Assessing the Impact of Industry 4.0 on Environmental Sustainability

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Abstract: Businesses achieve more industrial performance by integrating vertical and horizontal production processes and product linkage in Industry 4.0, at the beginning of the Industrial phase. To guarantee a sustainable progression of human life including social, environmental, and economic aspects, globalization currently confronts the challenge of satisfying the swiftly growing worldwide demand for industrial products. Industry 4.0, which provides increased industrial investments, simpler procedures, and improved production collaboration, redefines the digital revolution. Sustainability in the supply chain includes implementing systemic fixes and logistical procedures that make recycling and waste reuse easier while cutting emissions. The manufacturing industry is increasingly excited about using technology to identify areas that require improvement to reduce wastage and innovative methods by applying new techniques to become more sustainable. The study focuses on the impact of implementing the major technologies including lean production manufacturing, IOT, Blockchain, and Automated Robotics on the environmental sustainability of Indian Manufacturing firms. It contributes to generating a pillar of research on the actual benefits of Industry 4.0 by outlining its technology elements. It elaborates on the direct impact of Industry 4.0 enabling technologies on sustainability concerning the environment.

Keywords: Industry 4.0, sustainability, Technology, Manufacturing, Firms, Environment

1. Introduction

Industrial automation is the process of automating production processes and decentralizing industrial decision-making via the use of digital and advanced operational technology. It has been elevated to a strategic priority considering Industry 4.0's disruptive impact [1]. To increase productivity, profitability, and industry competitiveness, several

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manufacturing businesses have been pushed to adopt novel production procedures due to the growing unpredictability of the modern global market. Manufacturing industries view the idea of Industry 4.0 as a new frontier, and many of them have adopted it under different names and in different ways. An organization's success and longevity depend on its culture of ongoing development. Industries must reassess their procedures to make sure they are dependable, efficient, and responsive to customer feedback. By using cutting-edge manufacturing techniques and tactics, the Industry 4.0 idea aims to increase the productivity and efficacy of intelligent factories. Smart manufacturing maximizes earnings, optimizes facilities, reduces costs, and helps goods, machines, and technology work together [2]. Prior studies are devoid of coherent, tightly focused investigations by scholars to completely comprehend the implications of its deployment [3]. As shown in Fig.1, inputs like, information and raw material flow into different production phases along with the emergence of technology that impacts environmental sustainability [4]. Foremost, the principle of Industry 4.0 is interoperability which guarantees connections and communication between goods, machinery, and people through a variety of autonomous processes [5]. It fosters a trustworthy environment in a manufacturing system that enables partners to convey the information properly increases productivity and reduces cost [6]. Virtualization is employed in machine communication and monitoring the process. Stimulation-based models are connected to sensor data, to generate corresponding copies of real-time data [5].

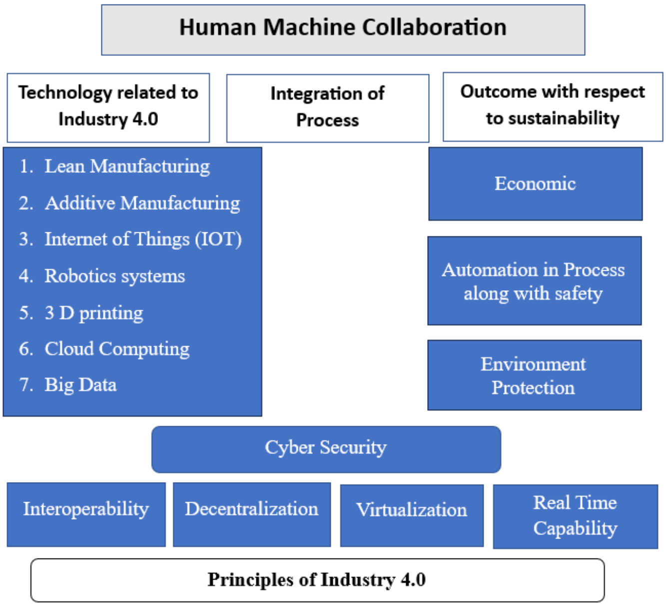

Fig.1. Industry 4.0 Sustainable Environment (Adopted from Oláh,2020)

The ability of business, personnel, and equipment to make decisions independently is termed decentralization. Any device which had autonomous decision-making capabilities is the result of an embedded system that increases flexibility and efficiency in decision-making [7]. Gathering the data and analyzing the real-time data transfer are a few examples of real-time capacity. It helps to reduce mistakes by continuously monitoring the real-time data [8]. It developed the framework model for the implementation of these technologies and associated approaches for examining a variety of aspects, advantages, implementation difficulties, and barriers [9]. These studies will facilitate increased knowledge about Industry 4.0. Big data, cloud computing, Artificial intelligence, and IOT are the foundational components that have been used to enable the transformational process in the digital era [10]. In addition to product design systems, simulation, augmented and virtual reality, additive manufacturing, and sophisticated robotics, base technologies also facilitate the utilization of technologies related to the sources of technologies consisting of front-end [11] [12].

