RECOGNIZING THE ROLE OF INDUSTRY 4.0 TECHNOLOGY IN ENHANCING ENVIRONMENTAL SUSTAINABILITY

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Kunjal Patel, MS, PGDL, BE

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by

Kunjal Patel

APPROVED BY

dr. Jaka Vadnjal

Dissertation Chair

RECEIVED/APPROVED BY:

Admissions Director

Dedication

I dedicate this work to Bhagwan Swaminarayan and Shri Krishna, whose guidance has given me strength and direction. I am deeply inspired by Pramukh Swami Maharaj and Mahant Swami Maharaj, whose wisdom has taught me resilience, humility, and the joy of serving others. To my parents, whose love, sacrifices, and unwavering belief in me have shaped my journey—this work is a reflection of their endless support.

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ABSTRACT

RECOGNIZING THE ROLE OF INDUSTRY 4.0 TECHNOLOGY IN ENHANCING ENVIRONMENTAL SUSTAINABILITY

Kunjal Patel
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Dissertation Chair:
Co-Chair:

The Indian pharmaceutical industry is at the forefront of addressing global challenges related to environmental sustainability and technological transformation. Industry 4.0 technologies, including Cloud Computing, IoT, advanced automation and Artificial Intelligence offer immense potential to increase operational efficiency, reduce environmental impacts, and foster innovation. However, their adoption within the pharmaceutical sector remains uneven, hindered by financial, technical, and organizational barriers. This research provides a comprehensive evaluation of Industry 4.0 technology adoption, analyzing its impacts, challenges, and strategic measures to overcome barriers.

Through a quantitative research design, this study collected primary data from 300 professionals across major Indian pharmaceutical companies. The findings reveal high adoption rates for foundational technologies like IoT and Cloud Computing, driven by their operational benefits. Emerging technologies, such as AR and VR, exhibit lower adoption due to significant barriers, including high capital investments, IT security concerns, and insufficient skilled workforce. Despite these challenges, the study highlights substantial environmental and economic benefits, including improved energy efficiency, reduced emissions, and enhanced resource management. The research underscores the influence of government policies, such as Digital India and Make in India, in promoting technological advancements, although their impact varies across regions and sectors. Orion Corporation and Pfizer CentreOne are just two of many worldwide case studies that have shown how these technologies may improve operational efficiency and environmental sustainability Furthermore, the pivotal roles of corporate governance and stakeholder engagement in driving successful adoption were emphasized, with leadership and collaborative strategies emerging as critical enablers. This study contributes to the academic understanding of Industry 4.0 by validating theoretical insights with empirical data and provides actionable recommendations for policymakers and industry practitioners. These include targeted training programs, phased implementation strategies, and stronger policy frameworks to support technology integration.

The findings have far-reaching implications for achieving sustainability goals and fostering innovation in the pharmaceutical sector. By addressing the identified barriers and leveraging the opportunities presented by Industry 4.0, the Indian pharmaceutical industry can position itself as a global leader in sustainable and technologically advanced practices.

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CHAPTER I

INTRODUCTION

1.1 Introduction

The development of a certain industry Manufacturers now have access to a spectrum of cutting-edge technologies that are revolutionizing the growth of the industrial sector thanks to the fourth industrial revolution (Carr et al, 2015). The latest industrial revolution is characterized by a desire for digitization and the adoption of modern technologies like the Internet of things (IoT), cyber physical systems (CPS), and cloud computing. These technologies enhance operational efficiency and creative activity in several industries (Thames and Schaefer, 2017). In contrast to the previous industrial revolutions, the predominant driver of Industry 4.0 is to digitize the production processes beyond optimizing the capabilities to produce products to make the businesses to respond promptly and flexibly to the changing market demands and challenges (Zonichenn and Gonçalves, 2018; Beier et al., 2021).

Today industries have improved process efficiency, flexibility and productivity with the advent of Industry 4.0 technologies. These advancements are bringing a new breed of digital integration into global manufacturing, leading to a more sustainable development being incorporated into organizational strategies (Zengin et al., 2021). The tools of Industry 4.0 leveraging innovative technologies help enhance sustainable operations and business to minimize the utilization of resources, process wastes, and machine life cycles (Adedokun-Shittu et al., 2020). In this global context, sustainability has turned out to be a compelling competitive factor in which companies are required not only to meet customer requirements but also to embrace sustainable practices within their core business strategies (Mei, 2020).

The motivation towards sustainable manufacturing that is being driven by the adoption of technologies related to Industry 4.0 is extremely apparent indeed, and it includes small and medium-sized businesses as well. These organizations are using this cutting-edge technology in order to enhance their output while also adhering to the ideals of sustainability (Caiado et al., 2022). For that reason, organizations are increasingly leveraging a range of techniques and strategies that make manufacturing their products more cost effectively and sustainably to meet the changing demands of today's dynamic business world (Osman et al., 2021).

Today it is clear that global commitment to the United Nations (UN) 2030 Agenda for Sustainable Development, adopted in 2015, encourages a shift towards sustainability. Ambitious, as this agenda aims to set 17 Sustainable Development Goals (SDGs) that enable organizational processes to be integrated with environmental, social and economic considerations (Vinuesa et al., 2020). These goals have received widespread acceptance by UN Member States and constitute a strategic blueprint for the sustainable development process in developed and developing nations (Verma et al., 2021). The focus of the SDGs is to save the Earth and protect better and sustainable environment. The goals speak to core global challenges related to poverty eradication, ensuring clean water, gender equality and economic growth. Organizations have to acknowledge the necessity of these environmental objectives deployed and risks that are entrapped in leveling any of these goals place. The

SDGs are structured around three pillars: They will focus on economic, social, and environmental, whilst stressing on its holistic approach to transformative and sustainable change. They include a wide variety of goals, such as ending world hunger, improving health and wellness, providing excellent education, reducing inequality, protecting terrestrial and aquatic ecosystems, engaging in responsible consumption and production, and taking action against climate change, among many others (Fatimah et al., 2020).

These changes provide the backdrop for discussions on how Industry 4.0 might help the Indian pharmaceutical industry become more environmentally sustainable. The study's overarching goal is to demonstrate how Industry 4.0 may significantly advance the global sustainability agenda by reshaping production processes via the integration of various technologies with sustainable practices.

In 2015, many countries have begun realigning their national strategy with the Sustainable Development Goals (SDGs) as many have shown increasing commitment to sustainable development. Since then, Industry 4.0 technologies have seen much uptake in improving sustainability, and adoption rates are as high as 72% in the latest studies (Kusuma et al., 2020). Against this backdrop of rising environmental awareness, the growing business case for sustainability and greater access to advanced technologies, this increase is occurring.

By centering on ideas like automation, resource optimisation, decentralised decision-making, and communication, Industry 4.0 has sparked a revolutionary shift in the industrial sector (Bag et al., 2021). This has only been possible with the incorporation of state-of-the-art technology, which includes the Internet of Things, Cyber-Physical

Systems, Big Data Analytics, Blockchain and Artificial Intelligence (Khan et al.,, 2022). Industry 4.0, on the other hand, has principally focused on production efficiency, real-time transparency, and autonomous management. This is because the "Smart Factory" idea of Industry 4.0 has emerged (Kayikci, 2018). The manufacturing industry's present use of nonrenewable resources and its unsustainable disposal and use methods greatly contribute to environmental harm and the overall degradation of the environment. Because of these factors, it is now widely recognised that sustainability concerns provide a significant danger to modern organisations(Gupta, Kumar, and Wasan, 2021); Bag and Pretorius, 2022). Therefore, the shift to a more sustainable production environment is very necessary. This has led to a shift away from the linear economic paradigm and towards more environmentally friendly alternatives, such as the circular economy. Industry 5.0 is an offshoot of Industry 4.0 that seeks to build on the foundation of digitalisation and connectivity while also including the ideas of sustainability, resilience, and a human-centric approach. The European Green Deal, launched by the European Commission in response to the topic's criticality, covers a wide range of industries—including transport and those that rely heavily on energy—in its pursuit of climate neutrality for the European Union by the year 2050 (European Commission, 2022). There is currently a lack of cohesive study in this field, even if the possible positive impacts of Industry 4.0 technology on sustainability are infrequently acknowledged. The logistics industry in particular needs more studies that investigate sustainability from an ecological, economic, and environmental perspective (Debnath et al., 2022; El Hamdi and Abouabdellah, 2022). It is necessary to raise the level of awareness within the industry about this concept before it can be fully commercialised. There are a lot of companies that aren't prepared to integrate the technologies that are part of Industry 4.0, and one reason for this is that they don't know enough about them. Specifically, this study will concentrate on promising areas in order to get a deeper understanding of how the technologies of Industry 4.0 could have an influence on production in a manner that is ecologically friendly. In this study, the current literature on the subject of the influence that manufacturing has on the environment as a consequence of the implementation of Industry 4.0 technology is uncovered and evaluated. As part of this process, you will be required to do a descriptive analysis as well as a comprehensive content analysis of the publications that you have selected after conducting a systematic literature review in order to find research that is relevant to the topic at hand. It is possible that academics, policymakers, and industry practitioners will be able to accomplish a seamless integration of new technology with sustainable practices in production if they work together to address the environmental sustainability implications of Industry 4.0. Through the addition of new information to what is already known, the purpose of this essay is to help pave the way for a manufacturing sector that is more environmentally friendly and makes use of tools from Industry 4.0.

1.2 Research Problem

Indian pharmaceutical industry is being forced to embrace sustainable practices either by legal pressure or by global sustainability agenda. The sector must keep providing the good quality products and keep encouraging innovation to stay competitive at the same time. Strong instruments to tackle these issues are seen as Industry 4.0 technologies. Indeed, it is not clear how extensively these technologies have been adopted in India's pharmaceutical industry, either, or how they might impact the country's sustainability. The aim of this research is to analyze the current state of industry 4.0 technology adoption when looked at within larger Indian pharmaceutical businesses, and also to identify specific financial, technical or legal constraints that may be stopping for the complete integration. Common case studies from a variety of firms will be analysed to identify how these technologies have influenced sustainability practice, particularly in helping with emissions reductions, efficiency in resource utilisation and waste management. Second, the research will also describe what techniques have proved the most effective in solving these problems as they are reported in sustainability reports. Additionally, this study will investigate the effect of national initiatives on the adoption of Industry 4.0 technology. The authors will also discuss how corporate governance and stakeholder involvement might help move these technologies forward. The objective is to generate realistic solutions that support the Indian pharmaceutical business in having a better success using Industry 4.0 technology to enhance both environmental and economic consequences.

1.3 Purpose of the Research

This research aims to explore industry 4.0 adoption levels in the major pharmaceutical companies on a case study basis using India as a context. The need to understand how early advances will enable sustainable practices that meet not only environmental standards, but add to operational efficiencies, drives this exploration. At the outset, this study seeks to determine and examine the particular barriers—which are financial, technical and regulatory barriers—suffered by large pharmaceutical companies when they seek to completely introduce Industry 4.0 approaches within their operations.

Moreover, the research aims to determine the tangible environmental and economic outcomes of these technologies both in greenhouse gas emissions reduction and in resource efficiency and waste management improvement in the sector. This assessment will yield a well delineated picture of the status quo of technology integration and its direct benefits and act as a base for industry standards and growth.

Another important objective is to propose solutions to help resolve barriers to technology adoption that are actionable. To this end a detailed review of successful case studies and sustainability reports will be undertaken to identify and propose suitable tactics and practices. Additionally, the research aims to investigate the impact of national policies like Digital India and Make in India on the technological changes in the pharmaceutical industry by analyzing how these policies propound or ameliorate adherence to environmental standards.

The study will finally look at the roles of corporate governance and stakeholder engagement in facilitating the uptake of Industry 4.0 technologies. This covers Investigation into such governance structures so as to determine how they can help or hinder technological developments and possible strategies for enabling development of a supportive ecosystem for the industry 4.0 technologies.

The research hopes to deliver insights and solutions that can be applied in the Indian pharmaceutical industry to make best use of Industry 4.0 technologies in achieving improved environmental as well as economic outcomes. Ultimately, the objective is to enable the industry’s move towards environmentally more sustainable manufacturing practices, and hence to be part of the larger global efforts toward environmental sustainability.

1.4 Significance of the Study

This research is significant because it provides, in a one stop fashion, an in depth, systematic investigation of I4.0 technologies as they apply to the crucial intersection of healthcare innovation and environmental stewardship in the Indian pharmaceutical sector. I4.0 has been globally recognized as the 'Fourth generation industrial revolution', leading to the integration of advanced technologies of the Internet of Things (IoT), Big Data Analytics and Artificial Intelligence into traditional manufacturing, and operational processes (Bai et al., 2020). The study is critical to understanding how these technologies could be utilized to help improve environmental sustainability in one of India's most important industry sectors.

Several research questions of major industrial, policy and academic significance will be addressed in this research. The study then firstly maps how far the industry has integrated these advanced technologies by way of assessing the I4.0 adoption of major pharmaceutical companies. Such an evaluation is important because it shows the industry's readiness to offer to satisfy both existing and next environmental standards and working efficiencies.

Second, this study will determine the nature of various specific challenges of I4.0 technological integration that limits the full integration of I4.0 technologies in the pharmaceutical sector. The research would help in developing strategies for safer technology adoption that would help make technology adoption smoother in a worldwide competitive market with great competitive advantages and operational efficiencies.

In addition, I4.0 technologies' influence on environmental sustainability practices and it provide valuable insights into how digital transformation is driven towards more sustainable manufacturing operations. The importance of this aspect of the research lends itself to being of relevance to global sustainability goals as exemplified by the goal of responsible production and consumption called forth by the United Nations Development Programme (United Nations, 2015).

This study will explore effective practice identified through sustainability reports that bypass barriers to technology adoption. This will present a working, practical framework of how companies can improve their technological footprint specifically, and specifically, it will supply documented evidence of integration strategies that work.

The role of national policies such as Digital India and Make in India in extending technology upgrades over the pharmaceutical sector will also be explored. Understanding governmental faces to encourage or hinder innovation in cutting edge technologies that are critical for both economic growth and environmental sustainability is very important.

The last is to dissect the role of corporate governance and stakeholder engagement in promoting the adoption of I4.0 technologies in order to understand how internal and external factors within companies affect technological transitions. The study of the dynamics of technology adoption and the necessary corporate governance reforms that can support such initiatives will be based on this analysis.

This research bridges the gap between how technology can be implemented practically in the Indian pharmaceutical industry; the potentials as well as the limitations in enhancing environmental sustainability using Industry 4.0. The results should help to guide policy, industry practice, and refine our understanding of this important area.

The study delves at the extent to which the Indian pharmaceutical industry is using Industry 4.0 technology to streamline operations and adopt sustainable practices that are in line with global sustainability objectives. Given India's position as a dominant player in the pharmaceutical industry—a sector that is both economically and technologically robust—this is of paramount importance. To become sustainable, incorporate Industry 4.0 technology. This study will better knowledge of the problems, tactics, and implications. Policymakers and business leaders may utilise the study's findings to inform choices that foster economic development while being environmentally responsible.

1.5 Research Questions

The main objective of this study is to look at the big pharmaceutical businesses in India and see how they've integrated and used Industry 4.0 (I4.0) technology. The following primary research questions served as the basis for the study:

1. What is the extent of Industry 4.0 technology adoption among the major pharmaceutical companies in India?

2. What specific challenges do major pharmaceutical companies face in fully adopting Industry 4.0 technologies?

3. How have Industry 4.0 technologies impacted the environmental sustainability practices of major pharmaceutical companies? What measurable benefits have been reported?

4. Based on the sustainability reports, what strategic measures have been most effective in overcoming the barriers to technology adoption in the pharmaceutical sector?

5. How do national policies and global sustainability goals influence the technological strategies of Indian pharmaceutical companies?

6. What role do corporate governance and stakeholder engagement play in advancing the adoption of Industry 4.0 technologies in the Indian pharmaceutical industry?

CHAPTER II

REVIEW OF LITERATURE

2.1 Introduction

When industrial revolutions evolved, we have witnessed a leap in manufacturing and technology, which have blurred edge and greatly influenced the pharmaceutical industry. The first industrial revolution occurred in the late 19th and early 20th centuries, when steam and new chemical processes replaced human labour in manufacturing machines. This was an era where machining tools were used, and mass production was set (Stearns, 2018).

Just before World War I, coal to electrical underwent a shift from the second industrial revolution. In this period, knowledge transfer increased and, in Europe, study tours to collect and improve the technological process became common practice. As a result industrial landscape became more and more globally connected (Stearns, 2018), technological leadership started to shift from Great Britain to United States and Germany.

The third revolution was digital technology and automation; large parts of the manufacturing process became robotic, making it more precise but also making it difficult and costly to customize and be flexible (Stearns 2018; Berger 2014). It gave birth to Industry 4.0 era focusing on the issue of above limitations through integration of latest technologies such as IoT, CPS, and AI and thus allowing more customization, efficiency and sustainability in Industry 4.0.

Industry 4.0 is critical to the transition of pharmaceutical industry. This revolution isn't just about automation; it wants to find ways of changing production through digitalization that will enable higher scalability and responsiveness in the manufacturing processes. In an increasingly scrutinized sector where the need to uphold high product quality standards, and rapidly respond to fast-changing markets, Industry 4.0 presents a means to improve operational efficiency and to integrate sustainable practices as a whole.

In this literature review, we turn to examine this trajectory and how Industry 4.0 can help the pharmaceutical industry to remain environmentally sustainable and operate more efficiently. The next sections will look into the different technologies and techniques that define Industry 4.0, and how they affect and how they pose challenges in the pharmaceutical manufacturing space.

2.2 Theoretical Framework

2.2.1 I4.0 Definition

Industry 4.0 (or simply I4.0) constitutes a new paradigm that infuses industrial and manufacturing landscapes, to the extent that companies are different from one another in terms of various dimensions. In this section, I4.0 is defined and the core technologies are described with their impacts on the industrial sector with respect to the pharmaceutical sector.

At the front of this industrial transformational process are the I4.0 technologies, which digitalise physical infrastructures, link digitised networks. However, as a result of these technological advancements, conventional value chains are being upended, compelling companies to reconsider their approaches to product development, production, service provision, and strategic alliance management. In the core of Industry 4.0 is the capacity to use massive amounts of data generated by interconnected systems and devices to derive valuable insights using sophisticated analytics and AI. Operational improvements, higher levels of automation and integration across entire value networks, are driven by these insights.

With the help of I4.0 technologies, data comes at us freely from different resources to be processed so the intelligence to support the decision-making process can be extracted. Not only is this good for operations, but there are major economic benefits as well — faster delivery times, lower inventory, lower working capital requirements. Behind the creation of a smart, responsive manufacturing environment that can anticipate a company's needs and streamline operations is the need to integrate application platforms and connectivity solutions that drive computation technologies.

I4.0 technologies can transform the drug development, production and distribution in the pharmaceutical sector. With machine learning algorithms, leveraged with AI, pharmaceutical companies can optimize their processes such that the quality of product increases, the yield rates increase and the time to market of new drugs gets accelerated. Moreover, these technologies support - and facilitate - more personalized medicine paradigms empowered by sophisticated analytics and coupled to more effective patient outcomes and treatment efficacy.

The roles of the enabler technologies in both the connectivity and computation landscapes that are essential in transforming the pharmaceutical industry are diagrammed in Figure 2.1 of the thesis. In the subsequent sections, more depth will be applied to specific

I4.0 technologies in the context of how they can be applied to improve environmental sustainability and operational efficiency within the pharmaceutical sector.

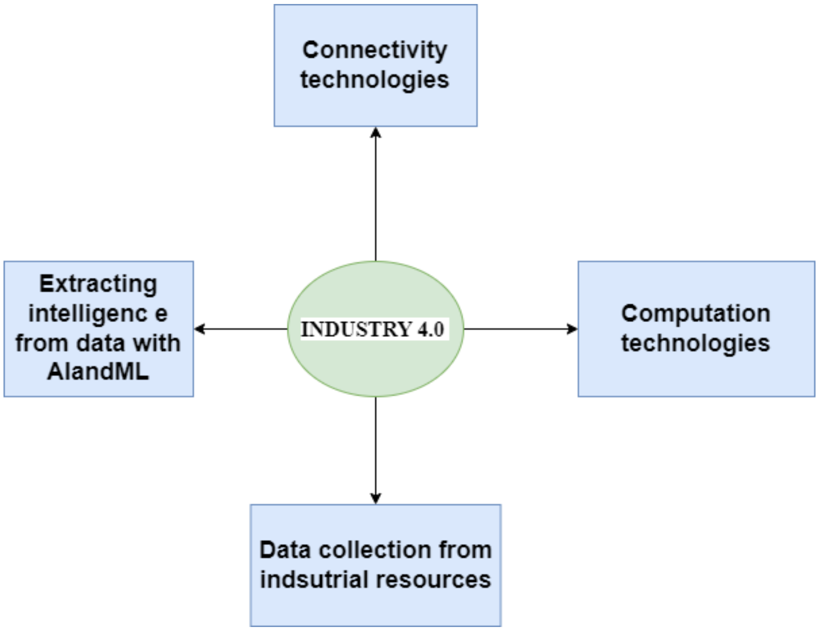


Figure 2. 1: Enabler technologies of I4.0

Fundamental enablers of connectivity and computation are the main enablers of the implementation of the industry 4.0 (I4.0), transforming the industry operations of differing sectors, such as pharmaceuticals. Figure 2.1 illustrates how these technologies are enabling the integration of whole value chains – from production processes, supply chains and business operations to customer interactions. This results in sheer huge data volumes which need to be communicated and computed robustly.

Connectivity and computation technologies play important roles in enabling seamless functionality of I4.0 systems, several scholars highlight. Ibarra et al. (2018) and Weking et al. (2020) have asserted that these technologies are indispensable for the digitization of the industrial environment. But Ibarra et al. (2018) and Weking et al. (2020) describe how these technologies serve to connect the separate parts of the value chain, as well as optimize operations with better data flow and greater decision-making power.

This ecosystem seamlessly integrates with the cloud computing because digital business interactions and creation of interoperable digital supply chains (Korpela et al., 2016) are the roles of the cloud computing in this ecosystem. A Cloud platform provides the capability to manage data and resources on a scale and flexibly capable of growing as the business adapts to fluctuations in demands and without the need to make large capital expenditure in IT infrastructure beforehand. In the pharmaceutical industry, companies must quickly respond to new health challenges and regulatory changes – and this adaptability is one hallmark of this industry.

In addition, as higher capacity wireless networks, such as 5G, emerge, alongside edge computing (i.e. where data processing occurs on local devices as opposed to centralized servers), there is a huge leap in supporting mission critical applications. Industries like industrial automation — from the operation of Autonomous vehicles and Drones to immersive technology such as augmented and virtual reality — depend on these technologies (Private Wireless Market Report, 2022). For instance, 5G and edge computing can ultimately make pharmaceutical manufacturing lines far more precise and more efficient, and even let you monitor quality in real time, which ultimately means less waste and safer production.

Using these sophisticated connectivity and computation technologies, the pharmaceutical industry can tap into better agility of operations, greater efficiency, and higher capacity to innovate drug development and drug production processes. The rest of this paper deals with the demonstration of specific applications of these technologies in the pharmaceutical sector and their contribution to sustainability and operational efficiency.

Industry 4.0 technologies have so fundamentally changed industrial infrastructure and value chain that the interconnectivity it enables has enhanced manufacturing processes in several critical ways. It applies from production to customer interaction, and from one partnership to another, throughout the industrial ecosystem, creating a more responsive, more integrated operational framework.

The industrial infrastructure has gone connected, and industrial automation has progressed a long way forward because the machines can learn from environments, self-diagnose, anticipate service needs and adapt to the preferences of the users (Porter &Heppelmann, 2014). Remote operation control, meanwhile, has become an essential and vital feature, helping the agility and responsiveness of the manufacturing operations (Ibarra et al., 2018). But these advancements also increase efficiency and provide enhanced accuracy and reliability in production processes and these advancements are key to fields such as pharmaceutical manufacturing, where the strictest regulations apply.

In addition, the supply chain is much interconnected, from which improved tracking and monitoring the supply chain process are ensured. This provides better visibility to the inventory and improves logistics, reduces cost of operations. Apart from that it helps to enhance and satisfying customer's requirement so that they can be more easily handled and thus satisfied when in contact with customers (Rao and Prasad, 2018).

It is crucial to understand that earlier revolutions laid the groundwork for the fourth industrial revolution in order to fully appreciate its revolutionary impact. The use of steam power laid the groundwork for subsequent industrial revolutions. The second revolution took electrical power further, and brought hard automation, heralding mass production. The previous revolution that led to the rise of computers and automated, flexible production capabilities allows for more versatile production capabilities (Huang et al., 2016).

Industrial 4.0 integrates cutting-edge information technology with automated manufacturing processes, built on top of these advancements. This integration enables features like smart production, enhanced human comphuman computer interaction, 3D printing, using data networks and modern manufacturing technology (Viryasitavat et al., 2018). These capabilities not only enhance efficiency and effectiveness of manufacturing process but also sustain their sustainability objectives by their application resource use optimization and avoidance of waste.

2.2.2 Evolution and Impact of Industry 4.0 in Manufacturing

Industry 4.0 is the term given to a transformational big step in manufacturing that has been coined smart manufacturing or integrated Industry 4.0 refers to a change in a highly digitalized and connected production environment where the product cycle consists of design, manufacturing and delivery (Sanders et al., 2016; Wang et al., 2017). While existing centralized production systems are still relied on by many organizations, Industry 4.0 provides a superior platform for the management of the production processes which can easily adapt to the changing nature of the modern manufacturing environment, most so in well developed economies.

Whilst Industry 4.0 is still becoming adopted (Wang et al., 2016; Xu et al., 2018), few have delved deeper to fully understand it or integrate its potential in a deeper way on the business practice realm. Manufacturers in the manufacturing sector have been forced to embrace new technological advancements and process innovations due to highly competitive pressures observed in industrial sector. The combination of digital technologies of Industry 4.0 with the methodology such as Six Sigma, lean manufacturing, Kaizen, Just-In-Time creates a sustainable manufacturing culture (Zhong et al., 2016). Beyond efficiency, this integration helps push the practices in these regions towards sustainable practices (Dolgui et al., 2018).

Industry 4.0 brings about the development of a global cyber physical network which creates a data exchange and control topology for machines, equipment, sensors, and facilities. The network provides support to develop smart factories made of flexible and intelligent factories (Yin et al., 2018). The presence of such environments brings about a significantly improvement to the overall performance of the business through the optimization of various components of business activity such as design processes, material requirements, machine operations, the product life cycle and supply chain management.

In addition, Industry 4.0 facilitates real time monitoring and control over critical production parameters like production status, energy consumption, material and customer order flow as well as supplier data. The importance of this comprehensive monitoring capability lies in supporting productivity increase and nurturing the greener manufacturing environment (Buer et al., 2018; Zhong et al., 2016). Taking the optimistic slant, synergy between Industry 4.0 and sustainability initiatives depicts a new business mindset of new business mindset that is sustainable and propagate sustainable development not only for the business organization but for the whole society. Table 2.1 features the scope and impact of some key enabling technologies of Industry 4.0 adopted in manufacturing industries of developing countries in practicing smarter and more sustainable manufacturing practice.

