators for each construct, the research can empirically assess the role of digital transformation in achieving sustainability and reducing carbon footprints in manufacturing industries.

3.3 Research Purpose and Questions

This research aims to investigate the role of digital transformation technologies in reducing carbon footprints in heavy manufacturing industries. It seeks to analyze the key factors contributing to carbon emissions and assess the effectiveness of digital solutions in achieving sustainability goals. Specifically, the study will:

- Identify the primary sources of carbon footprints in the manufacturing sector.
- Examine the latest digital transformation technologies currently adopted in manufacturing.
- Establish the scientific relationship between digitalization and carbon footprint reduction in smart factories.

The findings will provide valuable insights for manufacturing industries and digital transformation professionals, helping to develop best practices and advanced tools for measuring and optimizing sustainability efforts.

3.4 Research Design

This section outlines the research design employed in this study to investigate the impact of digital transformation technologies on carbon footprint reduction in manufacturing industries. The research adopts a qualitative approach, utilizing a combination of primary and secondary data sources to ensure a comprehensive analysis.

Primary data will be collected through structured questionnaires and in depth interviews with mid level and executive leadership across various manufacturing organizations. These insights will help assess the adoption of digital technologies, challenges faced, and their measurable impact on sustainability efforts. Additionally, the study integrates the author's professional experience and firsthand observations across multiple organizational settings, providing contextual depth and practical perspectives.

By combining industry insights with empirical data, this research aims to develop a holistic understanding of the role of digital transformation in carbon footprint reduction, offering valuable contributions to both academic and industrial sustainability discussions.

3.4.1 : Qualitiative Research Approach

Given the complexity and the involvement of multiple technologies, a qualitative research approach was deemed the most suitable. This method enables a deeper exploration of the subject, capturing rich, context specific insights that quantitative data alone may not fully reveal. By focusing on expert perspectives, industry experiences, and real world applications, this approach allows for a comprehensive understanding of the interplay between digital transformation technologies and carbon footprint reduction in manufacturing.

The decision to adopt a qualitative research approach, supplemented by personal experience and real world observations, arises from the complex and multifaceted nature of integrating digital transformation technologies with sustainability initiatives. This approach allows for a nuanced exploration of how these technologies function as a lever for carbon footprint reduction in manufacturing.

By combining questionnaire based data with practical insights, the study ensures a balanced and comprehensive perspective, enhancing both academic understanding and industry relevance. This multifaceted research design aims to generate actionable insights that organizations can leverage to effectively implement digital transformation technologies in pursuit of their sustainability goals.

3.4.2 Quantiative Research Approach

The quantitative research design for this study follows a positivist philosophy, emphasizing objectivity, measurement, and statistical analysis. This approach ensures that findings are based on empirical data rather than subjective interpretations. A survey-based methodology is employed, utilizing structured questionnaires to collect quantifiable insights from industry professionals on digital transformation and carbon footprint reduction.

The study adopts a deductive approach, testing predefined hypotheses and examining relationships between digital technologies and sustainability outcomes. Data is analyzed using statistical methods, allowing for trend identification, correlation analysis, and generalization of findings across different industries.

By leveraging a cross-sectional research design, the study captures a snapshot of current industry practices, challenges, and future intentions regarding sustainability. This structured and data-driven methodology ensures reliability, replicability, and actionable insights, making it a valuable tool for decision-makers and policymakers in optimizing digital transformation strategies for carbon footprint reduction.

3.5 Population and Sample

Sampling plays a pivotal role in qualitative research, as it determines the credibility and depth of insights obtained. For this study, a purposive sampling approach was chosen to ensure that participants possess relevant expertise and experience in digital transformation and sustainability.

Given the complexity of the research topic examining the role of digital technologies in carbon footprint reduction a carefully selected sample is more effective than a large, generalized group.

By prioritizing depth over breadth, this approach allows for a more nuanced exploration of the challenges, benefits, and real world applications of digital transformation in sustainability efforts. The selected participants, drawn from key industry roles, provide valuable insights that enrich the study with practical, experience based knowledge. This ensures that the data collected is both contextually relevant and analytically meaningful.

Ultimately, this sampling strategy strengthens the research by facilitating a focused, in depth investigation into how organizations integrate digital solutions to drive sustainability, making the findings more actionable and impactful.

3.6 Instrumentation

The study employs a multi method qualitative approach to collect and analyze data on the impact of digital transformation technologies on carbon footprint reduction in manufacturing industries. The following research instruments will be utilized:

1. **Questionnaires**
   A. A structured questionnaire will be designed to gather insights from mid level and executive leadership in manufacturing organizations.
   B. It will include open ended and Likert scale questions to explore perspectives on digital technology adoption, sustainability challenges, and carbon footprint reduction efforts.
2. **Semi Structured Interviews**
   A. In depth interviews will be conducted with industry experts, policymakers, and technology leaders to gain nuanced insights into implementation challenges, regulatory considerations, and best practices.

B. The semi structured format allows for flexibility in exploring emerging themes while maintaining research focus.

3. **Observational Data**

   A. The researcher's firsthand experience and observations from multiple manufacturing settings will be used to support or contrast findings from the primary data collection.

   B. This qualitative evidence adds depth and context, ensuring a comprehensive understanding of real world applications.

4. **Secondary Data Sources**

   A. Industry reports, case studies, and academic literature will be reviewed to validate findings and provide comparative insights.

   B. This will help contextualize the research within existing frameworks of digital transformation and sustainability.

By integrating these multiple research instruments, the study ensures data triangulation, enhancing the validity and reliability of the findings while offering practical recommendations for industry adoption.

3.8 Data Collection Procedures

Qustionaire Design: The primary data collection tool used is google form with qustonaire design comprising of 6 sections:

1. **Common qustions and Basic Details**

Purpose & Importance:

This section establishes the foundational context of the respondent by gathering essential details about their background, industry experience, and organization type. It ensures that responses are categorized accurately based on the respondent's role and professional expertise.

Key Aspects:

Identifies participant role (mid level manager, executive, sustainability officer, etc.).

Captures company details (industry type, size, geographic presence).

Establishes level of experience in sustainability and digital transformation initiatives.

Ensures data segmentation for comparative analysis based on sector, experience, and organizational role.

2. **Knowledge and Perception**

Purpose & Importance:

This section assesses the participant's awareness, understanding, and perceptions of digital transformation technologies and sustainability practices. It helps determine whether knowledge gaps exist and identifies prevailing industry attitudes toward technology adoption.

Key Aspects:

Measures familiarity with key technologies (IoT, AI, Digital Twins, Blockchain, etc.).

Assesses perception of technology's role in sustainability and carbon footprint reduction.

Identifies barriers to adoption from an awareness perspective (e.g., skepticism, misinformation).

Helps determine whether education and training are needed to improve adoption.

3. Current Practices and Technologies

Purpose & Importance:

This section explores the digital technologies currently in use within manufacturing organizations. It helps map industry adoption trends and provides a real world view of how digital transformation is being implemented for sustainability.

Key Aspects:

Identifies existing digital solutions adopted by the organization.

Examines which departments benefit from technology integration (production, supply chain, compliance, etc.).

Assesses the effectiveness of these technologies in improving efficiency and reducing emissions.

Helps distinguish between early adopters and laggards, revealing patterns in implementation across industries.

4. Challenges and Barriers

Purpose & Importance:

Understanding barriers to technology adoption is critical in identifying obstacles that hinder sustainability efforts. This section investigates the technical, financial, operational, and cultural challenges faced by manufacturing units.

Key Aspects:

Identifies high capital investment requirements and ROI concerns.

Examines employee resistance to change and workforce adaptability challenges.

Evaluates lack of technical expertise and skill gaps in digital transformation adoption.

Explores regulatory and policy constraints that slow down technological implementation.

Helps develop strategies to overcome these barriers, making adoption smoother and more feasible.

5. Future Intentions and Strategies

Purpose & Importance:

This section focuses on the long term vision of organizations regarding digital transformation and sustainability. It provides insights into planned initiatives, investment priorities, and policy shifts toward reducing carbon footprints.

Key Aspects:

Identifies future sustainability and digital transformation goals within the organization.

Assesses planned investments in emerging digital technologies.

Evaluates willingness to adopt more sustainable practices.

Helps policymakers and industry leaders understand what support is needed to facilitate digital adoption.

6. Demographics and Operations

Purpose & Importance:

This final section gathers demographic and operational data, ensuring the study accounts for regional, cultural, and industry specific differences in digital transformation adoption.

Key Aspects:

Captures geographic region of operation (Asia, Europe, North America, etc.).

Identifies factory size and production capacity.

Examines energy consumption patterns to correlate with sustainability efforts.

Ensures representation across different market segments (small, medium, large enterprises).

3.9 Data Analysis

The data collected from the questionnaires will be analyzed using thematic analysis, a qualitative method that systematically identifies, examines, and interprets recurring patterns or "themes" within the responses. This approach enables a structured exploration of key insights, allowing for a deeper understanding of how digital transformation technologies contribute to carbon footprint reduction. By categorizing data into meaningful themes, the analysis will highlight trends, common challenges, and opportunities that emerge from the participants' experiences.

To further enrich the study, anecdotal evidence and firsthand observations from the author's experience will be incorporated. This integration helps validate, contrast, or refine the findings, ensuring a more comprehensive interpretation of the data. By combining empirical data with practical insights, the study achieves a more nuanced understanding of the subject matter.

Additionally, this triangulated approach enhances the research's credibility by integrating multiple perspectives, thereby ensuring both academic rigor and real world applicability. The combination of structured thematic analysis with contextual observations strengthens the reliability of conclusions drawn, making them more actionable for industry stakeholders. Ultimately, this methodological framework not only deepens the analysis but also ensures that the findings are both theoretically sound and practically relevant for advancing sustainability through digital transformation.

3.10 Research Design Limitations

This study focuses specifically on the impact of digital transformation technologies on carbon footprint reduction in manufacturing industries, leaving certain aspects beyond its scope. It does not address other sustainability factors, such as water conservation, waste management, or biodiversity impact, which are also crucial for sustainable industrial practices.

Additionally, the research is limited to digital technologies relevant to manufacturing, excluding those applicable to other industries such as retail, logistics, or agriculture. While the study provides insights into economic considerations, it does not explore the commercial impact of digital transformation in significant depth, including aspects like cost benefit analysis, return on investment (ROI), or market competitiveness.

While this research aims to provide a comprehensive analysis of the impact of digital transformation technologies on carbon footprint reduction in manufacturing, several limitations exist in the research design that must be acknowledged. These limitations may influence the scope, depth, and generalizability of the findings.

1. Sample Size and Generalizability

This study relies on a qualitative research approach, incorporating expert interviews, surveys, and personal observations. However, the sample size may be relatively small compared to large scale quantitative studies. The findings, therefore, may not be fully generalizable across all manufacturing industries, particularly across different geographic, regulatory, and economic contexts.

2. Subjectivity in Qualitative Analysis

The research heavily depends on thematic analysis of qualitative data obtained from questionnaires and expert interviews. While this approach allows for a deeper understanding of industry challenges, perceptions, and strategies, it is inherently subjective and may introduce researcher bias in interpreting the findings.

3. Self Reported Data Reliability

Data from surveys and interviews relies on the self reporting of industry professionals, which may lead to biases, including social desirability bias (where respondents provide answers they believe are favourable) or recall bias (where participants may not accurately remember past events or challenges).

4. Rapidly Evolving Technological Landscape

The field of digital transformation and sustainability is rapidly evolving. Emerging technologies such as AI, blockchain, and digital twins are continuously developing, making it challenging to capture a fully up to date assessment. Some technologies that appear promising today may become obsolete in the near future.

5. Limited Access to Proprietary Industry Data

Many manufacturing organizations consider their digital transformation initiatives and carbon footprint data proprietary. This may result in limited access to real world implementation data, potentially affecting the accuracy and depth of the study's insights.

Despite these limitations, the study provides valuable insights into how digital transformation technologies can drive sustainability in manufacturing. Future research should consider larger sample sizes, mixed methods approaches, and longitudinal studies to address these limitations and further validate the findings.

3.11 Conclusion

This research methodology has been meticulously crafted to explore the impact of digital transformation technologies on reducing the carbon footprint in manufacturing industries. By adopting a qualitative research approach, the study delves deeply into how digital technologies contribute to sustainability goals while addressing the key challenges associated with their adoption.

The study employs a multi method approach, integrating surveys, expert interviews, and thematic analysis to ensure a comprehensive understanding of the subject. The questionnaire is structured into six sections, facilitating a systematic exploration of participants' knowledge, perceptions, current practices, barriers, and future strategies related to digital transformation and sustainability. By including participants from diverse geographic and industrial backgrounds, the study enhances the richness and applicability of its findings.

One of the key strengths of this methodology is its ability to capture real world insights from industry professionals. The use of thematic analysis allows for the identification of common patterns, challenges, and emerging trends, while the inclusion of personal observations and anecdotal evidence adds depth to the research. However, certain limitations must be acknowledged, such as the reliability of self reported data, researcher subjectivity, and restricted access to proprietary industry data. These factors may affect the generalizability of the findings, highlighting the importance of complementing qualitative insights with quantitative analysis and longitudinal studies in future research.

Despite these limitations, this research methodology ensures that the study is rigorous, structured, and aligned with the objectives of understanding and evaluating the impact of digital transformation technologies on carbon footprint reduction. The findings from this research will serve as a valuable resource for industry professionals, policymakers, and researchers, offering actionable insights into sustainable manufacturing practices. Future research can build upon this study by expanding the sample size, incorporating real time industrial case studies, and integrating data driven performance metrics to strengthen the empirical evidence.

In conclusion, this research methodology provides a robust framework for examining the role of digital transformation technologies in promoting sustainability within the manufacturing sector. By leveraging a qualitative approach and a multi method strategy, the study offers a nuanced understanding of the complex interplay between digital innovation and environmental responsibility. The insights gained from this research will not only inform industry practices but also guide policy development and academic inquiry, paving the way for more sustainable and efficient manufacturing processes. As digital technologies continue to evolve, ongoing research will be essential to fully realize their potential in driving environmental sustainability and achieving carbon reduction targets across industries.

CHAPTER IV:

RESULTS

This chapter explores how digital transformation technologies impacted industries achieve their sustainability goals, with a particular emphasis on reducing carbon footprints. By integrating advanced digital solutions, industries can enhance energy efficiency, optimize resource utilization, and minimize environmental impact.

To gain deeper insights, a comprehensive survey was conducted to gather perspectives on the effectiveness of these technologies from industry professionals, ESG experts, and technocrats with industrial exposure. The survey aimed to assess the adoption, challenges, and benefits of digital transformation in driving sustainability initiatives. It examined key factors such as automation, data analytics, IoT, AI-driven optimizations, and digital twins in improving operational efficiency and reducing emissions.

4.1 Survey Response Summery

The survey reveals strong adoption of digital technologies for sustainability, with varying carbon footprint reductions.

4.1.1. Survey Participant Demographics & Insights

A total of 122 participants from various countries, diverse expertise, experience levels, and industry domains contributed to this survey, providing valuable insights into digital transformation and sustainability. The findings provide valuable knowledge on how industries are leveraging digital advancements to align with global sustainability standards. By understanding expert opinions and real-world applications, this research highlights the crucial role of technology in fostering sustainable industrial practices and meeting ambitious ESG commitments.

Participants were selected based on their expertise in digital transformation and sustainability within the manufacturing & IT sector, ensuring a diverse yet focused representation of industry professionals. This section outlines the rationale, selection criteria, and justification for this approach, emphasizing its effectiveness in capturing rich, context specific insights that contribute to the study's objectives.

S.No	**Experience (yrs)**	**Participants**
1	<10	72
2	10 20	29
3	20 30	17
4	30+	4

Table 4.1: Participants Experience Details

As show in the above Table 4.1 total of 122 individuals participated in this survey, primarily consisting of those in mid-level and senior management roles. This makes the sample robust for understanding involvement in digital transformation technologies or ESG activities within organizations.

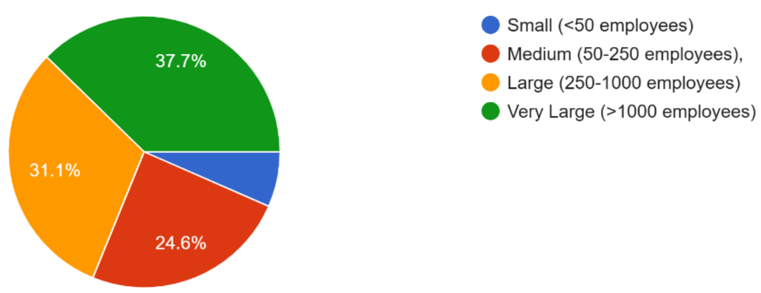

Figure 4.1: Participants vs size of organization

As per Figure 4.1, 37.7% of survey participants are from very large industries, while 31.1% represent large industries. This composition is crucial for the study of sustainability and smart factories, as larger industries typically have greater resources, infrastructure, and technological capabilities to implement digital transformation initiatives. Their insights provide valuable perspectives on the adoption of advanced technologies for carbon footprint reduction, energy efficiency, and operational sustainability. The participation of these industries ensures a robust understanding of industry trends, challenges, and best practices, making the survey results highly relevant for driving sustainable advancements in manufacturing and industrial sectors.

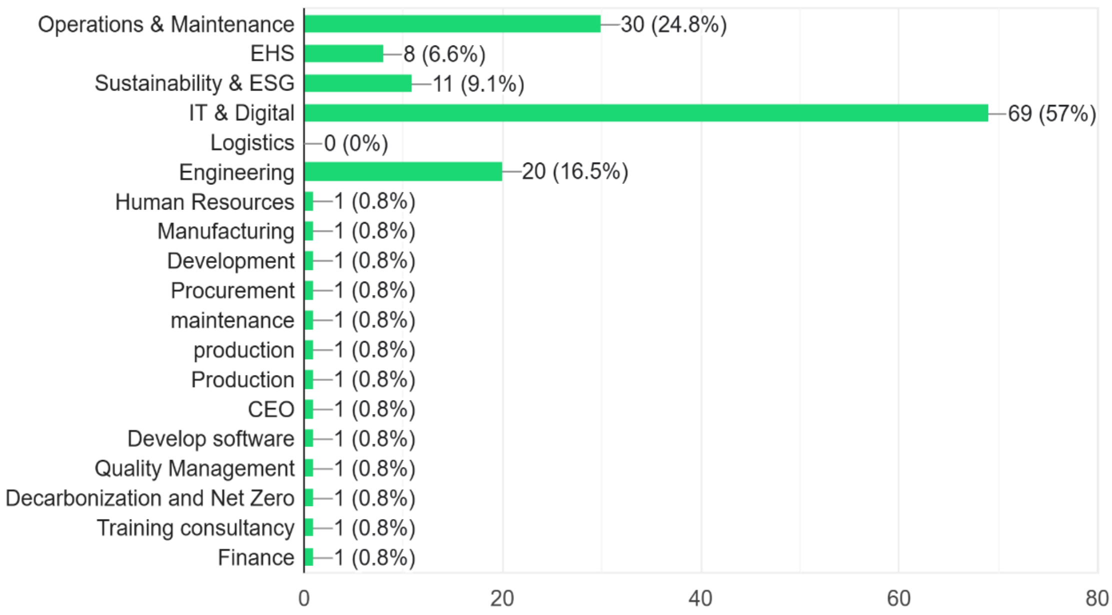

Figure 4.2: Participants Job roles

The figure 4.2 above illustrates that participants were chosen based on their expertise in digital transformation and sustainability within the manufacturing and IT sectors. This strategic selection ensured a diverse yet targeted representation of industry professionals, enhancing the study’s depth and relevance. This section details the rationale behind participant selection, the criteria used, and the justification for this approach. By carefully curating a pool of experts with hands-on experience, the study effectively captures nuanced, context-specific insights. These insights provide a comprehensive understanding of the intersection between digital transformation and sustainability, aligning with the study's objectives and contributing to meaningful, data-driven conclusions.

S.No	Industry of Working	No of Participants
1	Automotive	16
2	Battery	1
3	Ceramics	1
4	Chemical	4
5	Consultancy	1
6	Consulting	1
7	Electronics & Telecom	5
8	Film, TV and Video Production	1
9	FMCG	5
10	food	1
11	Glass	1
12	Heavy Manufacturing (Steel, Aluminum Etc)	13
13	Hospitality/Tourism	1
14	Insurance	1
15	IT & Digital	59
16	Manufacturing razors and razor blades	1
17	milk	1
18	Oil and Energy	1
19	Packaging	1
20	Packing supplies	1
21	Pharma & Healthcare	3
22	Professional Services	1

23	Textile	2
	Grand Total	**122**

Table 4.2: Participants Job Roles

While most respondents indicated they work in "Technology," this does not necessarily mean they are from traditional tech companies. Instead, they are likely contributing to technological implementation in manufacturing industries we can see the same data in table 4.2 for reference. Given the widespread presence of technology across all sectors, these respondents could be leading tech initiatives in various industries.