Reliability, accuracy, performance, and resilience to hazardous conditions are just a few of the advantages that robotics integration offers the manufacturing sector with the launch of these technologies. It offers a production procedure that is more trustworthy and productive. Robots that possess intelligence and can work quickly and precisely have simplified a lot of the industry's production procedures. Highly flexible systems that enable frequent, low-cost product alterations are required due to the current demand. Therefore, the best choice for assembly automation is industrial robots. Workers leave the production floor when dangerous robot tasks are delegated to them [13]. Embracing this technology in the literature of operational management raised at the full growth stage along with a broader range of solutions, is the latest industrial drift. [11] There are a variety of objectives, including higher production productivity, efficiency, increased functional elasticity; integration with the supply chain and customers; and safety and sustainability of operations for workers.

The core components of environmental sustainability consist of emissions and waste, energy consumption, greenhouse, and depletion of ozone. Industrial facilities need to invest heavily in machinery and technical equipment in a smarter way. Efficiency in the manufacturing system is attributed to these technologies because of the effective application of time, waste, and energy. Packaging of products related to the medical sector has improved with the implementation of technologies, especially relating to plastic packaging. [15] Automated Robots and electronics reduce the impact of plastics on water management systems. Manufacturers choose to integrate factory execution systems, warehouse databases, and enterprise resource planning systems. Many developed countries deploy these robots along with assembling lines by reducing production costs and ameliorating productivity. It ensures quality control, and energy consumption by the deployment of remote tools to streamline their automation process. It maximizes the speed of its powerpack application and reduces energy consumption.[16] Innovations in technology such as blockchain, virtual reality, and artificial intelligence provide new means of communication and interaction between people, things, and information. [4]

Health, safety, and environmental protection are the outcomes of sustainability. Productivity is enhanced through environment-friendly and organic input. Sustainable manufacturing leads to the reduction of unhealthy emissions by using energy-efficient resources. Improved life quality, health and safety, and better productivity with resources are some of the advantages of sustainability that yield environmental sustainability [17].

2. Literature Review

The Industrial Revolution had a significant contribution to value addition, production mobility, and product personalization on an economic level, all of which boosted customer satisfaction. The manufacturing organizations are driven to achieve shortened execution times, reduce production prices, and improve automation elements of Industry 4.0 Technologies. Sustainability and Industry 4.0 is gaining traction in the discussion of academics, managers, and policies. There are contradictions and synergies [18]. Effective resource use and decreased garbage output are two ways that enhance activity monitoring and favorably impact sustainability. Alternatively, it may result in a greater demand for energy resources and a rise in the generation of trash, such as electronic waste. Current assessments of the literature concentrate on specific facets of the connection between sustainability and Technology 4.0. Furthermore, the connection between specific technologies and sustainability remains unexplored along with the missing theoretical facts associated with it.

They have mostly concentrated on the idea of Industry 4.0 about sustainability rather than its underlying technologies. It aims to put forth a framework that connects individual technologies and the industry idea in totality to sustainability performance [19]**.** These conditions facilitate the monitoring of business operations and the development of trust among value-chain stakeholders, resulting in value-chain optimization and the integration of circularity into business and supply-chain operations. If implemented effectively, blockchain, can improve the functions that enhance resource efficiency, reduce costs, prevent pollution, and increase profit margins that promote a green environment. However, the favorable sustainability performance of blockchain highly relies upon the sequence in which businesses utilize these functions [20].

2.1 Sustainability and Industry 4.0

Advancement in organizational performance on all three sustainability aspects may be attributed to Industry 4 Technologies' capacity to enable high levels of process integration [21]. In terms of the environment, companies may more effectively deploy their manufacturing resource. It discusses the planning of transportation and logistics as well as the application of cutting-edge tracking and monitoring technologies to reduce wastage. Employees should expect a safer and better work environment using Industry 4 Technologies [22]. It had a more favorable influence on environmental sustainability through widespread digitalization that offers real-time event management for the external environment with high-quality [4].

H1: Industry 4.0 has a significant effect on environmental sustainability.