Within manufacturing sector, Industry 4.0 integrates different advanced technologies, which altogether support manufacturing industry in improvements in terms of efficiency, flexibility and sustainability of industrial undertaking. Below shows a summary table 2.1 for the key technology in Industry 4.0, including its major function and the contribution of smart manufacturing:

Table 2. 1: Industry 4.0 Enabling Technologies and Their Features

S.N.	**Technologies**	**Features**	**References**
1	Autonomous Robots	Robots with the ability to do a lot of tasks with high levels autonomy, improving operational efficiency and precision.	(Laskurain-Iturbe et al., 2021)
2	Internet of Things (IoT)	Enables communication between things, people, and processes, thus seamlessly connecting devices	(Hopkins, 2021)

		to the internet, and bridges the gap across the value chain.	
3	Simulation	So, it is to imitate real world activities like testing, training, safety engineering and operational optimization.	(Bosman et al., 2020)
4	Cloud Computing	It provides computing services like data storage, servers, and analytics over the cloud and make it resource efficient and fast innovation.	(Mubarak &Petraite, 2020)
5	Additive Manufacturing	Fast and enabling customization and rapid prototyping, it employs a layer-by layer approach to rapidly create three dimensional objects.	(Mubarak &Petraite, 2020)
6	Big Data Analytics	An advanced analytic technique used to extract insights and informed better decision in processing large dataset.	(Zheng et al., 2020)
7	Augmented Reality	Enables overlaying of digital information onto the real world to facilitate the user interaction with real environments useful for training and operation guidance.	(Pires et al., 2019)
8	Smart Sensors	Sensors that can act on specific inputs like light, heat, motion, process responsiveness and safety.	(Fettermann et al., 2018)

9	Automated Guided Vehicles (AGV)	It is used for automated transport of materials around the shop floor in a guided manner, for instance with the help of navigation systems such as wires or vision cameras.	(Zheng et al., 2020)
10	Image Processing System	It analyzes images and pulling out information that is useful for quality control and operational monitoring.	(Wu et al., 2015)
11	Artificial Intelligence (AI)	Such intelligence integrates human like intelligence into systems to carry out tasks that would otherwise be done by humans, including decision making and learning.	(Pasi et al., 2020c)

2.2.3 Porter's Five Forces Model

It is a robust framework for businesses to understand the competitive dynamics of the industry, assess competition intensity, and judge the attractiveness and profitability of entire industry (Porter, 2008).

Porter's Five Forces are replicated and applied in the smart manufacturing and Industry 4.0 context to emphasize how companies need to adjust their strategic stance to keep outpacing the competition in a technologically advanced marketplace (Porter & Heppelmann, 2014). A detailed breakdown of each force, and its implications in an Industry 4.0 driven market is given below:

1. **Competitive Rivalry**: The next part of this force has to do with the degree of competition inside the industry. Industry 4.0 increases competitive Rivalry as low

barriers to entry, means for more players to be involved through technological innovation. A significant number of the competitors are adopting Industry 4.0 technologies, such as IoT, AI, and automation – and these technologies can lead to highly productive processes that are much cheaper to operate.

2. **Threat of Substitute Products or Services**: Availability, quality, price and the switching costs associated with the substitutes shape the ability of customers to switch to substitute. The threat of substitutes is actually exacerbated by Industry 4.0 as they allow better and more customized product offerings through advanced data analytics and additive manufacturing, which increases customer choice, gradual product customizability and bargaining power.
3. **Bargaining Power of Buyers**: It looks at the power of customers to affect the pricing and quality. While Industry 4.0 technologies make the buyer armed with more information and other options, they empower the buyer with more bargaining power. The dynamic nature of this process is driven by factors of buyer concentration, the order size, and the ease with which buyers plans to switch to competitors.
4. **Bargaining Power of Suppliers**: Prices and quality of inputs are at the hands of the power of suppliers. Industry 4.0 brings together global supply chains and enables more access to supply chain data, thereby decreasing switching costs and lowering the supplier`s leverage and raising technology provider`s role.
5. **Threat of New Entrants**: Reducing the barriers to entry in many industries, Industry 4.0 could entail replacing traditional infrastructure investments, which

would no longer be needed due to the need for more modular and scalable digital solutions. Advanced technologies can liberally enable new entrants to accelerate operation and intrude to challenge the current market's prevailing.

If Porter’s Five Forces is applied in the context of Industry 4.0, you can not only see where companies fit within the industry but also prepare for the maze the digital transformation introduces. For companies in the pharmaceutical sector for which the implementation of Industry 4.0 affects the processes of production, the supply chains, and the competitive strategies, this analysis is essential. Knowing these forces will enable firms to better prepare themselves for the new industrial revolution challenges and opportunities.

2.2.4 Business models

Innovation and technology potential may be better understood and strategies can be developed with the help of theories of business models. There have been a number of various ways that researchers have looked at the business model, but one common thread is how it turns technical features and possibilities into monetary products (Chesbrough & Rosenbloom, 2002) and the business model describes a firm position in the value chain and does business (Zott et al., 2011).

A theoretical framework of (Osterwalder, 2010) business model definition & business model canvas was used to understand the deployment of I4.0 business model. The framework defines a business model as the foundation upon which an organization's value creation, delivery, and capture operations are built. As seen in figure 2.2, a business model canvas is shown.

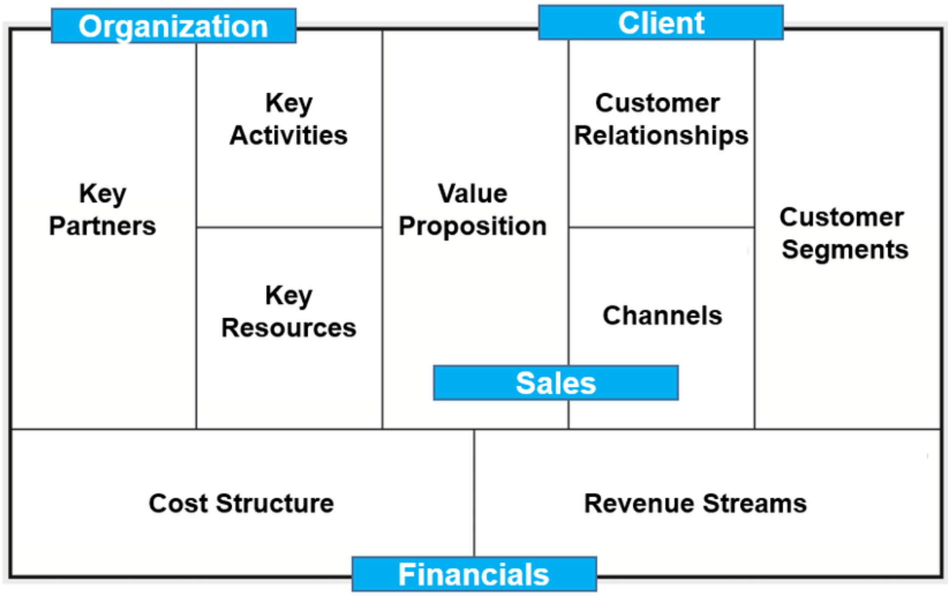


Figure 2. 2: An element of the business model canvas

The nine components of the business model canvas illustrate a company's rationale for making money (Osterwalder, 2010). The nine components are shown in figure 2.2. A Company's Structure Canvas is a management strategy tool for creating or documenting company models. Visualizing in a system appears to map the foundations of a company's business model on nine basic building blocks that explain how an organization creates, delivers, and captures value. In the context of Industry 4.0, this framework allows pharmaceutical companies to rethink and innovate their business model, as the digital transformation has led many companies to reevaluate their business models. Following are the main components:

1. **Customer Segments**: Can define the different types of people or fool some of the people some of the time people an enterprise operates on to reach or serves. As new

technologies drive personalized medicine or individualized healthcare, consumer segmentation may evolve within the framework of industry 4.0.

2. **Value Propositions:** It is defined as the bundle of products and services that add value for a given customer segment. It could lead to something as simple as personalized drug formulations enabled by big data analytics or much simpler, faster and more reliable diagnostics via advanced IoT devices.
3. **Channels:** Describes the channels by which a business interacts with its target audience in an effort to sell them something of value. This could be achieved in Industry 4.0 by integrating digital platform, for example, to help with pharmaceutical products in terms of accessibility and convenience.
4. **Customer Relationships:** Types of relationships that a company establishes with particular customer segments are described. Real time data exchange, mobile health applications could enhance interactive and responsive relationships through Industry 4.0 technologies.
5. **Revenue Streams:** This is the amount of cash a company earns from every customer segment. Smart technologies could introduce new revenue streams in the pharmaceutical industry — such as subscription health monitoring service or premium wellness app.
6. **Key Resources:** This is an asset that is the most critical in making your business model work. Among the possible incumbents to consider on their side is intellectual property in drug formulas, the most advanced manufacturing facilities, or proprietary data analytics software.

7. **Key Activities:** They describe the most important business model activities you need to take for your business of model to work. For pharmaceuticals it can be drug research and development, digital supply chain management of drugs or cyber secure data handling.
8. **Key Partnerships:** The set of suppliers, partners and other stakeholders on which the business model depends. These may include engagements with such biotech innovators, academic institutions, or technology providers of AI and IoT.
9. **Cost Structure:** Costs to operate a business model on a major level. If it's Industry 4.0, a lot of money could be invested in digital infrastructure but costs could drop as savings are made from automation and other predictive maintenance benefits.

Using this Business Model Canvas Pharmaceutical Companies can use Industry 4.0 technology to identify how each aspect of the business model can be enhanced or changed in order to keep their business competitive and respond quickly to an ever-changing industry landscape. New technologies can be integrated when they fundamentally change how companies work; they require new strategies, and present huge opportunities for great creation of both operational efficiency and customer satisfaction.

2.3 Strategic Innovations in Industry 4.0 Business Models

The advent of Industry 4.0 has brought about a paradigm change for how industries are operating and setting up their business models. With IoT, AI, and advanced robotics, new capabilities are now possible, and new business fashions need to be rethought. The adoption of I4.0 technologies has forced several scholars to study how I4.0 technologies have led to transformations in the business models adopted by companies, and by the way companies create, deliver, and capture value. Ibarra et al. (2018) identified the three primary predominant innovation patterns that are emerging as a result of Industry 4.0 integration:

1. **Service Orientation:** It is shifting between a product centric to a services centric model where the value that can be offered is increasingly providing a service for the growing capabilities and data that the I4.0 technologies will enable, not from the product itself.

2. **Networked Ecosystems:** By creating interconnected business ecosystems that support collaborative innovation and shared value creation that span across traditional industry boundaries, I4.0 enables the promotion of the creation of a highly integrated global industrial culture.

3. **Customer Orientation:** I4.0 technologies enable a stronger focus on customer needs and customization, leveraged by data analytics and real time feedback mechanisms.

Weking et al. (2020) further developed by defining a taxonomy of business models to transform I4.0 enablers into proactive strategies for firms. They proposed three patterns of integration that are pivotal in the I4.0 context:

- **Integration:** It is concerned with the undivided flow or an uninterrupted link of systems and processes, both internal to and external of organizational boundaries.
- **Servitization:** It's about augmenting physical product with services, commonly built around the data that a product generates.

- **Expertization:** Takes advantage of having specialized knowledge and capabilities to offer advanced consulting and solutions in highly specialist areas in which I4.0 has either created or dramatically increased.

2.4 Growth of Industry 4.0 Enabling Technologies

To further understand how long these technologies will be useful in India's industrial sectors, this section looks at the expansion of Industry 4.0 enabling technologies (Table 2.1).

2.4.1 Additive Manufacturing growth

The percentage of people using 3D printing technology rose from 28.4% in 2012 to 11.45% in 2017 (Hofmann and Rusch, 2017). As of today, 49.3% of users are using 3D printing technology. Currently, 3D printing technology is being used by 49.3% of users. Do not abuse 3D printing, as Ghobakhloo (2018) has noted. The sector has been dominated by 3D printing technology up till 14.74%. Despite being the ideal answer to every industrial challenge, industries are still avoiding 3D printing.

2.4. 2 Growth of Big Data Analytics

According to the findings of a research that was commissioned by Wipro and carried out by Economist Intelligence, data is without a doubt going to be the most important factor in the manufacturing sector of the future. According to the findings of the survey, 86 percent of respondents indicated a considerable increase in the amount of data collected, and 90 percent of respondents believed that their institutions were capable of managing sophisticated data analysis for the bulk of industrial operations (Yin et al., 2018).

In the period between now and 2032, it is anticipated that 1.8 billion individuals will become members of the global consuming class, and the quantity of the world's consumption is anticipated to almost quadruple to a total of 64 trillion dollars (Yin et al., 2018). In situations like these, data analytics presents a chance for manufacturers to make predictions, try new things, and even take action. The integration of data from a variety of sources has become a difficulty, and it is also difficult to derive insights that are potentially valuable (Yin et al., 2018).

2.4.3 Growth of Cloud Computing

The phrase "cloud computing" was first used in 1996, with the first recorded instance of its use being in a Compaq internal paper (Liao & Ling, 2017). However, the word became more widely known with the introduction of Amazon.com's Elastic Compute Cloud service in 2006. The term "cloud" was first used in 1993 to refer to the technologies that were used by AT&T's Telescript and Persona Link, as well as by Apple's spin-off company, General Magic (Brettel et al. 2014; Longo et al. 2017). The conventional style of production is being transformed with the assistance of information technology and, more recently, cloud-based technologies (Brettel et al. 2014). There are as wide varieties of ways in which cloud computing can be applied to the manufacturing industry (Kong et al., 2018). According to (Brettel et al. 2014), there are several areas in which cloud computing technologies can be easily incorporated into the manufacturing cycle:

1. Cloud-based business intelligence solutions
2. Cloud-built services and functions
3. Cloud-based collaboration for design

4. Managing marketing

5. Managing sales

6. Automatic customer service

7. Human resources automation

8. Faster new product development

2.4.4 The Internet of Things (IoT)

'Internet of things' (IoT) is likely named after the British pioneer Kevin Ashton, who was associated with Procter & Gamble and MIT's Auto-ID Centre before becoming famous as the IoT's "father." At the time, he held the belief that radio-frequency identification (RFID) was fundamental to the IoT, which would enable computers to control any and all objects (Rose et al., 2015).

The industrial sector reportedly spent a whopping $178 billion on the Internet of Things in 2016, according to figures published in early 2017 by IDC (Rose et al., 2015). Nearly a third of all Internet of Things (IoT) investment in the Asia-Pacific area will go into manufacturing in 2020. This figure includes hardware, software, services, and connectivity (Oesterreich and Teuteberg, 2016; Sanders et al., 2016). For instance, out of all the purchases made for the Internet of Things (IoT), the manufacturing sector in the United States will account for around 15% (Rose et al., 2015; Wu et al., 2015). Several factors are propelling the industrial sector to embrace the IoT: These range from the purely historical to those pertaining to the so-called Fourth Industrial Revolution (Industry 4.0) and the many applications and real-world deployments of the Internet of Things (IoT) that facilitate the quick turnaround and enable manufacturers to accomplish digital transformations from a variety of strategic stancess (Oesterreich and Teuteberg, 2016; Sanders et al., 2016).

2.4.5 Growth of Smart Sensors

According to the McKinsey analysis, the global smart sensor market was valued at USD 36.7 billion in March 2020 and is projected to reach USD 87.8 billion by 2025. The widespread use of smart sensors in fields as diverse as healthcare, consumer electronics, logistics, manufacturing, banking, building construction, aerospace and defence, industrial automation, and consumer electronics has led to their rapid expansion. The market is seeing a surge in demand for smart sensors such as image, motion, temperature, and pressure due to the dynamic nature of these industries. Companies like TE Connectivity, STMicroelectronics, NXP, and many more in the smart sensor manufacturing sector are continuously inventing new smart sensor technologies (Schluse et al., 2018).

2.4.6 Growth of Robot Arms

McKinsey report states that the global robot arms market size was USD 17.7 bn in 2018, which will rise to the highest amount of USD 39.4 bn by 2024. Nowadays, industries are preferring robotic arms over human labor because of the following reasons: By increasing wages in labor, workplace insurance cost, compensation and paid leave benefits and training expense (Schluse et al., 2018). Higher efficiency is possible with robot arms performing repetititive tasks, however it requires a higher initial capital cost (Zhong et al., 2016). But, robot arms companies like Fanuc Corporation, Mitsubishi Electric, ABB Ltd., etc. continuously making attempts to innovate robot arms (Yin et al., 2018; Kong et al., 2018).

2.4.7 Growth of Automated Guided Vehicles

A survey by McKinsey estimates that the global AGV market size was $4.6 billion in 2019 and will reach $12 billion by 2025. Automated guided vehicles (AGVs) have several applications in warehouses, including reducing operating costs, increasing worker safety, and more. AGVs are being used in the manufacturing shop floors of automobile manufacturing industry (Rose et al., 2015). For instance, SEAT (Spain) in 2019 used AGVs with induction battery charging, SLAM navigation and 4G connection. According to (Liao et al., 2017), till date the industry has 205 implemented AGVs for indoor operations and 10 for outdoor operations.

2.5 Sustainable Development Goals (SDGs) and Their Relevance to Industry 4.0

It calls for the end of poverty, the protection of the planet, and secure peace and prosperity for all people by 2030, and was agreed by its Member States in 2015 as part of a universal call to action: Sustainable Development Goals (SDGs). The 17 goals depicted here constitute such a holistic framework for sustainable development within all these broad dimensions, including environmental, social, and economic. On its side to contribute to global Sustainability, each goal is supported by specific targets and indicators planning the way out to guide organizations and people to achieve the purpose (Wang et al., 2021).

2.6 Impact of Industry 4.0 on Sustainability Pillars

Industry 4.0 will improve manufacturing efficiency and effectiveness while optimizing the supply chain, according to a few assessments from an economic standpoint. By streamlining stock management and distribution center operations, smart sensors installed along the assembly line may boost financial sustainability (Theorin et al., 2017).

There is an agreement that states that by eliminating inventory-related inaccuracies, IoT applications improve supply chain efficiency and effectiveness (Wu et al., 2015). To improve product life cycle management and optimize the industry's financial performance, one might mine data produced by Industry 4.0. As a result, Industry 4.0 equips the sector with the enhanced analytical capabilities necessary to do business properly (Moeuf et al., 2018). Errors and faults may be reduced in the manufacturing process using predictive analysis and predictive maintenance. That is why some have argued that the sustainability pillar of the economy is affected by the adoption of Industry 4.0.

Industry 4.0's defining feature is the ability to assess and forecast production behaviour in order to make efficient use of available energy, in line with the organization's actual demands. Industry 4.0 is all about reducing carbon emissions and making better use of energy, according to environmentalists. The degree of energy savings is directly proportionate to productivity as productivity is a measure of energy savings in manufacturing businesses. With the help of the Internet of Things (IoT), industrial companies may now remanufacture any material on-site by reusing it. The sustainability pillar's environmental component may be affected by the aforementioned Industry 4.0 adoption. The social pillar of sustainability is said to be favorably affected by the Industry 4.0 idea, according to social citations, as it makes the workplace safer. Employee morale takes a nosedive as the number of workplace accidents rises (Moeuf et al., 2018).

2.7 Barriers to Industry 4.0 Implementation and Sustainability

The internal dynamic of the company has to be adaptable and quick to accept new ideas in order to embrace and execute new technologies that are part of Industry 4.0.

Otherwise, it is very hazardous, if not impossible, to install and maintain new technology. Current workers are a burden for businesses as they are resistant to adopting the technology that will enable Industry 4.0(Rose, et al., 2015). Employees don’t feel secure in their jobs and responsibility (Moeuf, et al., 2018). The new smart technologies may be able to overcome this obstacle if management trains their staff to use them. (Hofmann, et al., 2017). The volume of data produced by an Internet of Things (IoT) setting is known as big data. The created massive amounts of data are then uploaded to the cloud, where data analytics are executed, ultimately yielding valuable insights.

2.8 Industry 4.0's Significance in the Health Care Industry

There are so much service-related challenges in the health industry, such as the management of diverse datasets created in the last few years (da Silveira et al. 2019). Because of this, a sea shift in the manufacturing sector was required. Thus, the advent of Industry 4.0 was a response to these difficulties. A good influence is achieved via the application of advanced technology. Computing on the cloud, artificial intelligence, cyber defence, the internet of things, big data, etc. are all components of Industry 4.0. When the Internet of Things (IoT), the Internet of Services (IoS), and other cutting-edge technology work together, they may expand the boundaries of modernisation and enhance the healthcare industry (da Silveira et al. 2019).

Adaptive robotics creates new medical equipment with the assistance of artificial intelligence. With the use of cloud computing, industrial system services are better able to generate data-driven judgements. Industry 4.0 broad data architectures are built using big data analysis. Data loss, financial theft, framework attacks, and pharmaceutical instrument dangers may all be mitigated with the use of cyber security. In Industry 4.0, each technology serves a unique purpose. When it comes to healthcare, Industry 4.0 offers new possibilities and possibilities for advancement. Industry 4.0 improves the hospital administration system by using modern technology. The pharmaceutical field stands to benefit greatly from Industry 4.0. Data analytics is used for the purpose of keeping track of patient information and providing useful details, such the patient's symptoms. Information about the patient's vitals, including their temperature and blood pressure, is provided via smart sensors. Recycling garbage is one of Industry 4.0's most impressive capabilities. As shown in Figure 2.3, it aids in preventing environmental degradation in the medical field. Modern technology has a beneficial effect on healthcare studies. The fourth industrial revolution, or Industry 4.0, allows for more pattern flexibility via the use of digital controls in the production system (Singh et al. 2019).

A smart factory within the context of Industry 4.0 has been presented by Shi et al. (2020). Integrating cyber and physical technologies, smart factories make connected technologies more complex and accurate, which improves manufacturing quality, controllability, performance, and transparency. Sensors, interoperability, VR methods, robots, and AI are the characteristics of smart factories. Smart factories have been made possible by the proliferation of modern technology, particularly in the realm of information. By implementing smart factories, industries may contribute to long-term sustainable growth. One goal of the smart factory is to create manufacturing systems that can change and adapt on their own. A smart factory's goal is to make the manufacturing process more transparent by making complex structures and procedures more understandable. In a smart factory, everything is linked, data is exchanged, and the real and virtual worlds blend seamlessly. To better satisfy consumers' demands, smart factories may enable reconfigurable and adaptable production (Arden et al. 2021). Supplier and customer connections are strengthened by smart factories. A "smart factory" is one that actively seeks for and rewards human input. Rather, it seeks to meet the need of the market while keeping costs reasonable.

The connection between Industry 4.0 and sustainability has been examined by Acioli et al. (2021). Specifically, we wanted to show how Industry 4.0 may help achieve sustainability goals. Reduced creation of scrap trash is one way Industry 4.0 stops environmental degradation. The needs of the present may be satisfied by the advanced technologies of Industry 4.0. More sophisticated and less expensive implementations of computer integrated manufacturing and flexible manufacturing systems are possible with the support of modern technology. Industry 4.0's role in sustainable development is to reduce research effort, identify investigational aims, and assess future research sector prospects.

By using Industry 4.0, Djunaedi (2019) intends to create social sustainability in the pharmaceutical industry. Researching the impact of supply chain integration and information-intensive services on social sustainability performance is the goal. A key component of Industry 4.0 is the integration of cyberphysical systems (CPS) and information and communication technologies (ICT) into business design and manufacturing processes. Due to Industry 4.0 and its growing fascination in inaccessible scientific research, the medical field is seeing a refocusing of its research efforts.

Sustainable pharmaceutical supply chains were created during the Fourth Industrial Revolution; these chains enhanced product management and communication across many industries.

Industry 4.0 is progressing as a result of technological advancements, globalisation, and intersectoral rivalry, according to Grzybowska and Lupicka (2017). Industry 4.0 manufacturing techniques are very adaptable and versatile. The most recent developments in manufacturing are provided by Industry 4.0. The analytical process makes use of a number of capabilities, including the following: research abilities, creativity, decision-making, conflict resolution, problem-solving, analytical thinking, and an efficiency focus. To comprehend the research process and its results, as well as to perform the study effectively, certain competencies are necessary. Computerisation, robotization, and automation have had a beneficial effect on the pharmaceutical sector globally. Improvements in living standards and societal well-being are outcomes of progress in cutting-edge technology and Industry 4.0. The potential for the Fourth Industrial Revolution to enhance the intelligence of the production system was assessed by Barenji et al. (2019). By facilitating the connectivity between instruments and reducing the need for human interventions, manufacturing systems may be transformed into smart factories. When it comes to protecting the production process from potential dangers, cyber-physical systems are crucial. Organizational optimization made possible by cyber-physical systems and cloud services allows for the use of influential computer resources and complex algorithms. Cyber security helps the industrial industry prevent the disturbance of large amounts of data. The use of artificial intelligence in smart factories allows for decentralization, virtualization, modularity, and real-time capabilities. Product quality and pricing are two of the numerous problems that the pharmaceutical manufacturing sectors are now encountering. The creation of smart factories, therefore, will allow the pharmaceutical production sector to triumph over these obstacles.

According to Aksu and Yeğen (2021), the goal of the Fourth Industrial Revolution in this modern era is to establish a society that finds solutions to the issues pertaining to sector life, also called industrial life, and social life. The industrial sectors have embraced cutting-edge technology such as cyber systems, the internet of things (IoT), and artificial intelligence (AI), and the workforce has been eliminated with the advent of Industry 4.0. Efforts will be reduced and manufacturing will be made more controllable by Industry 4.0. Improvements in safe and effective treatment will be brought about by the initiative of quality by design and process analytical methods. The goal of implementing quality by design is to enhance the produced goods' quality.

When it comes to industrial economic competitiveness, additive manufacturing is crucial, according to Duvoisin et al. (2018). The latest innovation is driving the growth of additive manufacturing in Industry 4.0. Manufacturing technology is advancing at a fast pace, which is increasing productivity. Some of the processes that may be utilised for 3D printing include photo polymerization, stereo lithography, fused deposition modelling, and selective laser sintering. 3D printing technology encompasses a wide variety of materials used in several industries, including aerospace, automotive, dentistry, jewellery, oil, orthopaedics, and more. Industry 4.0 makes use of 3D printing technology to streamline processes and cut down on complexity. There can be no question that 3D printing technology will trigger a major shift in the manufacturing sector. Additive manufacturing is crucial to Industry 4.0 because it simplifies processes, which in turn saves time and money.

Prajwal et al. (2020b) investigated how the Internet of Things affected healthcare. Results show that the health industry is one of the most successful areas for the Internet of Things (IoT). The Internet of Things is crucial to home automation. What we call "home automation" is really just the electronic and automated regulation of many aspects of daily life in the house. Electricity and climate regulation, security cameras, traffic lights, medical treatment, and countless more are all under the direction of the Internet of Things. Glucose, ECG, and blood pressure monitors are some of the medical devices that make use of the Internet of Things. Using IoT, hospital administration may find management faults and reduce medical equipment downtime. The Internet of Things (IoT) is revolutionising healthcare throughout the globe. IoT not only improves performance but also provides new benefits like cost reduction, reduction in human labor, better use of assets, and better business opportunities.

According to the research of Chiacchio et al. (2019), the manufacturing sector had an uptick during the Fourth Industrial Revolution. Products are guaranteed to be of high quality and safe to use by the pharmaceutical industry and its supply chain. The business makes upgrades in order to bring the plant up to date by using the technologies of Industry 4.0. Industry 4.0 allows for the easy and rapid detection of falsified pharmaceuticals, allowing them to be removed from the process. When it comes to making sure medications are safe to use, traceability is key. The pharmaceutical industry uses state-of-the-art technology to automate the creation of serial numbers, labels, and packaging. The pharmaceutical business has benefited from serialisation. Assigning a unique code or serial number to every pharmaceutical package is known as serialisation in the pharmaceutical sector. Reducing product loss, improving sales forecasting accuracy, and streamlining expiration date management are just a few of the ways it has benefited the pharmaceutical sector.