S.No	Country of Operations	Participants
1	Africa	31
2	Canada	7
3	Europe	34
4	France	1
5	India	10
6	Mexico	1
7	MENA	1
8	Mexico	2
9	Portugal	1
10	Rest of Asia	2
11	south africa	4
12	South Africa	3
13	South African	1
14	South America	1
15	UK	1
16	USA	22

	Grand Total	**122**

Table 4.3: Participants Country of Operations

The table 4.3 above highlights that participants were selected from diverse geographic regions, ensuring a broad representation of cultural perspectives and sustainability initiatives across different countries. This approach provides a comprehensive understanding of regional variations in digital transformation and sustainability practices.

The figure 4.3 below illustrates that participants represent various countries, ensuring a comprehensive understanding of how digital transformation technologies are adopted and their impact on carbon footprint reduction across different industrial and regulatory contexts. This diverse representation enables a nuanced analysis of regional variations in sustainability practices and technological integration..

Figure 4.3: Participants Geography

4.1.2 Perceptions and Awareness: Sustainability & Digital Transformation in Industry

The data shown in figure 4.4 below reveals that organizations with a strong belief in digital transformation's role in carbon footprint reduction exhibit an average digital transformation maturity level of 7.66. This suggests a direct correlation between an organization's commitment to sustainability and its progress in adopting digital technologies. Companies that recognize the impact of digitalization on sustainability are more likely to implement advanced solutions such as IoT, AI, and automation to optimize energy consumption and reduce waste. This insight underscores the importance of fostering a sustainability driven digital strategy, as higher digital maturity levels contribute to more effective carbon footprint reduction initiatives.

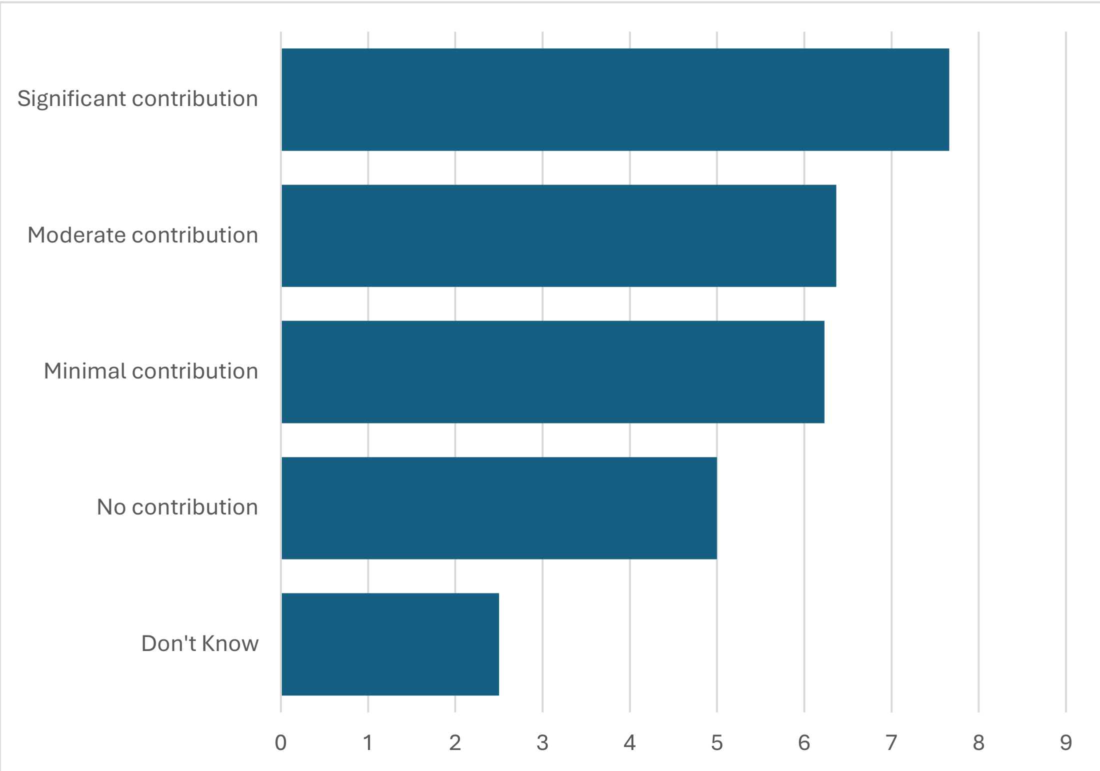

Figure 4.4: Digital Maturity vs Motive

The figure 4.5 shows many respondents demonstrate a strong familiarity with the concept, recognizing its critical importance to their organizations. The survey findings

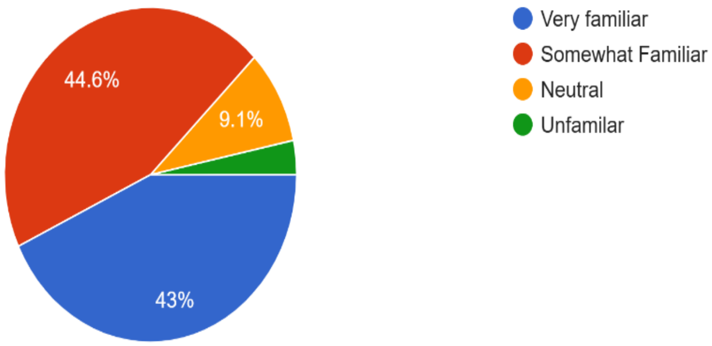

Figure 4.5: Participants familiarity on Digital Transformation & Sustainability

indicate that sustainability and digital transformation are widely acknowledged as essential for long term success. Organizations are increasingly prioritizing these initiatives, integrating them into their strategic frameworks to enhance efficiency, regulatory compliance, and environmental responsibility.

From figure 4.6 we can observe that 38% of ESG team are very familier with the digital transformation technologies. Less than 5% are unfamilier with the digital transofrmation technologies who are involved in sustainability practices. This widespread awareness reflects a positive trend toward adopting sustainable practices and leveraging digital technologies to achieve carbon footprint reduction. As businesses continue to evolve, the emphasis on these concepts is expected to drive more significant investments and innovations in sustainable manufacturing and digital transformation efforts.

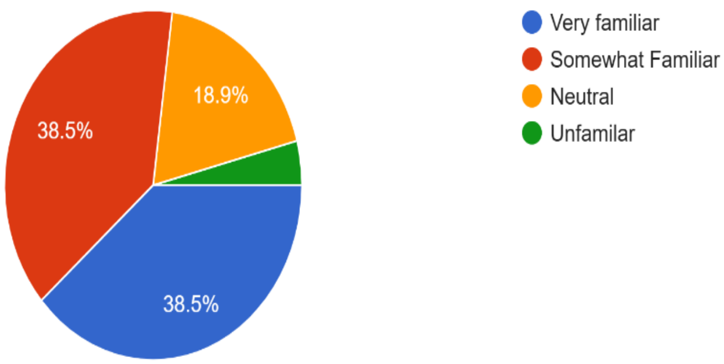

Figure 4.6: ESG team familiarity on Digital Technologies

The growing adoption of these technologies indicates a significant shift towards integrating digital transformation with sustainability efforts. Organizations are recognizing the potential of these advanced tools in meeting environmental goals while also improving operational efficiency.

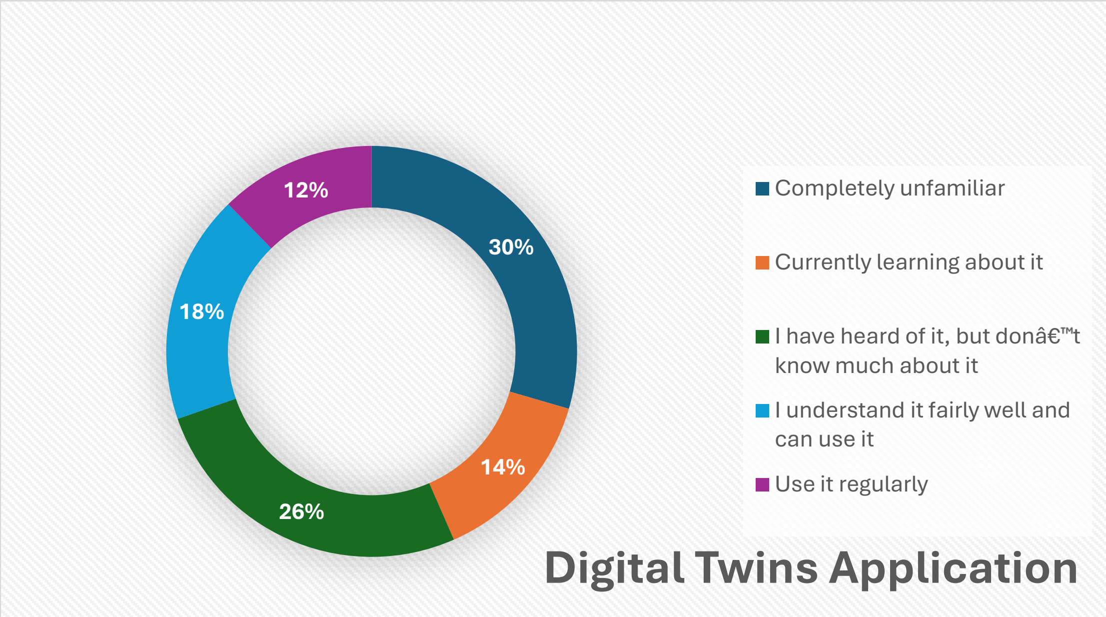

Figure 4.7: Digital Twins adoption

Figure 4.7 reveals that only 30% of participants are familiar with digital twin technologies, indicating limited awareness and adoption within the industry. This low familiarity suggests that while digital twins offer significant potential for enhancing efficiency and sustainability, their implementation remains in the early stages. The lack of widespread adoption could be attributed to factors such as limited technical knowledge, high implementation costs, or resistance to change. Addressing these barriers through targeted awareness programs, training, and industry collaborations can accelerate the adoption of digital twin technologies, driving greater innovation and sustainability in industrial operations.

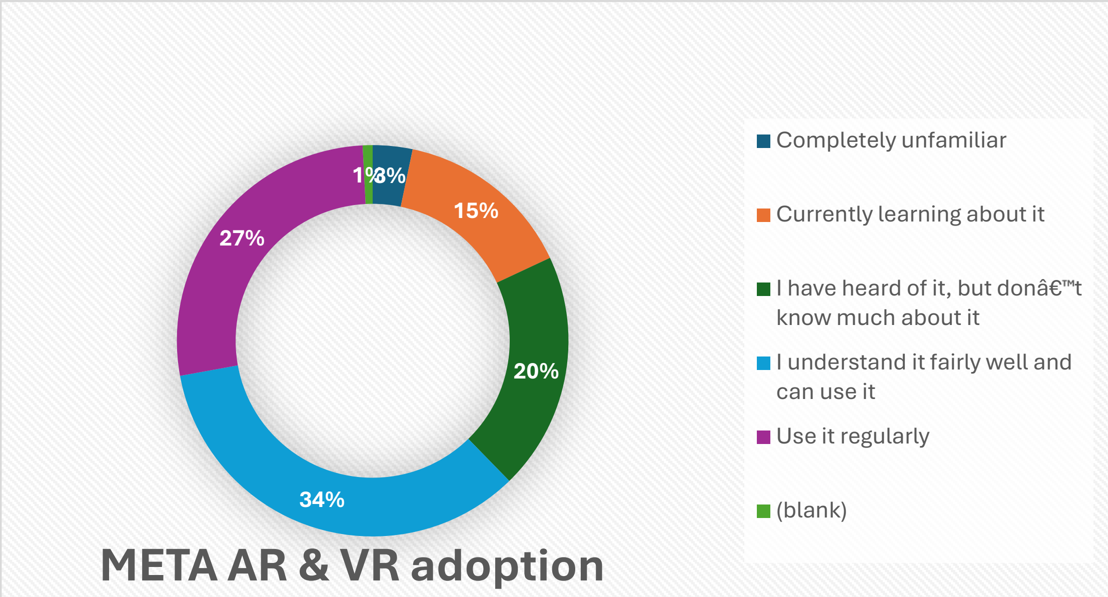

Figure 4.8: META AR &VR adoption in industries

Figure 4.8 highlights that more than 60% of industries have adopted Metaverse, AR, and VR solutions, indicating strong acceptance of these technologies. This high adoption rate presents a promising opportunity for leveraging Metaverse-driven solutions to reduce carbon footprints effectively. By integrating AR and VR, industries can optimize operations, minimize physical resource consumption, and enhance remote collaboration, reducing travel-related emissions. This widespread implementation suggests that industries are increasingly recognizing the benefits of immersive technologies in sustainability initiatives. With continued investment and innovation, these solutions can play a vital role in accelerating carbon footprint reduction across various sectors.

It can be observed from figure 4.9 More than 80% of participants actively use cloud technologies and are well aware of their applications, highlighting a strong foundation for digital adoption. This widespread familiarity creates an ideal platform for implementing carbon footprint reduction solutions through cloud-based systems.

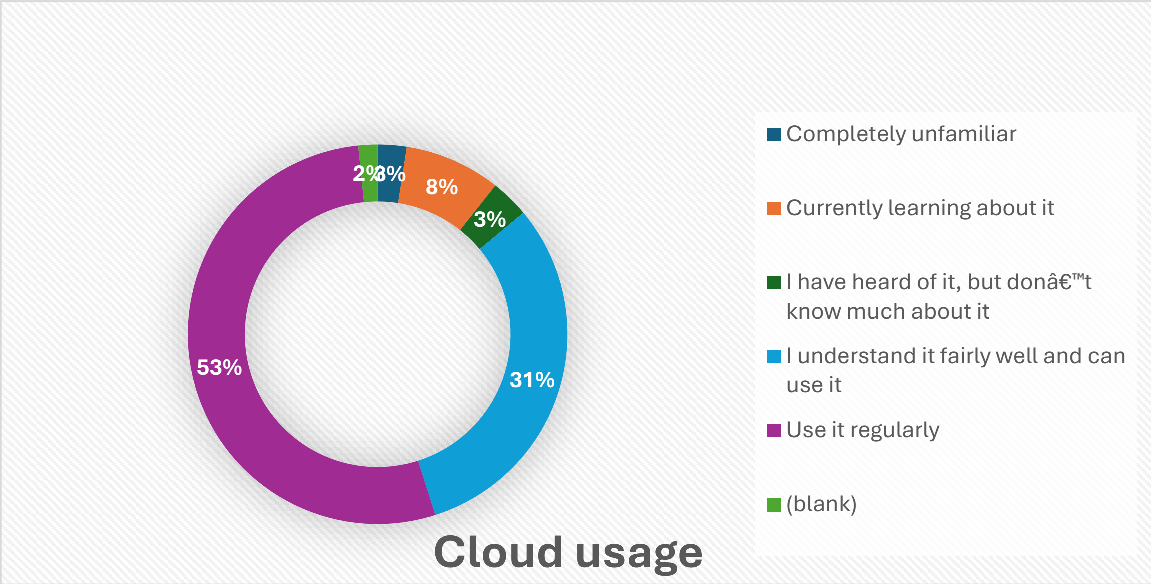

Figure 4.9: Cloud Usage

Cloud computing enables industries to optimize energy consumption, enhance data-driven decision-making, and reduce reliance on physical infrastructure, leading to lower emissions. With seamless scalability, remote accessibility, and cost efficiency, cloud technology serves as a powerful enabler for sustainability initiatives. Leveraging this existing adoption can accelerate the deployment of digital solutions aimed at reducing environmental impact across industries.

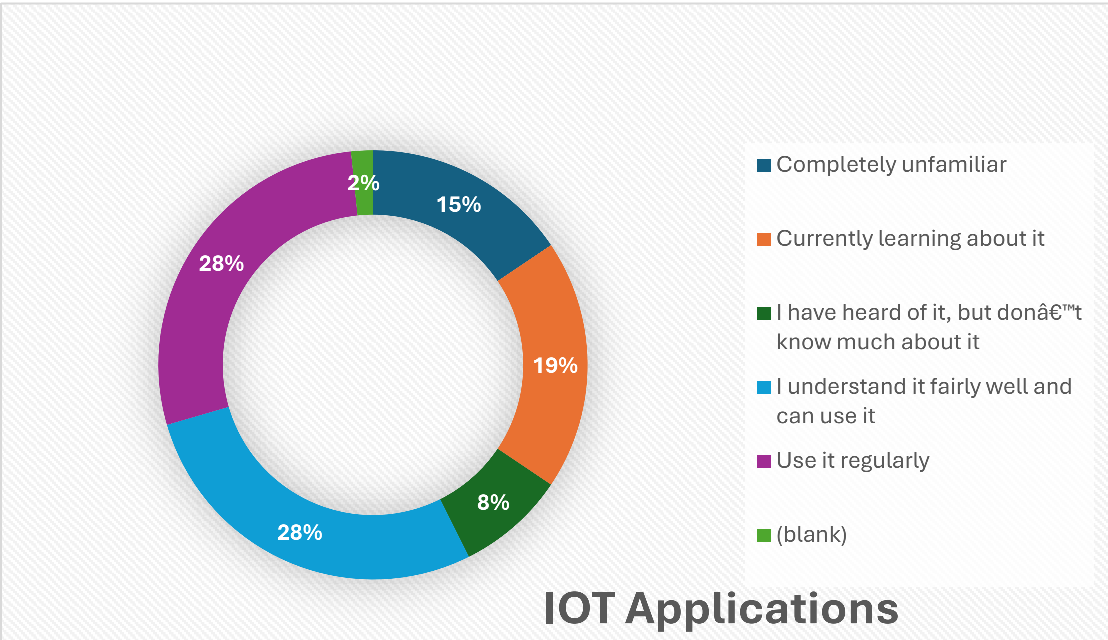

Figure 4.10: IOT usage

Figure 4.10 shows that IoT and IIoT technologies are widely adopted, with more than 60% usage across industries. These technologies play a critical role in monitoring, recording, and analyzing carbon footprints, making them highly effective in sustainability efforts. By enabling real-time data collection, predictive maintenance, and process optimization, IoT and IIoT help industries reduce energy consumption and minimize waste.

Their integration enhances transparency, compliance with environmental regulations, and overall efficiency. With continued advancements, these technologies can further drive carbon footprint reduction, making industrial operations more sustainable and environmentally responsible in the long run.

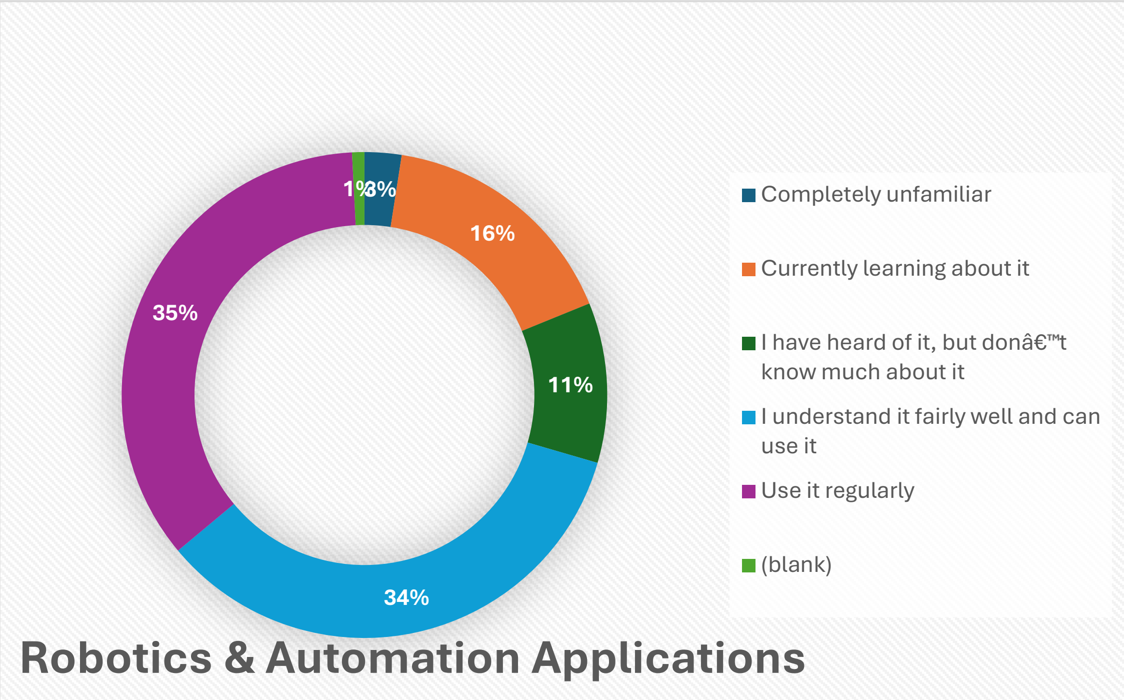

Figure 4.11: Robotics and automation Adoption

Figure 4.11 reveals that more than 70% of industries are familiar with robotics and automation technologies. The Industry 3.0 revolution significantly impacted automation adoption, making these systems widely accessible and setting the stage for Industry 4.0 advancements. Robotics and automation play a crucial role in optimizing processes, reducing energy consumption, and minimizing waste, contributing to lower carbon footprints.