2.2 Lean practices and sustainability

LMP promotes cost savings and greater profitability, which in turn leads to higher productivity and a competitive edge. Production houses generate maximum waste, as compared to other sectors by adopting lean manufacturing. It leads to generating more energy demands and decreases their output [23]. Using tools of quality control, use of a suitable basic approach, and utilizing the latest production technology were prominent alternatives to solutions that manufacturing companies should think about to get past challenges when implementing lean and sustainable systems [24]. For instance, automobile companies reduce pollution from their production process by adopting Just in time delivery model. The most popular lean technique, value stream mapping, has been shown to safeguard the environment [25]. It improves investment return and a reduction in problems relating to physical safety [26]. To prevent adverse impacts on the environment and dimensions of social sustainability, it is imperative to synchronize the lean implementation process with the sustainability strategy [27].

H2: Lean manufacturing has a significant effect on environmental sustainability.

2.3 Internet of Things and Sustainability

Although global prosperity has long been fuelled by technology, it has unfortunately also led to serious negative consequences, contributing to some of the most crucial issues of our time [28], for instance, human interactions between the physical and digital realms have become possible through the Internet and the increasing use of Internet-of-Things (IoT) devices, which are often eventually discarded. These discarded devices, known as e-waste, contain harmful substances that harm environmental sustainability [29]. However, over the last four decades, the world has witnessed an intriguing new trend wherein not just technologies are being developed and utilized specifically to improve the world, but also industries have emerged around clean energy, such as wind and solar power with an intent to contribute towards sustainability [28].To fully realize the potential for sustainable performance that has not yet been realized, the industry must have more value creation and less carbon release. Drawing on the TBL idea, it illustrates the significance of IoT in the environmental, economic, and social spheres. It assists in supply chain delivery tracking like routes, consumption of fuel and emission, and efficiency in logistics. Current road conditions are tracked use of geographic information systems (GIS), which allows path optimization algorithms to produce and display the best possible transport routing [30].

Using innovative Internet-based transactions can help gather garbage from the whole supply chain more quickly and sustainably, which will reduce the environmental costs of the recovery process. Concerning waste management, smart sensors deployed in the production line can easily categorize the waste into recycling and non-recycling products. It also promotes a healthy environment for employees and surrounding communities by measuring the quality of air through sensors leading to environmental sustainability [31]. It is the frontline of transformation in the manufacturing sector that combines innovation with sustainability. Gathering the data from various machine sensors from the production line, gave valuable information to production managers of their operations [32].

H3: IOT has a significant effect on environmental sustainability.

2.4 Additive Manufacturing and Sustainability

Sustainable manufacturing supports eco-friendly practices and inventions to reduce pollution. It is mandatory to promote the type of production that produces less amount of waste and has minimum effect on the environment. It is achieved by reducing the impact on the atmosphere and implementing practices for planning, monitoring, and quantifying pollutants in the environment [33] Industry 4.0 technology leads to reduced waste generation. Incorporating different types of sensors into different types of production processes. Sensors provide details like how they operate, model defects, indicators of performance, and level of pollution [34]. This data is applied to eliminate harmful effects on the environment and processes applying different simulation systems. Reduction in trash is the major advantage of additive manufacturing [35]. Reducing the energy and cost of resources required to scale production without making major changes, additive manufacturing helps companies to increase speed and profitability. Productivity can be increased and internal waste can be reduced by decreasing the level of pollutants by promoting sustainable production [36].

H4: Additive manufacturing has a significant effect on environmental sustainability.

This study highlight's role of technology in promoting green production by safeguarding the environment which is a useful strategy for quick and long-term growth. The study expands the role of Industry 4.0 through which businesses may expand into new markets and adjust to those that already exist, increasing their competitiveness and providing them with a competitive advantage. It opens the door to leveraging and incorporating quality into a more complete company strategy concerning technology benefits. Companies can frame the long strategy considering the role of Industry 4.0 as it improves efficiency. Additionally, efficiency results in less waste and less product costs.

Impact on Production due to climate change is constantly increasing pressure on manufacturing firms and raises the scope of research. It is possible to connect resources, goods, and all stakeholders into resources for setting the measures related to environmental sustainability. People all around the world are leading more eco-conscious lives, thus companies that they used to support will need to adapt their operations to better serve their target market. Consumer and product relationships yield important information through Industry 4.0 [15]. This shift in the creation and delivery of services and goods is being driven by data, analytics, and networking innovations. Fast production, new market entrants, and better user interfaces create a sustainable environment for manufacturers to create eco-friendly products. Designing of product and production processes instantly improved by implementing these technologies. It also leads to renewable energy sources [37].