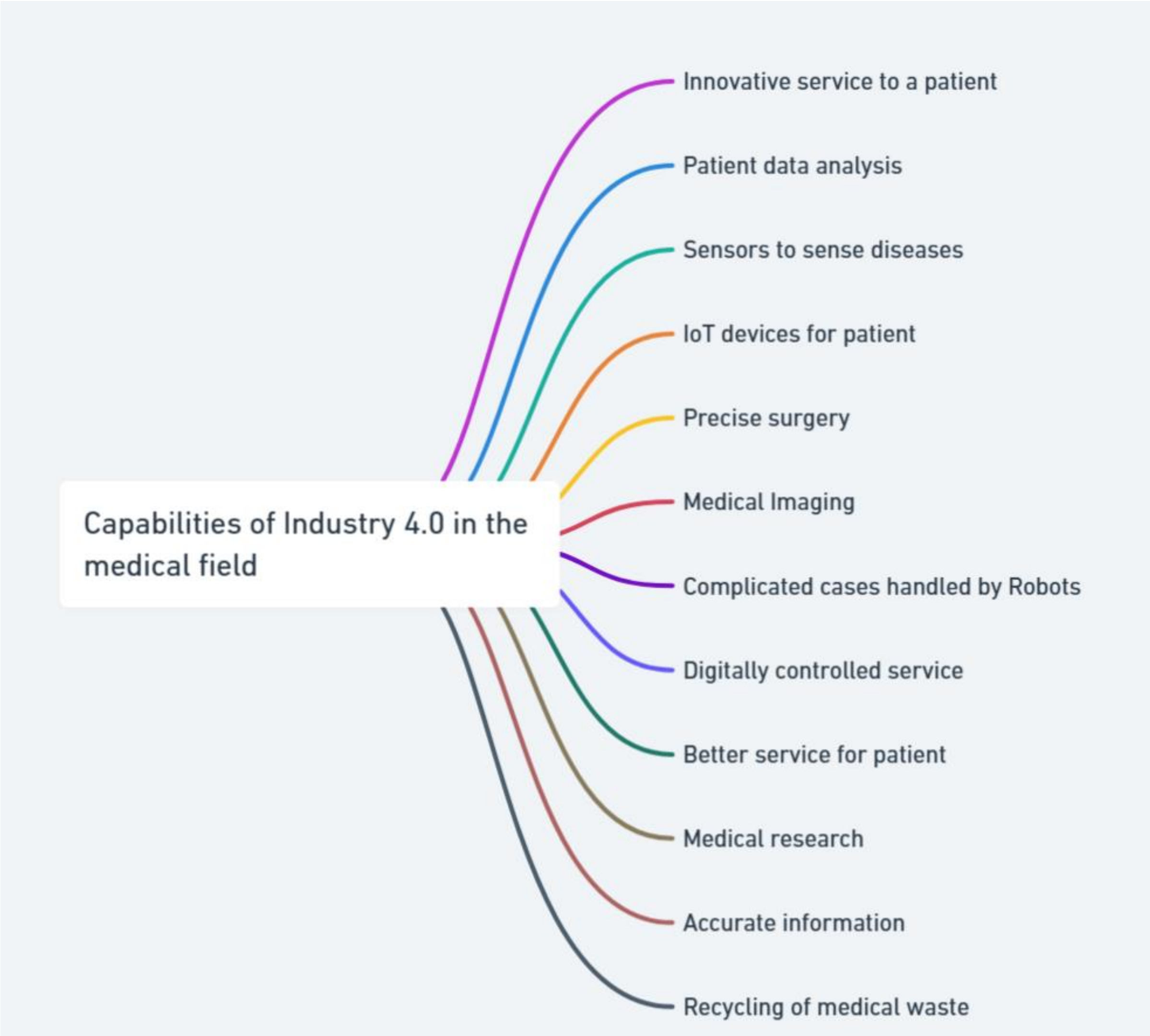


Figure 2. 3: Classification of Industry

Table 2. 2: Meta-Analysis Table: Comprehensive Review on Industry 4.0 in the Pharma Sector

Technology	Application	Main Finding	Reference
IoT (Internet of Things)	Tracking stock levels in hospital pharmacy shelves	As per this study, IOT enhances inventory management and operational efficiency in pharmacy settings.	Mostof & Jain (2021)
Robotics	Streamlining medication dispensing in healthcare facilities	As per this study, Robotics reduces medication errors and operational costs, addressing implementation challenges through Failure Mode and Effects Analysis (FMEA).	ElLithy et al. (2023)
Cloud Computing	Supporting data-driven decision making in manufacturing	As per this study, Cloud Computing increases flexibility, effectiveness, and sustainability by overcoming challenges like high costs and expertise shortages in supply chains.	Ding (2018)

Additive Manufacturing (3D Printing)	Manufacturing personalized medicine	As per this study, Additive Manufacturing produces complex drug designs, enhancing safety and effectiveness through sophisticated release profiles.	Ding (2018)
Cyber-Physical Systems (CPS)	Enabling reconfigurable smart factory operations for drug packing	As per this study, Cyber-Physical Systems (CPS) facilitates data-driven, reconfigurable production modes, improving agility, flexibility, and cost-efficiency in pharmaceutical manufacturing.	Wan et al. (2018)
Digital Twin	Simulation and optimization of manufacturing processes	As per this study, Digital Twin enhances operational efficiency and product quality through real-time simulation and process optimization.	Arden et al. (2021)

Artificial Intelligence (AI)	Advanced data analysis and decision-making support	As per this study, Artificial Intelligence improves quality control, reduces downtime, and supports predictive maintenance for more efficient and reliable manufacturing processes.	Arden et al. (2021)
Data Analytics	Real-time monitoring of production	As per this study, Data Analytics enables predictive analysis and agile decision-making, reducing waste and operational costs.	Silva et al. (2020)
Augmented Reality (AR) and Virtual Reality (VR)	Training and operational oversight in biopharmaceutical production	As per this study, Augmented Reality (AR) and Virtual Reality (VR) enhances accuracy and safety in manufacturing processes through real-time, interactive visual support and training.	Reinhardt et al. (2021)

Mixed Reality	Enhancing interaction and visualization in production processes	as per this study, Mixed Reality improves communication and operational efficiency in manufacturing through dynamic and interactive visualization technologies.	Bianchi et al. (2019)

2.9 Conclusion

This chapter provides a literature review on the transformative potential of Industry 4.0 technologies based on which the theory and practices of their applications are thoroughly understood. As the pace of industrial developments has quickened, latching onto an idea known as industry 4.0, many have come to understand that the future of industrial advancements is a future of smarter, more efficient and more environmentally friendly manufacturing practices. It brings technologies like IoT, AI, big data analytics, and cloud computing together to foster seamless integration, better decision making, and sustainable operations, in a manner especially well suited to the pharmaceutical field.

Industry 4.0 technologies integrate well and its implementation helps in building and developing the economic, the environmental and the social pillars of sustainability. For example, IoT applications reduce their environmental impact and reduce costs directly related to resource efficiency, while Predictive Analytics help to minimize operational errors and energy savings. Additionally, the acceptance of these technologies serves to shape a socially safer workplace environment, as well as the social pillar.

Although these advancements were made, there are still challenges with large scale Industry 4.0 implementation. These are major barriers that need to be conquered, as they include resistance to change in employees, cybersecurity vulnerabilities and high initial investment costs. And that will help mitigate these challenges towards successful adoption; strategic organizational agility and robust cybersecurity measures and comprehensive training programs.

Moreover, in this chapter, we have also pointed out the fast transformation of business models that are predicated on Industry 4.0 technologies to the increasingly service oriented and customer centric and to the network dominated ecosystems. These models can be embraced by the pharmaceutical industry to restructure production processes, improve the supply chain management and support sustainability.

The next set of chapters will discuss the empirical use of these insights in different forms of Industry 4.0 technology adoption within the Indian pharmaceutical industry, i.e. to what extent technology adoption in the sector is taking place, what are the key barriers to further use in the sector, as well as determining ways of enhancing the integration of these in the sector to support its sustainable development. This research is aimed to fill the identified gaps, in order to bridge it to the greater discourse on intersection of technological innovation and sustainability

CHAPTER III

RESEARCH METHDOLOGY

3.1 Overview of the Research Problem

For the Indian pharmaceutical industry, it stands at a crossroad — a balancing act between the importance of being environmental friendly and also being competitive in the global arena. Necessity for innovative practice of adopting newer processes that cause least impact on the environment arises due to increasing regulatory pressures and following globally accepted sustainability goals. At the same time, the industry must balance competing demands for high quality, affordable medicines with stimulating innovation to prevent losing competitiveness.

With the advent of Industry 4.0 technologies—the Internet of Things (IoT), Artificial Intelligence (AI), Big Data and smart manufacturing among them—there are opportunities that amount to upheavals. And these technologies can significantly increase operational efficiency, reduce emissions and optimize resource use. Despite all this, the extent to which they have been adopted in the Indian pharmaceutical sector appears unclear: most companies in the Indian pharmaceutical sector have and have experienced significant barriers to entry, including financial constraints, technical challenges, and regulatory hurdles.

To fill in these gaps, this study investigates the current adoption levels of Industry 4.0 technologies being implemented by major pharmaceutical companies in India. Furthermore, it addresses the special challenges that impede complete integration, assesses how they affect environmental sustainability practice, and explains how those obstacles may be overcome. In line with national initiatives such as “Digital India” and “Make in India”, it aims to deliver actionable insights for both increasing technological uptake and enhancing sustainability outcomes in the sector.

3.2 Theoretical Constructs:

The basis of the research is the tenets of Industry 4.0, and it zeroes in on the ways in which these technologies mesh with sustainability initiatives in India's pharmaceutical industry. This study delves into the complex relationship between sustainable development objectives and the use of new technologies, offering a thorough understanding of the effects and difficulties linked to this integration. The primary components of this research are as follows:

- **Industry 4.0 Adoption Levels**: This structure evaluates the level of Industry 4.0 integration in the operations of Indian pharmaceutical enterprises. The adoption levels are classified using a scale that represents the degree of maturity and integration of technology. It starts with early awareness and progresses to complete implementation and optimization.
- **Challenges in Technology Adoption**: This component identifies and analyzes the barriers that hinder the full integration of the Industry 4.0 technologies. Challenges are segmented into financial, technical, and regulatory categories, each affecting the adoption rates and the strategic approach to technology deployment in the sector.
- **Environmental Sustainability Impacts**: In this part, we look at how implementing Industry 4.0 technology affects ecological preservation. It looks at how these

technologies can lessen our impact on the environment by lowering energy use, better managing resources, and waste. In order to quantify the effects, many environmental performance indicators are used.

- **National Policy Influence**: The influence of national policies such as 'Digital India' and 'Make in India' on the adoption of Industry 4.0 technologies is assessed. This construct explores how governmental strategies and regulatory frameworks support or impede the pharmaceutical sector's technological upgrades and compliance with environmental standards.
- **Corporate Governance and Stakeholder Engagement**: This construct examines the role of corporate governance and stakeholder engagement in advancing the adoption of Industry 4.0 technologies. It considers how governance structures, including board involvement and policy setting, as well as stakeholder interactions (employees, suppliers, customers) influence organizational strategies and technology acceptance.

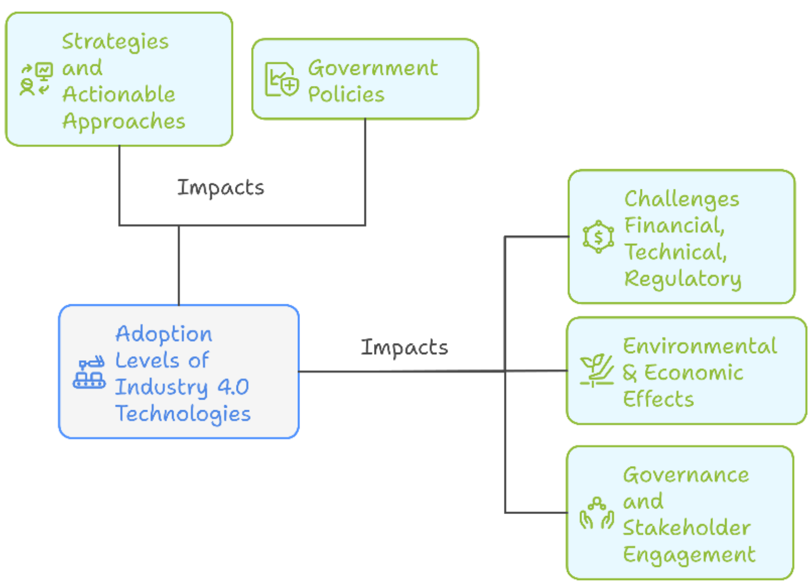


Figure 3.1: Conceptual framework

3.3 Research Purpose and Questions

The purpose of this study is to assess the adoption and impacts of Industry 4.0 technologies on environmental dimension and operational problems inherent in the Indian pharmaceutical industry. In pursuit of such goals, the scope of this research is to: barriers to full integration were identified and national and global economic and environmental benefits were measured, and strategies for advancement of technological adoption were developed. The study is guided by the following key questions to achieve the research objectives:

1. **Extent of Adoption:**

   What level of adoption of Industry 4.0 technology has the top pharmaceutical companies in India achieved?

2. **Challenges in Adoption:**

   As major pharmaceutical companies start to embrace Industry 4.0 technologies, what exactly are the challenges they are facing in doing so?

3. **Environmental Impacts:**

   What are the environmental sustainability practices of major pharmaceutical companies in the light of the Industry 4.0 technologies? What measurable benefits have been reported to date?

4. **Strategic Measures for Overcoming Barriers:**

   What are the most effective strategic measures based on the sustainability reports to enhance sustainability in the pharmaceutical sector with overcoming barriers to technology adoption in the pharmaceutical sector?

5. **Policy Influence:**

This papers examines the influence of national policies and global sustainability goals on the technological strategies of Indian pharmaceutical companies.

6. **Corporate Governance and Stakeholder Roles:**

How do corporate governance and stakeholder interactions actively facilitate the seamless implementation of Industry 4.0 technologies in the Indian pharmaceutical industry?

3.4 Research Design

In this study, Industry 4.0 technology adoption and its effects on environmental sustainability as an outcome in a pharmaceutical industry are evaluated through quantitative research design. For this data collection, structured surveys were administered to senior management, operations heads, sustainability officers and IT personnel in India from major pharmaceutical companies. Data on the extent of technology adoption as well as specific challenges such as the financial, technical, and regulatory barriers and environmental and economic impacts related to these technologies is captured from the survey instrument. Further, they ask questions related to the impact of strategic measures on effectiveness and the national policies on adoption of technology.

In order to have representation from companies of varying sizes, market positions, and geography, the study uses a stratified random sampling method. Statistically reliable and meaningfull insights have been determined from a sample size of 300 respondents. A combination of email, online platforms, and in person at industry events is used to distribute surveys to conclusively separate those who read the article from those who do not. Rigorous statistical analysis of the collected data on frequency, correlation, and regression are used to discover patterns and relationships to answer the main research questions. Besides, quantitative data are got from the responses gotten from the survey questionnaires while qualitative data are gathered from a business analysis of the Orion Corporation and the Pfizer CentreOne. Here are provided some realistic examples of the integration of advanced digital technologies and the influence of those technologies to the increase of the environmental sustainability. Industry 4.0 has given Orion Corporation a chance for creating the Easyhaler® product which produced without harming the environment as supported by sustainable standards like Montreal Protocol. Likewise, Pfizer CentreOne has been able to demonstrate through the strategic adoption of these technologies several improvements on resource consumption and emissions thus pointing to what ensues as high standards in the operational setup and use of environment in the pharmaceutical related production lines.

Thus, by incorporation of these global standards, the research seeks to offer recommendations aimed at increasing the technology usage and improving sustainable development impacts in the Indian pharmaceutical industry. It is done in a way that makes it possible to understand that the findings about Industry 4.0 will not only be research-based but also practical in target settings, thus providing better insights into how change could be achieved through these innovations and by how much. This work offers the necessary steps toward a quantitative and qualitative analysis that fits into filling the existing gaps regarding the technology adoption and provides a solid conceptual model to improve the environmental sustainability within industry. This research achieves objectivity, reliability, and actionable insights as to the Indian pharmaceutical sector's challenges and benefits of Industry 4.0 adoption by utilizing a structured and systematic quantitative approach.

3.5 Population and Sample

For the purposes of this study, the target population includes employees from major pharmaceutical companies in India who can play a decision making, operations, and sustainability initiative and technology integration roles. In other words, it includes senior management, operations heads, sustainability officers, and the technology people who are engaged in directly or indirectly the adoption and implementation of Industry 4.0 technologies. Because of this, we argue that they are well situated to add to what we know about the levels of technology adoption, the issues encountered as a consequence of the introduction of said technologies, as well as their potential effects on environmental sustainability practices.

To ensure that the sample consists of a wide variety of pharmaceutical company demographics, including company size, market position and geographic region, a stratified random sampling method is used. By departing from this tradition it is ensured that the findings can be generalized and that differences in organizational characteristics as well as contexts are taken into account.

300 respondents is set as the sample size, considering it enough that data is statistical significant and robust for analysis. They recruit people through professional networks, industry associations and direct focus on companies. Email surveys and online survey platforms are used; follow up reminders are used to increase response rates. In so

doing, in person distribution is also used where feasible during industry conferences and events.

This study has focused on Industry 4.0 adoption in the Indian pharmaceutical sector by choosing a carefully selected and representative sample, which allows us to draw conclusions from the findings that reflect, but also do not disregard, the general trends and issues accompanying the Indian pharmaceutical sector's adoption of Industry 4.0 technologies.

3.6 Participant Selection

The participants for this study are chosen as their roles and responsibilities within Indian pharmaceutical industry use direct or indirect impact on decisions and activities regarding Industry 4.0 technologies. With respect to selection criteria, they consider senior managers, operations heads, sustainability officers as well as IT personnel as individuals well placed to provide insights into research questions. The participants in this study are chosen because they play a role in implementation in their organizations of technological innovations and sustainability practices. The study employs stratified random sampling in order to achieve a representative sample of different companies in the pharmaceutical industry located in India. Factors determining the strata of such samples are company size (large, medium, small), geographic location, and market position. This approach thus guarantees that the perspectives of participants from a palette of organizational contexts are included in the analysis. We recruit from the combination of professional networks, industry associations, and direct approach with pharmaceutical companies. Emails are sent with an invitation to learn more about the survey, providing the purpose of the study and ensuring anonymity of participation. They conduct follow ups to participate and to reach the desired sample size of 300 respondents. The study uses the structured, inclusive method of selecting participants to enhance the reliability and generalizability of the study findings that correspond to the various realities of the Indian pharmaceutical sector's adoption of Industry 4.0.

3.7 Instrumentation

The primary instrument used in data collection for this study is a structured questionnaire. It measures the quantitative data on adoption of the Industry 4.0 technology, encountering difficulty faced by companies and perceived environmental and economic impacts. It also contains sections to study the effects of the national policies and corporate governance on technology adoption. The majority of questions are closed ended, using Likert scales, rank scales, or multiple choice, to make questions clear and consistent.

The questionnaire is broken up into the following major categories:

1. **Demographics and Organizational Information:** It captures respondent's role, company size and geographical location.
2. **Industry 4.0 Technology Adoption:** It assesses the integration of technology in all the operational areas.
3. **Challenges in Adoption:** Ranks financial, technical and regulatory barriers through weighted ranking questions.
4. **Environmental and Economic Impacts:** Examines the perceived potential consequences of Industry 4. adoption for sustainability practice in modern industries.

5. **Strategic Measures and Policy Influence:** Evaluates strategies and role of government intervention.

3.8 Data Analysis

The structured questionnaire data is analyzed through a combination of various statistical tools and techniques to provide a holistic and comprehensive picture of how Indian pharmaceutical sector is rapidly adopting the Industry 4.0 technologies and the significant impact those technologies bring on the sector for overall efficiency and growth. The research questions are answered systematically, and they are used to provide actionable conclusion.

1. Descriptive Statistics:

Demographic data and the key variables are comprehensively summarized through frequency analysis: Industry 4.0 adoption frequency analysis, and perceived challenges and impacts distribution. So, it gives you an overarching picture of what’s happening with the data.

$$f_i = n_i/N \tag{1}$$

Where f_i is the frequency of adoption category i, n_i is the number of responses in category, and N is the total number of responses.

2. Weighted Rank Distribution:

The challenges to Industry 4.0 adoption as identified by the respondents are ranked using weighted ranking analysis. It is a means to identify the most critical barriers, in terms of importance.

$$P_i = n_i/N \tag{2}$$

Where P_i represents the proportion of responses indicating a specific challenge or impact i, n_i is the number of responses for challenge or impact i, and N is the total number of responses.

3. Reliability Testing:

An internal consistency of the questionnaire is determined through calculating the Cronbach's Alpha. If we get a Cronbach's Alpha value of 0.7 or above, our instrument is measuring the constructs well.

$$W = \sum_{i=1}^{k} \omega_i \, r_i \tag{3}$$

Where W is the weighted rank score, ω_i is the weight assigned to rank i, r_i is the rank given by the particular respondent, and finally, k is the number of different ranks available.

4. Normality Testing:

Likewise used to test for normality of data distribution for the main variables is the Kolmogorov–Smirnov test. It is this test that helps decide between parametric or non-parametric statistical methods for further analysis.

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k} \sigma_i^2}{\sigma_x^2}\right) \tag{4}$$

Where α is Cronbach's Alpha, k is the number of items, σ_i^2 is the variance of the i^{th} item, and σ_x^2 is the total variance of the summed scores.

5. Inferential Statistics:

Depend upon the results of both normality test and then performed an exploration relationship between variables, like Industry 4.0 adoption and its impact on environmental sustainability. Through application of these analytical methods, the study also ensures that analyses of data are carried out rigorously with a systematic approach, to facilitate robust conclusions on issues such as challenges, impacts and strategic measures around Industry 4.0 technologies in the Indian pharmaceutical industry.

Correlation Analysis (if data is parametric):

$$r_{xy} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2(y_i - \bar{y})^2}} \tag{5}$$

Where r_{xy} is the correlation coefficient between variables x and y

Spearman's Rank Correlation Coefficient (if data is non-parametric):

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)} \tag{6}$$

Where ρ is Spearman's rank correlation coefficient, d_i is the difference between the two ranks of each observation, and n is the number of observations.

3.9 Research Design Limitations

This research provides a structured, data-driven assessment of Industry 4.0 adoption in the Indian pharmaceutical sector. However, certain limitations must be acknowledged. The study primarily relies on survey responses, which, while offering a broad quantitative perspective, may introduce self-reporting bias. Participants may overstate or understate their organization's technological maturity and sustainability impact.

To enhance the depth of analysis, case studies from global pharmaceutical firms such as Orion Corporation and Pfizer CentreOne are included to illustrate how Industry 4.0 technologies contribute to environmental sustainability. However, these case studies focus on specific implementations rather than providing a comprehensive view of adoption trends across the Indian pharmaceutical sector.

Another limitation is the evolving nature of Industry 4.0 technologies and regulatory policies. As advancements in AI, IoT, and automation continue, technology adoption levels and strategic approaches may shift, requiring periodic reassessment of the study's findings. Additionally, while the study examines environmental sustainability metrics, the analysis is based on survey perceptions rather than direct real-time environmental performance data. Real-time measurements could provide a more precise understanding of the actual impact of Industry 4.0 technologies.

Despite these limitations, the study employs a rigorous methodology, including stratified sampling and statistical validation techniques, to ensure the reliability of its findings. It provides a strong empirical foundation for understanding the challenges, opportunities, and strategic considerations in advancing Industry 4.0 adoption in the Indian pharmaceutical industry. Future research could expand on this work by incorporating real-time sustainability data and conducting longitudinal case studies to assess the long-term effects of technological integration.

3.10 Conclusion

This chapter outlined the methodology for assessing Industry 4.0 adoption in the Indian pharmaceutical sector and its impact on environmental sustainability. The study follows a quantitative research design, using survey-based data collection and stratified random sampling.

The research examines adoption levels, barriers, environmental impact, strategic solutions, policy influence, and governance roles. Case studies from Orion Corporation and Pfizer CentreOne offer real-world insights into Industry 4.0-driven sustainability efforts.

Statistical methods, including descriptive analysis, ranking, reliability testing, normality testing, and correlation analysis, ensure data reliability. While the study provides valuable insights, limitations include self-reported data, evolving technology trends, and a focus on perceived environmental benefits rather than real-time performance data.

Despite these constraints, the research establishes a structured framework for understanding technological adoption and sustainability challenges in the Indian pharmaceutical sector. The findings offer actionable insights for stakeholders and policymakers. Future research could integrate real-time sustainability data and longitudinal case studies for a more comprehensive evaluation of Industry 4.0's long-term impact.

CHAPTER IV

RESULTS

4.1 Introduction

As part of the research findings, this section gives a comprehensive evaluation of the gathered data and systematically displays the results in accordance with the study aims and queries. The purpose of this chapter is to provide a thorough analysis of the pharmaceutical industry's adoption of Industry 4.0 technologies in India, including the sector's successes, failures, environmental and economic effects, and solutions to these problems.

The discussion begins with an overview of the demographic distribution of respondents, ensuring the representativeness and diversity of the data. Subsequently, the chapter delves into objective-specific analyses, including evaluating current technology adoption levels, identifying barriers, assessing environmental and economic impacts, proposing actionable strategies, and reviewing the influence of policies like "Digital India" and "Make in India."

By employing a structured approach, the use of statistical tools, a combination of frequency analysis, weighted rank distribution, Cronbach's alpha, and the Kolmogorov-Smirnov test, the findings obtained from these methods are validated for reliability and consistency. The insights gleaned from these analyses ultimately aim to provide actionable recommendations for the effective adoption and integration of Industry 4.0 technologies, which plays a crucial role in fostering sustainability and innovation within the sector.

4.2 Demography of Respondents

To understand the demographic distribution of the respondents involved in this study, a frequency analysis categorized them by demographics. This analysis is critical to ensuring that the data collected spans across a diverse demography, potentially impacting the adoption of Industry 4.0 technologies in the pharmaceutical sector. The following table and figure illustrate the age distribution of the 300 respondents.

Table 4. 1: Frequency analysis on Age Group

Age Group	**Frequency**	**Percent**
Under 25	28	9.3
25-34	93	31
35-44	89	29.7
45-54	63	21
55 and above	27	9
Total	**300**	**100**

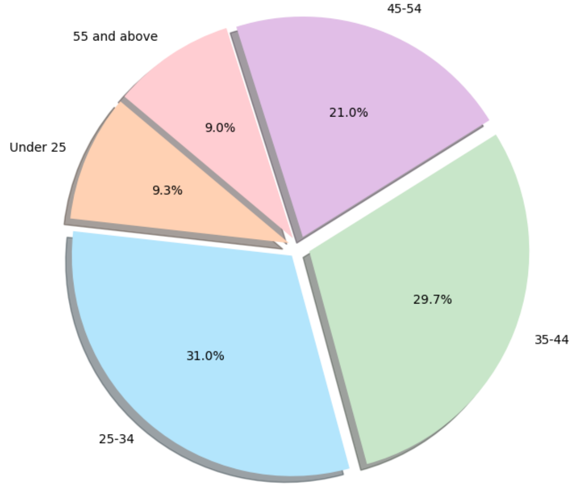


Figure 4. 1: Pie chart on frequency analysis on Age Group

The pie chart provides a visual representation of the age distribution, where the largest segments are the 25-34 and 35-44 age groups, comprising 31% and 29.7% of the respondents, respectively. These groups are followed by the 45-54 age group at 21%, and both the under 25 and 55 and above groups each hold around 9% of the total population surveyed. This distribution is essential in understanding the perspectives and inclinations toward technology adoption across different age demographics within the industry.