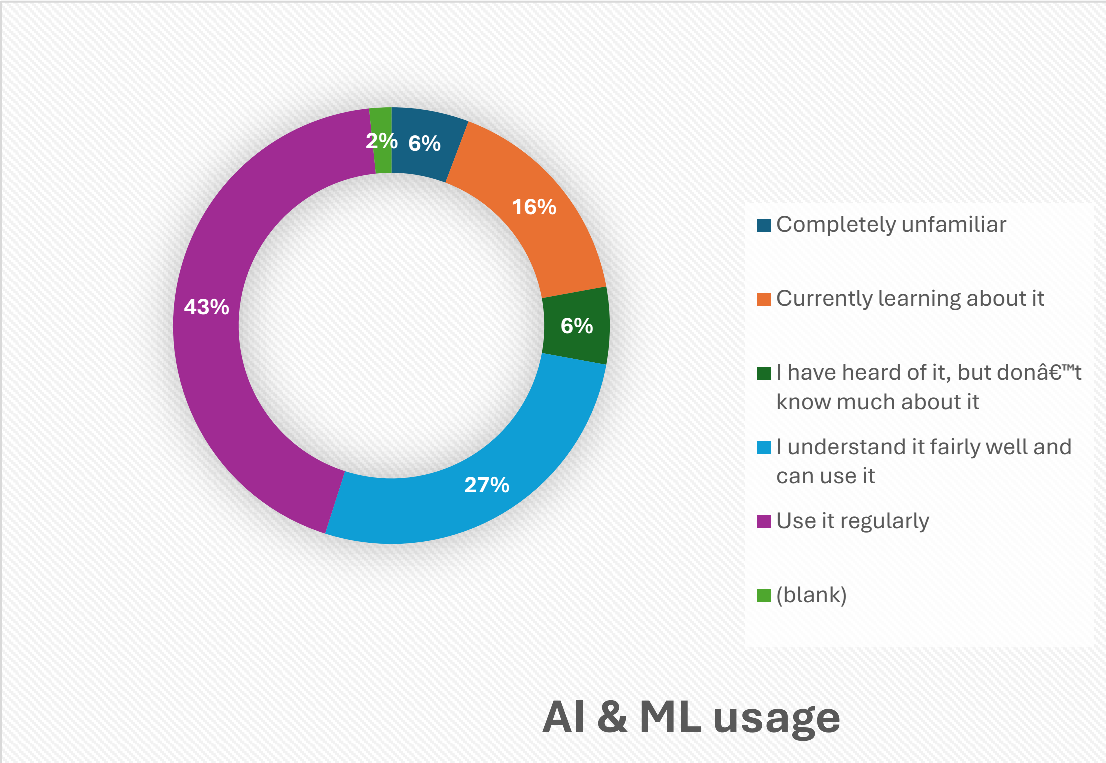

Figure 4.12: AI &ML usage

More than 70% familiarity with AI and ML is a significant indicator in fiure 4.12 of their growing influence in industries. With the increasing integration of AI-driven automation, businesses can enhance efficiency, sustainability, and environmental responsibility.

AI and ML enable predictive analytics, process optimization, and energy management, leading to reduced waste and lower carbon emissions. This strong foundation of familiarity and adoption positions AI-powered automation as a crucial driver of sustainability.

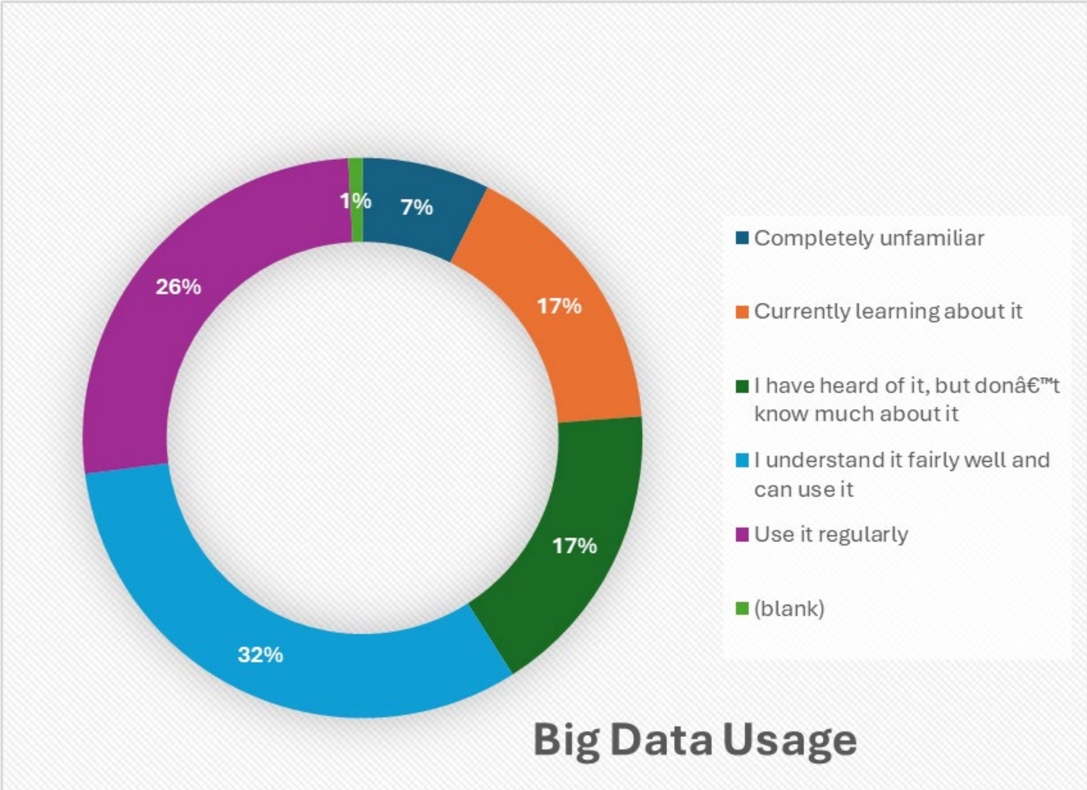

Figure 4.13: Big Data Usage

Figure 4.13 shows that Big Data has moderate usage in industries, with only around 30% actively utilizing it, while the rest have limited familiarity. Despite its potential to drive data-driven decision-making, optimize processes, and enhance sustainability efforts, its adoption remains relatively low.

Many industries recognize its importance but have yet to fully integrate it into their operations. Increasing awareness, training, and investment in Big Data analytics can help industries unlock its benefits, particularly in monitoring energy consumption, optimizing resource allocation, and reducing carbon footprints. Wider adoption can significantly contribute to efficiency and sustainability across various sectors.

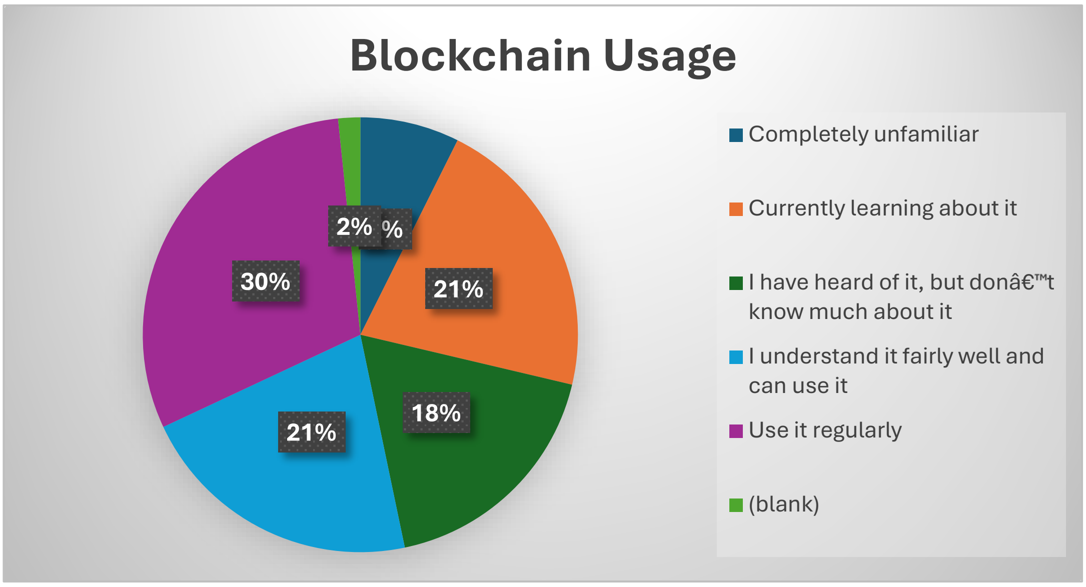

Figure 4.14: Blockchain Adoption

Figure 4.14 indicates that blockchain technology is used regularly by no more than 30% of industries. Despite its potential for enhancing transparency, security, and traceability in industrial operations, its adoption remains relatively low. Many industries are still exploring its applications, while others lack the necessary infrastructure or expertise for full-scale implementation. Increasing awareness and investment in blockchain solutions could drive wider adoption, enabling industries to improve data security, streamline supply chains, and support sustainability initiatives. As blockchain technology evolves, its role in industrial digital transformation and carbon footprint reduction is expected to grow significantly.

In addition to these widely adopted technologies, digital twins, blockchain, and cloud computing are gaining momentum in sustainability efforts. Digital twins create virtual replicas of physical assets, enabling manufacturers to simulate processes, optimize resource allocation, and minimize inefficiencies before implementation. Blockchain enhances transparency and traceability in supply chains, ensuring responsible sourcing and regulatory compliance. Meanwhile, cloud computing facilitates data centralization, reducing the need for extensive physical infrastructure and lowering overall energy consumption.

The integration of these digital transformation technologies not only helps manufacturing units meet sustainability goals but also drives long term cost savings and operational efficiencies. As industries continue to embrace digitalization, leveraging these advanced technologies will be critical in achieving carbon footprint reduction and fostering a more sustainable manufacturing ecosystem. Organizations that strategically implement these solutions can gain a competitive edge while contributing to global environmental conservation efforts.

4.1.3 Existing Sustainability Practices and Digital Technologies in Industrial Use

Organizations are adopting Sustainability and circular economy practices such as recycling, reuse, and remanufacturing to minimize waste and enhance sustainability. One of the key findings from the survey reveals that data analysis for waste reduction is widely utilized in factories.

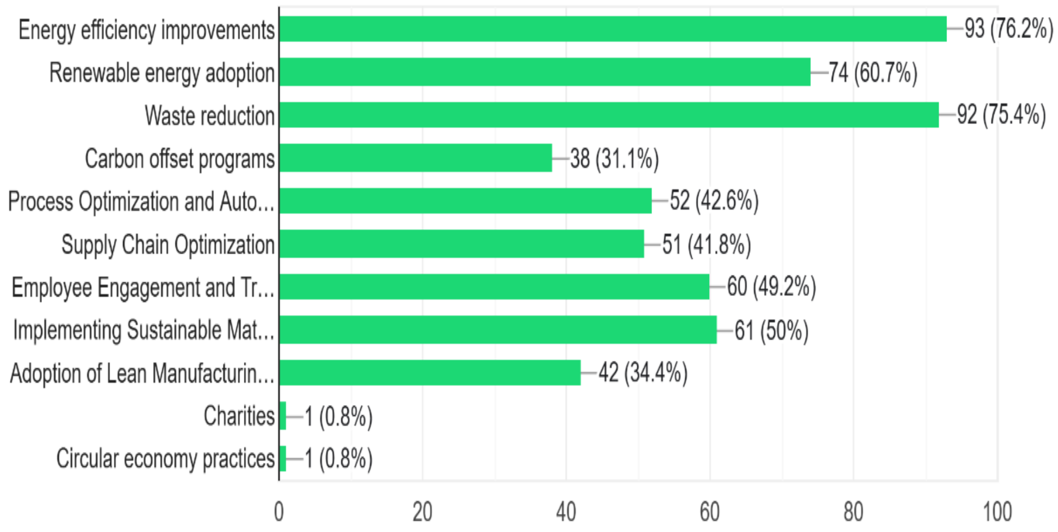

Figure 4.15: Sustainability initiative status in industries

As shown in Figure 4,15, more than 70% of industries have implemented key sustainability initiatives, including energy efficiency improvements, renewable energy adoption, waste reduction, and carbon reduction programs. These efforts reflect a strong commitment to reducing environmental impact and enhancing operational sustainability. However, circular economy initiatives remain significantly underutilized, with adoption rates below 5%. This gap highlights the need for greater focus on resource recycling, sustainable product design, and closed-loop systems. Encouraging industries to embrace circular economy principles can further enhance sustainability efforts, reduce waste, and create long-term economic and environmental benefits. Increased awareness and policy support can drive broader adoption.

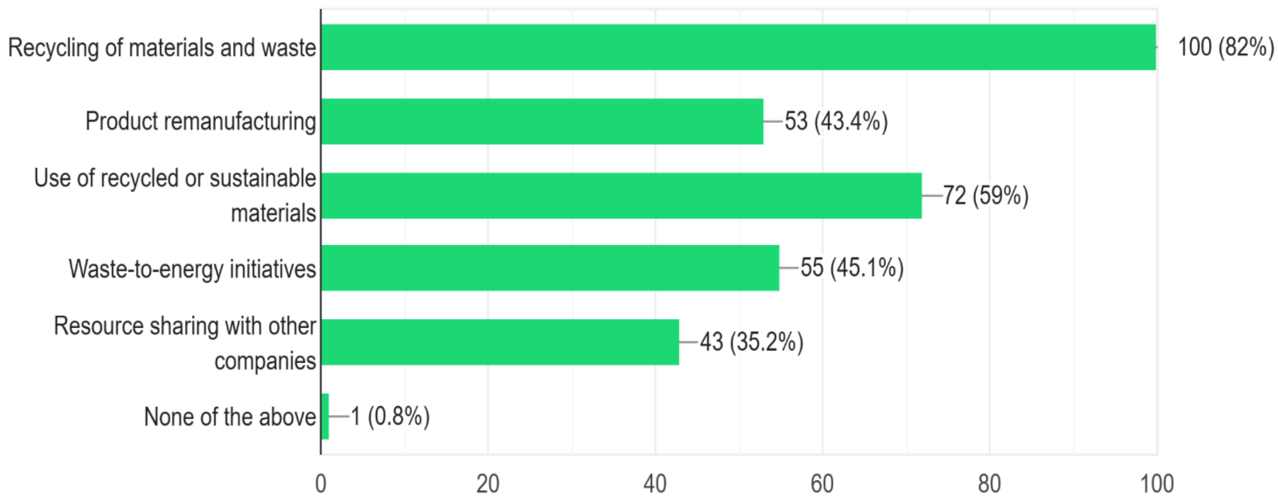

Figure 4.16: circular economy initiatives

As shown in Figure 4.16, recycling of materials and waste is a key circular economy initiative, with adoption exceeding 82% in industries. This strong implementation highlights the growing commitment to sustainability and resource efficiency. By repurposing waste and optimizing material usage, industries can significantly reduce environmental impact and operational costs.

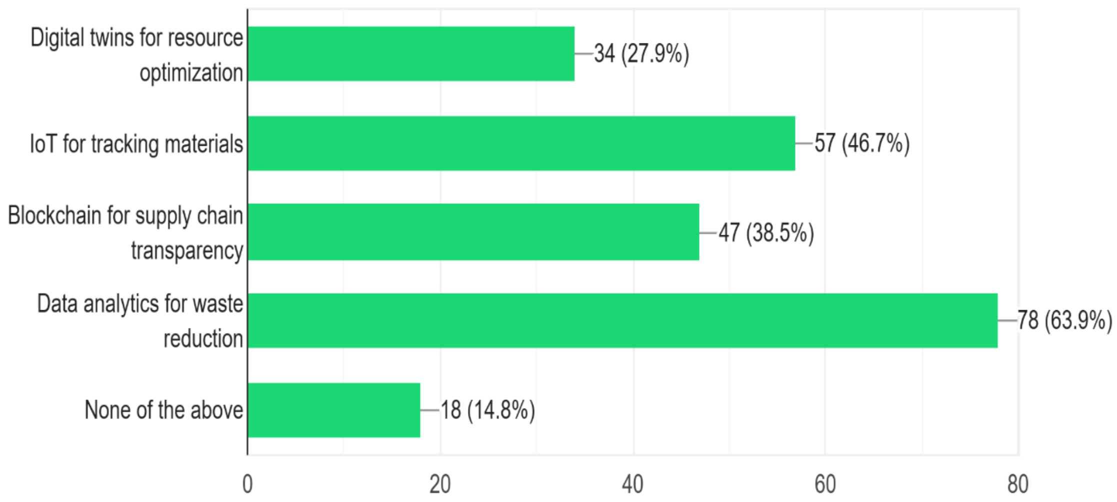

Figure 4.17: Technology use in circular economy activities

As shown in Figure 4.17, data analytics is the most widely used technology for waste reduction, with over 60% of industries leveraging it as part of their circular economy initiatives. IoT technology ranks second, with a 46% adoption rate, enabling real-time monitoring and optimization of resource usage. However, approximately 15% of industries have yet to implement any technological solutions for waste reduction, highlighting an opportunity for greater digital integration. Expanding the use of advanced technologies such as AI, blockchain, and automation can further enhance waste management strategies, improve efficiency, and accelerate the transition toward more sustainable industrial practices.

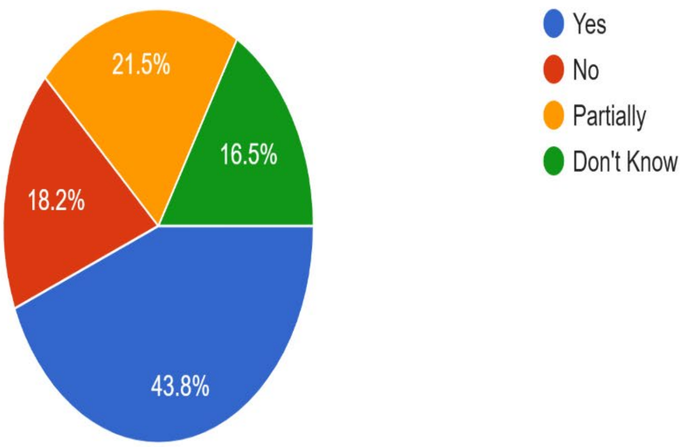

Figure 4.18: Carbon Footprint Monitoring using Digital tools

As shown in Figure 4.18, 43.8% of industries use digital tools for carbon footprint monitoring, demonstrating a growing commitment to sustainability and emissions reduction. These digital solutions enable real-time tracking, data analysis, and reporting, helping industries identify areas for improvement and implement effective carbon reduction strategies. However, a significant portion of industries have yet to adopt such technologies, indicating room for further digital integration.