3. Research Methodology

Industry 4.0 aims to force businesses to achieve the required success criteria. Automating development, enhancing customer service, boosting productivity, and fusing supply and production chains are the most popular strategic objectives for using these technologies. This study accomplishes conceptual association between Environmental sustainability and Industry 4.0.

India's developing economy serves as the study's backdrop. Given that the study wants to grow the manufacturing sector, India offers an intriguing research backdrop of the latest technologies. As part of its efforts to establish India as a global manufacturing powerhouse, the government of India has already implemented the "Make in India" program [6]. Studies already conducted have provided the study's components and measurements. Four components make up the questionnaire that is created. The company overview, including its years of existence, industry, and workforce size, was covered in the first part. The application of these technologies was determined by using the second portion of the questionnaire. On a Likert scale, ranging from strongly disagree to strongly agree the respondents working at the supervisory and manager level were asked to score Environmental sustainability concerning the industry 4.0 practices, which are typified [38], in their respective organizations. The measures of environmental sustainability were constructed from [17]. A structured Model (SEM) analyses the interrelationship among multiple variables in the model. It stated the different indicators and construct correlation supported theoretically and identified by the different factors. In this technique, the parameters stated in the model are evaluated in a manner so that the gap between the predicted and theoretical covariance matrix can be reduced. For determining the sample size, the free parameters were taken into consideration. The required sample size for applying SEM analysis [39] includes 200 respondents working in a manufacturing firm in the Delhi region.

3.1 Survey Items and Questionnaire Design

The questionnaire was developed from 50 manufacturing firms from Delhi's national capital region consisting of 200 respondents. The purposive sampling technique was used for selecting the manufacturing firm in Delhi because of time constraints. We purposively conducted the survey in the Delhi region by targeting the manufacturing firms registered under the Department of Delhi Government. The first section consisted of basic information like the type of manufacturing firm, firm existence, and count of employees. The next section consists of dimensions of environmental sustainability related to energy, Material, and waste & emissions. The third section includes statements stating the association between IOT, Lean Manufacturing, and additive manufacturing affecting environmental sustainability using the five ratings Likert scale.

3.2 Measurement Model

AVE intercept discriminant validity to determine if constructs are dissimilar from other variables. We suggest that the Heterotrait- Hetero method correlation evaluates discriminant validity. The arrows attached to the measures of non-identical constructs symbolize this correlation that should be insignificant [40].

3.3 Confirmatory Factor Analysis

To investigate further research, confirmatory factor analysis was applied. After the assessment of model fit, we calculated CR and AVE. In Figure 2 below, the normalized factor loading from the five latent variables on 28 observations is more than 0.5. Table 1 CMIN is the difference of Chi-square value. If CMIN is lower than 3, it means a better will be model fit. CFI and TLI ranging from 0 to 1 and near to 1, better will be the model. Table 2 RMR is the error root mean square, which is near 0 and represents a better model. Table 3 RMSEA depicting the value < 0.05 that is closely fit [39].

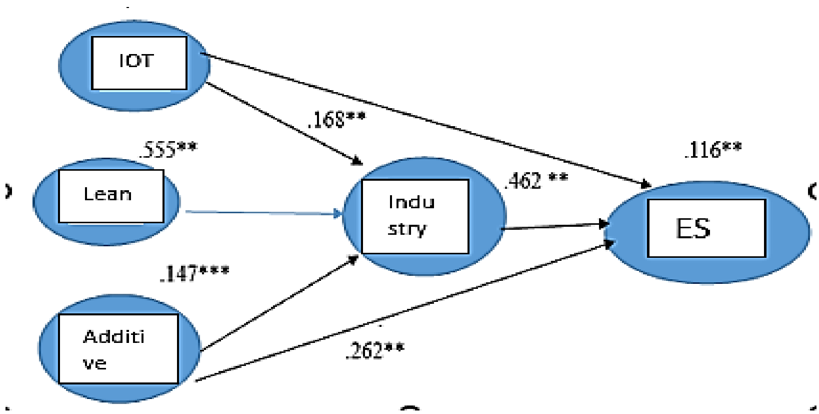

Fig. 2. Conceptual Model drawn using SPSS

TABLE 1
CMIN

Model	NPAR	CMIN	DF	P	CMIN/DF
Default model	66	464.115	259	.000	1.792
Saturated model	325	.000	0		
Independence model	25	2687.999	300	.000	8.960

(Results from SPSS Version 3.0)