Gender distribution is an important aspect of this study as it could influence perspectives on technology adoption given varying experiences and roles within the industry. The following table 4.2 and figure 4.2 present the gender distribution of the 300 respondents**:**

Table 4. 2: Frequency analysis on Gender

Gender	**Frequency**	**Percent**
Female	60	20
Male	240	80
Total	**300**	**100**

A frequency analysis was performed to assess the gender distribution of the respondents. The analysis revealed that out of 300 respondents, 240 are male (80%), and 60 are female (20%). The clear majority of male respondents could reflect the current gender dynamics within the industry sectors surveyed, particularly in roles that are impacted by or involved with Industry 4.0 technologies.

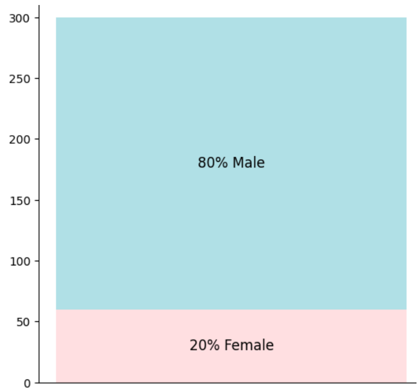


Figure 4. 2: Stacked bar plot on frequency analysis on Gender

The study also examined the educational background of the respondents to gauge the level of formal education within the context of Industry 4.0 adoption. The results (table 4.3 and figure 4.3 show a varied distribution of educational qualifications among the 300 participants: 13 respondents (4.3%) completed high school, diploma, or its equivalent; 181 respondents (60.3%) hold a bachelor's degree; 68 respondents (22.7%) have a master's degree; and 38 respondents (12.7%) have achieved a doctorate or higher.

Table 4. 3: Frequency analysis on Educational Background

Educational Background	**Frequency**	**Percent**
High school, diploma or its equivalent	13	4.3
Bachelor's degree	181	60.3
Master's degree	68	22.7
Doctorate or	38	12.7
Total	**300**	**100**

The data reflects a highly educated respondent pool, which is indicative of the advanced qualifications required within the industry sectors engaging with Industry 4.0 technologies.

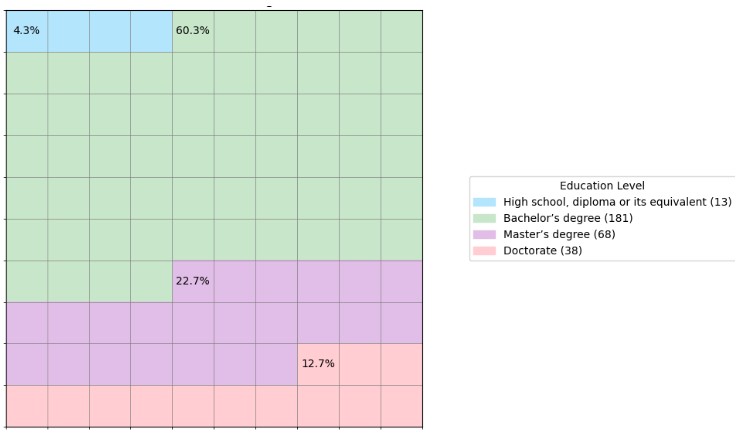


Figure 4. 3: Waffle chart on frequency analysis on Educational Background

According to the above table and graph, 13 (4.3%) of the 300 respondents had completed a high school diploma or its equivalent, 181 (60.3%) had completed a bachelor's degree, 68 (22.7%) had achieved a master's degree, and the remaining 38 (12.7%) had completed a doctorate or higher.

An analysis of the positions held by the 300 respondents within their companies was conducted to better understand their influence on and exposure to Industry 4.0 technologies. The frequency analysis (table 4.4 and figure 4.4) revealed that 71 respondents (23.7%) hold entry-level positions; 73 (24.3%) are executives; 86 (28.7%) are at mid-level; 23 (7.7%) work in research and development (R&D); and 47 (15.7%) are senior managers.

Table 4. 4: Frequency analysis on Position In Company

Position In Company	**Frequency**	**Percent**
Entry-level	71	23.7
Executive	73	24.3
Mid-level	86	28.7

Research & D	23	7.7
Senior manager	47	15.7
Total	**300**	**100**

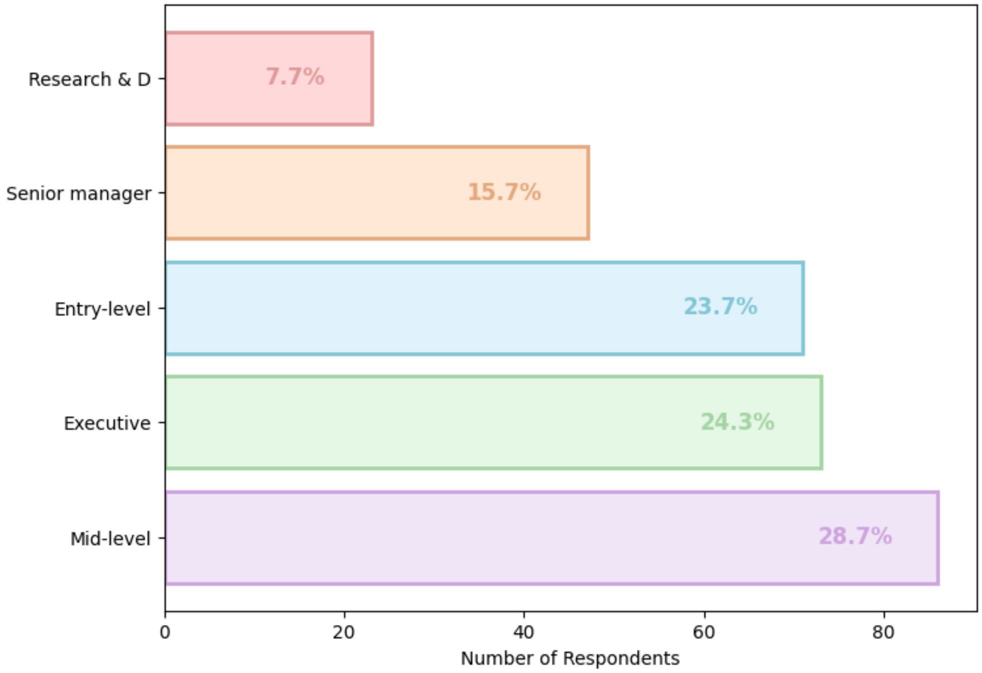


Figure 4. 4: Pyramid chart on frequency analysis on Position In Company

The study thoroughly investigated the detailed departmental breakdown of the 300 respondents to identify where the participants are primarily located within their various organizational structures. This crucial and pivotal categorization effectively helps in better understanding the significant spread of Industry 4.0 technologies across various operational sectors. The comprehensive frequency analysis (table 4.5 and figure 4.5) notably shows that 33 respondents (11%) work in IT and Tech Support; 32 (10.67%) in Production; 91 (30.33%) in Quality Control; 59 (19.67%) in Research and Development

(R&D); 54 (18%) in Sales and Marketing; and 31 (10.33%) are categorized under other departments. This representative data reflects a diverse involvement across different functional areas, highlighting the widespread interdisciplinary impact of Industry 4.0 technologies.

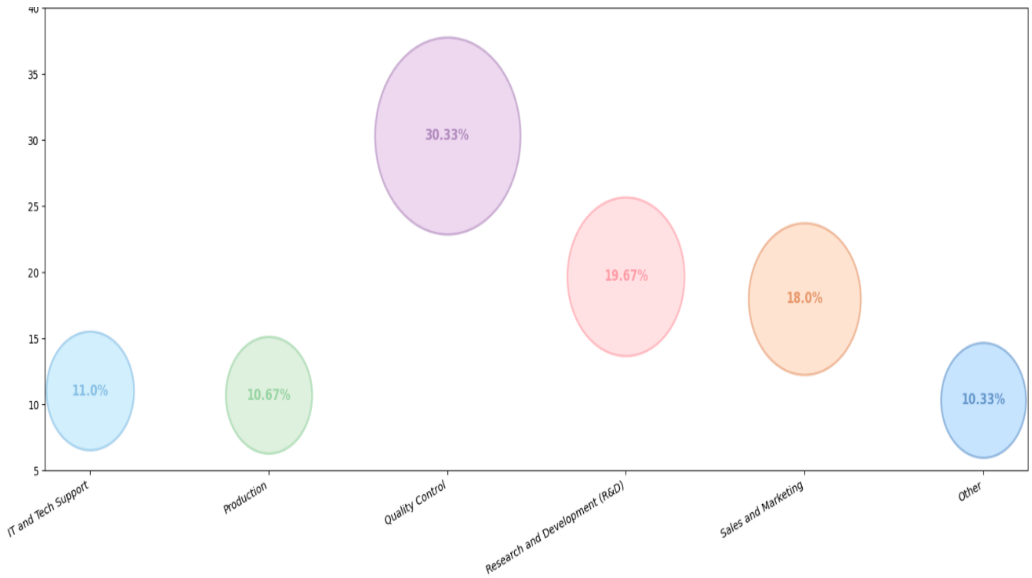


Figure 4. 5: Scatter plot on frequency analysis on Department

Table 4. 5: Frequency analysis on Department

Department	**Frequency**	**Percent**
IT and Tech Support	33	11.00
Production	32	10.67
Quality Control	91	30.33
Research and Development (R&D)	59	19.67

Sales and Marketing	54	18.00
Other	31	10.33
Total	**300**	**100**

The study investigated the departmental breakdown of the 300 respondents to identify where the participants are primarily located within their organizations. This categorization helps in understanding the spread of Industry 4.0 technologies across various operational sectors. Out of the 300 respondents (table 4.6 and figure 4.6), 61 (20.33%) had less than a year's experience in the pharmaceutical industry, 31 (10.33%) had one to five years' experience, 28 (9.33%) had six to ten years' experience, 87 (29%) had eleven to twenty years' experience, and the remaining 93 (31%) had more than twenty years' experience. The aforementioned table and graph display this data.

Table 4. 6: Frequency analysis on Years of Experience in the Pharmaceutical Industry

Years of Experience in the Pharmaceutical Industry	**Frequency**	**Percent**
Less than 1 year	61	20.33
1-5 years	31	10.33
6-10 years	28	9.33
11-20 years	87	29.00
More than 20 years	93	31.00
Total	**300**	**100**

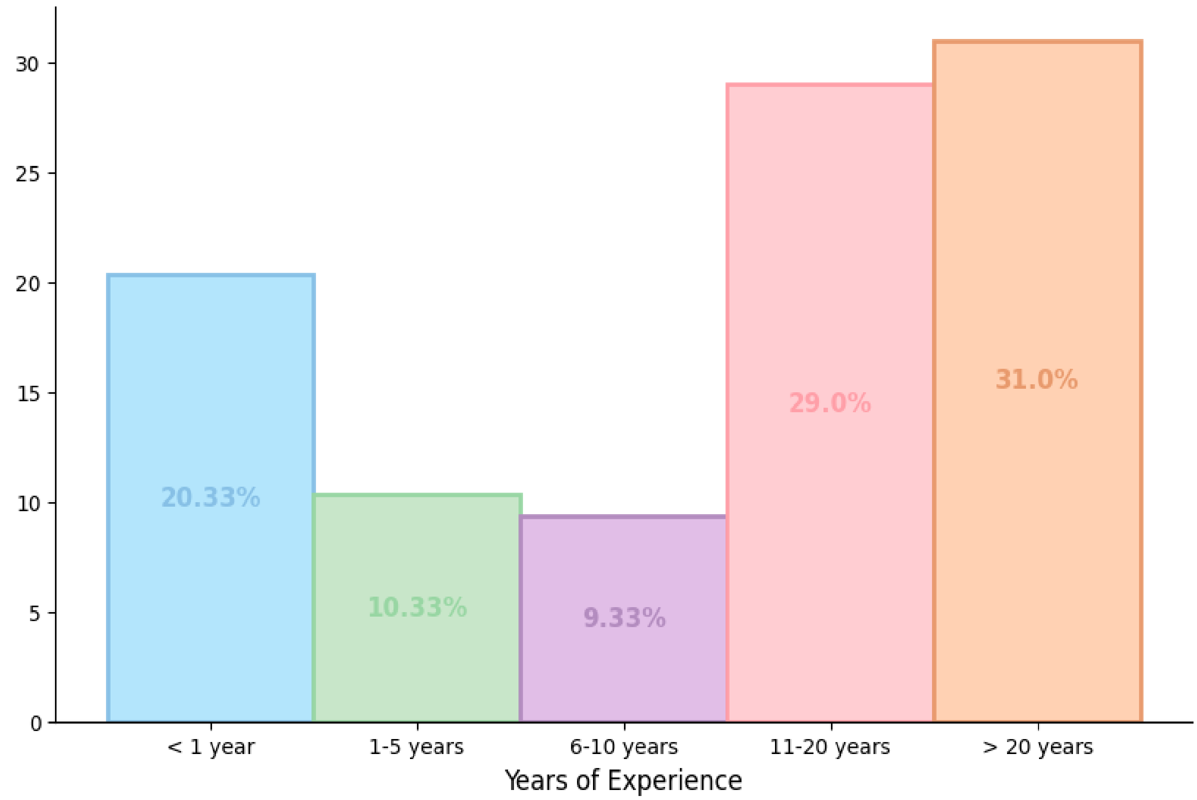


Figure 4. 6: Bar chart on frequency analysis on Years of experience in the Pharmaceutical Industry

The survey assessed the respondents' experience with Industry 4.0 technologies to determine their familiarity and proficiency levels. The frequency analysis revealed that among the 300 participants: 61 (20.3%) of the 300 responders are beginners (less than two years). 93 (31%) of them have intermediate (2–5 years) experience with Industry 4.0 technologies. 108 (36%) have experience with Industry 4.0 technologies, with more than five years of expertise. 38 people (12.7%) had no experience with Industry 4.0 technologies, while the remaining 30 had experience. The aforementioned table and graph display this data.

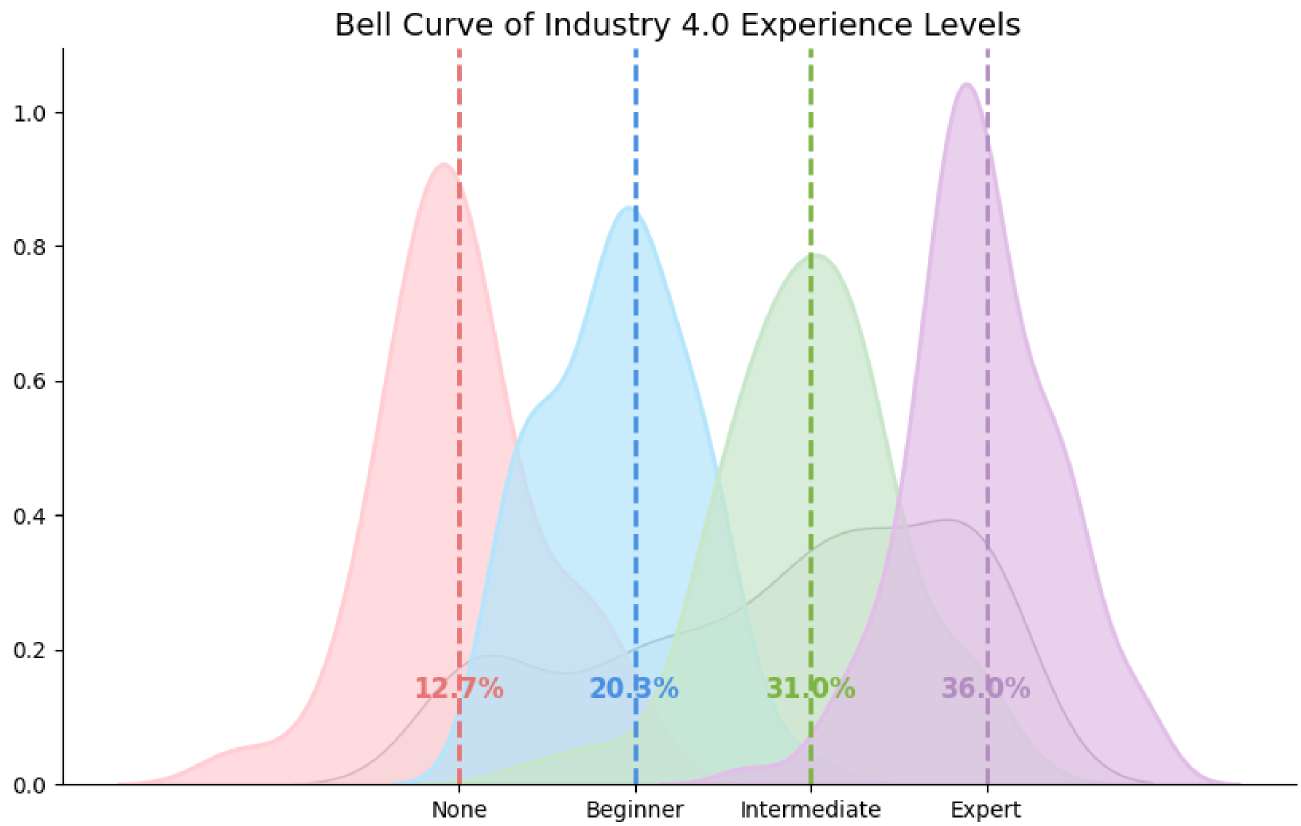


Figure 4. 7: Bell curve chart on frequency analysis on Experience with Industry 4.0 Technologies.

Table 4. 7: Frequency analysis on Experience with Industry 4.0 Technologies

Experience with Industry 4.0 Technologies	**Frequency**	**Percent**
Beginner (less than 2 years)	61	20.3
Intermediate (2-5 years)	93	31
Expert (more than 5 years)	108	36
None	38	12.7
Total	**300**	**100**

4.3 Analysis as per Objective

To systematically and comprehensively assess the research objectives outlined in this study, an methodical and structured in-depth analysis was conducted, focusing on the various key areas of Industry 4.0 adoption, associated challenges, environmental impacts, practical and evidence-based strategic measures, policy influence, and corporate governance. Each section delves into specific findings, providing insights into how these factors shape the implementation and effectiveness of Industry 4.0 technologies in the Indian pharmaceutical sector. The following sections present detailed observations aligned with each research objective.

4.3.1 Obj 1: Evaluate Adoption Levels of Industry 4.0 Technologies

Now we will examine Objective 1 Evaluating the Current Adoption Levels of Industry 4.0 Technologies results in details. It examines the extent of implementation of various Industry 4.0 technologies, ranging from no adoption to full integration, providing insights into their current usage within the pharmaceutical sector.

Table 4. 8: Frequency analysis for Objective 1

Industry 4.0 Related Technologies	**No Implementation at All**	**Low Implementation**	**Medium Implementation**	**High Implementation**	**Full/Advanced Implementation**
“Autonomous and Collaborative robots (Cobots)”	7	6	6	154	127

"Software Systems like ERP, MES, CRM, and PLM tools"	2	10	21	201	66
"Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR)"	5		11	185	99
"Additive manufacturing: 3D printing"	4	3	19	187	87
"Identifiers like Bar code, QR code, or Radio Frequency Identifier (RFID) and Real-time Location System (RTLS)"	3		20	180	97
"Intelligent sensors, actuators, embedded systems, and Programmable Logic Controllers (PLCs)"	4	27	46	143	80
"Mobile devices and Wearable's"	4	29	22	154	91
"Cloud computing"	1			177	122
"Machine to Machine (M2M) and Human to			19	152	129

Machine (H2M) communication”					
“Internet of Things (IoT) and Internet of Services (IoS)”	7	6	6	151	130
“Big data, real-time data processing, and Simulation tools”	2	11	23	195	69
“Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL)”	6		11	182	101
“Industrial Cyber security”	4	3	26	176	91
“Digital platforms for supplier and customer integration”	3		26	168	103
“Smart products technology”	5	38	32	143	82
“Block chain technology”	7	6	6	152	129

Interpretation: "Autonomous and Collaborative robots (Cobots)" is one example. Seven respondents indicated that there was no implementation at all, six indicated that there was low implementation, six indicated that there was medium implementation, 154 indicated that there was high implementation, and 127 indicated that there was full/advanced implementation.

For instance, two respondents indicated that there was no implementation at all for "Software Systems like ERP, MES, CRM, and PLM tools," ten indicated that there was low implementation, twenty-one indicated that there was medium implementation, 201 indicated that there was high implementation, and sixty-six indicated that there was full/advanced implementation.

Five respondents indicated that "Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR)" was not implemented at all, eleven indicated that it was, 185 indicated that it was, and 99 indicated that it was fully or advanced.

Regarding "Additive manufacturing: 3D printing," for instance, 4 respondents indicated that it was not implemented at all, 3 indicated that it was implemented low, 19 indicated that it was implemented medium, 187 indicated that it was implemented high, and 87 indicated that it was implemented fully or advanced.

Regarding "Additive manufacturing: 3D printing," for instance, 4 respondents indicated that it was not implemented at all, 3 indicated that it was implemented low, 19 indicated that it was implemented medium, 187 indicated that it was implemented high, and 87 indicated that it was implemented fully or advanced.

For instance, "Identifiers such as bar codes, QR codes, or Real-time Location Systems (RTLS) and Radio Frequency Identifiers (RFID)" of those surveyed, three reported they had no implementation at all, twenty reported they had medium implementation, 180 reported high implementation, and 97 reported full and advanced implementation.

Four respondents indicated that there was no implementation at all for "Intelligent sensors, actuators, embedded systems, and Programmable Logic Controllers (PLCs)," 27 indicated that there was low implementation, 46 indicated that there was medium implementation, 143 indicated that there was high implementation, and 80 indicated that there was full/advanced implementation.

Regarding "Mobile devices and wearable," for instance, 4 respondents indicated that there was no implementation at all, 29 indicated that there was low implementation, 22 indicated that there was medium implementation, 154 indicated that there was high implementation, and 91 indicated that there was full or advanced implementation.

Regarding "cloud computing," for instance, 122 respondents indicated full/advanced implementation, 177 indicated high implementation, and 1 indicated no implementation at all.

For instance, among the following, 19 respondents rated "Machine to Machine (M2M) and Human to Machine (H2M) communication" as Medium Implementation, 152 as High Implementation, and 129 as Full/Advanced Implementation.

Seven respondents indicated that "Internet of Things (IoT) and Internet of Services (IoS)" were not implemented at all, six indicated that it was lowly implemented, six indicated that it was medium implemented, 151 indicated that it was highly implemented, and 130 indicated that it was fully or advanced implemented.

"Big data, real-time data processing, and simulation tools," for instance Of those surveyed, two reported no implementation at all, eleven reported low implementation, twenty-three reported medium implementation, 195 reported high implementation, and 69 reported full/advanced implementation.

For instance, "Deep Learning (DL), Machine Learning (ML), and Artificial Intelligence (AI)"; six respondents indicated that there was no implementation at all, eleven indicated that there was medium implementation, 182 indicated that there was high implementation, and 101 indicated that there was full or advanced implementation.

For instance, 4 respondents indicated that "Industrial Cyber security" was not implemented at all, 3 indicated that it was implemented low, 26 indicated that it was implemented medium, 176 indicated that it was implemented high, and 91 indicated that it was implemented fully or advanced.

For instance, when asked if they had implemented "digital platforms for supplier and customer integration," 3 respondents said they had not done so at all, 26 said they had done so, 168 said they had done so, and 103 said they had done it fully or significantly advanced.

"Smart products technology," for illustration, was rated as having no implementation at all by only five respondents, low implementation was marked by 38, medium implementation by 32, high implementation by 143, and full/advanced implementation by 82.

For instance, 129 respondents indicated full/advanced implementation, 152 indicated high implementation, relatively few, 6 indicated low implementation, 6 indicated medium implementation, and 7 indicated no implementation at all for "block chain technology."

Table 4. 9: Rank wise descriptive analysis

Variables	**Rank**	**Weighted Mean**	**Std. Deviation**
“Autonomous and Collaborative robots (Cobots)”	11	4.2933	0.80589
“Software Systems like ERP, MES, CRM and PLM tools”	5	4.0633	0.69349
“Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR)”	10	4.2433	0.67748
“Additive manufacturing: 3D printing”	7	4.1667	0.69798
“Identifiers like Bar code, QR code, or Radio Frequency Identifier (RFID) and Real-time Location System (RTLS)”	8	4.2267	0.65579
“Intelligent sensors, actuators, embedded systems, and Programmable Logic Controllers (PLCs)”	2	3.8933	0.94424
“Mobile devices and Wearable’s”	3	3.9967	0.94142
“Cloud computing”	15	4.4033	0.49815
“Machine to Machine (M2M) and Human to Machine (H2M) communication”	14	4.3667	0.60007
“Internet of Things (IoT) and Internet of Services (IoS)”	13	4.3033	0.80839

“Big data, real-time data processing, and Simulation tools”	4	4.06	0.71515
“Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL)”	9	4.24	0.70526
“Industrial Cyber security”	6	4.1567	0.72609
“Digital platforms for supplier and customer integration”	8	4.2267	0.6857
“Smart products technology”	1	3.8633	1.01064
“Block chain technology”	12	4.3	0.80757

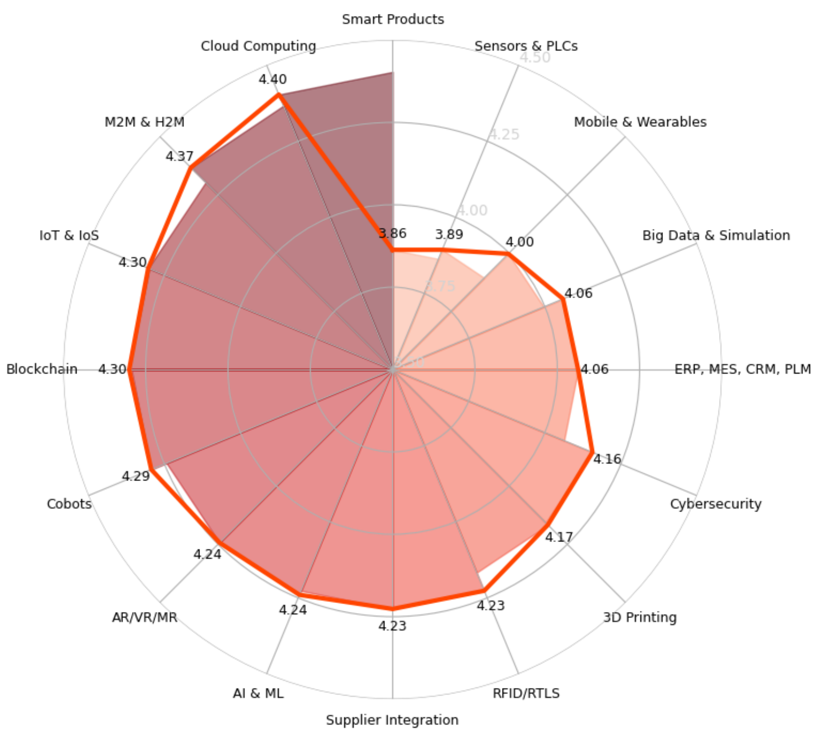


Figure 4. 8: Rank (Weighted mean) distribution of Evaluate the Current Adoption Levels of Industry 4.0 Technologies

To determine the descriptive statistics of the items, statistical tests were performed on the data. The table and graph above provide a summary of the mean, standard deviation, and rank (based on mean score) for each maturity item.