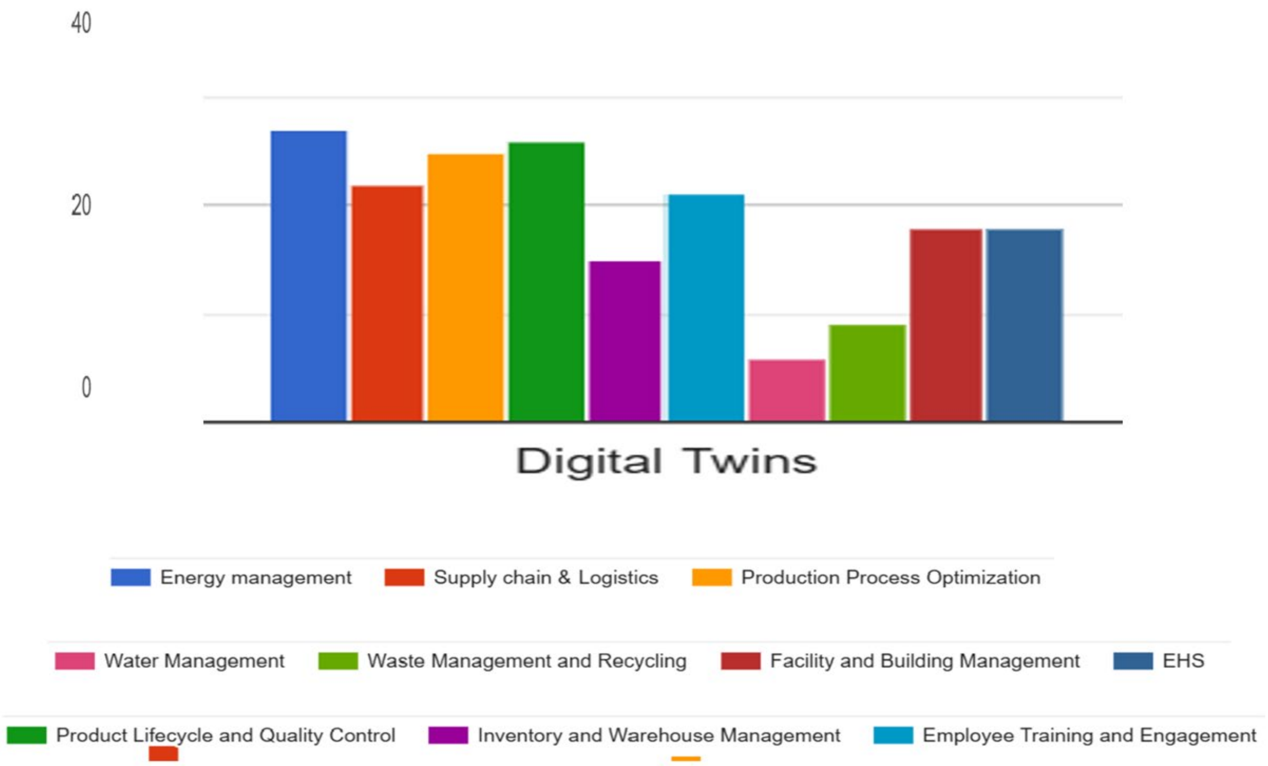

Figure 4.19: Application of Digital Twins vs Operational Areas

As shown in Figure 4.19, digital twin technology has limited adoption in the water and waste management sector, while its usage in other areas remains moderate. Despite its potential to optimize resource utilization, enhance predictive maintenance, and improve efficiency, adoption in this sector is still in its early stages.

Expanding the use of digital twins in water and waste management could significantly enhance sustainability efforts by enabling real-time monitoring, reducing waste, and optimizing treatment processes. Increasing awareness and investment in this technology can drive broader implementation and maximize its impact across various industries.

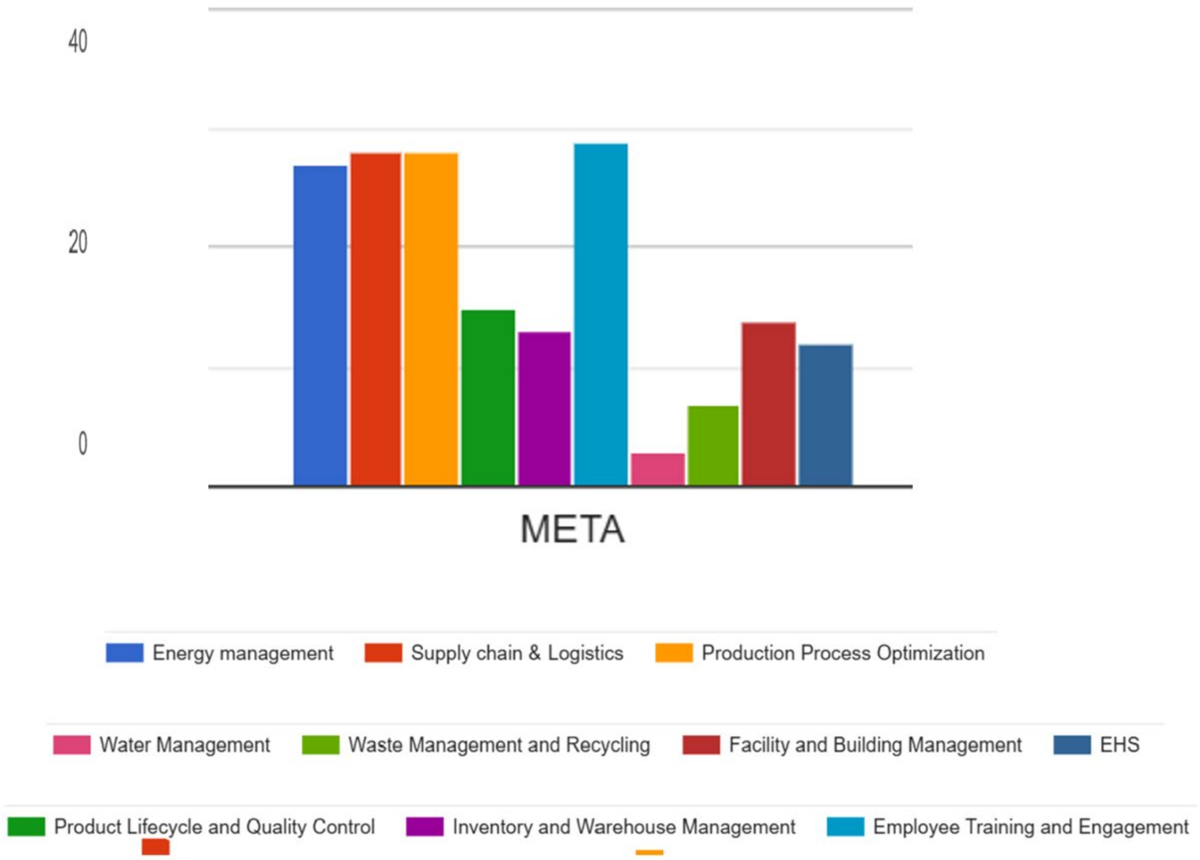

Figure 4.20: Meta technology adoption

As shown in Figure 4.20, Metaverse technology has minimal adoption in water management, while its potential remains largely untapped. EHS (Environmental, Health, and Safety) is another sector where Metaverse applications can be effectively leveraged for training, simulations, and safety compliance. However, learning and development have shown strong adoption of Metaverse solutions, indicating its effectiveness in immersive training and skill enhancement. Expanding Metaverse applications in water management and EHS could enhance monitoring, predictive analysis, and safety training, driving efficiency and sustainability. Increased awareness and strategic implementation can further accelerate its adoption across these critical sectors.

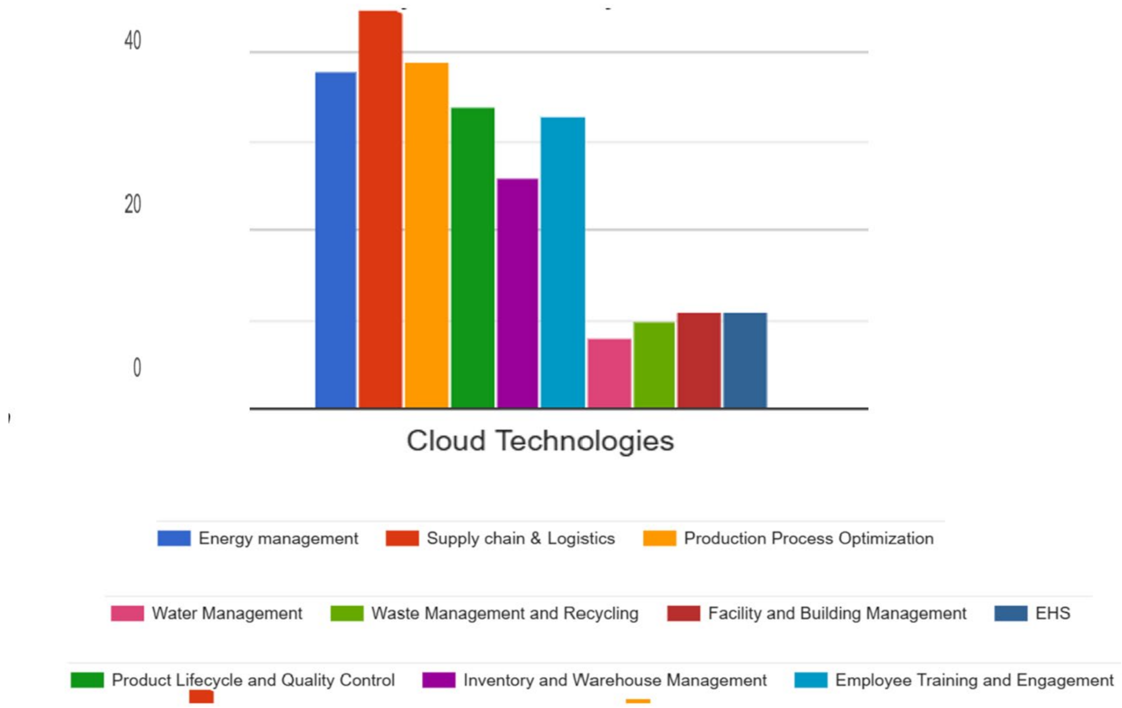

Figure 4.21: Cloud Technologies usage in operations

As shown in Figure 4.21, cloud technologies are widely adopted in supply chain and logistics, energy management, and production, demonstrating their effectiveness in optimizing operations and improving efficiency. However, their utilization in waste and water management remains minimal. AI and ML are widely utilized in production, demonstrating their effectiveness in optimizing processes and improving efficiency. However, their adoption in other areas, including waste and water management, remains significantly low. Implementing AI/ML in these sectors could enhance predictive analytics, automate monitoring, and optimize resource utilization, leading to more sustainable and efficient operations.

Expanding AI/ML applications in waste and water management can drive data-driven decision-making, improve treatment processes, and reduce environmental impact. Increased awareness, investment, and technological advancements can help accelerate adoption across these underutilized sectors.

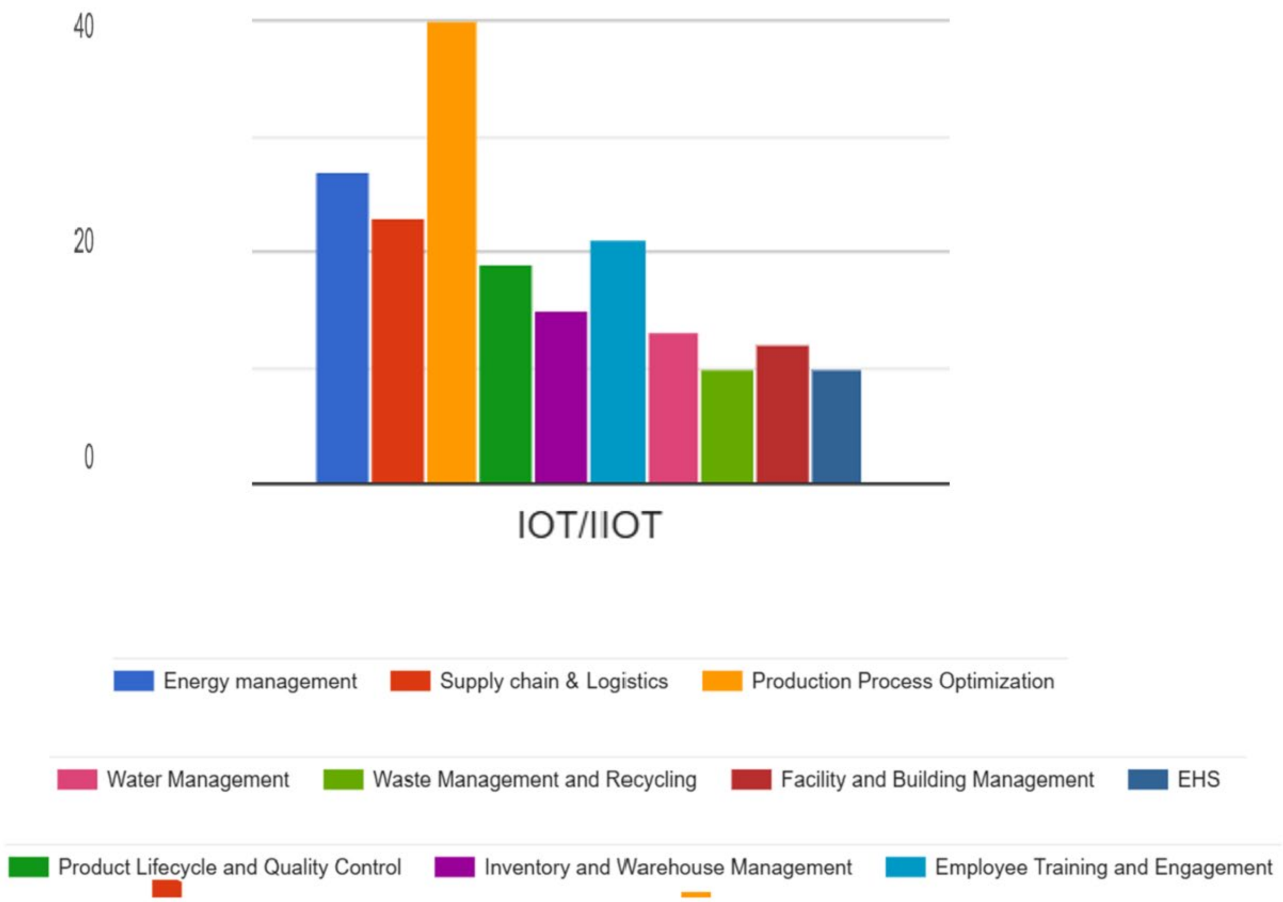

Figure 4.22: IOT application in operations

As shown in Figure 4.22, IoT technology adoption is strong in production, demonstrating its effectiveness in optimizing operations and enhancing efficiency. However, its implementation in other areas, such as waste and water management, remains limited.

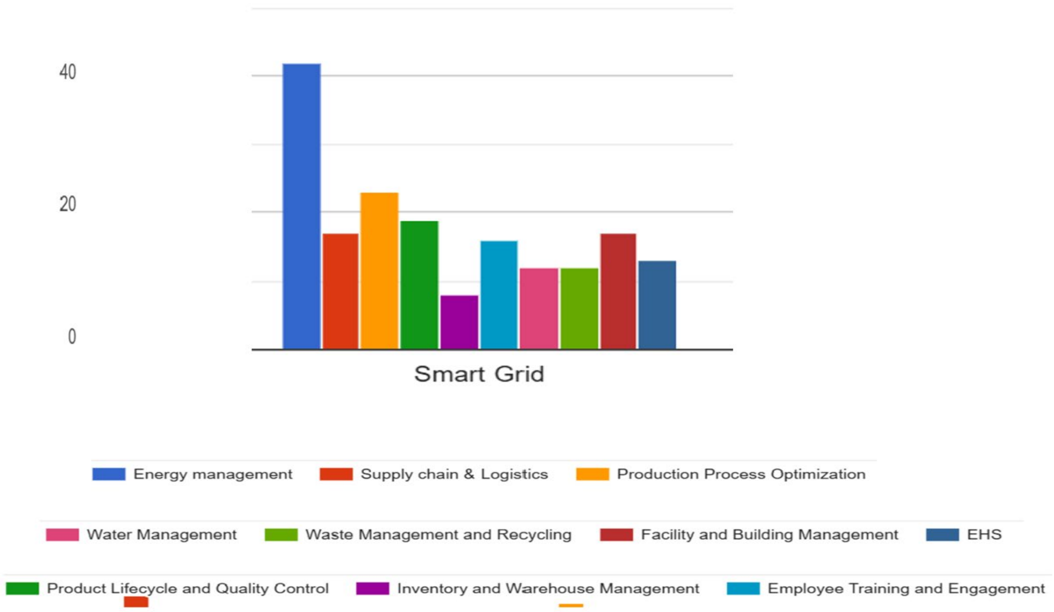

Figure 4.23: SMART Grid Application in operations

As shown in Figure 4.23, smart grid technologies are effectively utilized in energy management, but their adoption in other industrial areas remains minimal. Expanding their use across sectors such as production, waste management, and logistics could enhance energy efficiency, optimize resource distribution, and improve sustainability efforts.

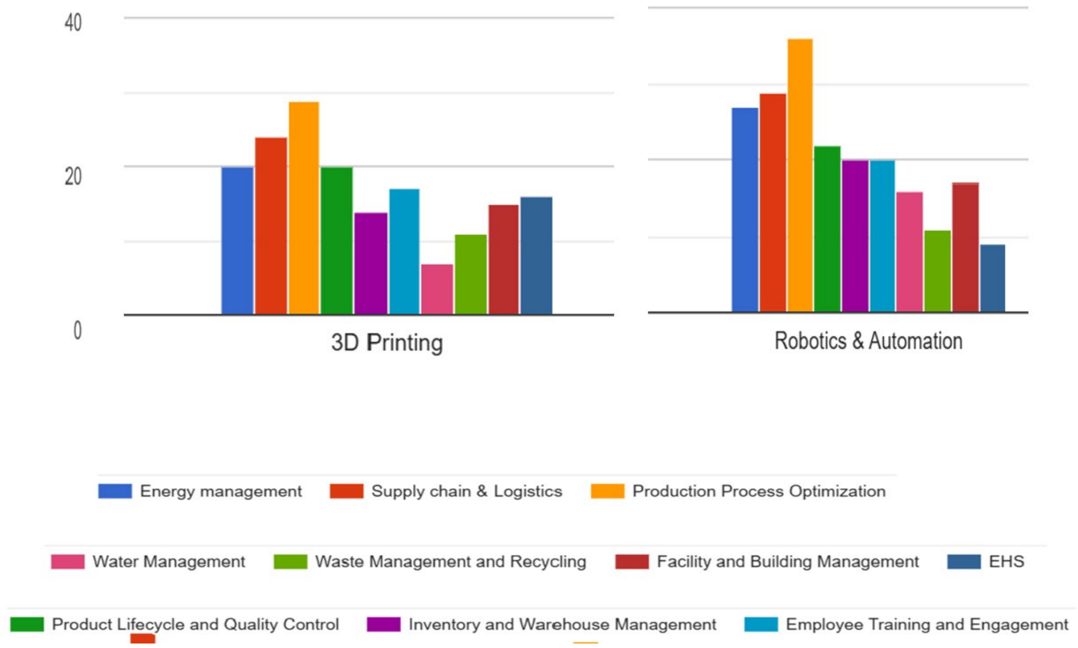

Figure 4.24: Robotics automation and 3D printing usage in operations

As shown in Figure 4.24, 3D printing and robotics automation are primarily effective in production, while their adoption in other areas remains limited. Expanding these technologies beyond production could enhance efficiency, reduce waste, and improve sustainability across various industrial sectors. In areas such as supply chain, maintenance, and waste management, robotics and 3D printing can streamline operations, enable rapid prototyping, and support customized solutions.

Expanding cloud adoption in these areas could enhance data-driven decision-making, real-time monitoring, and resource optimization, leading to improved sustainability outcomes. Integrating cloud-based solutions in waste and water management can facilitate better tracking, predictive analytics, and automation, ultimately contributing to more efficient and environmentally responsible industrial practices. Increased awareness and investment can help bridge this gap and drive broader adoption.

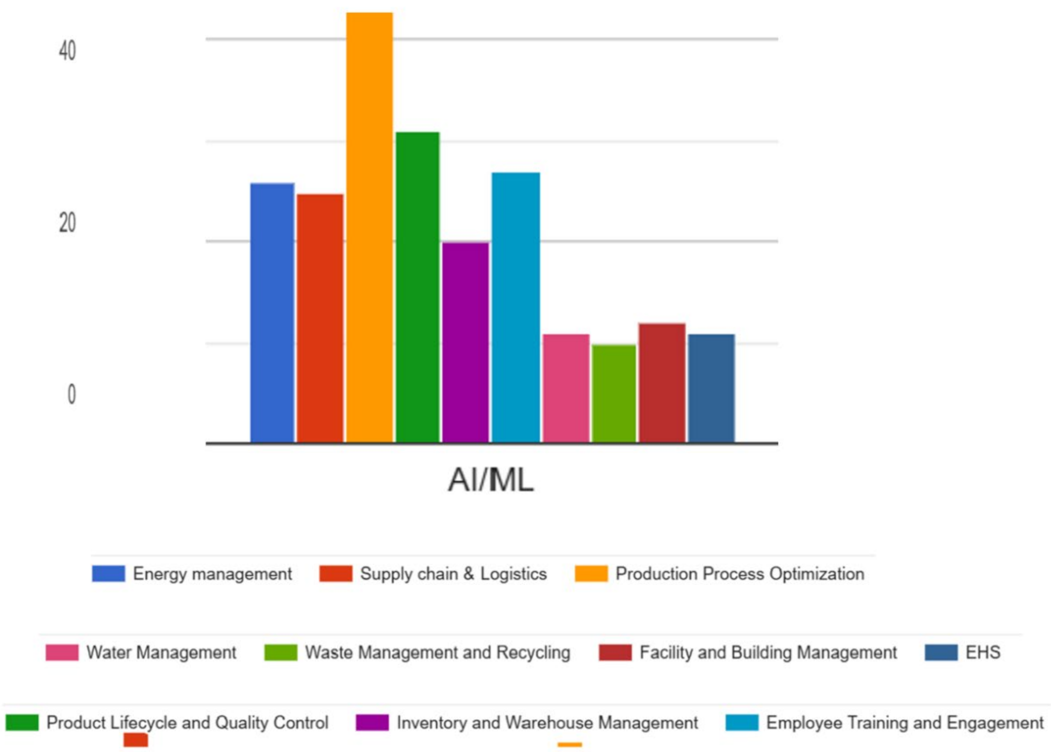

Figure 4.25: AI/ML usage in operations

As shown in Figure 4.25, AI and ML are widely utilized in production, demonstrating their effectiveness in optimizing processes and improving efficiency. However, their adoption in other areas, including waste and water management, remains significantly low. Implementing AI/ML in these sectors could enhance predictive analytics, automate monitoring, and optimize resource utilization, leading to more sustainable and efficient operations. Expanding AI/ML applications in waste and water management can drive data-driven decision-making, improve treatment processes, and reduce environmental impact. Increased awareness, investment, and technological advancements can help accelerate adoption across these underutilized sectors.