Table 2

RMR, GFI

Model	RMR	GFI	AGFI	PGFI
Default model	.080	.842	.802	.671
Saturated model	.000	1.000		
Independence model	.504	.216	.150	.199

(Results from SPSS Version 3.0)

Table 3
RMSEA

Model	RMSEA	LO 90	HI 90	PCLOSE
Default model	.063	.053	.072	.014
Independence model	.199	.192	.205	.000

(Results from SPSS Version 3.0)

4. Discussions & Conclusions

Table 4 highlights that IOT directly affected Industry 4.0 Practices ($\beta = 0.168, p < 0.005$), supporting the H1 hypothesis. Lean manufacturing affects Industry 4.0 practices ($\beta = 0.555, p = 0.000$), supporting the H2 hypothesis. Additive manufacturing had an insignificant effect on Industry 4.0 practices ($\beta = 0.147, p = 0.099$), supporting the H3 hypothesis. Industry 4.0 significantly affects environmental sustainability ($\beta = 0.462, p = 0.000$), supporting the H4 hypothesis. IoT significantly affects sustainability ($\beta = 0.116, p = 0.005$). Additive manufacturing significantly affects environmental sustainability ($\beta = 0.262, p = 0.000$) as per the conceptual model drawn from Figure 2. The normalized regression coefficient of the index lies between 0.5 and 0.8. In the IOT, "it results in scrap reduction" had a great degree of impact of 0.673 as compared to “efficient use of resources" where the regression coefficient was 0.618. In Lean manufacturing, “reduction in carbon emissions" had a great degree of impact where the regression coefficient is 0.802. Concerning additive manufacturing “reuse of material in manufacturing” has a greater regression coefficient of 0.739. In Industry 4.0, "resulted in overall economic sustainability" had more regression coefficient of 0.777. For environmental sustainability, "recycling of material" with a higher regression coefficient of 0.739. Production sustainability creates an environment to produce items with less environmental effect along with employing less energy-intensive technology. It enables research by introducing cutting-edge sensing technology and analyzing manufacturing procedures. It assists the manufacturing process, by utilizing intelligent technologies and renewable resources, lowering the frequency of dangerous emissions and waste from natural resources. An ecosystem that uses less energy-intensive technologies and produces goods with fewer environmental effects is created by sustainable manufacturing.

Additionally, by using intelligent technologies and renewable resources, this manufacturing process lowers the frequency of dangerous emissions and waste from natural resources.

Table 4
Path Coefficient and Testing of Hypothesis

	Hypothesized Path	SRW	p-value	Remarks
H1	IOT → Industry 4.0 Practices	.168	.005	Supported
H2	Lean Manufacturing → Industry 4.0 Practices	.555	.000	Supported
H3	Additive Manufacturing → Industry4.0Practices	.147	.099	Not supported
H4	Industry 4.0 → 4 Environmental Sustainability	.462	.000	Supported
H5	IOT → Environmental sustainability	.116	.005	Supported
H6	Additive Manufacturing → Environmental sustainability	.262	.000	Supported

***p < 0.001, **p < 0.01, *p < 0.05 (PLS through Structural Equation Modeling (SEM) software version 3.0

5. Future Scope

In the future, human-machine connection and collaboration will be enriched by the current trend of Industry 5.0. The extent to which people and equipment cooperate will shift as automation, machine learning, and even robotics become more prevalent and help workers by taking over significant portions of production, distribution, and operations. Every employee, state, legislator, and regulator is faced with obstacles due to the fast pace of change. All workers, states, legislators, and regulators face issues due to the quick rate of change. Industry 4.0 has been blamed for highlighting the need to incorporate people in the process. New business models, greater efficiency, and flexible production are all expected from digital solutions. All the same, manufacturing's future is even more promising and will create new avenues for the process and discrete sectors to cater to the specific demands of their target markets. The process of product development and manufacturing products through technologies results in the creation of the digital twin. With far fewer resources, Industry 4.0 technologies enable faster and more effective innovation. It will become very relevant and important in manufacturing for several reasons. Industry 4.0, to put it as simply as possible, is the technological advancement that will propel operational performance. Several primary factors will drive manufacturers to progressively integrate Industry 4.0 technology. Predictive maintenance strategies, machine monitoring tools, and other cutting-edge operational technologies will assist manufacturers in reducing downtime, increasing productivity, and lowering the total cost of manufacturing high-quality components. More sample sizes and companies from other different regions may be included in future studies in this area. Prospective research endeavors may employ longitudinal data design to get insight into the ever-changing character of technologies and sustainability.

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