The table 4.9 makes clear that autonomous and collaborative robots (Cobots), software systems such as ERP, ERP, CRM, MES,and PLM tools, virtual reality (VR), augmented reality (AR), additive manufacturing , mixed reality (MR), identifiers such as bar codes, QR codes, or radio frequency identifiers (RFID), machine-to-machine (M2M) and human-to-machine (H2M) communication, the Internet of Things (IoT) and Internet of Services (IoS), big data, real-time data processing, simulation tools, machine learning (ML), artificial intelligence (AI), and deep learning (DL), industrial cyber security, digital platforms for supplier and customer integration, and block chain technology (had higher mean above 4.0). Programmable Logic Controllers (PLCs), intelligent sensors, actuators, embedded systems, mobile devices, wearable technology, and smart products have the lowest readiness (mean below 4.0).

Table 4. 10: Croanbach alpha test of Current Adoption Levels of Industry 4.0 Technologies

Variables	**Cronbach's Alpha**	**N of Items**
“Autonomous and Collaborative robots (Cobots)”	0.932	16
“Software Systems like ERP, MES, CRM, and PLM tools”		
“Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR)”		

“Additive manufacturing: 3D printing”		
“Identifiers like Bar code, QR code, or Radio Frequency Identifier (RFID) and Real-time Location System (RTLS)”		
“Intelligent sensors, actuators, embedded systems, and Programmable Logic Controllers (PLCs)”		
“Mobile devices and Wearable’s”		
“Cloud computing”		
“Machine to Machine (M2M) and Human to Machine (H2M) communication”		
“Internet of Things (IoT) and Internet of Services (IoS)”		
“Big data, real-time data processing, and Simulation tools”		
“Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL)”		
“Industrial Cyber security”		
“Digital platforms for supplier and customer integration”		
“Smart products technology”		
“Block chain technology”		

Interpretation: Cronbach's alpha measures internal consistency, or the extent to which a collection of elements are commonly related to one another. It is acknowledged as a scale reliability metric. Cronbach's alpha increases with the number of items. Additionally, if the average inter-item correlation is low, alpha will also be low. When the number of items stays the same, Cronbach's alpha increases according to the average inter-item correlation. The validity of the data is shown by our study's Current Adoption Levels of Industry 4.0 Technologies surveys (0.932).

Table 4. 11: Kolmogorov Simornov test

Variables	**Test statistics**	**Asymp. Sig. (2-tailed)**
"Smart products technology"	5.103	0.000
"Intelligent sensors, actuators, embedded systems, and Programmable Logic Controllers (PLCs)"	6.125	0.000
"Mobile devices and Wearable's"	5.374	0.000
"Big data, real-time data processing, and Simulation tools"	5.525	0.000
"Software Systems like ERP, MES, CRM, and PLM tools"	5.402	0.000
"Industrial Cyber security"	4.994	0.000
"Additive manufacturing: 3D printing"	5.509	0.000
"Identifiers like Bar code, QR code, or Radio Frequency Identifier (RFID) and Real-time Location System (RTLS)"	6.656	0.000

"Digital platforms for supplier and customer integration"	5.186	0.000
"Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL)"	5.03	0.000
"Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR)"	6.003	0.000
"Autonomous and Collaborative robots (Cobots)"	5.372	0.000
"Block chain technology"	5.276	0.000
"Internet of Things (IoT) and Internet of Services (IoS)"	4.957	0.000
"Machine to Machine (M2M) and Human to Machine (H2M) communication"	5.262	0.000
"Cloud computing"	5.054	0.000

Together with a degrees of freedom parameter, the test statistics generated by the widely recognized Kolmogorov Smirnov test are used to check for normalcy. Here, we can carefully observe that for every relevant and significant variable taken into consideration for the Current Adoption Levels of Industry 4.0 Technologies, the Kolmogorov Smirnov statistic notably takes value greater than 4 which indicates a deviation from normal distribution.

The SPSS-provided p-value, which is reported as p <.001 and cited under Sig. for Kolmogorov-Smirnov, is.000. As a result, the null hypothesis (Evaluate the Current

Adoption Levels of Industry 4.0 Technologies) that the variable has a normal distribution is strongly refuted.

4.3.2 Obj 2: Determine Specific Challenges

Now, we will examine Objective 2: Determine Specific Challenges—Financial, Technical, or Regulatory—That Hinder Full Integration of These Technologies in detail. This analysis explores the key barriers affecting the widespread adoption of Industry 4.0 technologies in the pharmaceutical sector, including financial constraints, technical limitations, and regulatory challenges.

Table 4. 12: Frequency analysis for Objective 2

Barriers to Industry 4.0 Adoption	Not Important	Slightly Important	Important	Very Important	Most Important
"Large capital investment in new technology"	2	11	29	189	69
"IT security and safety issues"	6		11	182	101
"Lack of awareness about the benefits and implications of Industry 4.0"	4	3	20	182	91
"Lack of standards and reference architectures"	3		20	167	110

“Lack of a skilled workforce”	4	29	58	140	69
“Poor infrastructure”	5	38	32	144	81
“Interoperability issues”	8	6	6	151	129
“Resistance to change or reluctance to adopt new technologies”	3	11	23	195	68

Interpretation: In the case of "Large capital investment in new technology," for instance, two respondents rated it as Not Important, eleven as Slightly Important, 29 as Important, 189 as Very Important, and 69 as Most Important.

Regarding "IT security and safety issues," for instance, notably 6 respondents rated it as Not Important, 11 as Important, 182 as Very Important, and 101 as Most Important. "Lack of awareness about the benefits and implications of Industry 4.0," for instance, was rated as Not Important by 4 respondents, Slightly Important by 3, Important by 20, Very Important by 182, and Most Important by 91.

For instance, 3 respondents rated "Lack of standards and reference architectures" as Not Important, 20 as Important, 167 as Very Important, and 110 as Most Important.

For instance, four respondents rated "Lack of a skilled workforce" as Not Important, 29 as Slightly Important, 58 as Important, 140 as Very Important, and 69 as Most Important.

A small fraction of Five respondents rated "poor infrastructure" as Not Important, 38 as Slightly Important, 32 as Important, 144 as Very Important, and 81 as Most Important.

Regarding "interoperability issues," for instance, eight respondents rated it as Not Important, six as Slightly Important, six as Important, 151 as Very Important, and 129 as Most Important. For instance, "Reluctance to adopt new technologies or resistance to change" Three respondents rated it as Not Important, eleven as Slightly Important, twenty-three as Important, 195 as Very Important, and 68 as Most Important.

Table 4. 13: Rank wise descriptive analysis

Variables	**Rank**	**Weighted Mean**	**Std. Deviation**
"Large capital investment in new technology"	3	4.04	0.73042
"IT security and safety issues"	6	4.24	0.70526
"Lack of awareness about the benefits and implications of Industry 4.0"	5	4.1767	0.70743
"Lack of standards and reference architectures"	7	4.27	0.67226
"Lack of a skilled workforce"	1	3.8033	0.94568
"Poor infrastructure"	2	3.86	1.00853
"Interoperability issues"	8	4.29	0.82957
"Resistance to change or reluctance to adopt new technologies"	4	4.0467	0.73459

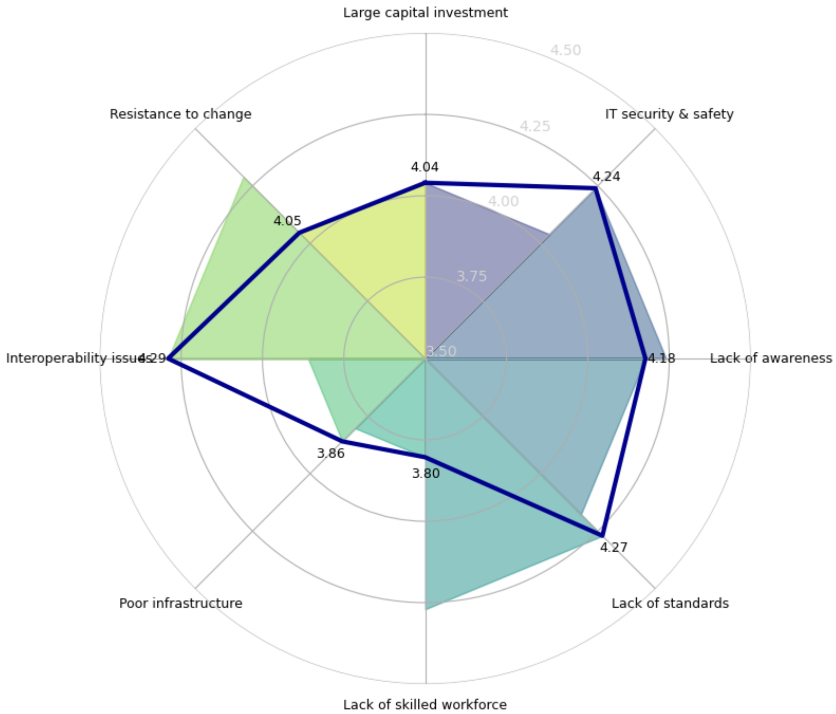


Figure 4. 9: Rank (Weighted mean) distribution of Determine Specific Challenges—Financial, Technical, or Regulatory—That Hinder Full Integration of These tech

To determine the descriptive statistics of the items, statistical tests were performed on the data. The table and graph above provide a summary of the mean, standard deviation, and rank (based on mean score) for each maturity item.

Large capital expenditures in new technology, IT security and safety concerns, ignorance of the advantages and ramifications of Industry 4.0, a lack of reference architectures and standards, interoperability problems, and resistance to change or hesitancy to embrace new technologies (mean above 4.0) are all clearly shown in the table. The two areas with the lowest readiness (mean < 4.0) are inadequate infrastructure and a shortage of skilled labor.

Table 4. 14: Croanbach alpha test of Determine Specific Challenges—Financial, Technical, or Regulatory—That Hinder Full Integration of These Technologies

Variables	**Cronbach's Alpha**	**N of Items**
"Large capital investment in new technology"	0.88	8
"IT security and safety issues"		
"Lack of awareness about the benefits and implications of Industry 4.0"		
"Lack of standards and reference architectures"		
"Lack of a skilled workforce"		
"Poor infrastructure"		
"Interoperability issues"		
"Resistance to change or reluctance to adopt new technologies"		

Interpretation: Cronbach's alpha measures internal consistency, or the extent to which a collection of elements are commonly related to one another. It is acknowledged as scale reliability metric. Cronbach's alpha increases with the number of items. Additionally, if the average inter-item correlation is low, alpha will also be low. When the number of items stays the same, Cronbach's alpha significantly increases according to the average inter-item correlation.

The validity of the data is shown by our study's surveys on Identify Specific Challenges—Financial, Technical, or Regulatory—That Prevent Full Integration of These Technologies (0.88).

Table 4. 15: Kolmogorov Simornov test

Variables	**Test statistics**	**Asymp. Sig. (2-tailed)**
"Large capital investment in new technology"	5.857	0.000
"IT security and safety issues"	5.372	0.000
"Lack of awareness about the benefits and implications of Industry 4.0"	5.394	0.000
"Lack of standards and reference architectures"	5.012	0.000
"Lack of a skilled workforce"	4.833	0.000
"Poor infrastructure"	5.286	0.000
"Interoperability issues"	5.138	0.000
"Resistance to change or reluctance to adopt new technologies"	6.085	0.000

Together with a degrees of freedom parameter, the test statistics generated by the Kolmogorov Smirnov test are used to check for normalcy. Here, we can observe that for every variable taken into consideration for identifying specific challenges—financial, technical, or regulatory—that impede the full integration of these technologies, the Kolmogorov Smirnov statistic takes value greater than 4.

The SPSS-provided p-value, which is reported as $p <.001$ and cited under Sig. for Kolmogorov-Smirnov, is.000. As a result, the null hypothesis (Identify Particular Financial, Technical, or Regulatory Obstacles to Complete Integration of These Technologies) that the variable has a normal distribution is strongly refuted.

4.3.3 Obj 3: Measure the Environmental and Economic Impacts

This analysis will evaluate how the adoption of Industry 4.0 technologies influences environmental sustainability and economic efficiency, including factors such as energy consumption, cost reduction, and resource optimization.

Table 4. 16: Frequency analysis for Objective 3

Environmental and Economic Impacts	**No Impact**	**Low Impact**	**Moderate Impact**	**High Impact**	**Significant Impact**
"Reduction in energy consumption"	7		11	182	100
"Reduction in carbon emissions"	5	3	20	182	90
"Improvement in resource efficiency (e.g., water, energy, raw materials)"	4		20	167	109
"Better waste management and recycling practices"	5	29	64	134	68

“Creation of new business opportunities and revenue streams”	8	6	5	151	130
“Cost reduction in production and operations”		6	17	198	79
“Improvement in product quality and innovation”			10	182	108
“Reduction in operational costs (e.g., labor, maintenance, downtime)”	2	28	53	145	72

Interpretation: "Reduction in energy consumption," for instance, was rated as having no impact by seven respondents, whereas the option moderate was opted by eleven, high by 182, and significant by ten.

For “Reduction in carbon emissions” these were the observations marked by responders. For instance, there were five respondents who said there they observe no impact, three who said there was a low impact, twenty who said there was a moderate impact, eighty-two who said there was a high impact, and ninety who said there was a significant impact.

"Improved resource efficiency (e.g., water, energy, raw materials)" is one example. Twenty respondents said it had a moderate impact, 167 said it had a high impact, 109 said it had a significant impact, and four said it had no impact.

"Better waste management and recycling practices," for instance Of those surveyed, 5 reported no impact, 29 reported low impact, 64 reported moderate impact, 134 reported high impact, and 68 reported significant impact.

Eight respondents indicated that "Creation of new business opportunities and revenue streams" had no impact, six indicated that it had a low impact, five indicated that it had a moderate impact, 151 indicated that it had a high impact, and 130 indicated that it had a significant impact.

For instance, six respondents rated "Cost reduction in production and operations" as having a low impact, seventeen as having a moderate impact, 198 as having a high impact, and 79 as having a significant impact.

For instance, 108 respondents rated "Improvement in product quality and innovation" as having a Significant Impact, 182 as having a High Impact, and 10 as having a Moderate Impact.

"Reduction in operational costs (e.g., labor, maintenance, downtime)" is one example. Of those surveyed, two reported no impact, twenty-eight reported low impact, fifty-three reported moderate impact, 145 reported high impact, and seventy-two reported significant impact.

Table 4. 17: Rank wise descriptive analysis

Variables	**Rank**	**Mean**	**Std. Deviation**
“Reduction in energy consumption”	5	4.2267	0.72828
“Reduction in carbon emissions”	3	4.1633	0.72922
“Improvement in resource efficiency (e.g., water, energy, raw materials)”	6	4.2567	0.69695

“Better waste management and recycling practices”	1	3.77	0.96273
“Creation of new business opportunities and revenue streams”	7	4.2967	0.82721
“Cost reduction in production and operations”	4	4.1667	0.61112
“Improvement in product quality and innovation”	8	4.3267	0.53627
“Reduction in operational costs (e.g., labor, maintenance, downtime)”	2	3.8567	0.91227

Figure 4. 10: Rank (Weighted mean) distribution of Measure the Environmental and Economic Impacts of Adopting Industry 4.0 Technologies

To determine the descriptive statistics of the items, statistical tests were performed on the data. The table and graph above provide a summary of the mean, standard deviation, and rank (based on mean score) for each maturity item.

The table makes it clear that lowering carbon emissions, reducing energy use, increasing resource efficiency (such as with regard to energy, water, and raw materials), developing new business prospects and revenue streams, Production and operational costs are decreased, while product quality and innovation are improved (mean over 4.0). The least preparedness for improved recycling and trash management is shown. decrease in operating expenses (mean less than 4.0) for labor, maintenance, and downtime, for example.

Table 4. 18: Croanbach alpha test of Measure the Environmental and Economic Impacts of Adopting Industry 4.0 Technologies

Variables	**Cronbach's Alpha**	**N of Items**
"Reduction in energy consumption"	0.845	8
"Reduction in carbon emissions"		
"Improvement in resource efficiency (e.g., water, energy, raw materials)"		
"Better waste management and recycling practices"		
"Creation of new business opportunities and revenue streams"		
"Cost reduction in production and operations"		
"Improvement in product quality and innovation"		
"Reduction in operational costs (e.g., labor, maintenance, downtime)"		

Interpretation: Cronbach's alpha measures internal consistency, or the extent to which a collection of elements are commonly related to one another. It is acknowledged as a scale reliability metric. Cronbach's alpha increases with the number of items. Additionally, if the average inter-item correlation is low, alpha will also be low. When the number of items stays the same, Cronbach's alpha increases according to the average inter-item correlation.

The validity of the data is shown by our study's Measure the Environmental and Economic Impacts of Adopting Industry 4.0 Technologies questionnaires (0.845).

Table 4. 19: Kolmogorov Simornov test

Variables	**Test statistics**	**Asymp. Sig. (2-tailed)**
“Reduction in carbon emissions”	5.509	0.000
“Improvement in resource efficiency (e.g., water, energy, raw materials)”	4.855	0.000
“Better waste management and recycling practices”	4.637	0.000
“Creation of new business opportunities and revenue streams”	5.137	0.000
“Cost reduction in production and operations”	5.961	0.000
“Improvement in product quality and innovation”	6.388	0.000

“Reduction in operational costs (e.g., labor, maintenance, downtime)”	4.949	0.000

Together with a degrees of freedom parameter, the test statistics generated by the Kolmogorov Smirnov test are used to check for normalcy. Here, we can observe that for every element taken into consideration for measuring the economic and environmental impacts of adopting industry 4.0 technologies, the Kolmogorov Smirnov statistic takes value greater than 4.

The SPSS-provided p-value, which is reported as p <.001 and cited under Sig. for Kolmogorov-Smirnov, is.000. The null hypothesis (Measure the Environmental and Economic Impacts of Adopting Industry 4.0 Technologies) that the variable has a normal distribution is so strongly refuted by the findings.

4.3.4 Obj 4: Propose Actionable Strategies to Overcome Barriers

In this subsection of analysis we will dwel into details what proposed, actionable trategies compnies have used to overcome barriers and augment the adoption of industry 4.0 technologies

Table 4. 20: Frequency analysis for Objective 4

Strategies to Overcome Barriers	**Not Effective**	**Slightly Effective**	**Moderately Effective**	**Very Effective**	**Highly Effective**
“Increased investment in employee training and skill development”	8	131	70		91

"Collaboration with technology vendors and experts for implementation"	6	133	80	1	80
"Government incentives or subsidies for Industry 4.0 technology adoption"	17	136	63		84
"Improving IT infrastructure and cyber security measures"	21	132	69		78
"Establishment of industry standards and reference architectures"	13	136	77		74
"Improving internal awareness and education about Industry 4.0"	7	11	83	81	118
"Enhancing cross-departmental collaboration and communication"	12	16	79	72	121
"Phased, incremental implementation of	12	16	79	72	121

Industry 4.0 technologies”					

Interpretation: For instance, 91 respondents rated "Increased investment in employee training and skill development" as Highly Effective, 70 as Moderately Effective, 131 as Slightly Effective, and 8 as Not Effective.

For instance, 133 respondents rated "Collaboration with technology vendors and experts for implementation" as somewhat effective, whereas 80 as moderately effective, only 1 had marked as very effective, and 80 have marked as highly effective Strategy. Six respondents rated this as not effective.

For instance, 84 respondents rated "Government incentives or subsidies for Industry 4.0 technology adoption" as Highly Effective, 136 as Slightly Effective, 63 as Moderately Effective, and 17 as Not Effective.

For instance, 78 respondents rated "Improving IT infrastructure and cyber security measures" as Highly Effective, 69 as Moderately Effective, 132 as Slightly Effective, and 21 as Not Effective.

As an illustration, 13 respondents rated the "Establishment of industry standards and reference architectures" as Not Effective, 136 as Slightly Effective, 77 as Moderately Effective, and 74 as Highly Effective.

For instance, notable seven respondents have rated "Improving internal awareness and education about Industry 4.0" strategy as Not Effective, whereas eleven of the pool thinks that it is Slightly Effective, On other hand eighty-three has marked as Moderately Effective, Finally eighty-one has marked as Very Effective, and 118 as Highly Effective.

As an illustration, twelve respondents rated "Enhancing cross-departmental collaboration and communication" as Not Effective, 16 as Slightly Effective, however 79 has agreed it to be Moderately Effective strategy, 72 responders think that has been Very Effective approach, and 121 as Highly Effective. As an illustration, 12 respondents rated the "phased, incremental implementation of Industry 4.0 technologies" as Not Effective, 16 as Slightly Effective, 79 as Moderately Effective, 72 as Very Effective, and 121 as Highly Effective.

Table 4. 21: Rank wise descriptive analysis

Variables	**Rank**	**Mean**	**Std. Deviation**
“Increased investment in employee training and skill development”	5	3.1167	1.32245
“Collaboration with technology vendors and experts for implementation”	4	3.0533	1.26325
“Government incentives or subsidies for Industry 4.0 technology adoption”	3	2.9933	1.34387
“Improving IT infrastructure and cyber security measures”	1	2.94	1.32751
“Establishment of industry standards and reference architectures”	2	2.9533	1.27143

"Improving internal awareness and education about Industry 4.0"	7	3.9733	1.01459
"Enhancing cross-departmental collaboration and communication"	6	3.9133	1.11203
"Phased, incremental implementation of Industry 4.0 technologies"	6	3.9133	1.11203

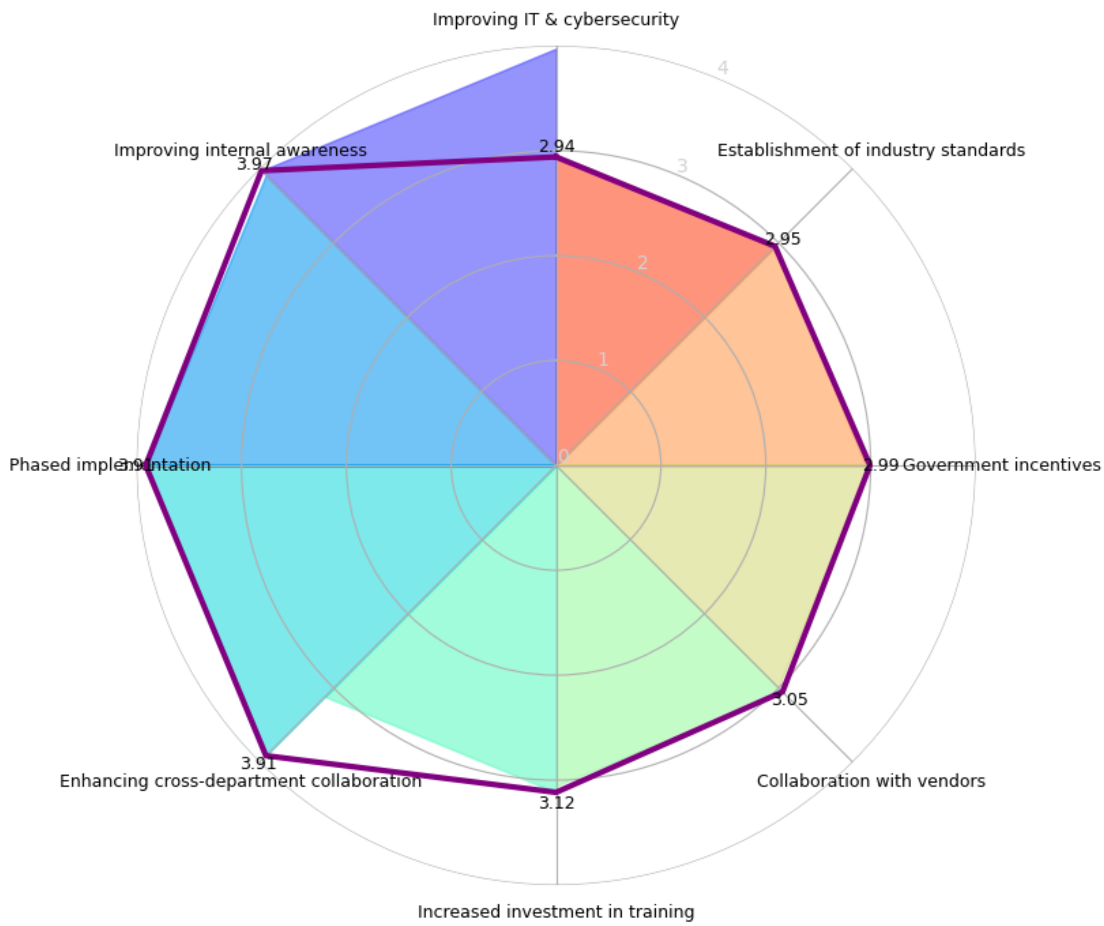


Figure 4. 11: Rank (Weighted mean) distribution of Propose Actionable Strategies to Overcome Identified Barriers and Enhance the Adoption of Industry 4.0 Technologies

To determine the descriptive statistics of the items, statistical tests were performed on the data. The table and graph above provide a summary of the mean, standard deviation, and rank (based on mean score) for each maturity item.

The table makes it clear that: Enhanced cross-departmental collaboration and communication; improved internal awareness and education regarding Industry 4.0; increased investment in employee training and skill development; cooperation with technology vendors and experts for implementation; and phased, incremental implementation of Industry 4.0 technologies (mean calculated above 3.0). Clearly establishing that the industry standards and reference architectures, enhancing IT infrastructure and cyber security measures, and providing government incentives or subsidies for the adoption of Industry 4.0 technologies are the areas with the lowest preparedness (mean below 2.0).

Table 4. 22: Croanbach alpha test of Propose Actionable Strategies to Overcome Identified Barriers and Enhance the Adoption of Industry 4.0 Technologies

Variables	**Cronbach's Alpha**	**No. of Items**
"Increased investment in employee training and skill development"	.880	8
"Collaboration with technology vendors and experts for implementation"		
"Government incentives or subsidies for Industry 4.0 technology adoption"		

“Improving IT infrastructure and cyber security measures”		
“Establishment of industry standards and reference architectures”		
“Improving internal awareness and education about Industry 4.0”		
‘Enhancing cross-departmental collaboration and communication”		
“Phased, incremental implementation of Industry 4.0 technologies”		

Interpretation: Cronbach's alpha measures internal consistency, or the extent to which a collection of elements are commonly related to one another. It is acknowledged as a scale reliability metric. Cronbach's alpha increases with the number of items. Additionally, if the average inter-item correlation is low, alpha will also be low. When the number of items stays the same, Cronbach's alpha increases according to the average inter-item correlation.

The validity of the data is shown by our study's surveys on Propose Actionable Strategies to Overcome Identified Barriers and Enhance the Adoption of Industry 4.0 Technologies (0.880).

Table 4. 23: Kolmogorov Simornov test

Variables	**Test statistics**	**Asymp. Sig. (2-tailed)**
“Increased investment in employee training and skill development”	4.574	0.000

"Collaboration with technology vendors and experts for implementation"	4.523	0.000
"Government incentives or subsidies for Industry 4.0 technology adoption"	4.851	0.000
"Improving IT infrastructure and cyber security measures"	4.686	0.000
"Establishment of industry standards and reference architectures"	4.676	0.000
"Improving internal awareness and education about Industry 4.0"	4.114	0.000
"Enhancing cross-departmental collaboration and communication"	4.141	0.000
"Phased, incremental implementation of Industry 4.0 technologies"	4.141	0.000

Together with a degrees of freedom parameter, the test statistics generated by the Kolmogorov Smirnov test are used to check for normalcy. Here, we can observe that for every variable taken into consideration for Propose Actionable Strategies to Overcome Identified Barriers and Enhance the Adoption of Industry 4.0 Technologies, the Kolmogorov Smirnov statistic takes value greater than 4.