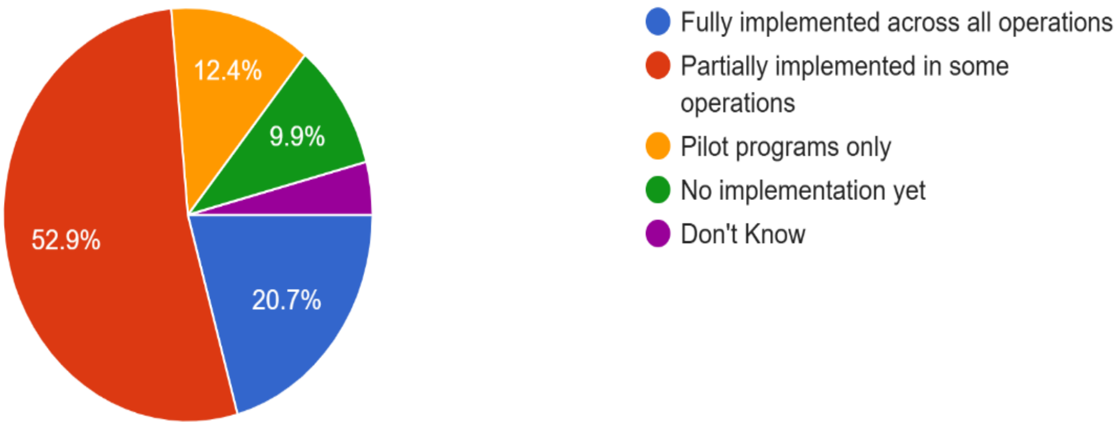

Figure 4.26: digital technologies usage operations for carbon footprint reduction

As shown in Figure 4.26, around 20% of industries have fully implemented digital transformation technologies in their operations to reduce carbon footprints, while 53% have adopted them partially. This indicates a growing awareness of the role digital solutions play in sustainability. However, a significant portion of industries have yet to fully leverage these technologies for maximum impact. Overall The reeal time monitoring of energy consumption, equipment performance, and emissions, helping organizations make data driven decisions for sustainability improvements. Data Analytics provides actionable insights by identifying inefficiencies and predicting areas for optimization. AI & ML enhance predictive maintenance, process automation, and energy optimization, further driving carbon footprint reduction. Meanwhile, Blockchain is increasingly being leveraged for supply chain transparency, ensuring responsible sourcing, waste tracking, and regulatory compliance.

S.No	Carbon Footprint Monitoring Level	Digital Transformation Maturity Level
1	Full	7.943396
2	No	6.5
3	Partially	6.269231
4	Unknown	5.9

Table 4.4: Carbon Footprint monitoring with respect digital maturity

As shown in the table 4.4, organizations with a digital maturity level above 7 have fully implemented carbon footprint monitoring. Their advanced digital capabilities enable real-time tracking, data-driven decision-making, and optimization of sustainability initiatives. These organizations leverage technologies like IoT, AI, and cloud computing to measure, analyze, and reduce emissions effectively. High digital maturity allows for seamless integration of automation, predictive analytics, and reporting systems, ensuring continuous improvement in carbon management.

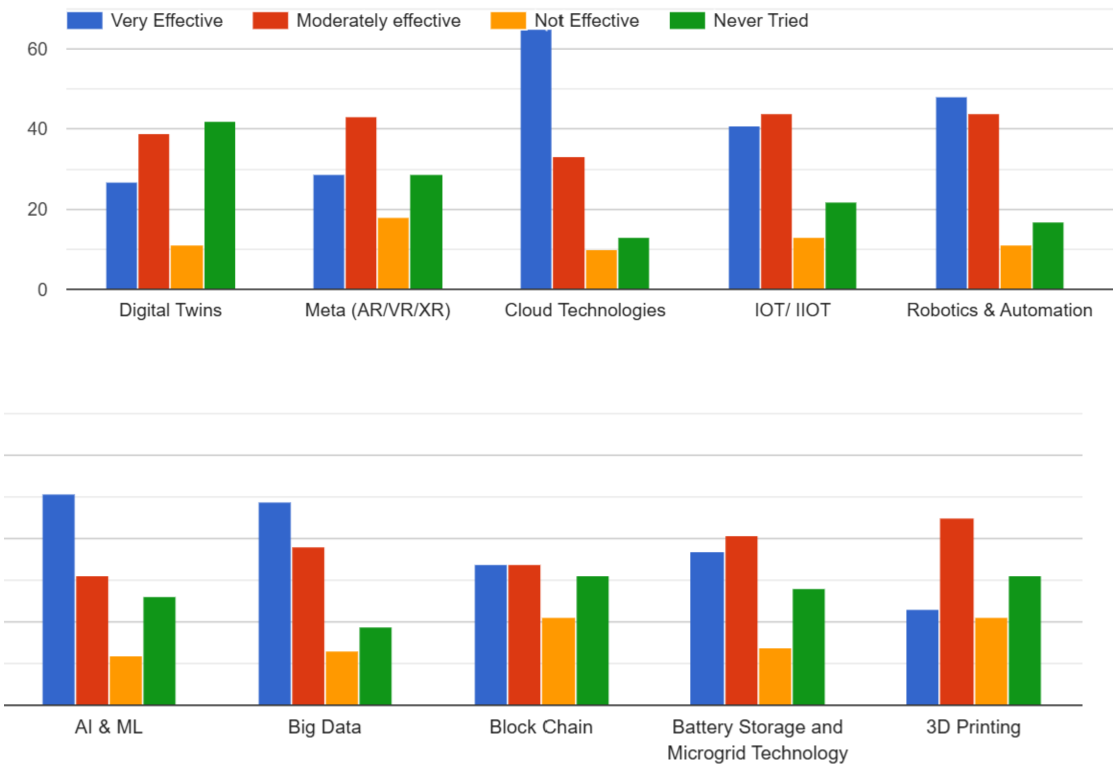

Figure 4.27 digital technologies effect in reducing factory's carbon emissions

As per Figure 4.27, cloud technologies have proven to be highly effective in reducing factory carbon emissions by optimizing data management, energy consumption, and process efficiency. Robotics and automation also contribute to sustainability but are moderately effective, primarily enhancing productivity and reducing waste in specific operations. Blockchain and 3D printing, while innovative, have not demonstrated significant impact on carbon footprint reduction, possibly due to limited adoption and industry-specific constraints. Digital twin technology remains the least explored, despite its potential to simulate, monitor, and optimize industrial processes for better sustainability outcomes. Increasing awareness and investment in digital twins could unlock new opportunities for real-time monitoring, predictive maintenance, and resource efficiency. To maximize the environmental benefits of digital transformation, industries should focus on scaling up proven technologies like cloud computing while further exploring emerging solutions such as digital twins and blockchain for enhanced carbon reduction strategies.

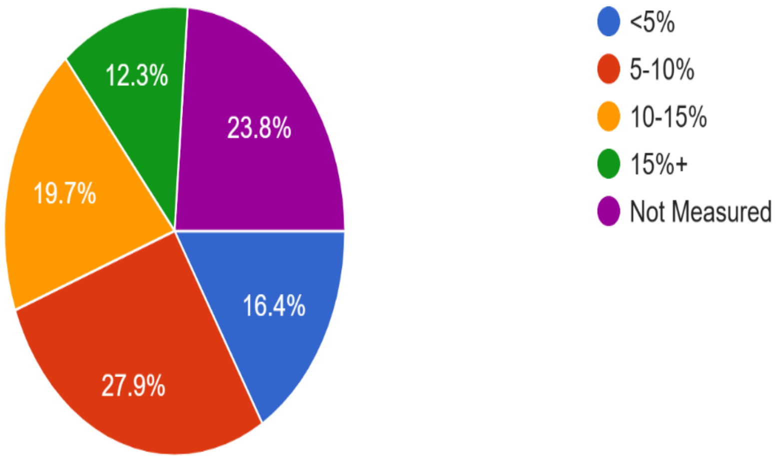

Figure 4.28: Carbon Footprint Reduction rate using digital technologies

As per Figure 4.28, more than 12% of industries have achieved over a 15% reduction in carbon footprints through the adoption of digital technologies. Additionally, 27.9% of industries have experienced a reduction between 10-15%, showcasing the significant impact of digital transformation on sustainability efforts. Around 20% of industries reported a carbon footprint reduction of 5-10%, while 16% observed a decrease of less than 5%. These figures highlight the varying degrees of success in implementing digital solutions. Expanding the use of advanced technologies like AI, IoT, and digital twins can further enhance carbon reduction across industries.

4.1.4 Challenges and Barriers to Implementing Sustainability Practices and Digital Technologies

Challenges and barriers to implementing sustainability practices and digital technologies include high initial costs, lack of technical expertise, resistance to change, data security concerns, and regulatory complexities. Integration issues, limited infrastructure, and unclear ROI further hinder adoption, slowing the transition to sustainable, technology-driven industrial operations.

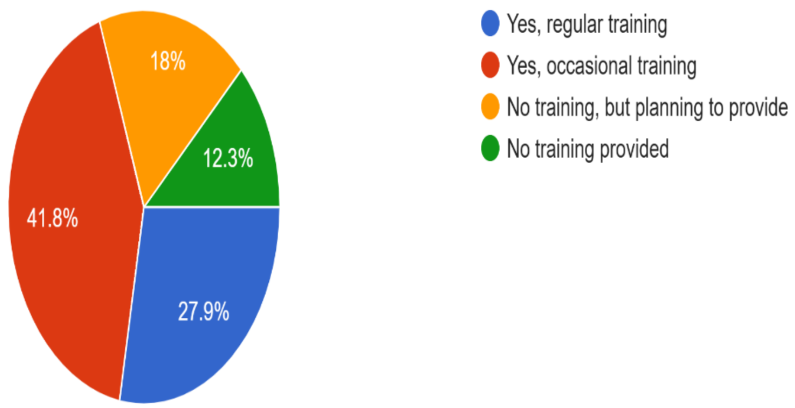

Figure 4.29: Skill gap in digital technologies

As shown in Figure 4.29, it is observed that less than 30% of the workforce possesses the necessary skills to understand and implement digital transformation technologies. This skills gap presents a significant challenge to the widespread adoption of advanced digital solutions in industries. Without adequate expertise, organizations struggle to leverage technologies like AI, IoT, digital twins, and cloud computing for sustainability and efficiency improvements. Addressing this issue requires targeted training programs, upskilling initiatives, and industry-academic collaborations to build a workforce capable of driving digital transformation. Investing in skill development is crucial for accelerating technology adoption and achieving long-term sustainability goals.

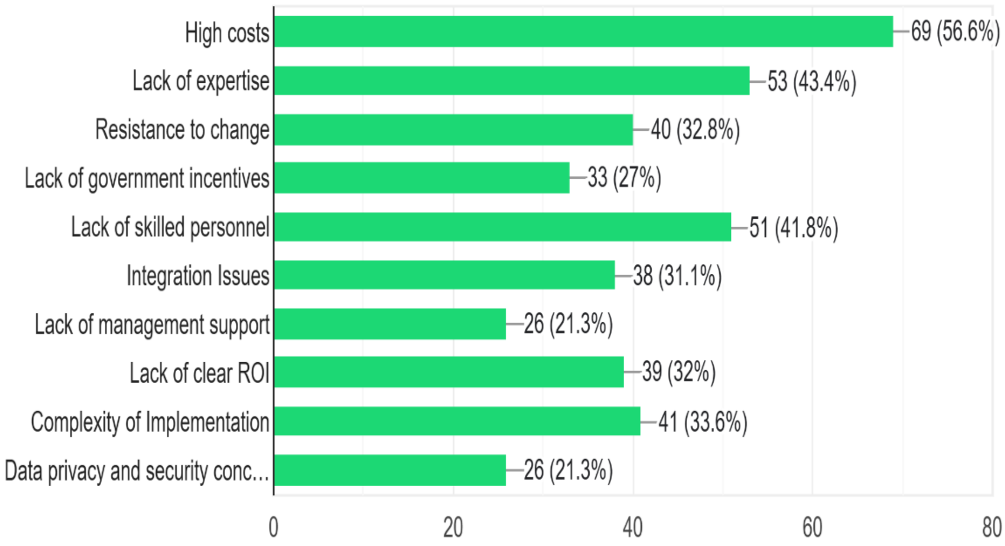

Figure 4.30: Main barriers to adopting digital solutions for carbon footprint reduction

As show in figure 4.30 the adoption of digital solutions for sustainability in manufacturing is often hindered by several key challenges. High initial investment costs remain one of the most significant barriers, as implementing advanced technologies such as IoT, AI, and digital twins requires substantial financial resources. Many organizations, particularly small and mid sized enterprises, struggle to allocate the necessary capital for digital transformation, slowing down sustainability initiatives. Additionally, the lack of skilled personnel presents a critical challenge.

The successful implementation of digital solutions requires expertise in data analytics, cybersecurity, and emerging technologies. However, many manufacturing units face a shortage of trained professionals, making it difficult to manage and optimize digital tools effectively. Resistance to change among employees further complicates the transition, as workers may be hesitant to adopt new technologies due to concerns about job security, workflow disruptions, or the complexity of digital systems.

It is interesting to observe that lack of management support is the least reported challenge in adopting digital technologies for sustainability activities in factories. This indicates a positive shift, as strong leadership backing is crucial for driving digital transformation. With management actively supporting sustainability initiatives, organizations are better positioned to allocate resources, implement innovative solutions, and overcome other barriers such as high costs and integration challenges. This trend suggests a promising future for the adoption of digital technologies in achieving sustainability goals, as executive commitment plays a key role in fostering long term environmental and operational improvements.

Regulatory Compliance and Brand Reputation as Key Drivers for Sustainability Adoption. Compliance with environmental regulations serves as a major catalyst for organizations to adopt sustainable practices. With stricter global policies and industry specific regulations, companies are increasingly compelled to implement eco friendly measures to avoid penalties, maintain operational licenses, and align with government mandates. Regulatory bodies continue to push for carbon footprint reduction, waste management, and energy efficiency, making compliance an essential part of corporate strategy.

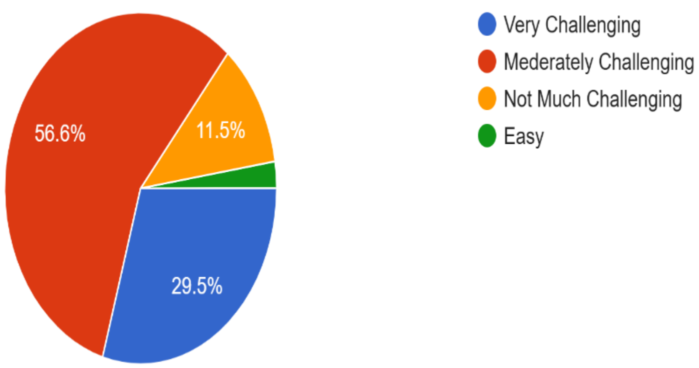

Figure 4.31: measuring carbon emissions

As shown in Figure 4.31, more than 85% of participants consider measuring carbon footprints to be highly or moderately challenging. This indicates significant difficulties in accurately tracking and analyzing emissions across industries. Challenges include data collection complexities, lack of standardized measurement frameworks, integration issues with existing systems, and the need for advanced digital tools. Without precise measurement, industries struggle to implement effective carbon reduction strategies. Addressing these challenges requires adopting robust digital solutions such as IoT, AI, and blockchain for real-time monitoring and reporting. Improved regulatory guidelines and standardized methodologies can further enhance accuracy and ease of implementation.

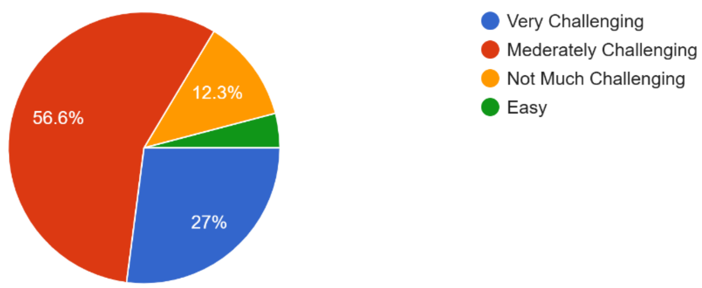

Figure 4.32: Legacy System Digitization Challenges

As shown in Figure 4.32, more than 80% of respondents find integrating digital transformation technologies with their factory's existing legacy systems to be highly or moderately challenging. Key difficulties include compatibility issues, high implementation costs, data migration complexities, and resistance to change. Many legacy systems lack the flexibility needed for seamless integration with advanced technologies like IoT, AI, and cloud computing. Overcoming these challenges requires strategic planning, phased implementation, and investment in middleware solutions that bridge the gap between old and new systems. Enhanced workforce training and strong IT support can also facilitate a smoother transition toward digital transformation.

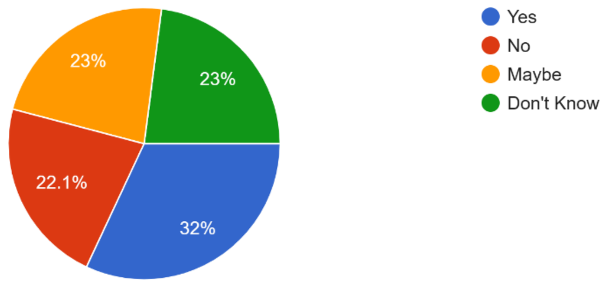

Figure 4.33: Regulatory Challenges

As shown in Figure 4.33, 32% of respondents identified regulatory and compliance-related challenges as key barriers to adopting digital transformation technologies for carbon reduction. Strict regulations, evolving environmental policies, and complex compliance requirements make implementation difficult for industries. Navigating these legal frameworks often demands significant time, resources, and expertise, delaying the adoption of advanced technologies such as AI, IoT, and blockchain. To overcome these challenges, industries need clearer regulatory guidelines, government incentives, and collaborative efforts between policymakers and businesses.

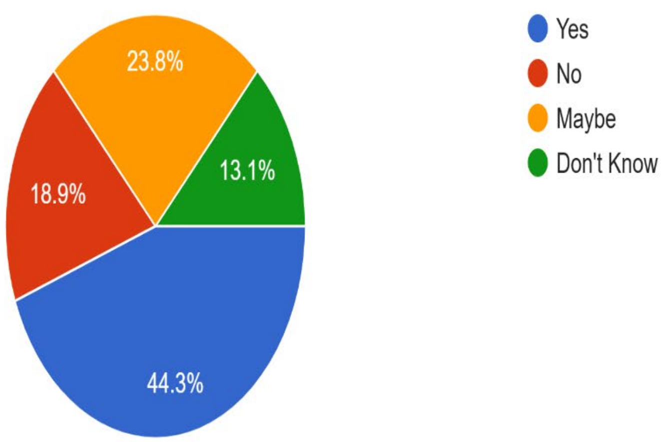

Figure 4.34: ROI Challenges

Streamlining compliance processes and aligning digital strategies with regulatory frameworks can accelerate the adoption of sustainable, technology-driven solutions.

As shown in Figure 4.34, more than 43% of respondents believe that uncertainty regarding return on investment (ROI) impacts their organization's commitment to digital transformation for carbon reduction. Many industries hesitate to invest in advanced technologies like AI, IoT, and digital twins due to unclear financial benefits, long payback periods, and high initial costs.

This uncertainty slows adoption, despite the potential for long-term sustainability and efficiency gains. To address this, organizations need clear ROI assessments, government incentives, and successful case studies demonstrating cost savings and environmental benefits. A well-defined digital strategy can enhance confidence and drive greater investment in sustainable transformation.

S.No	Organizations	Digital Maturity Rating
1	That have clear goals	7.454545455
2	That have some unclear goals	5.826086957
3	That don't have clear goals	5.454545455

Table 4.5: Digital Maturity vs Sustainability goals

As shown in Table 4.5 Organizations that prioritize sustainability goals tend to exhibit higher digital maturity compared to those with limited or no sustainability initiatives. Survey findings indicate that companies actively pursuing carbon footprint reduction and resource optimization are more likely to adopt advanced digital technologies such as IoT, AI, and digital twins. These technologies enable real time monitoring, predictive analytics, and process automation, contributing to both sustainability and operational efficiency.

In contrast, organizations with minimal or no sustainability goals often lag in digital transformation, primarily due to a lack of strategic focus and investment in emerging technologies. Without clear environmental objectives, there is less motivation to integrate data driven solutions for energy efficiency, waste reduction, and emissions tracking.

This correlation suggests that sustainability driven companies are more inclined to leverage digital innovation for long term environmental and economic benefits. As regulatory pressures and stakeholder expectations increase, businesses without sustainability goals may find themselves at a disadvantage in both compliance and competitiveness.

To overcome these challenges, businesses must adopt a structured approach, including phased integration strategies, middleware solutions, and robust cybersecurity frameworks. Proper planning and investment in digital transition efforts will be crucial for industries aiming to align their operations with sustainability goals. Successfully bridging the gap between legacy and digital systems can unlock significant efficiencies, reduce energy consumption, and drive meaningful progress in carbon footprint reduction initiatives.

4.1.5 Vision and Strategies for Digital Technologies in Sustainability and Carbon Reduction

Despite the challenges, overcoming these barriers is essential for industries to leverage digital transformation for sustainability. Investing in workforce training, developing scalable integration strategies, and ensuring data security will be crucial in accelerating the adoption of digital solutions. By addressing these obstacles, organizations can unlock the full potential of technology to drive sustainability and carbon footprint reduction.

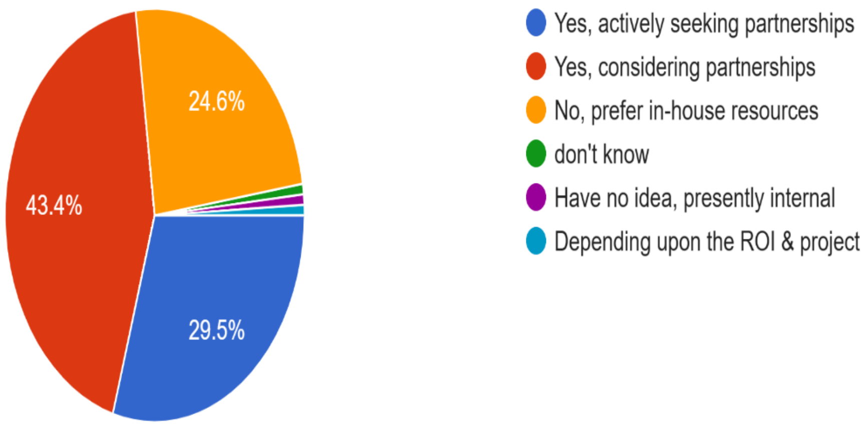

Figure 4.35: Interest on collaborations

As shown in figure 4.35 It is observed that more than 70% responses intersted in Collaboration with external partners including technology providers, sustainability consultants, and industry associations plays a crucial role in advancing sustainability initiatives in manufacturing. These partnerships offer access to specialized expertise, cutting edge innovations, and industry best practices, enabling organizations to navigate the complexities of digital transformation for sustainability.

Technology providers offer state of the art digital solutions such as IoT, AI, and blockchain, helping factories optimize resource efficiency, reduce waste, and improve carbon footprint tracking. Sustainability consultants bring in depth knowledge of environmental regulations, carbon reduction strategies, and corporate sustainability frameworks, ensuring organizations align their digital efforts with compliance requirements and global standards.

Industry associations foster knowledge sharing, benchmarking, and collaboration opportunities among peers, providing valuable insights into successful sustainability models and emerging trends. Engaging with these entities allows businesses to stay ahead of regulatory changes, adopt proven strategies, and access funding or incentives for green initiatives.

By building strong cross sector partnerships, organizations can accelerate their sustainability goals, enhance operational efficiency, and drive long term business value. These collaborations empower businesses to implement holistic, scalable, and innovative sustainability strategies, ensuring they remain competitive in an increasingly eco conscious industrial landscape.

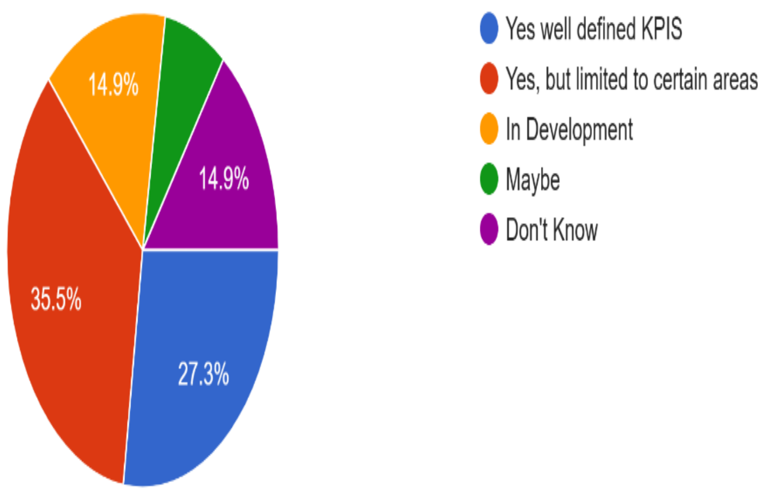

Figure 4.36: KPIs for tracking carbon emissions reduction through digital technologies

As shown in fiure 4.36 less than 30% have clear KPI in reduction of carbon emmission with digital technologoies. Survey findings indicate that key performance indicators (KPIs) related to sustainability and digital transformation challenges are not well defined in many organizations. The absence of clear metrics makes it difficult to measure progress, assess the effectiveness of digital initiatives, and drive continuous improvement.

To address this gap, organizations should establish well structured KPIs that align with their sustainability goals. These KPIs should cover energy efficiency, carbon footprint reduction, waste management, and digital adoption rates, ensuring a data driven approach to sustainability. Additionally, tracking digital transformation efforts—such as the integration of IoT, AI, and data analytics—can help assess the impact of technology on reducing emissions and optimizing resource usage. Regular monitoring and transparent reporting of sustainability metrics are essential for maintaining accountability and identifying areas for improvement. Organizations should implement real time tracking systems and dashboards that provide insights into progress and highlight areas requiring corrective action.By defining measurable and actionable KPIs, businesses can create a structured framework for their sustainability initiatives. This approach not only enhances operational efficiency and regulatory

Compliance but also fosters a culture of continuous improvement and innovation, ultimately driving long term success in digital sustainability efforts.

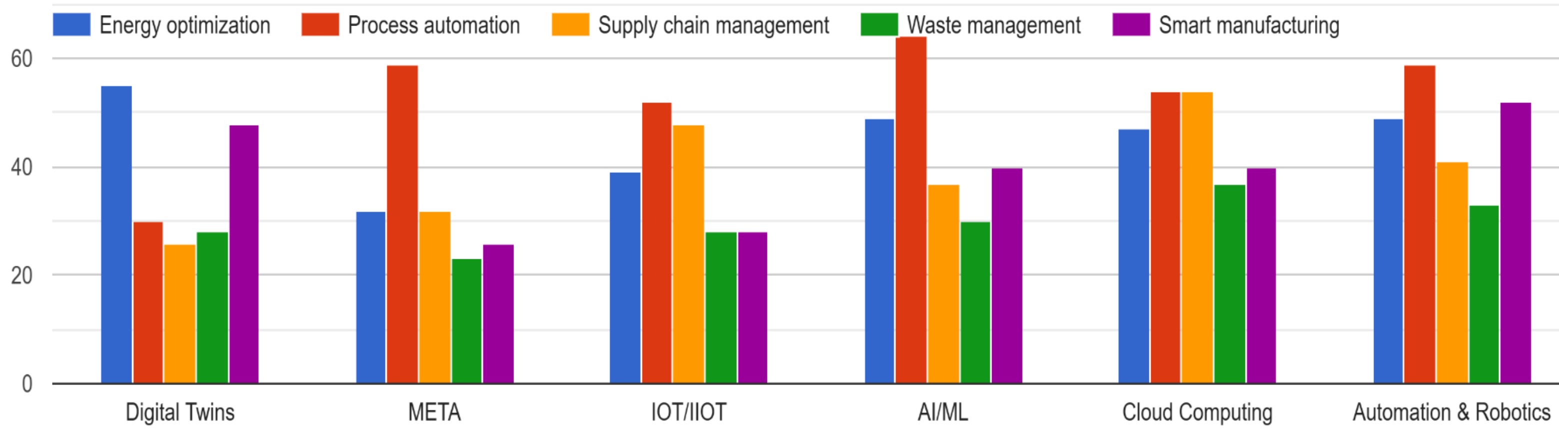

Figure 4.37: Technologies vs areas for carbon footprint reduction

AS Showin in figure 4.37 Survey findings highlight that digital twins are emerging as a highly promising technology for energy optimization in carbon footprint reduction. By creating virtual replicas of physical assets, digital twins enable real time monitoring, predictive maintenance, and simulation based improvements, significantly enhancing energy efficiency and reducing emissions in manufacturing operations.

For process optimization, technologies such as the Metaverse (META), IoT, and AI are considered the most effective. IoT facilitates seamless data collection from interconnected devices, providing real time insights that enhance operational efficiency. AI, with its advanced analytics and machine learning capabilities, enables predictive decision making, automates complex workflows, and reduces resource wastage. META applications, including augmented and virtual reality, enhance visualization, training, and remote monitoring, streamlining factory processes and improving workforce efficiency.

Cloud computing is recognized as the preferred solution for logistics and waste management. It provides scalable storage, real time data processing, and advanced analytics that help optimize supply chains, reduce transportation related emissions, and improve material reuse and recycling efforts. Cloud based platforms enable better tracking and coordination, ensuring sustainable logistics operations while minimizing environmental impact.

Automation and robotics are the top choices for smart manufacturing, enabling precision, consistency, and efficiency in production processes. Automated systems reduce human intervention in hazardous environments, enhance operational speed, and minimize material wastage, all of which contribute to sustainability efforts. Robotics driven smart manufacturing improves product quality while reducing energy consumption, making it a crucial driver for the future of digitalized, sustainable factories.

Overall, the findings indicate that a combination of these digital transformation technologies can effectively support carbon footprint reduction by optimizing different aspects of manufacturing. However, their successful implementation requires strategic planning, infrastructure investment, and workforce training to maximize their sustainability benefits. Organizations that embrace these technologies holistically will be better positioned to achieve their environmental and operational efficiency goals.

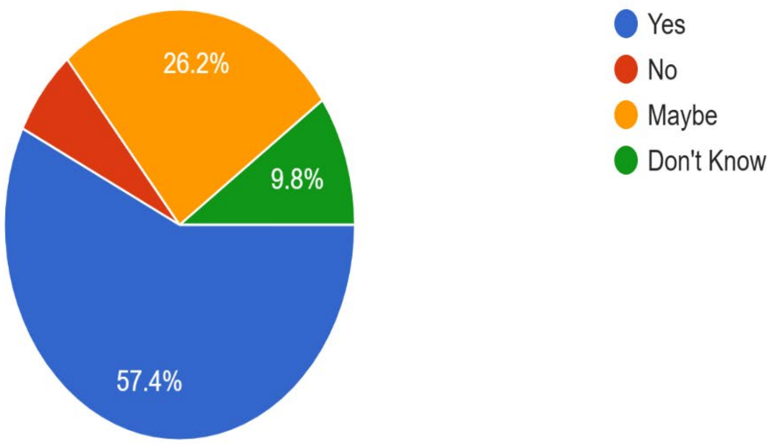

Figure 4.38: Future invest plans in digital technologies to reduce carbon footprint

As show in in figure 4.38 Organizations are increasingly prioritizing investments in digital technologies specifically aimed at carbon footprint reduction. Survey findings indicate that many companies are planning to allocate additional resources toward advanced solutions over the next 1–3 years. Key areas of focus include IoT for real time energy monitoring, AI driven process optimization, and digital twins for enhanced efficiency and predictive analytics.

Additionally, cloud computing and blockchain are gaining traction for sustainable logistics and transparent carbon tracking. This proactive approach reflects a growing commitment to sustainability goals, regulatory compliance, and operational efficiency, positioning organizations to achieve long term environmental and economic benefits through digital transformation.

4.2 Interview Results

As part of the research, comprehensive interviews were conducted with 15 industry experts in ESG and digital transformation, offering key insights into sustainability challenges, technology adoption, and carbon footprint reduction strategies.

What are the critical areas in factories for carbon footprint generation?

Understanding the critical areas in factories responsible for carbon footprint generation is essential for identifying key sources of emissions and developing effective strategies for carbon reduction. This question plays a pivotal role in this research as it helps establish a scientific foundation for assessing how digital transformation technologies can mitigate carbon emissions in manufacturing industries.

Factories are complex systems with multiple sources of carbon emissions, including energy intensive machinery, inefficient supply chains, waste generation, and transportation logistics. By pinpointing the most significant contributors, industries can prioritize targeted interventions for emission control.

A thorough analysis of critical emission areas enables industries to set baseline measurements and track the effectiveness of sustainability initiatives. Without this understanding, implementing digital solutions such as AI driven energy management or IoT based monitoring systems may lack precision and impact.

Each emission source may require a different technological solution. For example:

Energy management systems can optimize power consumption in high energy processes.

Digital twins can simulate and improve operational efficiency.

Blockchain can enhance supply chain transparency for carbon tracking.

By addressing this question, the research ensures that digital transformation strategies are aligned with real world industrial challenges, maximizing their effectiveness.

Governments and regulatory bodies worldwide are implementing carbon reduction mandates. Identifying critical carbon emitting areas helps industries align with regulations and achieve compliance, avoiding financial penalties while enhancing sustainability efforts.

What digital transformation technologies implemented in the manufacturing unit reduced the carbon footprints and how did you measure it?

This question is fundamental to the research as it bridges the gap between technological adoption and sustainability impact in manufacturing. By addressing this, the study aims to determine which digital transformation technologies have successfully reduced carbon footprints and establish a standardized approach for measuring their effectiveness.

Identifying Effective Digital Technologies

Manufacturing industries are adopting various Industry 4.0 technologies, including:

Internet of Things (IoT): Real time monitoring of energy consumption and emissions.

Artificial Intelligence (AI): Predictive analytics to optimize energy usage.

Digital Twins: Virtual simulations to improve efficiency and reduce waste.

Blockchain: Transparent tracking of carbon emissions across the supply chain.

Automation & Robotics: Minimizing manual inefficiencies and reducing energy intensive operations.

By answering this question, the research can categorize technologies based on their effectiveness in different manufacturing processes, helping industries make informed investment decisions.

- Establishing Measurement Metrics
- Understanding how companies measure carbon footprint reduction is crucial for validating the success of digital transformation initiatives. This involves exploring:
    - Energy consumption data before and after implementation.
    - Carbon emission tracking using digital tools.
    - Operational efficiency improvements linked to emission reductions.
    - Regulatory compliance and industry benchmarks.

Without proper measurement methods, sustainability claims may lack credibility. This research provides a structured framework for quantifying impact through data driven insights.

By determining which technologies work best and how to measure their impact, this study offers valuable insights for industry leaders, policymakers, and researchers. It helps in shaping future sustainability policies, setting carbon reduction targets, and guiding factories toward greener manufacturing practices.

This question is critical as it ensures that digital transformation in manufacturing is not just an industry trend but a measurable, impactful solution to carbon footprint reduction. The research findings will provide a roadmap for industries to adopt effective technologies and develop standardized carbon measurement practices, contributing to long term sustainability.

This research question is integral as it provides a comprehensive view of how digital technologies contribute to accurate carbon credit calculations. By answering it, the study will help industries align with global sustainability goals, maximize carbon credit benefits, and enhance their transition to greener manufacturing practices.

4.5 Conclusion

The integration of digital transformation in carbon footprint management within factories remains at a nascent stage. While industries have taken initial steps by transitioning to alternative fuel sources and implementing renewable energy solutions, the adoption of advanced digital technologies such as AI, IoT, and blockchain remains limited.

Measurement and monitoring play a crucial role in reducing carbon footprints. Without accurate tracking systems, industries cannot effectively implement reduction strategies. Digital tools such as IoT enabled sensors and AI powered analytics can help factories gain real time insights into their emissions, facilitating proactive decision making and optimizing energy usage. Furthermore, predictive maintenance can minimize waste and improve equipment efficiency, contributing to overall carbon footprint reduction.

A major barrier to large scale carbon reduction in factories is the lack of adequate incentives. Previously, carbon credits provided industries with financial benefits for reducing emissions, but their discontinuation has created a gap in motivation. Policymakers and industry leaders must explore alternative incentives, such as tax benefits, expedited regulatory approvals, and subsidies for implementing green technologies. Such measures will ensure that sustainability efforts align with financial and operational benefits, encouraging more industries to adopt eco friendly practices.

Moving forward, industries must focus on a holistic approach to digital transformation in carbon management. Rather than relying solely on fuel substitution, they should integrate technology driven solutions that enhance efficiency and transparency. Governments and regulatory bodies must also play an active role in promoting sustainability by introducing supportive policies and incentives.

In conclusion, the future of carbon footprint reduction in factories lies in a synergy between technology, policy, and industry commitment. Through the strategic implementation of digital tools and well structured incentives, the industrial sector can significantly contribute to global sustainability goals, reducing greenhouse gas emissions and mitigating climate change impact. Only by embracing innovation and collaboration can factories achieve long term environmental and economic sustainability.

CHAPTER V:

DISCUSSION

5.1 Discussion of Results

This discussion section analyzes the findings in the context of existing literature and industry practices. It highlights the importance of digital transformation for sustainability and the need for strategic investments in technology and training. The discussion also addresses the challenges faced by organizations and the strategies employed to overcome these barriers.

The findings of this research highlight that while digital transformation has significantly reshaped various industries, its role in reducing carbon footprints in manufacturing facilities remains underdeveloped. Although some industries have embraced renewable energy sources to address Scope 2 emissions, Scope 1 emissions continue to be managed largely through fuel substitution rather than the integration of

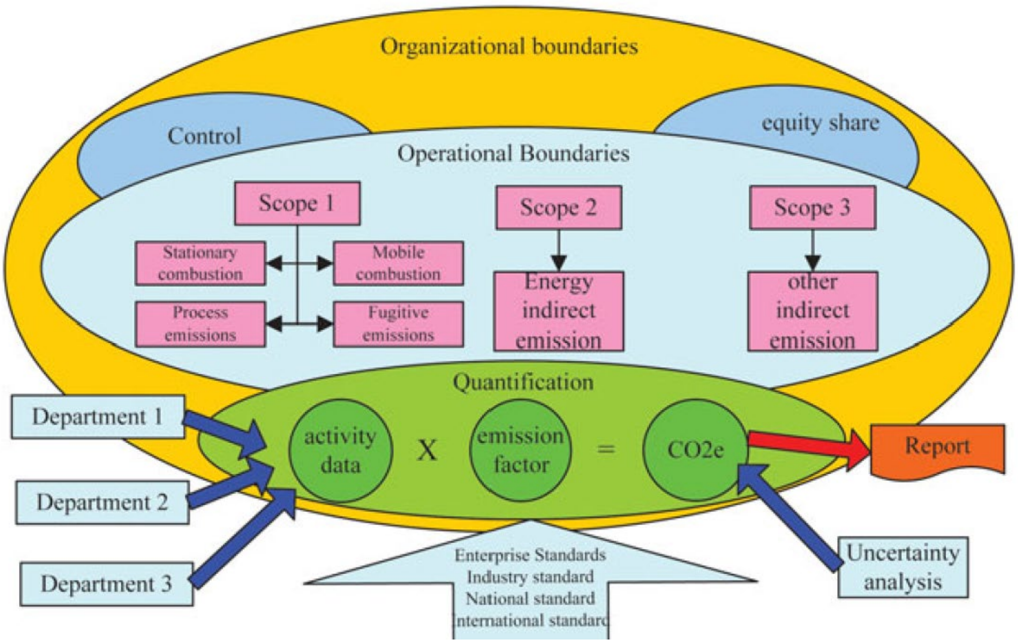

Figure 5.1 Assessment Procedure of the Carbon Footprints

advanced digital technologies. This limited adoption suggests that industries are yet to leverage the full potential of digital transformation in carbon management (Gao et al., 2014b).