The SPSS-provided p-value, which is reported as p <.001 and cited under Sig. for Kolmogorov-Smirnov, is.000. The null hypothesis (Propose Actionable Strategies to Overcome Identified Barriers and Enhance the Adoption of Industry 4.0 Technologies) that the variable has a normal distribution is thus strongly refuted by the evidence.

4.3.5 Obj 5: If Policies Influence Tech Upgrades and Environmental Std

This section observes our 5th Objective (Review How Policies Like Digital India and Make in India Have Influenced Technological Upgrades and Compliance with Environmental Standards) the role of Indian government initiatives in driving technological advancements and regulatory compliance. It will also assess their impact on the adoption of Industry 4.0 technologies in the pharmaceutical sector.

Table 4. 24: Frequency analysis for Objective 5

Government Policies and Influence	**No Influence**	**Slight Influence**	**Moderate Influence**	**Significant Influence**	**Strong Influence**
"Digital India initiative has positively impacted technology adoption"	12	16	79	72	121
"Make in India initiative has encouraged local manufacturing capabilities for Industry 4.0"	4	145	44		107
"Government subsidies or tax incentives for adopting Industry 4.0 technologies"	4	156	59		81

“Policy support for improving infrastructure and internet connectivity”	7	139	74		80
“Environmental regulations have guided sustainable technology implementation”	20	125	72		83

Interpretation: Twelve respondents indicated that the Digital India program had no influence, sixteen said that it had a slight influence, seventy-nine said that it had a moderate influence, seventy-two said that it had a significant influence, and 121 said that it had a strong influence.

The Indian government policy "Make in India initiative has encouraged local manufacturing capabilities for Industry 4.0," for occurrence, received four negative responses, 145 positive responses, 44 moderate negative responses, and 107 strong positive responses.

For instance, when asked if government subsidies or tax incentives for implementing Industry 4.0 technologies had any influence, 4 respondents replied that it did not, 156 said that it did, 59 said that it had a moderate influence, and 81 stated that it had a strong influence.

Regarding "Policy support for improving infrastructure and internet connectivity," for instance, seven respondents indicated that it had no influence, 139 indicated that it had a slight influence, 74 indicated that it had a moderate influence, and 80 indicated that it had a strong influence.

For instance, 20 respondents indicated that environmental restrictions had no influence, 125 said that they had a slight influence, 72 said that they had a moderate influence, and 83 said that they had a strong influence on the application of sustainable technology.

Table 4. 25: Descriptive analysis by rank

Variables	**Rank**	**Mean**	**Std. Deviation**
"Digital India initiative has positively impacted technology adoption"	5	3.9133	1.11203
"Make in India initiative has encouraged local manufacturing capabilities for Industry 4.0"	4	3.2033	1.38867
"Government subsidies or tax incentives for adopting Industry 4.0 technologies"	1	2.9933	1.28795
"Policy supports for improving infrastructure and internet connectivity"	3	3.0233	1.27602
"Environmental regulations have guided sustainable technology implementation"	2	3.0033	1.34014

Figure 4. 12: Rank (Weighted mean) distribution of Review if Policies Have Influenced Technological Upgrades and Compliance with Environmental Standards

To determine the descriptive statistics of the items, statistical tests were performed on the data. The table and graph above provide a summary of the mean, standard deviation, and rank (based on mean score) for each maturity item.

The table makes it clear that the Digital India initiative has had a positive impact on the adoption of technology, the Make in India initiative has incentivized local manufacturing capabilities for Industry 4.0, policy support for enhancing internet connectivity and infrastructure, and environmental regulations have guided the implementation of sustainable technology (mean above 3.0). Government tax breaks or subsidies for effectively implementing Industry 4.0 technologies are the least prepared (mean > 2.0).

Table 4. 26: Croanbach alpha test of Review How Policies Like Digital India and Make in India Have Influenced tech Upgrades and Compliance with Environmental Std

Variables	**Cronbach's Alpha**	**N of Items**
"Digital India initiative has positively impacted technology adoption"	0.854	5
"Make in India initiative has encouraged local manufacturing capabilities for Industry 4.0"		
"Government subsidies or tax incentives for adopting Industry 4.0 technologies"		
"Policy supports for improving infrastructure and internet connectivity"		
"Environmental regulations have guided sustainable technology implementation"		

Interpretation: Cronbach's alpha measures internal consistency, or the extent to which a collection of elements are commonly related to one another. It is acknowledged as a scale reliability metric. Cronbach's alpha increases with the number of items. Additionally, if the average inter-item correlation is low, alpha will also be low. When the number of items stays the same, Cronbach's alpha increases according to the average inter-item correlation. The validity of the data is demonstrated by our study's questionnaires on Review How

Policies Like Digital India and Make in India Have Influenced Technological Upgrades and Compliance with Environmental Standards (0.854).

Table 4. 27: Kolmogorov Simornov test

Variables	**Test statistics**	**Asymp. Sig. (2-tailed)**
Digital India initiative has positively impacted technology adoption	4.141	0.000
Make in India initiative has encouraged local manufacturing capabilities for Industry 4.0	5.258	0.000
Government subsidies or tax incentives for adopting Industry 4.0 technologies	5.422	0.000
Policy support for improving infrastructure and internet connectivity	4.77	0.000
Environmental regulations have guided sustainable technology implementation	4.439	0.000

Together with a degrees of freedom parameter, the test statistics generated by the Kolmogorov Smirnov test are used to check for normalcy. We can observe that all of the variables taken into consideration for the Review How Policies Like Digital India and Make in India Have Influenced Technological Upgrades and Compliance with Environmental Standards have values above 4 according to the Kolmogorov Smirnov statistic.

The SPSS-provided p-value, which is reported as $p < .001$ and cited under Sig. for Kolmogorov-Smirnov, is.000. The null hypothesis (Review How Policies Like Digital India and Made in India Have Influenced Technological Upgrades and Compliance with Environmental Standards) that the variable has a normal distribution is thus strongly refuted by the facts.

4.3.6 Objective 6: Evaluate the Role of Governance

This section comprehensively assesses our final objective (what role do corporate governance and stakeholder engagement play in advancing the adoption of industry 4.0 technologies). Robust governance frameworks and stakeholder collaboration play a pivotal role in shaping how organizations adapt to technological advancements. Here, we explore how leadership commitment, regulatory alignment, and strategic decision-making influence industry 4.0 adoption while addressing challenges like compliance, investment barriers, and organizational resistance. Effectively aligning governance frameworks with clear and well-defined industry objectives ensures streamlined and structured implementation and successfully drives long-term sustainability in the pharmaceutical sector.

Table 4. 28: Frequency analysis for Objective 6

Corporate Governance and Stakeholder Engagement Factors	**No Role**	**Minor Role**	**Moderate Role**	**Significant Role**	**Key Role**
"Corporate governance (e.g., board involvement, policy setting) has a	7	142	52		99

significant role in adopting Industry 4.0 technologies”					
“Regular engagement with stakeholders (e.g., employees, suppliers, customers) influences technology adoption decisions”	4	134	56		106
“Clear communication of Industry 4.0 adoption goals and benefits from leadership has motivated the workforce”	2	135	64	99	
“Stakeholder feedback and involvement are regularly integrated into the decision-making process for technology adoption”	10	129	66		95
“The alignment of corporate governance with technology adoption strategies has accelerated Industry 4.0 integration”	5	129	66		100

Interpretation: As an illustration, "Corporate governance (such as board participation and policy setting) has a significant role in adopting Industry 4.0 technologies."99 people said it was a key role, 52 said it was a moderate role, 142 said it was a minor role, and 7 said it was no role.

For instance, "Decisions about technology adoption are influenced by regular engagement with stakeholders (e.g., employees, suppliers, and customers)."56 people said it was a moderate role, 106 said it was a key role, 134 said it was a minor role, and 4 said it was no role.

For instance, "The workforce has been motivated by leadership's clear communication of Industry 4.0 adoption goals and benefits."99 people said it was a large role, 64 said it was a moderate role, 135 said it was a little role, and 2 said it was no role. For instance, "The decision-making process for technology adoption regularly incorporates stakeholder input and involvement."95 said it was a key role, compared to 10 who said it was no role, 129 who said it was a minor one, and 66 who said it was a moderate role.

For instance, "Industry 4.0 integration has been expedited by the alignment of corporate governance with technology adoption strategies."129 people said it was a little role, 66 said it was a moderate role, 100 said it was a key one, and 5 said it was no role.

Table 4. 29: Rank wise descriptive analysis

Variables	**Rank**	**Mean**	**Std. Deviation**
"Corporate governance (e.g., board involvement, policy setting) has a significant role in adopting Industry 4.0 technologies"	2	3.14	1.36869
"Regular engagement with stakeholders (e.g., employees, suppliers, customers) influences technology adoption decisions"	5	3.2333	1.36569

“Clear communication of Industry 4.0 adoption goals and benefits from leadership has motivated the workforce”	3	3.1967	1.32811
“Stakeholder feedback and involvement are regularly integrated into the decision-making process for technology adoption”	1	3.1367	1.3481
“The alignment of corporate governance with technology adoption strategies has accelerated Industry 4.0 integration”	4	3.2033	1.33964

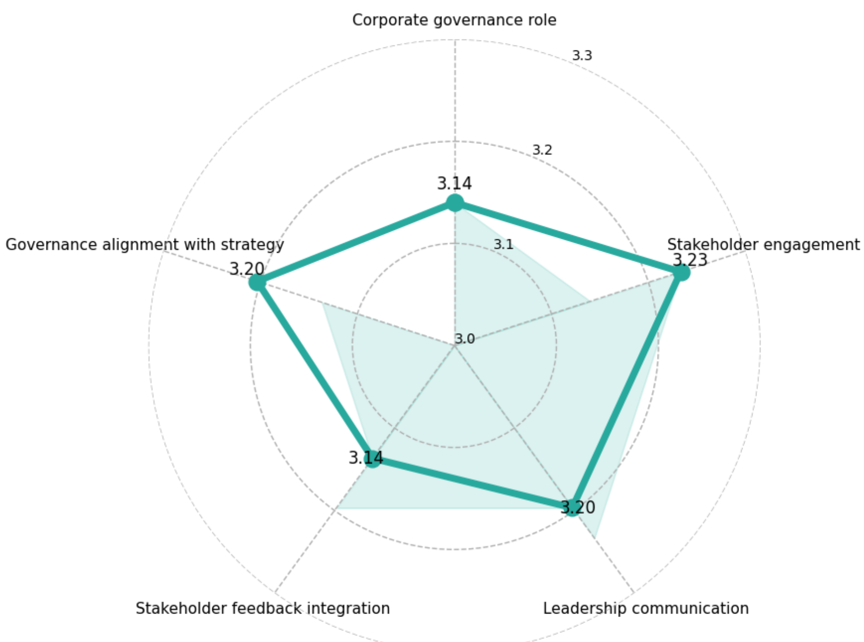


Figure 4. 13: Rank (Weighted mean) distribution of what Role Do Corporate Governance and Stakeholder Engagement Play in Advancing the Adoption of Industry 4.0 Technologies

To determine the descriptive statistics of the items, statistical tests were performed on the data. The table and graph above provide a summary of the mean, standard deviation, and rank (based on mean score) for each maturity item.

The table makes it clear that corporate governance—such as board participation and policymaking—plays a big part in implementing Industry 4.0 technologies. Decisions on the use of technology are influenced by regular interaction with stakeholders, including as suppliers, customers, and employees. Leadership's clear explanation of Industry 4.0 adoption objectives and advantages has inspired employees and the integration of Industry 4.0 has been accelerated (mean above 3.0) by the linkage of corporate governance with technology adoption initiatives. Stakeholder input and involvement are routinely incorporated into the technology adoption decision-making process, revealing the lowest readiness (mean below 3.1367).

Table 4. 30: Croanbach alpha test ofdistribution of what Role Do Corporate Governance and Stakeholder Engagement Play in Advancing the Adoption of Industry 4.0 Technologies

<table>
<tr><th>Variables</th><th>Cronbach's Alpha</th><th>N of Items</th></tr>
<tr><td>“Corporate governance (e.g., board involvement, policy setting) has a significant role in adopting Industry 4.0 technologies”</td><td rowspan="2">0.928</td><td rowspan="2">5</td></tr>
<tr><td>“Regular engagement with stakeholders (e.g., employees, suppliers, customers) influences technology adoption decisions”</td></tr>
</table>

"Clear communication of Industry 4.0 adoption goals and benefits from leadership has motivated the workforce"		
"Stakeholder feedback and involvement are regularly integrated into the decision-making process for technology adoption"		
"The alignment of corporate governance with technology adoption strategies has accelerated Industry 4.0 integration"		

Interpretation: Cronbach's alpha measures internal consistency, or the extent to which a collection of elements are commonly related to one another. It is acknowledged as a scale reliability metric. Cronbach's alpha increases with the number of items. Additionally, if the average inter-item correlation is low, alpha will also be low. When the number of items stays the same, Cronbach's alpha increases according to the average inter-item correlation.

The validity of the data is shown by our study's surveys on the role that stakeholder engagement and corporate governance play in promoting the adoption of industry 4.0 technologies (0.928).

Table 4. 31: Kolmogorov Simornov test

Variables	**Test statistics**	**Asymp. Sig. (2-tailed)**
"Corporate governance (e.g., board involvement, policy setting) has a significant role in adopting Industry 4.0 technologies"	5.096	0.000

"Regular engagement with stakeholders (e.g., employees, suppliers, customers) influences technology adoption decisions"	4.794	0.000
"Clear communication of Industry 4.0 adoption goals and benefits from leadership has motivated the workforce"	4.726	0.000
"Stakeholder feedback and involvement are regularly integrated into the decision-making process for technology adoption"	4.569	0.000
"The alignment of corporate governance with technology adoption strategies has accelerated Industry 4.0 integration"	4.54	0.000

Together with a degrees of freedom parameter, the test statistics generated by the Kolmogorov Smirnov test are used to check for normalcy. Here, we observe that for every variable taken into consideration for the role that corporate governance and stakeholder engagement play in promoting the adoption of industry 4.0 technologies, the Kolmogorov-Smirnov statistic takes value is more than 4.

The SPSS-provided p-value, which is reported as p <.001 and cited under Sig. for Kolmogorov-Smirnov, is.000. The null hypothesis (Role Do Corporate Governance and Stakeholder Engagement Play in Advancing the Adoption of Industry 4.0 Technologies) that the variable has a normal distribution is thus strongly refuted by the findings.

4.4 Summary of Findings

This study examines the adoption, challenges, impacts, and strategies related to Industry 4.0 technologies in the Indian pharmaceutical sector. The research is based on a survey of 300 respondents, representing a diverse workforce in terms of age, gender, education, job roles, and experience levels. The majority (60.7%) of respondents were between 25-44 years old, reflecting the active workforce driving Industry 4.0 adoption. The gender distribution was predominantly male (80%), indicating a workforce imbalance. In terms of education, over 60% held a bachelor's degree, and 35% had postgraduate qualifications, suggesting that most respondents possessed the necessary technical expertise. Additionally, over 60% had more than 10 years of experience in the pharmaceutical sector, and 67% had prior exposure to Industry 4.0 technologies, indicating a workforce with significant experience and familiarity with digital advancements. The study explores six key objectives, providing insights into technology adoption, existing barriers, economic and environmental impacts, policy influences, and governance roles.

The first objective assesses the current adoption levels of Industry 4.0 technologies. The findings indicate that cloud computing (177 companies with high implementation), AI (182 with high implementation), and big data analytics (195 with high implementation) are widely adopted. However, smart products (82 with full implementation), mobile devices and wearables (91 with full implementation), and intelligent sensors (80 with full implementation) have lower integration. Software systems such as ERP and MES (201 with high implementation) are well established, while block chain (129 with full implementation) and augmented reality (99 with full implementation) remain emerging technologies.

The second objective identifies challenges hindering Industry 4.0 adoption, including financial, technical, and organizational barriers. The most critical challenges reported include high capital investment (69 respondents rated it most important), lack of awareness (91 rated it most important), IT security concerns (101 rated it most important), and interoperability issues (129 rated it most important). Additionally, resistance to change (68 rated it most important) and a shortage of skilled labor (69 rated it most important) highlight the need for workforce training and structured implementation strategies.

The third objective examines the economic and environmental impacts of Industry 4.0 adoption. The study found that reduced energy consumption (100 respondents rated it as a significant impact), lower carbon emissions (90 rated it as a significant impact), and improved resource efficiency (109 rated it as a significant impact) were among the key environmental benefits. On the economic front, cost reduction in production and operations (79 rated it as a significant impact) and increased business opportunities (130 rated it as a significant impact) were key advantages. However, waste management and recycling practices remain underdeveloped (68 rated it as a significant impact), highlighting the need for sustainability-focused initiatives.

The fourth objective explores actionable strategies to overcome barriers and facilitate Industry 4.0 adoption. The most effective strategies identified include improving internal awareness (118 respondents rated it highly effective), enhancing cross-departmental collaboration (121 rated it highly effective), and phased implementation (121 rated it highly effective). Employee training (91 rated it highly effective) and collaboration with technology vendors (80 rated it highly effective) also ranked highly. However, government incentives and infrastructure development were rated as less effective (government subsidies had 84 rating it highly effective, but 136 rated it slightly effective), suggesting that private-sector initiatives play more significant role in Industry 4.0 adoption.

The fifth objective evaluates the impact of government policies, particularly Digital India and Make in India, on Industry 4.0 adoption. The Digital India initiative had a strong influence on technology adoption (121 respondents rated it as a strong influence), while Make in India supported local manufacturing (107 rated it as a strong influence). However, tax incentives and infrastructure policies had limited success (only 81 rated government subsidies as a strong influence, while 156 rated it as slightly influential), suggesting that better execution of these policies is necessary to drive adoption across industries.

The final objective examines the role of corporate governance and stakeholder engagement in Industry 4.0 adoption. The study found that corporate governance and leadership involvement play a significant role (99 respondents rated board participation as a key role). Regular engagement with stakeholders (106 rated it as a key role) and leadership communication of Industry 4.0 goals (99 rated it as a key role) also strongly influenced adoption. Additionally, incorporating stakeholder feedback (95 rated it as a key role) and aligning corporate governance with technology adoption strategies (100 rated it as a key role) helped accelerate Industry 4.0 integration.

These findings collectively highlight the current state of Industry 4.0 adoption in the Indian pharmaceutical sector, emphasizing the need for strategic investments, workforce development, and collaborative governance to overcome barriers and maximize the benefits of digital transformation.

4.5 Conclusion

This study provides a detailed assessment of Industry 4.0 adoption in the Indian pharma sector, highlighting its current implementation status, key challenges, economic and environmental impacts, policy influences, and governance roles. The findings indicate that while technologies like AI, cloud computing, and big data are widely adopted, others such as block chain, smart products, and augmented reality remain underutilized. Several barriers persist, particularly high capital investment, IT security concerns, workforce skill gaps, and resistance to change, which require targeted interventions.

Despite these challenges, Industry 4.0 has demonstrated significant benefits, including cost reduction, energy efficiency, and operational optimization. However, sustainability efforts, particularly in waste management and recycling, require further development. The study identifies effective strategies such as phased implementation, employee training, and cross-departmental collaboration as critical to overcoming these barriers.

Government initiatives like Digital India and Make in India have positively influenced Industry 4.0 adoption, but tax incentives and infrastructure policies require better execution to enhance accessibility and effectiveness. Corporate governance and stakeholder engagement also play a critical role, with leadership support, clear digital transformation goals, and active stakeholder involvement accelerating adoption.

In conclusion, while Industry 4.0 adoption is advancing in the Indian pharmaceutical sector, strategic investments, policy improvements, and stronger governance frameworks are essential for its full-scale implementation. Future research should focus on long-term impacts on efficiency, sustainability, and competitiveness, providing deeper insights into optimizing digital transformation for industry-wide growth.

CHAPTER V

DISCUSSION

5.1 Discussion on Demographic Distribution

Interpreting the survey data within the context of this Industry 4.0 technology adoption requires knowledge of the age demographic distribution of the respondents. A substantial portion of the workforce is maintained in active participation in the operational/strategic roles in what is arguably the single most prolific age range in the workplace (25-54), encompassing both early and mid-career professionals. The distribution of the survey responses implies that the responses are related to the views of people directly or indirectly engaged in the technological changes at work in the pharmaceutical sector. Such a link is also reinforced by the significant representation of 25-34 and 35-44 age groups, representing a stage in their careers that is commonly characterized by the higher openness to new technologies: openness to Industry 4.0 technologies might be higher among members of such group. If their responses reveal what they believe are the accepted and practical applications of these technologies in their work surroundings, they may respond, on the one hand, that using these technologies is viable, and on the other, that these technologies are being accepted by them.

5.1.1 Discussion of Gender Distribution

The respondents' gender distribution, indicating one in which the majority are male, indicates the potential for a gender imbalance in sectors of the pharmaceutical industry that were a part of our study. The disparity in questions the equality of access to opportunities of engagement with Industry 4.0 technologies for men and women. Moreover, this may imply that the views collected involve more of the male workforce’s experience and attitudes relating to these technologies. Decoding this inequality is paramount to effectively designing strategies for inclusivity and equal participation of technology adoption and technology innovation initiatives in the industry.

5.1.2 Discussion of Educational Background Distribution

The respondents' educational background shows that there is a large number of highly educated people, with over 95% of respondents having at least a bachelor degrees. This is relevant as it casts a workforce that may be prepared enough to comprehend and roll out Industry 4.0 technologies. The high percentage of respondents with advanced degrees may also suggest that it takes a great deal of education to incorporate these technologies, resulting in the shape of educational programs that meet industry needs. Along with this, the respondents' advanced educational profile could be accounting for their readiness and skill at adaptation to technology advancements, which may lead to lowered pace and scope of the adoption of Industry 4.0 across the industry.

5.1.3 Discussion of Position Distribution in Company

The position distribution of respondents indicates global engagement with Industry 4.0 technologies across the company hierarchy. Furthermore, the findings of this study are informed by a substantial representation of executive and midlevel and senior management positions who account for nearly 69% of the survey population, which likely indicates that these respondents’ potential decision-making natural power, and direct involvement in adopting technological strategies, is not modest. Despite this, the relative lack of representation of R&D personnel leads to questions about the extent to which the adoption of these technologies is a direct by product of the input of innovation focused staff.

Additionally, the large proportion of respondents located in executive and senior management levels may contribute to addressing the strategic priorities and get the leadership prepared to use Industry 4.0 technologies in their operational practices. At the entry-level, however, employees have some perspectives of their own about how these technologies were received and the practical challenges faced with adoption.

5.1.4 Discussion of Departmental Distribution

Substantial exposure to Industry 4.0 technologies of monitoring and product standards and compliance is indicated through the departmental distribution of respondents, concentrating in Quality Control. The need for Quality Control can be due to the industry’s priority on precision, reliability and compliance with the regulatory standards, which are aided by technological development.

This strong representation from R&D and Sales and Marketing departments is strong evidence about the influence of Industrial 4.0 on enabling innovation and enhancing market strategies and customer interaction. On the other hand, the fact that many of them were in IT and Tech support reflects the principle foundational role these department play in efforts to facilitate and manage technological integration.

5.1.5 Discussion of Departmental Distribution

It is worthy to note that the respondents are distributed on a departmental basis with Quality Control appearing to be the most, suggesting a firm engagement in the use of Industry 4.0 technologies both in monitoring and ensuring product standards and compliance. The industry's focus on Quality Control may be a result of the industry’s obsession with precision, efficiency and adherence to regulatory standards that are served through advanced technological implementations.

As well, the presence of substantial representation in R&D and Sales and Marketing departments indicates Industry 4.0's potential for accelerating innovation and enhancing the processes that transform industry marketing strategies and customer interactions. At the same time, the tangible number of people in IT and Tech Support substantiates the basic role of these departments in supporting and managing the establishment of technology.

5.1.6 Discussion of Experience Distribution in the Pharmaceutical Industry

From the years of experience within the respondents, there is a clear level of industry knowledge as 60% of the respondents have more than 11 years of experience together. This implies that most of the survey population does not consist of newcomers who are likely to have the least amount of experience with the development and unification of new technologies into their industry. Through its long term insight, the company can help understand the historical and developmental impact of these technologies on the industry. On the other hand, the respondents with less than one year of experience are 20.33% and in addition to that they can also give different perspectives from which people can adopt the new curricula of the educational systems as well as modern attitudes towards technology working in organizations. Although smaller, representation of respondents with less experience is important to reflect the current educational focus on new technologies and the immediate application of these technologies in the industry setting.

5.1.7 Discussion of Experience with Industry 4.0 Technologies

Intuitively, our respondents have a relatively high level of prior experience in Industry 4.0 technologies, and 36% classify themselves as experts. It implies this technology is well incorporated in some sectors of the pharmaceutical industry, where many people have five or more years experience and, possibly, contributed to the consolidation of efficient operations and innovation. Ongoing adoptions and learning curves associated with these technologies are shown by 31% represented by the intermediate group and 20.3% represented by the beginner group. These groups indicate that while there is a strong base of experience, the ongoing development and adaptation are also happening as more employees become proficient over time. Twelve point seven percent (12.7%) of respondents have no experience with Industry 4.0 technologies and they rate areas that are either slow to adopt or yet to adopt Industry 4.0 technologies in their operations. This is a group with a lot of leverage for targeted, focused training and development programs that improve the whole technological base of the industry.

5.2 Discussion on Objective wise analysis

5.2.1 Evaluate the Current Adoption Levels of Industry 4.0 Technologies

Across different areas, the adoption of Industry 4.0 technologies varies greatly owing to the complexity and diversity of industrial priorities and capabilities. High levels of adoption in such core technologies such as Cloud Computing and IoT is a testimony to their intrinsic importance in improving operational efficiency and enabling efficient data exchange. Modern industrial practice cannot exist without these technologies, which act as the backbone for connectivity and real time decision making. This strong uptake of these technologies shows that they are becoming mature and have value in many industries.

Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR) are proliferating. Their integration implies that interactive experiences and advanced visualization techniques are becoming important for tasks involving precision, like training simulations and operational planning. Stepping out of the realms of exploratory development into practical applications, these technologies are a potentially powerful force for industries to rethink the way they do business.

Yet not all Industry 4.0 technologies are equally adopted. Lower levels of adoption of such technologies as Smart Products Technology and Intelligent Sensors, Actuators and PLCs suggest that there is more work to be done. However, challenges in the form of large amounts of investment, technical skills, and compatibility with current systems could be to blame for these technologies lacking in the lower readiness. It is crucial to address these gaps for the global industry to be fully integrated with the different types of Industry 4.0 technologies.

Finally, the descriptive analysis complements the lack of maturity of different technologies. The industry prioritizes connectivity and data management, both of which enjoy high adoption rates for Cloud Computing and IoT. On the other hand, although industries are quick to recognise the potential of technologies such as AR and VR, their adoption is still slow, which may suggest that they are still in progress of implementation. To bridge these gaps and realise their full potential, strategic initiatives will need to focus on technologies in lower adoptions.

Results of Kolmogorov–Smirnov test show adoption levels of Industry 4.0 technologies are not normally distributed. Disparities in adoption show up through nonnormality here with some technologies widely adopted and others adopted minimally. The results indicate that readiness and capabilities for each industry differ. For example, the usage of Intelligent Sensors and Identifiers is highly polarized: some organizations are fully equipped, other organizations have big barriers. To address these disparities, there are strategies that have to be targeted to lagging sectors and technologies.