Industrial operations are a major source of greenhouse gas (GHG) emissions, primarily due to direct fuel consumption, extensive electricity use, and supply chain logistics. Despite growing global awareness and regulatory pressures surrounding climate change, digital innovations aimed at reducing industrial carbon footprints are not widely implemented. The study identifies key challenges, including the absence of real time emission monitoring systems, limited deployment of AI driven energy optimization tools, and insufficient adoption of predictive analytics for carbon reduction.

A critical aspect discussed in this research is the role of measurement in emission control. Without accurate data, industries struggle to identify high emission areas and implement effective reduction strategies. Digital solutions such as IoT based sensors, AI powered analytics, and blockchain led carbon tracking can significantly improve transparency and accountability in emission management. However, widespread industrial adoption of these technologies remains slow, necessitating targeted interventions.

Integration issues with legacy systems also pose a significant obstacle. Many manufacturing units rely on outdated infrastructure that is incompatible with modern digital solutions, making the transition costly and time consuming. Ensuring seamless interoperability between new and existing systems requires careful planning, extensive upgrades, and robust cybersecurity measures.

Training people is crucial in overcoming the critical challenge posed by a lack of skilled personnel. The successful implementation of digital solutions hinges on expertise in data analytics, cybersecurity, and emerging technologies. However, many manufacturing units struggle with a shortage of trained professionals, which hampers their ability to manage and optimize digital tools effectively. Additionally, resistance to change among employees can further complicate the transition. Workers may be hesitant to adopt new technologies due to concerns about job security, workflow disruptions, or the complexity of digital systems. Investing in comprehensive training programs is essential to equip the workforce with the necessary skills and to facilitate a smoother transition to digital solutions.

Furthermore, the study emphasizes the necessity of incentives to encourage industries to prioritize carbon reduction. Historically, carbon credits and other financial benefits played a significant role in motivating factories to lower emissions. However, with the discontinuation of such incentives in many regions, there is a lack of strong financial motivation for industries to invest in sustainable digital solutions. The research underscores the importance of reinstating carbon credits or introducing alternative benefits such as tax reductions, streamlined regulatory approvals, or subsidies for green technology implementation.

In summary, while digital transformation has the potential to revolutionize carbon management in industrial operations, its adoption remains fragmented. Addressing this gap requires a multi faceted approach, including increased investment in digital technologies, robust measurement frameworks, and the reintroduction of incentives that align sustainability with financial and operational benefits. Future policies and industrial strategies must prioritize digital innovations to accelerate carbon footprint reduction and contribute to global sustainability goals.

Recommendations

Based on the findings, the following recommendations are made:

- Invest in Training and Development: Provide regular training programs to upskill employees on digital tools and sustainability practices.
- Prioritize High Impact Technologies: Focus on adopting highly effective digital tools such as IoT, data analytics, AI & ML, and digital twins.
- Address Cost and ROI Concerns: Conduct thorough cost benefit analyses and explore government incentives to justify investments in digital technologies.
- Enhance Data Privacy and Security: Implement robust cybersecurity measures and conduct regular security audits.
- Foster Collaboration and Partnerships: Collaborate with external partners to access technical expertise and innovative solutions.
- Integrate Digital Technologies with Existing Processes: Develop strategies for seamless integration of digital technologies with legacy systems.
- Focus on Circular Economy Practices: Continue to implement and expand circular economy practices using digital tools.
- Monitor and Measure Progress: Establish clear KPIs and metrics to track progress in sustainability initiatives.
- Secure Management Support: Ensure top management support for digital transformation projects.
- Promote a Culture of Sustainability: Engage employees in sustainability initiatives and foster a culture of sustainability.

5.2 Discussion of Research Question One Carbon emissions from industrial activities contribute significantly to global greenhouse gas emissions. This paper examines the primary sources of carbon footprint generation in factories, categorizing them into Scope 1, Scope 2, and Scope 3 emissions. The analysis considers direct emissions from combustion processes, indirect emissions from electricity usage, and additional emissions from logistics and supply chains. A comprehensive understanding of these sources is crucial for developing effective sustainability strategies. Industries are among the highest contributors to carbon emissions globally, producing greenhouse gases (GHGs) through various operational processes. The carbon footprint of a factory is the total amount of carbon dioxide (CO2) and other GHGs released due to energy consumption, raw material usage, transportation, and waste management ('Climate Change 2021: The Physical Science Basis | Climate Change 2021: The Physical Science Basis', 2021). Identifying the major emission sources helps industries implement mitigation strategies and transition towards sustainable operations.

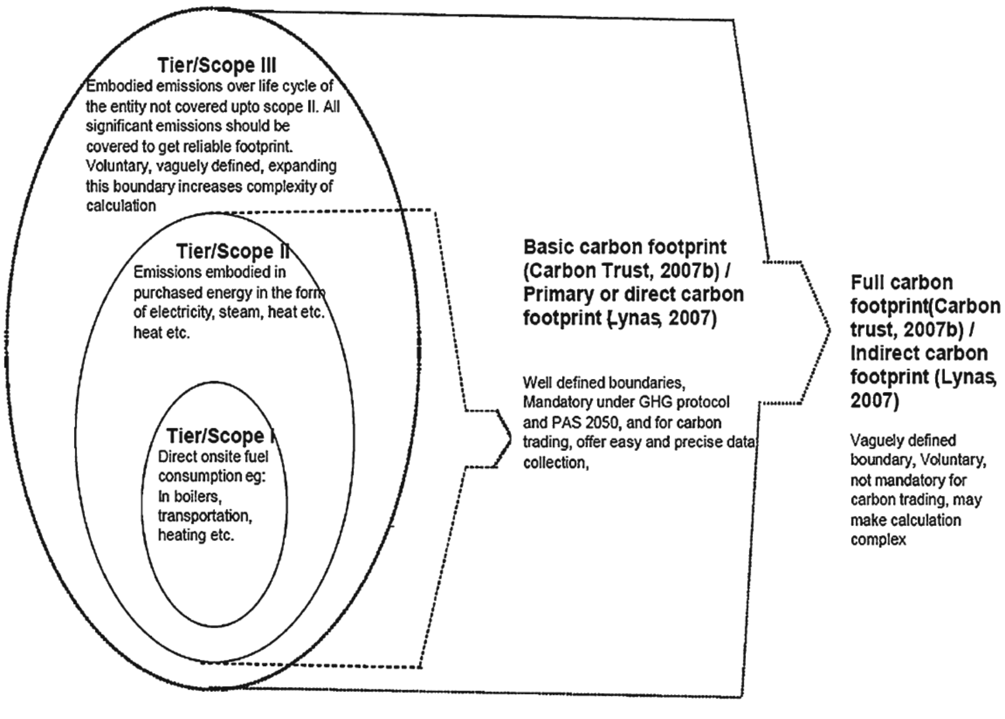

Figure 5.2: Boundaries for calculation of Carbon footprint (Pandey et al., 2011)

Factories generate carbon footprints from multiple sources, primarily due to fuel combustion, electricity consumption, and supply chain operations.(Pandey et al., 2011) These sources are categorized as follows:

Scope 1: Direct Emissions

Scope 1 emissions originate directly from industrial processes and fuel combustion within the facility. The primary contributors include:

- Boilers and Furnaces: The combustion of fossil fuels such as coal, natural gas, and oil for heating and production generates significant CO2 emissions ('Sources of Greenhouse Gas Emissions | US EPA', n.d.)
- Diesel Generators: Factories often rely on diesel generators as backup power sources, leading to direct emissions from diesel combustion (Energy Efficiency Energy System   IEA, no date)
- Process Emissions: Certain industrial processes, such as cement production and steel manufacturing, release CO2 as a byproduct ('WRI's Sustainability Data | World Resources Institute', n.d.)

Scope 2: Indirect Emissions from Energy Usage

Scope 2 emissions result from the purchase of electricity, heat, or steam produced by external sources. These emissions occur at power plants but are associated with the factory's energy consumption. Major factors include:

- Electricity Usage Points: Factories depend on electricity for machinery, lighting, and climate control, indirectly generating emissions based on the energy mix of the grid

- Renewable vs. Non Renewable Energy: The extent of Scope 2 emissions varies depending on the proportion of fossil fuel based electricity versus renewable energy sources (Energy Efficiency   Energy System   IEA, no date)

Scope 3: Supply Chain and Transportation Emissions

Scope 3 emissions extend beyond the factory's immediate operations and encompass indirect emissions from upstream and downstream activities, including:

- Employee Commuting: Daily transportation of employees using fossil fuel powered vehicles contributes to carbon emissions
- Raw Material Transportation: The procurement of raw materials from suppliers, often involving long distance shipping and trucking, results in significant emissions ('ENGAGING THE CHAIN: DRIVING SPEED AND SCALE CDP Global Supply Chain Report 2021', 2022)
- Product Distribution and Logistics: Transporting finished products to customers, whether via road, rail, air, or sea, adds to the overall carbon footprint ('WRI's Sustainability Data | World Resources Institute', n.d.)
- Waste Management: Industrial waste disposal, including landfill emissions and recycling processes, contributes to Scope 3 emissions ('ENGAGING THE CHAIN: DRIVING SPEED AND SCALE CDP Global Supply Chain Report 2021', 2022)

3. Mitigation Strategies for Carbon Footprint Reduction

To minimize industrial carbon emissions, factories can adopt the following measures:

- Energy Efficiency Improvements: Upgrading to energy efficient machinery and optimizing production processes can significantly reduce Scope 1 and Scope 2 emissions (Energy Efficiency   Energy System   IEA, no date)
- Renewable Energy Adoption: Transitioning to solar, wind, or hydroelectric power can lower indirect emissions from electricity usage (‘WRI’s Sustainability Data | World Resources Institute’, n.d.)
- Sustainable Transportation: Encouraging employee carpooling, electrified transport, and optimizing logistics routes can mitigate Scope 3 emissions (‘ENGAGING THE CHAIN: DRIVING SPEED AND SCALE CDP Global Supply Chain Report 2021’, 2022)
- Carbon Capture and Storage (CCS): Implementing CCS technologies can help capture and store CO2 emissions from industrial processes
- Supply Chain Optimization: Partnering with low emission suppliers and adopting circular economy principles can further reduce emissions across the value chain (‘Sources of Greenhouse Gas Emissions | US EPA’, n.d.)

5.3 Discussion of Research Question Two

Digital transformation has revolutionized various industries, yet its application in reducing carbon footprints within factories remains limited. While some industries have adopted renewable energy sources to mitigate Scope 2 emissions, efforts in Scope 1 emissions are primarily restricted to fuel substitution rather than digital innovations. This research explores the current state of digital transformation in carbon management, the role of measurement in emission control, and the necessity of incentives to drive sustainability efforts in industrial operations.

Current Status of Digital Adoption

Industries have begun implementing renewable energy solutions, such as solar power, to mitigate Scope 2 emissions. However, digital technologies play a minimal role in Scope 1 emission reduction, as factories primarily rely on fuel substitution rather than automation or AI driven efficiency measures. Some key changes observed include:

- Transition from furnace oil to natural gas to lower Scope 1 emissions and other similar practices for the high carbon footprint contributing resources and raw materials.
- Use of alternative fuel sources with lower carbon footprints.
- Limited adoption of real time monitoring systems for emissions control.

Measuring Carbon Footprints: Importance and Methods

Accurate carbon footprint measurement is essential for implementing reduction strategies. Factories typically calculate emissions using globally available data models. For instance:

- Boiler Efficiency Calculations: Determining how much gas is consumed per unit of steam produced.
- Emission Monitoring Systems: Digital tools that track real time emissions and predict environmental impact.
- Carbon Accounting Software: Platforms that quantify emissions and recommend sustainability strategies.

Without measurement, industries lack insight into their emissions, making reduction efforts ineffective. Digital transformation can enhance this process through IoT sensors, AI based analytics, and blockchain led carbon tracking.

The Role of Incentives in Carbon Footprint Reduction

The Need for Incentivization

Factories are more likely to engage in carbon reduction efforts if financial or operational benefits are attached. Governments and regulatory bodies can implement policies such as:

- Tax Benefits for Low Carbon Emissions: Industries that reduce emissions beyond a certain threshold receive tax exemptions.
- Faster Approval Processes: Factories demonstrating sustainability efforts can benefit from streamlined regulatory approvals.
- Carbon Credit Trading: A system where factories earn credits for emission reduction, which can be traded for financial gain.

The Current State of Carbon Credits

Previously, carbon credits served as a significant motivator for factories to lower emissions. However, these credits have been discontinued in many regions. The absence of such incentives discourages factories from investing in emission reducing technologies. Policymakers must rethink ways to make carbon reduction attractive for industries, ensuring sustainability is both an environmental and economic priority.

Recommendations for Enhancing Digital Transformation in Carbon Management

To accelerate carbon footprint reduction, industries should adopt the following digital strategies:

- AI Driven Energy Optimization: Implementing AI to analyze energy consumption and recommend efficiency improvements.
- IoT Based Emission Tracking: Deploying real time sensors to monitor emissions and detect anomalies.
- Blockchain for Carbon Accounting: Using decentralized ledgers for transparent emission reporting and verification.
- Predictive Maintenance for Energy Efficiency: Leveraging machine learning to optimize equipment performance and minimize waste.

CHAPTER VI:

SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

6.1 Summary

This research explored the role of digital transformation technologies in reducing the carbon footprint of manufacturing industries. As factories remain one of the largest contributors to global carbon emissions, industries are under increasing pressure to adopt sustainable practices while maintaining operational efficiency. The study investigates how smart factory technologies such as IoT, AI, Digital Twins, Blockchain, and Big Data Analytics optimize energy consumption, minimize waste, and enhance sustainability efforts. While industries have made some progress in mitigating Scope 2 emissions through renewable energy adoption, Scope 1 emissions remain largely controlled through traditional fuel substitution rather than digital innovations. The study explored the current state of digital adoption, the importance of accurate emission measurement, and the necessity of financial incentives to drive sustainability in factories.

In this research we used the qualitative research approach, utilizing survey data, industry surveys, expert interviews, and real world observations across multiple manufacturing sectors. Participants included mid level and executive leaders from diverse geographic regions to ensure a broad perspective. Thematic analysis was applied to identify key trends, challenges, and best practices in emissions reduction.

Key Findings & Contributions

Limited Digital Adoption for Carbon Reduction:

While industries have begun integrating renewable energy sources (e.g., solar power) to address Scope 2 emissions, Scope 1 emissions continue to rely on traditional fuel substitution rather than digital innovations.

The use of AI driven optimization, IoT based emission tracking, and blockchain led carbon accounting remains minimal in manufacturing operations.

Importance of Accurate Measurement in Emission Reduction:

Without precise carbon footprint measurement, industries lack insight into their actual emissions and struggle to implement targeted reduction strategies.

Technologies such as real time IoT sensors, AI powered predictive analytics, and automated carbon reporting systems can significantly enhance emission tracking and management.

The Role of Financial Incentives in Sustainability Efforts:

Historically, carbon credit programs encouraged industries to reduce emissions, but the discontinuation of these programs in many regions has decreased motivation for sustainable practices.

The adoption of digital sustainability technologies in industries requires strong incentives such as tax benefits, expedited regulatory approvals, and direct subsidies. These incentives can help overcome financial constraints and encourage industries to implement emission-reducing strategies effectively. Collaboration between governments and industries is essential to create policies that support digital solutions for carbon footprint management. By fostering innovation through well-structured policy frameworks, carbon reduction efforts can be accelerated on a larger scale.

Technologies such as IoT and AI-driven analytics play a crucial role in emissions tracking, energy optimization, and predictive maintenance, improving overall efficiency. Digital twin technology enables industries to simulate various operational scenarios, facilitating better decision-making and carbon footprint reduction. Additionally, blockchain technology enhances transparency in carbon credit trading and regulatory compliance, ensuring accountability in sustainability initiatives.

Despite these advancements, significant barriers remain, including high implementation costs, workforce resistance, and regulatory limitations. Establishing a structured framework to measure the impact of digital transformation on sustainability is critical to overcoming these challenges and ensuring long-term success.

Industrial facilities are significant contributors to greenhouse gas (GHG) emissions, primarily due to direct fuel combustion, high electricity consumption, and complex supply chain logistics. Despite increasing global attention on climate change, the adoption of advanced digital solutions for carbon footprint reduction remains slow. Key challenges include the lack of real time monitoring systems, limited integration of AI driven energy efficiency tools, and insufficient implementation of predictive analytics for emission control.

A critical aspect of carbon management is accurate measurement. Without precise data, industries struggle to identify and mitigate high emission sources. Emerging technologies such as IoT sensors, AI powered analytics, and blockchain led carbon tracking offer innovative solutions, yet widespread adoption remains limited. The study highlights the necessity of digital transformation in creating a transparent and efficient emission management framework.

Additionally, financial incentives play a crucial role in encouraging industries to prioritize carbon reduction. The discontinuation of carbon credit programs in many regions has reduced motivation for industries to invest in sustainability. The research emphasizes the need for alternative incentives, such as tax benefits, fast track regulatory approvals, and subsidies for green technology adoption, to drive industrial engagement in carbon footprint reduction.

This research provides valuable insights into the current state of digital transformation for sustainability, highlighting key challenges, adoption trends, and the tangible benefits organizations experience in their carbon footprint reduction journey. Here are is the key summary:

6.2 Implications

This research has significant implications for the manufacturing industry, policymakers, technology providers, and sustainability advocates. By examining the impact of digital transformation technologies on carbon footprint reduction, this study offers actionable insights into how industries can balance economic growth with environmental responsibility.

Operational Efficiency: Factories must integrate digital technologies such as IoT based emission monitoring, AI driven energy optimization, and blockchain enabled carbon accounting to enhance sustainability efforts. Digital technologies like IoT, AI, and Digital Twins enable real time monitoring and predictive analytics, leading to optimized energy consumption, reduced waste, and improved process efficiency.

Cost Savings: Digital transformation can improve energy efficiency, optimize resource utilization, and lower operational costs, providing long term financial benefits while reducing emissions. Implementing these technologies can reduce energy costs and regulatory fines while improving long term sustainability.

Competitive Advantage: Companies that proactively implement digital carbon management strategies can position themselves as leaders in sustainable manufacturing, enhancing brand reputation and market value. Companies that adopt sustainable digital solutions gain a market advantage by aligning with green manufacturing trends.

Standardization & Compliance: The research highlights the need for clear policies and frameworks for measuring and regulating digital sustainability initiatives. Governments and global regulatory bodies should mandate digital carbon accounting systems to ensure transparency and accountability in emission reporting. Stronger partnerships between industries, governments, and technology providers can drive large scale sustainability initiatives.

Carbon Credit Systems: Findings support the development of transparent and reliable carbon credit mechanisms, leveraging blockchain technology for accountability. Policymakers should reconsider carbon credit programs or introduce alternative benefits such as tax reductions, fast track regulatory approvals, and grants for green technology implementation.

Incentives & Funding: Governments can use insights from this study to design incentives and subsidies that encourage manufacturers to adopt digital sustainability solutions. Governments must introduce policies that encourage industries to adopt smart technologies for carbon reduction, including incentives for digital emission tracking and AI driven energy management.

Product Development: The research identifies gaps in existing digital solutions, guiding technology firms in designing more effective, industry specific tools for carbon footprint reduction.

Adoption Challenges: Understanding barriers such as high capital investment and workforce resistance helps in developing cost effective and user friendly solutions. Widespread adoption of digital technologies can significantly reduce industrial greenhouse gas (GHG) emissions, contributing to global climate change mitigation.

6.3 Recommendations for Future Research

This research provides a foundational understanding of how digital transformation technologies contribute to carbon footprint reduction in manufacturing industries. However, given the rapid evolution of technology and sustainability practices, further research is necessary to expand and refine these insights. Several areas require further exploration to enhance sustainability strategies. Future studies should focus on the following:

1. Advancing Digital Technologies for Carbon Reduction

Investigate the impact of AI driven predictive analytics on optimizing energy consumption and reducing emissions in manufacturing.

Explore the use of blockchain technology for transparent and tamper proof carbon accounting in industrial supply chains.

Assess the effectiveness of industrial IoT based real time monitoring systems in reducing Scope 1, Scope 2, and Scope 3 emissions.

Future research should conduct long term studies on how digital transformation technologies impact carbon footprint reduction over extended periods.

Measuring real time data from smart factories over multiple years can provide a more accurate cause and effect analysis of digital adoption on sustainability.