These results have many implications. The varied adoption levels warrant strategic policy actions that can induce the adoption of the less adopted technologies, by offering barriers such as subsidies or incentives. Ultimately, it would also be wise for companies to think about seminars, training programs made for new technologies that enable their workers to possess the knowledge needed for the process. Moreover, the ubiquitous availability of previously emerging technologies, such as AR, VR and AI provides opportunities for research and development in extending their access and application.

Thus, this study's evaluation of the current Industry 4.0 technology adoption level matches reasonable well with secondary literature findings. Industry 4.0 is primarily about the use of some of such technologies as IoT, Cloud Computing, Big Data and Analytics, and Cyber-Physical Systems (CPS), in their core to facilitate and support new manufacturing practices that bring about significant changes through better connected and automated processes (Frank et al., 2019; Fatorachian and Kazemi, 2018; Roblek et al., 2016). Secondary data demonstrates that IoT enables real time interactions and new collaborative business models, which supports the conclusions of this study that Cloud Computing and IoT are extensively implemented across the entire industrial sector.

In addition, Big Data and Analytics are identified as playing a pivotal role in the processing and usage of the enormous amount of data generated via CPS and IoT, which is in line with this study's conclusion that such technologies are increasingly embracing the industrial operations. The high adoption rates in the primary study depend in part on the integration that such integration facilitates, which in turn enhances decision making and resource utilization.

Monostori et al. (2016) also validate Cloud Computing's capacity for high speed data processing and storage along with the ability to provide access from any location while Fatorachian and Kazemi (2018) note the technology's capacity to support seamless data & information access across cloud network. This matches with what we’ve observed in the widespread adoption of Cloud Computing in the primary data which highlights its major role in Industry 4.0 frameworks.

As in the secondary literature CPS combines the physical and the virtual world by gathering, storing and analysing real tim data, which matches with the primary study findings on the adoption of intelligent sensors and actuators (Kagermann et al., 2013; Monostori, et al., 2016). For the autonomous operations of smart factories, the integration of these technologies are of essence, which implicates on the need for focused adoption strategies that would follow on readiness levels currently lower.

Further, as per both the primary study and secondary literature, the emerging technologies of AR, VR and MR are identified as extremely indispensable in these planning and training simulations, their value and growth is being witnessed and there is a slow adoption from experimental to practical use (Sharma, 2022).

Overall, this study's findings align with the previous studies found in many different scholarly sources who document the varying levels of adoption on Industry 4.0 technologies and how these technologies are playing a role in modernization of industrial operations. It validates this by showing that while foundational technologies such as IoT and Cloud Computing are mature it is necessary to seriously consider the addition of the further adoption of newer technologies, like AR, VR and smart sensors to further reap the benefits of Industry 4.0.

5.2.2 Financial Challenges, Technical Challenges, Regulatory Challenges that Prevent Full Integration of These Technologies

The frequency analysis leads to the range of financial, technical and organizational barriers which hinder the full integration of the Industry 4.0 technologies. One of the most pressing categories of challenge is high capital investment into technology acquisition, infrastructure development, and continual maintenance. A majority of respondents rate this barrier as "Very Important" or "Most Important", indicating the financial burden that it imposes on organizations however resource constrained they may be.

IT security and safety is another major item because it's one of the big barriers because of privacy of data, cyber threats and safety of interconnected systems. And these are all very relevant as we approach Industry 4.0, where increased data sharing and real time communication makes organizations highly exposed to cyber security risks.

As a significant obstacle too it is also stemmed from a lack of awareness about the benefits and implications of those Industry 4.0 technologies. This informational gap indicates that although there is progress made in technology, many stakeholders do not see new technology advantages of this IC technology. This gap must be filled through targeted communications, as well as targeted educational initiatives aimed at fostering informed decision making and adoption.

The process of adopting is further complicated by the absence of standards and reference architectures. Without standardized frameworks, organizations lack compatibility with new, as well as legacy technologies. Like so, a skilled workforce was another major issue hit on as respondents also highlighted the need for training and up skilling programs targeting the bridge of the skills gap and preparing employees to manage advanced systems.

Such underlying infrastructure limitations, e.g. outdated facilities and insufficient digital networks, constitute equally critical challenges as they are at the very basis of enabling technology adoption. Challenges compound with the fact that interoperability makes it difficult to coordinate constructs and communication between new and existing technologies.

The 4th cultural and organizational barrier to change is finally resistance to change or unwillingness to invest in new technologies. This, however, requires the right change management strategies to deal with employee issues and tie organizational priorities to technological objectives.

Further insights into the relative importance of these challenges are provided through the rank-wise descriptive analysis. The primary barrier is the absence of a workforce, making the urgency for workforce development missions in all sectors to mitigate the skill gap. Something similar is recorded regarding poor infrastructure, due to which there are different levels of readiness for different regions or organizations.

Large capital investments are exquisitely high, indicating how financial expensive it is for organizations to adopt the technologies of Industry 4.0. Also highlighted is the role that organizational and cultural barriers, including resistance to change, play in affecting the change, for which leadership driven change management strategies are a must. The rankings end with IT security issues, lack of interoperability and standards, and technical challenges like these that all add up to becoming one thing.

The secondary sources classifying and insights fit well well with the analysis of specific challenges impeding the full integration of Industry 4.0 technologies. The systematic literature review categorizes key barriers to Industry 4.0 transition in scientific, technological, organizational, socio-political and economic dimensions, embracing the view of challenges encountered during industry 4.0 transition (Horváth and Szabó 2019).

The literature identified economic barriers agreeing with the financial barriers in the light of large capital investments needed for technology acquisition and infrastructure development. Common challenges associated with these implementations include high cost of implementation and high financial resources required (Horváth and Szabó, 2019). This emphasizes the need for substantial investment in building smart devices and infrastructure, as well as the big money shown in the main analysis.

Similarly reflected in the secondary data are technical challenges, namely IT security and safety, shortage of standards, and interoperability problem. We believe that a major technological hurdle in realizing smart factory environments lies in the need for commonly accepted standards and reference architectures (Kagermann et al., 2014). Furthermore, the critical of cybersecurity is in line with concerns over unauthorized access and data misuse (Türkeş et al., 2019) as well to due to the increasing threats that are inherent to such systems, and especially in its current state they are interconnected.

The secondary literatures well support organizational barriers such as resistance to change, lack of awareness, and unqualified skilled workforce. The barriers include the question of how to align business models with new technologies while managing the complexity and transformation associated with digital transformation (Fettermann et al., 2018). The literature is consistent with this emphasis on organizational readiness and capability building, and it is consistent with the identified need for extensive training and professional development to prepare employees for high tech environments.

In the secondary sources, socio political barriers that are discussed regarding demographic changes and the possibility of Industry 4.0 manufacturing jobs reshoringdue to automation, provide a context to the cultural and societal barriers to the Industry 4.0. Among others, the impacts envision changes in employment and they necessitate regulatory frameworks in preserving data and guaranteeing safety (Mehta and Awasthi, 2019).

The results of the primary research on Industry 4.0 adoption are expanded to provide an overall view of the identified barriers (in terms of different dimensions the secondary literature also highlights these barriers on). This validation demonstrates that challenge faced are multidimensional and the strategic areas needed to promote broader adoption and integration of Industry 4.0 technologies.

5.2.3 The Environmental and Economic Contributions of adopting Industry 4.0 technologies

While the exploration of environmental and economic impacts of Industry 4.0 technologies has revealed their immense positive impacts in multiple sectors, these enablers hence stand out as pivotal enablers of sustainability and resulting operational efficiency. Based on both primary data and a comprehensive review of the related literatures, this analysis addresses how these technologies reconfigure industrial practices through massive energy consumption and carbon emission reductions, and greatly enhance resource efficiency, in line with global sustainability objectives.

A particular benefit of Industry 4.0 is energy efficiency, with a lot of studies that confirmed that Industry 4.0 technologies like advanced automation and optimization processes are able to reduce drastically wastage of energy. Firstly, it can help in reducing operational cost of industry while supporting broader environmental goal by reducing carbon footprint from industry activity. These outcomes match with Aulbur and Gangal (2017) and the PwC report (2016) findings indicating that the potentials of these technologies lie in their capacity to boost energy efficiency and environmental protection. The fact that these benefits are now broadly understood illustrates the alignment of Industry 4.0 with global efforts to reduce carbon emissions, and makes it a key element of the transition to more climate-friendly industrial operations.

On top of providing environmental benefits, Industry 4.0 technologies lead to economic benefits through the creation of new business opportunities as well as activation of new business models and operational efficiencies. These technologies have been proven to encourage innovation: the ability to create customized products and new service models that open up the market and increase the source of revenues. In his working papers, Müller et al. (2018) and Villa (2018) further emphasize this dimension by showing how digital developments make it possible for companies to introduce better service delivery and customer satisfaction based on new and innovative solutions adjusted to the needs of the markets.

However, the application of Industry 4.0 technologies has resulted in substantial increase in resource management effectiveness. As Arnold et al. (2017) and Kamble et al. (2018) demonstrate, precision monitoring and control are both possible and can improve resource efficiency via waste minimization and material and energy use optimization. Not only does this benefit sustainability, but it also plays a large role in delivering big cost savings, a very important consideration for industries that are trying to get profitable and minimize environmental impacts.

These technologies go further to enhance their impacts on product quality as well as the ability to innovate. Industry 4.0 technologies bring high standards in manufacturing processes and result in product, which meets high quality demands, as documented by Fatorachian and Kazemi (2018) and Gökalp et al. (2017). This creates a competitive advantage for businesses, enabling them to thrive higher in the market and trust the customers as their customers will trust on their products, every time they will deliver superior and innovative products to the customers.

Adoption thereof is not without its challenges however. However, there is variability in the effectiveness of these technologies across different industries and while some organizations reap significant benefits, others cannot fully exploit these technologies' potential. Industry 4.0 therefore needs industry specific strategies to deal with their specific challenges and opportunities so that all economic sectors would be able to properly incorporate Industry 4.0 technologies into their operations.

In conclusion, environmental and economic impacts of Industry 4 technologies are valided through extensive literature and show that these technologies are highly transformative. At the same time, these efforts support global sustainability as well as economic benefits, thereby improving operational and product efficiency, as well as the competitiveness of the market. While industries are still on their way to embrace a new wave of technologies, powerful technological advancements that bring with them change and disruption, there is a need to develop strategies that are tailored to overcome these barriers and enjoy the benefits of these breakthroughs.

5.2.4 Barriers, Propose Actionable Strategies to Overcome them and Enhance Adoption of 4th Generation Industry Technologies

Strategies to broaden the adoption of Industry 4.0 technologies are examined in light of a complex interplay of organizational practices, technological advancements, and policy frameworks: a function of one or the other (or all of them) to varying extents overcomes prevailing barriers. This nuanced analysis, based on data synthesis between primary data and corroborative literature, identifies critical interventions to address the challenges of realizing industry 4.0 in all industrial landscapes.

While many point to the high effectiveness of investment in training and skill development, programs often deliver small impact as many of them are not specific or do not match the specific demands of Industry 4.0 technologies. According to the literature more bespoke training approach is needed, which means programs deeply integrated with real use of technology inside an industry tend to bridge the skill gap more successfully (Fatorachian and Kazemi, 2018). Such targeted training is focused on technical skills but also brings strategic understanding for employees to plan and to master Industry 4.0 processes.

Because collaborative efforts with technology vendors and experts are variably effective, the effectiveness of these collaborations has to do with the alignment between external expertise and specific technological needs and strategic goals of the organization (Kiel et al., 2017). Successful collaborations are not just transactional, but are strategic partnerships which would lead to long term integrations and adaptations of advanced technologies in the organization's operations.

Governments need to provide financial incentives to make new technologies easier to adopt, but those drivers are usually considered insufficient if not complemented by other support measures. But the literature suggests that these incentives should only be part of a larger package of technical support and infrastructure building to effectively work (Rajput and Singh, 2018). An approach like this means that financial barriers aren't the only things being taken into consideration, and substantive adoption hurdles are also addressed.

In this context, Industry 4.0 demands high requirements in this area, and rests on interconnected systems and data exchange, so a strong background in robust IT infrastructure and cybersecurity measures is a must. In the conditions of Industry 4.0, the complexity of cybersecurity makes sophisticated solutions needed that extend traditional IT security frameworks and address the vulnerabilities that emerge from the highly integrated networks (Kamble et al., 2018).

Industry standards and reference architectures come to play a vital role in having Industry 4.0 technologies interoperable and efficient. Though the benefits of these standards are often not immediately obvious to all stakeholders, more effective communication, and effective demonstration of how these standards add real value to stakeholders in this sector (Luthra and Mangla, 2018).

Growth of the organizational culture receptive to Industry 4.0 technologies necessitates the implementation of strategies and procedures that put in place internal awareness and education of the potentials and operations of Industry 4.0 technologies. With appropriate educational and internal marketing of the benefits and strategic importance of these technologies, resistance can be lowered and engagement can increase, across the workforce (Oesterreich and Teuteberg, 2016).

An effective risk management strategy is advocated for the phased, incremental implementation of Industry 4.0 technologies which allows organizations to respond and learn incrementally. In particular, this approach is relatively well suited for scaling and complexity of digital transformation in industrial settings, allowing companies to learn and adapt their strategy iteratively (Türkeș et al., 2019).

In other words, industry 4.0 adoption, as in any organizational change, requires the application of multiple strategies that vary by their degree of generality (complexity), its level of specificity (their linkage to context), and the necessary tailoring (capacity and willingness to adapt) to fit the organizations' specific faults and opportunities. Overcoming the barriers to adoption requires that these strategies be aligned with internal capabilities and external technological developments. An adoption of a holistic and strategic approach to deploy Industry 4.0 technologies allows organizations not only to enhance their operational efficiency, but also to spur innovation and maintain competitive advantage in the fast-digitalizing industrial boundary.

5.2.5 Barriers and Propose Actionable Strategies to Overcome Adoption of 4th Generation Industry Technologies

Discussion of the Effect of Government Policy on the Industry 4.0 Adoption

The study finds that the adoption of Industry 4.0 technologies as well as the uptake to regulatory standards has not been significantly affected by government initiatives such as Digital India and Make in India. The medium to high level of influence by Digital India initiative on technology adoption is reflected across majority of the respondents. More advanced technologies are being broadly implemented under the patronage of this initiative relying on improvement of online infrastructure and internet connectivity. Nevertheless, the differing degrees of impact across regions and sectors suggest that even though the initiative has accomplished what it has, its coverage and efficacy has been uneven.

While Industry 4.0 launched the Make in India initiative, it has not received unanimous positive feedback on its role in enabling local manufacturing capacity to contribute to the realization of Industry 4.0. Although many respondents observed a powerful effect, a significant number justified a modest effect, indicating a mismatching between the broader objectives of the initiative and the precise technological requirements of various industries as they undergo a shift to more advanced manufacturing processes. Government subsidies and tax incentives were also seen as beneficial; however, their limited effectiveness points to a number of problems with regard accessibility, adequacy and awareness. They clearly do not put forward a serious effort to cover all the explicit and implicit upfront costs and ongoing burdens that encompass Industry 4.0 integration, let alone contemplate the global final benefit derived from such paths.

In terms of delivering policy support for infrastructure and internet connectivity, this has had limited effectiveness reinforcing the central role of digital infrastructure as an enabler of technology upgrades. Responses, however, bring forward how infrastructure development remains skewed in underserved regions, highlighting the need for further and more equitable investments. Generally, environmental regulations directed sustainable practices, but the impact perceived was very broad. The variability reflects inconsistent enforcement and sector specific difficulties complying to sustainability mandates.

Overall, it was found that these policies offer a good umbrella to move towards advancing Industry 4.0 adoption and environmental compliance however specific areas of improvement were identified. Specific barriers can be tailored strategies that address them and maximize their impact, as the strategies should align policy objectives with the needs of diverse industries.

On Rank-wise Descriptive Analysis of Policy Influence

The descriptive analysis of different government efforts, done by rank, presents some valuable information regarding the perceived effectiveness of those initiatives. Skepticism about the efficacy of government subsidies and tax incentives are indicated by a mean around 3.0 and below, ranked lowest. Large variability in responses indicates that barriers to accessibility and applicability of these incentives undermine potential benefit. Just slightly more effective, environmental regulations also bear resemblance to the same inconsistencies, indicating a need for clearly outlined rules and the enforcement of more tight controls.

The fact that some policy support for improving infrastructure and internet connectivity goes slightly higher than others is because of the central role of digital infrastructure in driving Industry 4.0. While this moderate performance suggests they continue to limit gaps in regional infrastructure development that would enable its full potential. The Forth ranked Make in India initiative highlights the importance of helping developing Industry 4.0 based local capabilities. It is generally well received, though its impact is uneven and probably sectoral differences in readiness and support.

The ranking of highest mean of 3.9133 of the Digital India initiative show its strong impact on technology adoption. We can see its sustained positive reception as an indication of the effectiveness of the investments in digital infrastructure that have prompted technological upgrades. Still, even in such a highly regarded initiative, response variability suggests there is an opportunity for improvement in how this initiative ensures equitable and pervasive impact across regions and sectors.

These results suggest that more targeted and sector specific approaches to policy implementation are needed. This analysis can help bridge these gaps through strengthening policy frameworks, improving access to financial incentives as well as maintaining a steady infrastructure development. Furthermore, mechanisms for providing continuous feedback to promote the relevance and effectiveness of government supported Industry 4.0 technology and environmental compliance initiatives can be developed as part of this approach.

The varying impact of governmental policies like Digital India and Make in India on the adoption of Industry 4.0 technologies and environmental compliance is discussed. Digital India has effectively helped in wider adoption of advanced technologies in different domains. This initiative is given its due for moderate to strong influence on technology adoption since the initiative is an integral part of India's digital transformation strategy. Nevertheless, there are gaps in influence across various places and sectors, which echoes the result that this type of strategic initiatives, such as Germany's Industrie 4.0 and China's Made in China 2025, also highlight, of bolstering manufacturing capacity by improving digital and infrastructural utilization.

The Make in India is a mixed success in that it intends to increase local manufacturing but has been less effective in achieving that. However, these varied impacts among respondents suggest possible misalignment between the initiative's goals and the industry level needs of those industries that are moving to Industry 4.0. This is consistent with wider issues pertaining to international contexts where industrial policies may not always reflect neatly with particular sector-level technological developments (Kagermann et al., 2014).

In the same way, it is assumed that government subsidies and incentive policies do not have significant effects in promoting technological upgrades, and this is attributed to the limitations in accessibility, adequacy and applicability to real costs of Industry 4.0 technologies. This parallels global trends where financial supports are not always capable of bridging the many diverse barriers to technology integration (Mehra et al., 2017).

The analysis also suggests variability in the efficacy of environmental regulations, which define and influence sustainable behavior, and which are inconsistently policed and have sectoral impacts. The second area is the need for clearer, more adaptive to industry specific conditions regulatory frameworks and enforcement mechanisms that may be globally recognized in the adoption of new technologies in regulated sectors.

Further descriptive analysis of the rank wise treated these initiatives for perceived effectiveness. Financial incentives and environmental regulations are cited as areas of the highest variability and skepticism in the areas of difference between policy and policy execution. However, while highest in terms of positive impact upon technology adoption, Digital India fares better than the previous two schemes, but still shows weakness in the area of uniform effectivity.

Reliability and distribution tests, such as Cronbach's alpha and Kolmogorov-Smirnov, sustain that the collected data about Digital India and about accessibility on one hand and unavailability on the other hand are internally consistent. Results indicate that although some policies are very well received, the overall perception and effectiveness of government initiatives are highly diversified and that the implementation of government policies combines policy design, implementation strategies and sector-specific dynamics.

Taking the broader picture, Digital India and Make in India are both solid frameworks for technological advancement and environmental compliance, but the effectiveness of the policies in achieving these objectives are patchy, which suggests the need of more tailored, industry specific policies, better aligned with the wide variety of industry needs. Policies need to be continuously adapted and refined to serve the diverse needs of industry 4.0 adoption and can't do so unless leadership aligns its process and technology with the continuous improvement stages of the implementation of assets, departments of the business, and other units sharing responsibility in planning and deployment.

5.2.6 Corporate Governance and Stakeholder Engagement Contributes to Adopting the Technology of Industry 4.0

The analysis identifies the extent to which the recourse to corporate governance and stakeholder engagement constitutes a way to promote Industry 4.0 technologies. Many respondents make clear that corporate governance, in the concept of board involvement and setting of policy, is a major driver of uptake. This high-level support for leadership in setting strategic priorities, reallocation of resources and formulation of policies towards technological innovation is underscored. Yet the variability of responses – with many organizations seeing governance as playing only a peripheral role – implies that there is some way to go to align governance structures with Industry 4.0 goals in all firms.

However, engagement of another regular stakeholder group – employees, suppliers and customers – turns out to be another very important factor. Several respondents noted that it helped shape technology adoption decisions, and urged focused effort to develop collaborative relationships and incorporate perspectives. While engaged, however, the effectiveness of engagement appears to vary widely with some organizations not fully leveraging stakeholder input. This also identifies a motivating factor for the workforce being clear communication of Industry 4.0 goals and the benefits that can be derived from it from the leadership. A moderate level of agreement across respondents demonstrates further room for improvement in the communication strategies employed and transparent and consistent messaging builds employee buy in as well as reducing resistance to change.

The author refers to stakeholder input and involvement in decision making as vital to the tailoring of adoption strategies to needs and conditions that are specific to it. While important, this practice is yet to become standard in most organisations and is still not perceived as a major role by the large numbers of respondents who think so. Additionally, it highlights corporate governance alignment to technology adoption strategies as a critical enabler of Industry 4.0 integration. Many organizations still struggle, however, to align efforts at the level of a cohesive governance framework that prioritizes and supports technological transformation.

Although industry 4.0 research deserves attention, consequently corporate governance and stakeholder engagement play a critical role in the adaption of industry 4.0 technologies as evidenced by broader research trends on integrated governance and comprehensive stakeholder involvement in technological transformations (Liao et al. (2017). The results show that strong corporate governance comprised of active board involvement and strategic policy setting is important. These findings corroborate those of Kagermann et al. (2014) who suggested that leadership is necessary to orientate the organizational strategy with technological advancements in their steering the agendas of digital transformations such as Industrie 4.0 in Germany.

In line with the mixed perceptions of the effectiveness of stakeholder engagement, broader industry practices show that successful digital transitions rely fundamentally on the collective work of all stakeholders as well including employees, suppliers and customers (Bienhaus and Haddud, 2018). This is especially important in industries whose supply chains are complex, and whose technological dependence is high. The variation in the results of stakeholder engagement indicates the need for a more structured way in which we could improve integration and take advantage of different perspectives that stake holders are able to bring to the table.

And perhaps more so than anything, we focus on the need for clear, easy to understand communication and the need for stakeholders to be involved in the decision-making processes. By aligning these processes with corporate governance structures, technology adoption strategies will be much more adaptable and effective (Bodrow, 2017). Unfortunately though, the current inequities in how well an organization aligns its governance with its technology strategy indicate a divide, like the findings of Horstkemper and Hellingrath (2016) that the alignment of strategy and operations is critical to the flexibility and responsiveness of the supply chain with respect to Industry 4.0 technologies.

In addition, the analysis points to the strategic implications of governance and engagement practices, indicating that organizations with well-integrated and proactive governance frameworks will be more successful in undertaking their digital transformation initiatives. This is congruent with the major determinant of readiness and capability for such a substantive change as it is identified by Kohlegger et al. (2009), namely the maturity level of an organization.

In short, successful adoption of Industry 4.0 hinges on the alignment of corporate governance with the technological strategies and active and structured engagement with stakeholders. The study advocates for stronger focus on these issues in strategy, and suggests the need for organizations to have clear communication strategies, strong governance frameworks, and good stakeholder engagement to navigate the complexities involved in adopt Industry 4.0. The utilization of tools such as maturity assessments for the consistent evaluation of governance and engagement strategies can help organizations see which strategies are proving effective and which can be refined to bring the best value to integration of Industry 4.0 technologies.

5.3 Case Studies

5.3.1 Case Study 1: Orion Corporation

Leveraging Industry 4.0 Technologies for Enhanced Environmental Sustainability in the Pharmaceutical Sector (www.orionpharma.com)

Orion Corporation from Espoo, Finland has effectively implemented Industry 4.0 technologies in order to enhance environmental standards in pharmaceutical production. Easyhaler® DPI was designed not only as a response to the ozone depletion regulation by the Montreal protocol, which has banned several substances including chlorofluorocarbons (CFCs), but also to have digitally integrated and data analysis based modern techniques that are characteristic of Industry 4.0. These technologies facilitate in systematic evaluation and minimization of environmental effects of products that Orion deals in.

For six forms of Easyhaler namely budesonide-formoterol, salmeterol-fluticasone, salbutamol, formoterol, budesonide, and beclomethasone, Orion in the year 2021 conducted Carbon Footprint LCA. It has been carried out by Carbon Footprint Ltd which is an independent organization that is used to validate the information provided. According to IMA, it took Orion to gather point I 4.0 digital analytics to gather acres of data from the procurement of raw materials for making the inhalers to the manufacturing, sales, usage, and disposal of the inhalers. As indicated this assessment brought out that manufacturing processes account for approximately 63 % of the overall impact of the inhalers on the environment, an area that needs to be addressed for greater sustainability. On the other hand, the evaluations provided by the digital monitoring suggested that emission costs in distribution were below 2% proving the effectiveness of the actual manufacturing processes.

Digital technologies made it possible to estimate the average carbon footprint of the Easyhaler products to be 0.580 kg CO_2e per unit; however, the values slightly fluctuated within 0.484–0.650 kg for various types. This is significantly better positioned compared to MDIs which are known to have a 10-37 times CO2 emissions from the HFC propellants. They will further strengthen the description of Orion’s sustainability activities, strengthen its credibility both to the stakeholders, physicians, and patients who are more conscious of the environmental impact of the company and its products.

Environmental Impact Distribution of Easyhaler Production:

1. Short standing, a minimal impact and aimed at components required for manufacture of API and carriers (0.1%).
2. **Raw materials transport (1.9%):** Small environmental cost due to the logistics of transport of the raw materials.
3. **Packaging materials from inhaler components and such (24.5%):** This category has small impact on resources used and waste produced of producing inhaler components and packaging materials.

4. **Material transport (1.6%):** Very similar to product distribution.
5. It also shows that disposal processes (9.6%) are marked as significant, indicating the importance of having better waste management.
6. As a considerable impact, the assembly of the final product and the packaging of it to ship from the factory.

Even product design is secondary to the wider environmental management strategy that ORION puts in place. It includes reducing manufacturing's reliance on renewable energy sources, enhancing the sustainability and being more transparent in the supply chain, and wastewater treatments. These initiatives emphasize that Industry 4.0 technologies can significantly and measurably effect sustainability outcomes in the pharmaceutical industry. We also provide insights of Orlion case that can be adopted by other pharmaceutical companies seeking to have a similar impact in reducing their environmental footprint through technological innovations.

5.3.2 Case Study 2: Pfizer CentreOne

Leveraging Industry 4.0 Technologies for Enhanced Environmental Sustainability and Patient Outcomes (www.pfizercentreone.com)

As a standard bearer for pharmaceutical industry adoption of Industry 4.0 technologies, Pfizer CentreOne has become one of the industry's leading providers for commercial scale technologies. This is a new beginning aligned with Pharma 5.0 idea of bringing in digital innovation, Artificial Intelligence (AI), Machine Learning (ML), and system automation and creating more sustainable business and patient outcomes. In his description of Pharma 5.0, Tom, Global Contract Manufacturing Lead at Pfizer CentreOne, describes Pharma 5.0 as a new way for the industry in which he advocates for the operational efficiency, environmental sustainability and patient centered solutions.