2. Policy, Skill Building and Economic Frameworks for Industrial Sustainability

Analyze the effectiveness of government incentives and regulatory policies in promoting digital sustainability initiatives.

Study the potential for public private partnerships in scaling digital transformation for carbon management.

Investigating the role of government policies, incentives, and international regulations in shaping digital transformation adoption for sustainability.

Research can explore how global sustainability policies such as Net Zero Emission Goals, ESG frameworks, and UN Sustainable Development Goals (SDGs) influence manufacturing industries.

Research on the human and organizational challenges in adopting digital sustainability technologies is crucial.

Future studies should focus on training frameworks, change management strategies, and skill development programs to ease the digital transformation process.

3. Industry Specific Digital Transformation Strategies

Conduct sector specific research on digital sustainability in energy intensive industries like steel, cement, and chemical manufacturing.

Investigate how small and medium sized enterprises (SMEs) can adopt cost effective digital solutions for carbon footprint reduction.

Explore digital twin technology applications for simulating and optimizing factory emissions in real time.

Comparative studies across different industries such as automotive, textiles, pharmaceuticals, and energy sectors can help identify industry specific digital sustainability strategies.

Understanding how digital transformation technologies perform in various industrial contexts can enhance best practices and policy frameworks.

6.4 Conclusion

The research highlights the transformative potential of digital technologies in reducing industrial carbon footprints. However, despite advancements in digital innovation across various sectors, its application in carbon management remains fragmented and underutilized. A structured, technology driven approach that integrates accurate measurement tools, real time monitoring systems, and regulatory incentives is crucial for accelerating industrial sustainability efforts.

One of the primary findings of this research is that industries have taken initial steps toward mitigating Scope 2 emissions by adopting renewable energy sources, such as solar power. However, Scope 1 emissions resulting from direct fuel combustion in boilers, furnaces, and diesel generators remain largely dependent on fuel substitution rather than comprehensive digital interventions. The slow adoption of technologies such as AI driven process optimization, IoT based emission tracking, and blockchain enabled carbon accounting has limited the effectiveness of emission reduction strategies.

Additionally, this research underscores the importance of precise carbon footprint measurement in developing effective sustainability initiatives. Factories often rely on standard emission calculations and efficiency models to estimate their carbon outputs. However, integrating digital tools such as real time IoT sensors, AI powered analytics, and automated carbon reporting systems can significantly enhance accuracy and provide actionable insights. Without proper measurement, industries lack visibility into their actual emissions, making it challenging to implement targeted reduction strategies.

Beyond technological integration, the study also highlights the necessity of financial and regulatory incentives to drive carbon footprint reduction in industries. Historically, carbon credit programs served as a key motivator for emission control. However, with the discontinuation of these programs in many regions, industries have limited motivation to invest in emission reducing technologies. The research suggests reintroducing carbon credits or developing alternative incentive models, such as tax reductions, fast track regulatory approvals, and subsidies for green technology adoption. Such incentives can play a vital role in encouraging industries to embrace sustainable practices.

Furthermore, the research emphasizes the need for stronger collaboration between industries, policymakers, and technology developers. Governments must implement policies that mandate digital carbon accounting and reward industries that invest in emission reduction technologies. Similarly, industrial leaders should prioritize digital transformation in sustainability strategies, leveraging AI, IoT, and blockchain to drive efficiency and reduce environmental impact. Technology developers and sustainability advocates can contribute by designing cost effective, scalable solutions tailored to industrial needs.

In summary, this research bridges the gap between digital transformation and sustainability, offering practical recommendations for regulatory frameworks, technological advancements, and industry collaboration. The findings highlight that digital transformation is not merely an option but a necessity for modern industries striving to reduce their carbon footprint. By fostering a structured approach that combines technology, accurate measurement, and incentivization, industries can move toward a more sustainable and eco friendly future.

To achieve meaningful progress, a collective effort from stakeholders across the industrial ecosystem is required. Digital adoption must go beyond compliance and become an integral part of operational strategies. The research underscores that with the right policies, financial incentives, and technological advancements, industries can significantly reduce their carbon footprint while maintaining economic growth and operational efficiency. Ultimately, the successful integration of digital transformation into carbon management will play a critical role in shaping a sustainable future for the global manufacturing sector.

APPENDIX A

SURVEY COVER LETTER

Introduction:

As part of an academic research thesis, this survey aims to investigate the role of digital transformation technologies in reducing carbon footprints within factory operations. Given the rising importance of sustainable practices in industrial settings, this research focuses on understanding how digital tools and innovations can be leveraged to minimize environmental impact, improve energy efficiency, and contribute to overall sustainability goals in manufacturing.

Purpose:

This survey seeks to gather insights from industry professionals on the current adoption, challenges, effectiveness, and future potential of digital transformation technologies for carbon footprint reduction. The findings will help identify best practices, common obstacles, and key areas where digital technologies can drive significant improvements in carbon emissions management within factories.

Who Should Participate:

I invite professionals involved in factory operations, sustainability, environmental health and safety (EHS), information technology, or any role that intersects with digital transformation and environmental sustainability efforts. Your experience and insights are crucial to understanding the practical impact and potential of digital technologies in reducing industrial carbon footprints.

Topics Covered:

- Familiarity with and attitudes toward carbon footprint reduction in factory settings.

- Current technologies in use for reducing carbon emissions and their perceived effectiveness.
- Challenges faced in implementing digital transformation technologies.
- Plans for future adoption and investment in digital technologies for sustainability.
- Specific areas where digital transformation has the highest potential for carbon reduction.

This survey aims to understand the current use, effectiveness, challenges, and potential of digital transformation technologies for carbon reduction in factories, while also gathering background information on respondents and their facilities. Thank you

APPENDIX B

INFORMED CONSENT

Interview Consent Form

Research project title: SUSTAINABLE SMART FACTORIES: DIGITALIZATION'S IMPACT ON CARBON EMISSION REDUCTION

Research investigator: GNV Maruthi Kasyap

Research Participants name:

The interview will take approximately 15min time. We don't anticipate that there are any risks associated with your participation, but you have the right to stop the interview or withdraw from the research at any time.

Thank you for agreeing to be interviewed as part of the above research project. Ethical procedures for academic research require that interviewees explicitly agree to being interviewed and how the information contained in their interview will be used. This consent form is necessary for us to ensure that you understand the purpose of your involvement and that you agree to the conditions of your participation. Would you therefore read the accompanying information sheet and then sign this form to certify that you approve the following:

- the interview will be recorded and a transcript will be produced
- you will be sent the transcript and given the opportunity to correct any factual errors
- the transcript of the interview will be analysed by (name of the researcher) as research investigator
- access to the interview transcript will be limited to (name of the researcher) and academic colleagues and researchers with whom he might collaborate as part of the research process
- any summary interview content, or direct quotations from the interview, that are made available through academic publication or other academic outlets will be anonymized so that you cannot be identified, and care will be taken to ensure that other information in the interview that could identify yourself is not revealed
- the actual recording will be (kept or destroyed state what will happen)
- any variation of the conditions above will only occur with your further explicit approval

Or a quotation agreement could be incorporated into the interview agreement

Quotation Agreement

I also understand that my words may be quoted directly. With regards to being quoted, please initial next to any of the statements that you agree with:

I wish to review the notes, transcripts, or other data collected during the research pertaining to my participation.
I agree to be quoted directly.
I agree to be quoted directly if my name is not published and a made up name (pseudonym) is used.
I agree that the researchers may publish documents that contain quotations by me.

All or part of the content of your interview may be used;

- In academic papers, policy papers or news articles
- On our website and in other media that we may produce such as spoken presentations
- On other feedback events
- In an archive of the project as noted above By signing this form I agree that;

1. I am voluntarily taking part in this project. I understand that I don't have to take part, and I can stop the interview at any time;
2. The transcribed interview or extracts from it may be used as described above;
3. I have read the Information sheet;
4. I don't expect to receive any benefit or payment for my participation;
5. I can request a copy of the transcript of my interview and may make edits I feel necessary to ensure the effectiveness of any agreement made about confidentiality;
6. I have been able to ask any questions I might have, and I understand that I am free to contact the researcher with any questions I may have in the future.

Printed Name

Participants Signature **Date**

Researchers Signature **Date**

Contact Information

This research has been reviewed and approved by the Edinburgh University Research Ethics Board. If you have any further questions or concerns about this study, please contact:

Name of researcher Full address

Tel:

E mail:

You can also contact (Researchers name) supervisor:

Name of researcher

Full address Tel:

E mail:

What if I have concerns about this research?

If you are worried about this research, or if you are concerned about how it is being conducted, you can contact SSBM by email at contact@ssbm.ch.

Add names of any associated funding bodies and their logos

APPENDIX C

INTERVIEW GUIDE

I, ………………………………………………………. agree to be interviewed for the research which will be conducted by ………………………………………………...a doctorate students at the Swiss School of Business and Management, Geneva, Switzerland.

I certify that I have been told of the confidentiality of information collected for this research and the anonymity of my participation; that I have been given satisfactory answers to my inquiries concerning research procedures and other matters; and that I have been advised that I am free to withdraw my consent and to discontinue participation in the research or activity at any time without prejudice.

I agree to participate in one or more electronically recorded interviews for this research. I understand that such interviews and related materials will be kept completely anonymous and that the results of this study may be published in any form that may serve its best.

I agree that any information obtained from this research may be used in any way.

thought best for this study.

…………………………………… ………………

Signature of Interviewee Date

APPENDIX D

SURVEY QUSETIONS

SUSTAINABLE SMART FACTORIES: DIGITALIZATION'S IMPACT ON CARBON EMISSION REDUCTION

Introduction:

As part of an academic research thesis, this survey aims to investigate the role of digital transformation technologies in reducing carbon footprints within factory operations. Given the rising importance of sustainable practices in industrial settings, this research focuses on understanding how digital tools and innovations can be leveraged to minimize environmental impact, improve energy efficiency, and contribute to overall sustainability goals in manufacturing.

Purpose:

This survey seeks to gather insights from industry professionals on the current adoption, challenges, effectiveness, and future potential of digital transformation technologies for carbon footprint reduction. The findings will help identify best practices, common obstacles, and key areas where digital technologies can drive significant improvements in carbon emissions management within factories.

Who Should Participate:

I invite professionals involved in factory operations, sustainability, environmental health and safety (EHS), information technology, or any role that intersects with digital transformation and environmental sustainability efforts. Your experience and insights are crucial to understanding the practical impact and potential of digital technologies in reducing industrial carbon footprints.

Topics Covered:

- Familiarity with and attitudes toward carbon footprint reduction in factory settings.
- Current technologies in use for reducing carbon emissions and their perceived effectiveness.
- Challenges faced in implementing digital transformation technologies.
- Plans for future adoption and investment in digital technologies for sustainability.
- Specific areas where digital transformation has the highest potential for carbon reduction.

This survey aims to understand the current use, effectiveness, challenges, and potential of digital transformation technologies for carbon reduction in factories, while also gathering background information on respondents and their facilities. Thank you

Email*

☐ Record as the email to be included with my response

Full Name*

……………………………………………………………………………

Country*

…………………………………………………………….

Company Name*

………………………………………………………….

Job Title*

……………………………………………………….

Years of experience*

- ○ <10yrs
- ○ 10 20yrs
- ○ 20 30yrs
- ○ 30+yrs

What is your role within the organization? *

- Operations & Maintenance
- EHS
- Sustainability & ESG
- IT & Digital
- Logistics
- Engineering
- Other: …………………………………………………………..

What is the primary industry of your organization *

- Pharma & Healthcare
- Automotive
- IT & Digital
- Heavy Manufacturing (Steel, Aluminium Etc)
- FMCG
- Chemical

- Textile
- Electronics & Telecom
- Other:

Consent form Acceptance:

https://docs.google.com/document/d/1bULDyL AIfVuDHDG9HxZhHgKAPcEUEIOAiZPUHcUAvU/edit?usp=sharing

Please check the "I Agree" box below to confirm:

1) I have read and understood the information provided in the consent form.

2) I understand that my participation is voluntary.

3) I understand that I may withdraw from the survey at any time.

If you agree to participate in this survey under these conditions, please click "Continue".

☐ I Agree

How familiar are you with the concept of carbon footprint reduction? *

- Very familiar
- Somewhat Familiar
- Neutral
- Unfamiliar

How important is reducing carbon emissions to your organization? *

- Very important
- Important
- Neutral
- Not important

How much familiar are you with the following digital technologies? *

	Use it regularly	I understand it fairly well and can use it	Currently learning about it	I have heard but don't know much about it	Completely unfamiliar
Digital Twins	○	○	○	○	○
Meta (AR/VR/XR)	○	○	○	○	○
Cloud Technologies	○	○	○	○	○
IOT/ IIOT	○	○	○	○	○
Robotics & Automation	○	○	○	○	○

AI & ML	○	○	○	○	○
Big Data	○	○	○	○	○
Block Chain	○	○	○	○	○
Battery Storage and Microgrid Technology	○	○	○	○	○
3D Printing	○	○	○	○	○

How familiar are you with the concept of digital transformation for sustainability?

- Very familiar
- Somewhat Familiar
- Neutral
- Unfamiliar

How familiar is your ESG team about Digital Technologies? *

- Very familiar
- Somewhat Familiar
- Neutral
- Unfamiliar

How significant is carbon footprint reduction within your organization's digital transformation strategy?

- Very important
- Important

- Neutral
- Not Important

How important is carbon footprint reduction to your organizations operational strategy?

- Very important
- Important
- Neutral
- Not important

What level of importance does your organization place on adopting circular economy practices (e.g., recycling, reuse, remanufacturing)?

- Not important
- Slightly important
- Moderately important
- Very important
- Critical

What carbon reduction initiatives are currently implemented in your Organization? (Select all that apply)

- Energy efficiency improvements
- Renewable energy adoption
- Waste reduction
- Carbon offset programs
- Process Optimization and Automation
- Supply Chain Optimization
- Employee Engagement and Training
- Implementing Sustainable Materials
- Adoption of Lean Manufacturing and Green Practices
- Other: ………………………………………………………………………

Which of the following circular economy initiatives are currently in place at your facility? (Select all that apply)

- Recycling of materials and waste
- Product remanufacturing
- Use of recycled or sustainable materials

- Waste to energy initiatives
- Resource sharing with other companies
- None of the above
- Other: ……………………………………………………..

Which digital technologies does your organization use to support circular economy initiatives?

- Digital twins for resource optimization
- IoT for tracking materials
- Blockchain for supply chain transparency
- Data analytics for waste reduction
- None of the above
- Other: …………………………………………………………..

Does your factory monitor its carbon footprint with digital tools?*

- Yes
- No
- Partially
- Don't Know

Please select the areas of your operations that currently utilize digital technologies, and specify which technologies are implemented in each selected area. (Select all that apply)

	Energy Management	Supply Chain & Logistics	Production process optimization	Product Lifecycle & Quality Control	Inventory & Warehouse
Management					
Digital Twins	○	○	○	○	○
META	○	○	○	○	○
Cloud Technologies	○	○	○	○	○
AI/ML	○	○	○	○	○

Big Data	○	○	○	○	○
Block Chain	○	○	○	○	○
IOT/IIOT	○	○	○	○	○
Robotics & Automation	○	○	○	○	○
3D Printing	○	○	○	○	○
Smart Grid	○	○	○	○	○

To what extent have digital transformation technologies been implemented in your operations for carbon footprint reduction?

- Fully implemented across all operations
- Partially implemented in some operations
- Pilot programs only
- No implementation yet

- Don't Know

Does your factory have specific KPIs for tracking carbon emissions reduction through digital technologies?

- Yes well defined KPIS
- Yes, but limited to certain areas
- In Development
- Maybe
- Don't Know

How effectively do the digital technologies help reduce your factory's carbon emissions?

	Very Effective	Moderately Effective	Not Effective	Never Tried
Digital Twins	○	○	○	○
Meta (AR/VR/XR)	○	○	○	○
Cloud Technologies	○	○	○	○
IOT/ IIOT	○	○	○	○
Robotics &				

Automation	○	○	○	○
AI & ML	○	○	○	○
Big Data	○	○	○	○
Block Chain	○	○	○	○
Battery Storage and Microgrid Technology	○	○	○	○
3D Printing	○	○	○	○

What percentage of your factory's total carbon footprint has been reduced due to digital transformation efforts?

- <5%
- 5 10%
- 10 15%
- 15%+
- Not Measured

Has your organization provided training on digital tools and carbon reduction practices to staff?

- Yes, regular training
- Yes, occasional training
- No training, but planning to provide
- No training provided

To what extent does your organization use data analytics to optimize operations for carbon reduction?

- Extensively used
- Moderately used
- Minimally used
- Not used

What Benefits of Integrating Circular Economy and Digital Transformation are observed in your facility?

- Reduced resource consumption
- Increased operational efficiency
- Lowered production costs
- Improved regulatory compliance
- Enhanced brand reputation
- Other: ………………………………………..

What are the main barriers to adopting digital solutions for carbon footprint reduction in your organization? Select all that apply

- High costs
- Lack of expertise
- Resistance to change
- Lack of government incentives
- Lack of skilled personnel
- Integration Issues
- Lack of management support
- Lack of clear ROI
- Complexity of Implementation
- Data privacy and security concerns
- Other: ……………………………………………………

How challenging is it to measure carbon emissions in your factory operations? Select all that apply

- Very Challenging
- Moderately Challenging

- Not Much Challenging
- Easy

How challenging is it to integrate digital transformation technologies with your factory's existing legacy systems? Select all that apply

- Very Challenging
- Moderately Challenging
- Not Much Challenging
- Easy

Are there regulatory or compliance related challenges that hinder the adoption of digital transformation technologies for carbon reduction?

- Yes
- No
- Maybe
- Don't Know

Does uncertainty regarding the return on investment (ROI) affect your organization's commitment to digital transformation for carbon reduction?

- Yes
- No
- Maybe
- Don't Know

To what extent do you believe digital transformation can contribute to carbon footprint reduction?

- Significant contribution
- Moderate contribution
- Minimal contribution
- No contribution
- Don't Know

Which areas do you believe have the most potential for carbon footprint reduction using digital transformation technologies?

	Energy Optimization	Process Automation	Supply Chain Management	Waste Management	Smart Manufacturing
Digital Twins	○	○	○	○	○
META	○	○	○	○	○
IOT/IIOT	○	○	○	○	○
AI/ML	○	○	○	○	○
Cloud Computing	○	○	○	○	○

Automation

& Robotics ○ ○ ○ ○ ○

Is your organization planning to invest in additional digital technologies specifically for carbon footprint reduction in the next 1 3 years?

- Yes
- No
- Maybe
- Don't Know

Is your organization planning to invest in new digital technologies to reduce carbon footprint over the next 1 3 years?

- Yes
- No
- Maybe
- Don't Know

What percentage of your sustainability budget is expected to be dedicated to digital transformation technologies for carbon footprint reduction in the coming years?

- <5%
- 5 10%
- 10 25%
- 25 50%
- 50%+
- Don't Know

What resources would be most beneficial for supporting future digital transformation efforts aimed at carbon reduction?

- Increased budget
- Government incentives
- Access to technical expertise
- Training and development for staff
- Improved data and analytics tools
- Partnerships with technology providers

Is your organization interested in collaborating with external partners (e.g., technology providers, sustainability consultants) to achieve carbon reduction goals through digital transformation?

- o Yes, actively seeking partnerships
- o Yes, considering partnerships
- o No, prefer in house resources
- o Other: ………………………………..

What are your organization's key priorities for digital transformation in the context of sustainability?

…………………………………………………………………………………………

…………………………..

What is the size of your organization? *

- Small (<50 employees)
- Medium (50 250 employees),
- Large (250 1000 employees)
- Very Large (>1000 employees)

How many production lines does your factory operate? *

- 1 3
- 3 6
- 6 10
- 10+
- Not Applicable

Does your organization have established sustainability or carbon reduction goals?

- Yes
- No

- Maybe

How would you rate your organization's overall maturity level in digital transformation?

1 2 3 4 5 6 7 8 9 10

○ ○ ○ ○ ○ ○ ○ ○ ○ ○

What is your organization's approximate annual carbon emissions?

- <1,000 tons
- 1,000 5,000 tons
- 5,000 10,000 tons
- 10,000+ tons
- Not measured

What is the approximate square footage of your primary facility? *

- <50,000 sq. ft
- 50,000 100,000 sq. ft
- 100,000 500,000 sq. ft
- 500,000+ sq. ft

Where is your primary facility located? *

- USA
- MENA
- India
- Europe
- Africa
- Australia
- South America
- Rest of Asia
- Other: …………………………………………………………..

How long has your organization been in operation? *

- <5yrs
- 5 10yrs
- 10 20yrs
- 20+yrs

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