Given the rise of pharmaceutical expenditures to $1.9 trillion globally in the next five years, the need for the rapid, efficient, and sustainable production processes is more urgent than ever. In response to this, Pfizer CentreOne has recently invested heavily in generative AI and advanced analytics to become a part of the Pharma 5.0 strategy. However, industry forecasts indicate that the pharmaceutical companies will invest between $50 billion and $50 million on deployment of AI and ML solutions in the next 10 years. These investments are intended to speed up the work one has to do to develop a drug, to streamline the manufacturing process and to reduce significantly the environmental impacts (Pfizer CentreOne, n.d.).

Several areas of Pfizer's manufacturing operations have been adopted by Pfizer using advanced digital technologies. It includes ML based techniques of predictive maintenance, anomaly detection and real time visual inspection using AI. One notable use of digital twin models is that Pfizer employs virtual replicas of physical processes known as digital twin models that enable effective production efficiency optimization, product quality improvement, and waste minimization. These models enable methodical monitoring in real time so that anomalies can be detected early, decrease energy, and cut carbon emissions from traditional manufacturing processes (Pfizer CentreOne: n.d.).

Automated robotic handling and inspection systems are one of the most significant implementations of Industry 4.0 at Pfizer across global manufacturing sites. For these kinds of tasks, such as loading and unloading materials, or performing automated visual inspections, or assembly and packaging operations, these robots are involved. Operation efficiency and accuracy has been increased with automation, resulting in drastic cut of material waste and energy consumption. As an example, a material waste reduction of 70% and energy use decrease of 35 percent can be demonstrated in Pfizer's internal performance analysis (Pfizer CentreOnen.d.).

Key findings from this case reveal that the implementation of **Pharma 5.0 technologies**, including AI, ML, and robotics, has driven substantial improvements in sustainability and efficiency. **Material waste** was reduced by **70%**, **energy consumption** decreased by approximately **35%**, and **operational efficiency** saw a **50% boost** compared to pre-Pharma 5.0 manual processes. These results highlight the transformative potential of intelligent automation in pharmaceutical manufacturing.

Pfizer's agility and speed in the market response were accentuated by its Industry 4.0 investments during the COVID-19 pandemic. Under Pfizer's Integrated Manufacturing Excellence (IMEx) system, digital twin models, automation and AI analytics reduced drug development timelines to the extent of speeding up the production and distribution of vaccines globally (Pfizer CentreOne, n.d.).

Finally, the strategic implementation of Industry 4.0 technologies practicing by Pfizer CentreOne show not only a high degree of environmental benefits but also a major role on improving patient care in the country. Pfizer takes the lead in steering pharmaceutical industry towards more responsible and efficient future, and this case study is evidence to that.

CHAPTER VI

SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

6.1 Summary

This thesis looked at the adoption of Industry 4.0 technologies in the Indian pharmaceutical industry, and how they are integrated, the associated challenges, impacts on environment and economics and ways to overcome these barriers. Combining quantitative primary data at two camps with secondary literature, the analysis guided by six research objectives has produced actionable insights.

We find substantial variation in adoption rates of Industry 4.0 technologies, with initial foundational technologies like Cloud Computing and IoT high uptake and emerging technologies such as AR and VR underutilized. The study revealed hurdles to adoption of S&OP including high capital investment IT security concerns and lack of skilled workforce. Despite challenges, the analysis revealed the massive potential of Industry 4.0 technologies to increase operational efficiency, minimize emissions and optimise resource management with a positive impact on both environment and economy for sustainable growth.

However, the role of governmental policies such as the Digital India and Make in India have had a tremendous influence in the realm of evolutions in technology, although they are not consistent in influencing the scenario in all the regions, sectors. Among the critical enablers corporate governance and stakeholder engagement: leadership, communication, and collaborative decision-making beamed success.

The findings in this research are in line with the current underlying literature on Industry 4.0 adoption and point to the necessity to have meaningfully tailored strategies for its respective niche challenges. Advanced technologies should further boost the benefits of improving the pharmaceutical industry; by utilizing structured governance frameworks, targeted training programs and smart policy measures, it shall be possible for the pharmaceutical industry to overcome difficulties with the use of advanced technologies.

Further substantiation to these findings is made in the case studies of Orion Corporation and Pfizer CentreOne, which present instances where Industry 4.0 technologies have been and can be applied and utilized in the global pharmaceutical setting. The digitization allowed Orion Corporation Easyhaler® product line to significantly reduce its carbon footprint in comparison to traditional processes as the product had to meet stringent environmental standards. Nostra and Pfizer CentreOne utilized its implementation of the most advanced technologies like AI and ML to resolve that problem and created efficiencies in manufacturing as well as significant reduction in material waste and energy consumption.

The case studies showed that Industry 4.0 can bring about a lot of environmental improvement and give pharmaceutical industry a competitive edge. They also point at the need to make strategic integration of these technologies to contribute specific environmental challenges in manufacturing processes.

By validating the theoretical insights with empirical data and making practical recommendations for stakeholders actively working to accelerate Industry 4.0 technology adoption in line with global sustainability commitments, this study enriches academic knowledge.

6.2 Implications

6.2.1 Theoretical Implications

The empirical validation of the theoretical frameworks constructs facilitated by this study contributes significantly to the academic discourse on Industry 4.0 technologies in the context of the Indian pharmaceutical industry. It significantly reasserts the importance of the underlying technologies (for instance, IoT and Cloud Computing, etc) and stresses the sluggishness of the adoption of more recent technologies, such as AR and VR. The findings bridge gaps in the current literature by identifying specific barriers, such as financial constraints, technical complexities, and organizational resistance, which have historically been discussed abstractly. The study brings these challenges into the context of the pharmaceutical industry and proposes insight for future research in global sectors.

6.2.2 Practical Implications

The study highlights actionable insights for industry stakeholders:

1. **Workforce Development:** The results put a large emphasis on the need for targeted training and upskilling to compensate for the skills gap. Industry 4.0 requirements should be coordinated with educational institution curricula by industry stakeholders.
2. **Strategic Investment:** The major barrier has remained financial constraints. What companies should do is to seek partnerships, subsidies, or phased adoption of technology to minimise upfront costs as well as manage the financial risk.

3. **Operational Efficiencies:** The real benefits observed include significantly reduced emissions and resource optimization, which certainly support the adoption of Industry 4.0 technologies. By looking at technologies with proven impacts, like IoT and Cloud Computing, companies can start from that level of integration for broader adoption.

4. **Governance and Stakeholder Engagement:** It is effective leadership and structured stakeholder engagement that will drive successful adoption. Organisations should set up governance frameworks and increase the communication to all (stakeholders) with the accomplishment of objectives through technologies.

6.2.3 Policy Implications

This study also demonstrates how government policies can spur technologiest advancements. Digital India and Make in India have triggered the adoption, but the uneven impact warrants more focused and effective policy design and execution. Policymakers should:

- **Increase Accessibility of Incentives:** Facilitate process of applying for suburbanite y and grant for everyone.
- **Strengthen Infrastructure Development:** It should focus on bridging the gap on digital and physical infrastructure among the regions.
- **Encourage Sector-Specific Support:** Policies should be created to suit the challenges that industries transitioning to Industry 4.0 face.

Collectively, these implications indicate the need for coordinated efforts among government, academia, and industry to drive Industry 4.0 technologies adoption rapidly and promote sustainable industrial growth.

6.3 Recommendations for Future Research

Several recommendations for further research are based on the results and limitations of the present study:

1. Broader Industry Focus

The Indian Pharmaceutical Industry forms the focal point of this study, offering market intelligence on industry 4.0 adoption in the domain. Research could also be expanded to other sectors like the car manufacturing industry or the logistics or health care industry and research if they face different kinds of challenges and how they can be approached. A holistic view of Industry 4.0 integration on a larger scale would be formed through comparative studies across industries.

2. Longitudinal Studies

This study’s cross-sectional design captures current levels of Industry 4.0 adoption in a snapshot. This longitudinal research could help us understand how these technologies have transforming impacts over time by tracking adoption patterns and their evolving benefits. It enables us to learn from the ways organizations navigate challenges as they learn about the outcomes and iteratively refine strategies for maximizing efficiency and sustainability.

3. Exploration of Emerging Technologies

Still this study points to the foundational and emerging technologies while future research could explore under-used areas such as Artificial Intelligence (AI), Blockchain and Augmented Reality (AR). Their barriers to adoption, sector specific applications and long-term benefits would bring in more about their potential.

4. Regional Comparisons

This study also showed that there have been observed regional disparities in the adoption of Industry 4.0 technologies. One avenue for future research then would be to compare trends of adoption across the regions of India or similar regions globally. It would be able to identify factors that contribute to disparities in order to inform region specific policy and strategic interventions.

5. Integration with Sustainability Goals

When sustainability becomes a major business priority, future studies may seek to investigate an interaction between Industry 4.0 adoption and specific sustainability measures. As an example, researchers can discover the direct effect of these technologies on carbon footprint reduction, energy efficiency and waste management.

6. Corporate Governance and Stakeholder Engagement

One lesson from this study is how governance and stakeholder matter. It may also be the topic of future research in terms of evaluating which governance models or stakeholder engagement strategies contribute most in driving towards Industry 4.0 adoption. Good governance frameworks in many organizations are known case studies that could be treated as actionable best practices.

7. Policy Impact Assessment

This study suggests the impact of the sort of policies like Digital India and Make in India but could quantitatively analyze how effective these types of policy has in fact been. In particular, we would advocate examining the consequences of policy changes for adoption rates and outcomes to the extent possible, creating more targeted and effective policy development.

8. Role of Small and Medium Enterprises (SMEs)

Major pharmaceutical companies are largely what this study is focusing on. Future research could also extend the focus to understand how SMEs overcome the unique challenges and opportunities they face with industry 4.0 technologies in adopting and implementing these techs when they have limited resources and strategic priorities.

9. Human-Centric Technology Integration

Since Industry 4.0 technologies will affect the workforce, additional studies may be needed to understand how human centered approaches to the integration of technology, focusing on employee education, well-being, and adaptability, impacts adoption success and organizational outcomes.

10. Interdisciplinary Approaches

Interdisciplinary frameworks combining technological, organizational, economic and sociocultural dimensions could be taken over in future studies. This would yield a multi-faceted picture of Industry 4.0 adoption.

This study lays a foundation for future research to address those areas to push the boundaries of Industry 4.0 technologies across sectors and regions.

6.4 Conclusion

This study presents a detailed analysis of challenges, impacts on the environment and economics of Industry 4.0 technology adoption in the Indian pharmaceutical sector. The research integrates quantitative primary data with secondary literature to provide insights in the state of adoption of Industry 4.0, which aligns with the global drive towards digital transformation and sustainability.

The good news is that the adoption rate of foundational technologies, like IoT and Cloud Computing, is high, providing evidence of wide importance for operational efficiency and connectivity. But the tools such as AR, VR, and smart sensors are underutilized as of yet, and research shows the need for targeted strategies to improve their adoption. Financial constraints, IT security concerns and lack of skilled workforce are the key challenges contributing to the lack of integration, some being key challenges in their own right.

The study emphasizes the transformative capabilities of Industry 4.0 technologies to cut emissions, enhance resource efficiency and stimulate innovation. Policies such as Digital India and Make in India have been positive drivers for adoption however their patchy impact highlights the desirability of more targeted and more industry specific interventions. Successful technology adoption was also driven by corporate governance and stakeholder engagement.

Validating theoretical insights with empirical data and bridging a gap in existing literature, this research contributes to the academic understanding of Industry 4.0. It also suggests practical outcomes for industry stakeholders — from focused training initiatives to phased implementation strategies and better matching governance frameworks to technology targets.

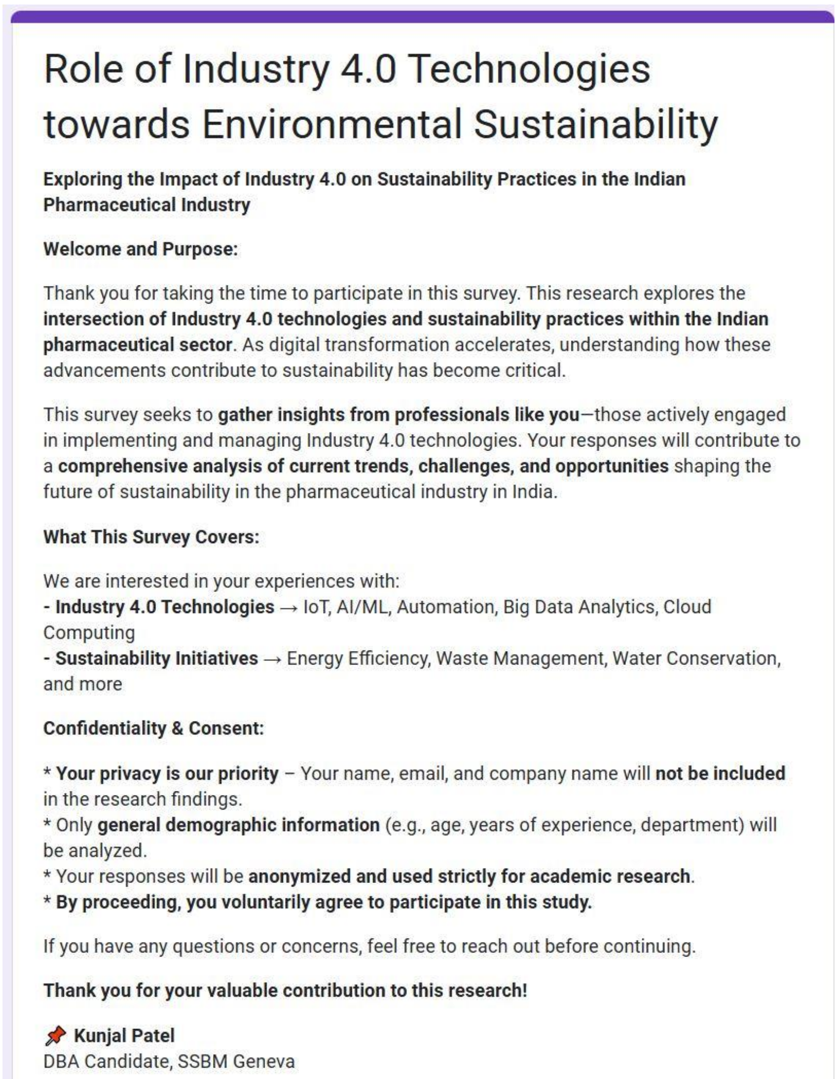
In the midst of ongoing digital transformation in the pharmaceutical sector, the obstacles faced must be overcome and opportunities must be seized by the technologies of industry 4.0. Collaboration between policymakers, businesses and academia is fostered in the sector, while achieving its twin goals of operational excellence and environmental sustainability, creating a norm for other sectors to follow.

This work concludes with a roadmap to foster Industry 4.0 adoption based on the development of strategic investments, inclusive policies, and robust governance frameworks. The lessons learned from this research will be a guiding framework for future efforts to advance the use of the full potential of Industry 4.0 technologies in industries in the digital era.

APPENDIX A

SURVEY COVER LETTER

The following image represents the cover page of the survey used for data collection in this study. It provides respondents with an overview of the survey's purpose and scope.



Role of Industry 4.0 Technologies towards Environmental Sustainability

Exploring the Impact of Industry 4.0 on Sustainability Practices in the Indian Pharmaceutical Industry

Welcome and Purpose:

Thank you for taking the time to participate in this survey. This research explores the **intersection of Industry 4.0 technologies and sustainability practices within the Indian pharmaceutical sector**. As digital transformation accelerates, understanding how these advancements contribute to sustainability has become critical.

This survey seeks to **gather insights from professionals like you**—those actively engaged in implementing and managing Industry 4.0 technologies. Your responses will contribute to a **comprehensive analysis of current trends, challenges, and opportunities** shaping the future of sustainability in the pharmaceutical industry in India.

What This Survey Covers:

We are interested in your experiences with:
- **Industry 4.0 Technologies** → IoT, AI/ML, Automation, Big Data Analytics, Cloud Computing
- **Sustainability Initiatives** → Energy Efficiency, Waste Management, Water Conservation, and more

Confidentiality & Consent:

* **Your privacy is our priority** – Your name, email, and company name will **not be included** in the research findings.
* Only **general demographic information** (e.g., age, years of experience, department) will be analyzed.
* Your responses will be **anonymized and used strictly for academic research**.
* **By proceeding, you voluntarily agree to participate in this study.**

If you have any questions or concerns, feel free to reach out before continuing.

Thank you for your valuable contribution to this research!

📌 **Kunjal Patel**
DBA Candidate, SSBM Geneva

APPENDIX B

INFORM CONCENT

Appendix B includes the survey's image where participants are required to mandatorily agree that they have read the informed consent. The document linked in the survey has also been added here for reference.

Please read the consent document before proceeding. *

click here

☐ I have read and understood the consent form and voluntarily agree to participate in this research.

Consent Form for Research Participation

Research Title

RECOGNIZING THE ROLE OF INDUSTRY 4.0 TECHNOLOGY IN ENHANCING ENVIRONMENTAL SUSTAINABILITY

Researcher Information
Researcher: Kunjal Patel
Institution: SSBM Geneva
Program: Doctor of Business Administration (DBA)
Email: kunjgemi@gmail.com

Introduction
You are invited to participate in a research study that explores the impact of Industry 4.0 technologies (e.g., IoT, AI/ML, Automation, Big Data Analytics, Cloud Computing) on sustainability practices in the Indian pharmaceutical sector.

This study seeks to understand how digital transformation is shaping sustainability efforts, including **energy efficiency, waste management, and water conservation**. Your participation will provide valuable insights into the adoption and challenges of Industry 4.0 in sustainability-driven pharmaceutical practices.

What Participation Involves
- The survey will take approximately **15 minutes** to complete.
- You will be asked about your **experience with Industry 4.0 technologies and sustainability initiatives** in the pharmaceutical industry.
- Your participation is **completely voluntary**, and you may choose to withdraw at any time.

Confidentiality & Data Protection
- **Your name, email, and company name will NOT be collected** or included in the research findings.
- Only **general demographic information** (e.g., age, years of experience, department) will be analyzed.
- Your responses will be **anonymized and used strictly for academic research**.
- Data will be securely stored and used solely for research purposes.

Your Rights as a Participant
- You may **skip any question** you do not wish to answer.
- You may **withdraw from the survey at any time** without providing a reason.
- If you have any questions about this study, you may contact me before proceeding.

Consent Confirmation
By participating in this survey, you confirm that:
- You have **read and understood** the purpose of this study.
- You **voluntarily agree** to participate.
- You understand that your responses will remain **anonymous** and used only for research purposes.

APPENDIX C

EMAIL INVITATION TO SURVEY PARTICIPANTS

Appendix C presents the message that was sent via email to potential respondents. This email outlined the purpose of the study, provided the survey link, and included confidentiality and consent details to ensure informed participation

Gmail **Kunjal Patel <kunjgemi@gmail.com>**

Shape the Future of Sustainable Pharma! Participate in Our Survey

Kunjal Patel <kunjgemi@gmail.com> Mon, Mar 18, 2024 at 9:48 PM
To: [redacted]

Dear [redacted],

I hope you are doing well.

As you have experience in the pharmaceutical industry, I would like to invite you to participate in my thesis research on Industry 4.0 technology adoption and its role in enhancing environmental sustainability in the pharmaceutical sector. Your insights will be invaluable in understanding how digital transformation is shaping sustainability efforts, optimizing resource efficiency, waste management, and overall environmental impact.

The survey is brief and should take only 1**5 mins** to complete. Your participation would be greatly appreciated and will help in advancing research in this critical area.

You can access the survey here

Confidentiality Statement:

- Your name, email, and company name will **not** be included in the survey results.
- The data collected will be **anonymized and used strictly for research purposes.**
- Only general demographic information, such as **age, years of experience, and department (e.g., IT, Production, R&D, Quality Control, etc.),** will be analyzed.

Consent Statement:

By submitting your responses, you **agree to contribute to this research study.** Your insights will be instrumental in shaping a deeper understanding of how Industry 4.0 technologies support environmental sustainability in the pharmaceutical sector.

Help Expand the Impact – Forward This Survey!

Know any colleagues in **pharmaceutical production, R&D, quality control, or other related departments**, who might be interested to participate? Please feel free to forward this message—their participation will help create a more comprehensive understanding of technology adoption and sustainability in the pharmaceutical industry.

Thank you in advance for your time and support. If you have any questions, please feel free to reach out.

Sincerely,
Kunjal Patel
DBA Candidate
SSBM, Geneva

P.S. Sustainability is a growing concern in the pharmaceutical industry. Your participation shows your commitment to a greener future!

APPENDIX D

SURVEY QUESTIONNAIRES

This section contains the survey questionnaire used for data collection in the study

Section A: Demographic Questionnaire All questions under this is required except Q7, therefore the survey has None responses

1. What is your age group?
    - Under 25
    - 25-34
    - 35-44
    - 45-54
    - 55 and above
2. What is your gender?
    - Male
    - Female
3. What is your highest level of educational background?
    - High school diploma or equivalent
    - Bachelor’s degree
    - Master’s degree
4. What is your current position in the company?
    - Entry-level
    - Mid-level
    - Senior management
    - Executive
5. In which department do you currently work?
    - Research and Development (R&D)
    - Quality Control
    - IT and Tech Support
    - Production
    - Sales and Marketing
    - Other
6. How many years of experience do you have in the pharmaceutical industry?
    - Less than 1 year
    - 1-5 years
    - 11-20 years
    - More than 20 years
7. What is your experience with Industry 4.0 technologies?
    - Beginner (less than 2 years)
    - Intermediate (2-5 years)

- Expert (more than 5 years)

Section B**: Research Objective Questionnaire** All questions in this section were mandatory, and a three-tier follow-up process was implemented to ensure maximum survey participation and minimize missing responses from participants.

A) Current Adoption Levels of Industry 4.0 Technologies

Kindly rate the current implementation level of the following Industry 4.0 related technologies in your company.

1: No Implementation at All 2: Low Implementation 3: Medium Implementation 4: High Implementation 5: Full/Advanced Implementation

Sl. No.	Industry 4.0 Related Technologies	1:	2:	3:	4:	5:
1	Autonomous and Collaborative robots (Cobots)					
2	Software Systems like ERP, MES, CRM, and PLM tools					
3	Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR)					
4	Additive manufacturing: 3D printing					
5	Identifiers like Bar code, QR code, or Radio Frequency Identifier (RFID) and Real-time Location System (RTLS)					
6	Intelligent sensors, actuators, embedded systems, and Programmable Logic Controllers (PLCs)					
7	Mobile devices and Wearables					
8	Cloud computing					
9	Machine to Machine (M2M) and Human to Machine (H2M) communication					
10	Internet of Things (IoT) and Internet of Services (IoS)					
11	Big data, real-time data processing, and Simulation tools					
12	Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL)					
13	Industrial Cybersecurity					
14	Digital platforms for supplier and customer integration					

15	Smart products technology					
16	Blockchain technology					

B) Specific Challenges—Financial, Technical, or Regulatory—That Hinder Full Integration of These Technologies

Kindly rate the barriers to the adoption of Industry 4.0 technologies in your organization. (Consider the following factors on a 5-point Likert scale: 1 = “Not Important”; 3 = “Important”; 5 = “Most Important”)

Sl. No.	Barriers to Industry 4.0 Adoption	1: Not Important	2: Slightly Important	3: Important	4: Very Important	5: Most Important
1	Large capital investment in new technology					
2	IT security and safety issues					
3	Lack of awareness about the benefits and implications of Industry 4.0					
4	Lack of standards and reference architectures					
5	Lack of a skilled workforce					
6	Poor infrastructure					
7	Interoperability issues					
8	Resistance to change or reluctance to adopt new technologies					

C) The Environmental and Economic Impacts of Adopting Industry 4.0 Technologies

Kindly rate the environmental and economic impacts your company has experienced from the adoption of Industry 4.0 technologies.

(Consider the following factors on a 5-point Likert scale: 1 = “No Impact”; 3 = “Moderate Impact”; 5 = “Significant Impact”)

Sl. No.	Environmental and Economic Impacts	1: No Impact	2: Low Impact	3: Moderate Impact	4: High Impact	5: Significant Impact
1	Reduction in energy consumption					
2	Reduction in carbon emissions					
3	Improvement in resource efficiency (e.g., water, energy, raw materials)					
4	Better waste management and recycling practices					
5	Creation of new business opportunities and revenue streams					
6	Cost reduction in production and operations					
7	Improvement in product quality and innovation					
8	Reduction in operational costs (e.g., labor, maintenance, downtime)					

D) Actionable Strategies to Overcome Identified Barriers and Enhance the Adoption of Industry 4.0 Technologies

Kindly rate the following strategies for overcoming barriers to the adoption of Industry 4.0 technologies in your organization.

(Consider the following factors on a 5-point Likert scale: 1 = “Not Effective”; 3 = “Moderately Effective”; 5 = “Highly Effective”)

Sl. No.	Strategies to Overcome Barriers	1: Not Effective	2: Slightly Effective	3: Moderately Effective	4: Very Effective	5: Highly Effective
1	Increased investment in employee training and skill development					
2	Collaboration with technology vendors and experts for implementation					
3	Government incentives or subsidies for Industry 4.0 technology adoption					
4	Improving IT infrastructure and cybersecurity measures					
5	Establishment of industry standards and reference architectures					
6	Improving internal awareness and education about Industry 4.0					
7	Enhancing cross-departmental collaboration and communication					
8	Phased, incremental implementation of Industry 4.0 technologies					

E) How Policies Like Digital India and Make in India Have Influenced Technological Upgrades and Compliance with Environmental Standards

Kindly rate how government policies such as Digital India and Make in India have influenced the adoption of Industry 4.0 technologies in your organization.

(Consider the following factors on a 5-point Likert scale: 1 = "No Influence"; 3 = "Moderate Influence"; 5 = "Strong Influence")

Sl. No.	Government Policies and Influence	1: No Influence	2: Slight Influence	3: Moderate Influence	4: Significant Influence	5: Strong Influence
1	Digital India initiative has positively impacted technology adoption					
2	Make in India initiative has encouraged local manufacturing capabilities for Industry 4.0					
3	Government subsidies or tax incentives for adopting Industry 4.0 technologies					
4	Policy support for improving infrastructure and internet connectivity					
5	Environmental regulations have guided sustainable technology implementation					

F) What Role Do Corporate Governance and Stakeholder Engagement Play in Advancing the Adoption of Industry 4.0 Technologies

Kindly rate the role of corporate governance and stakeholder engagement in advancing the adoption of Industry 4.0 technologies in your organization.

(Consider the following factors on a 5-point Likert scale: 1 = “No Role”; 3 = “Moderate Role”; 5 = “Significant Role”)

Sl. No.	Corporate Governance and Stakeholder Engagement Factors	1: No Role	2: Minor Role	3: Moderate Role	4: Significant Role	5: Key Role
1	Corporate governance (e.g., board involvement, policy setting) has a significant role in adopting Industry 4.0 technologies					
2	Regular engagement with stakeholders (e.g., employees, suppliers, customers) influences technology adoption decisions					
3	Clear communication of Industry 4.0 adoption goals and benefits from leadership has motivated the workforce					
4	Stakeholder feedback and involvement are regularly integrated into the decision-making process for technology adoption					
5	The alignment of corporate governance with technology adoption strategies has accelerated Industry 4.0 integration					

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