Study of select issues in context to Sustainable Manufacturing Systems

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By

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I, Deepak Sharma, hereby certify that the thesis work entitled **"STUDY OF SELECT ISSUES IN CONTEXT TO SUSTAINABLE MANUFACTURING SYSTEMS"** is an original work carried out by me under the supervision of Dr. Pravin Kumar, Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi and Dr. Rajesh Kr. Singh. Professor, Management Development Institute, Gurgaon. The thesis has been prepared in conformity with the rules and regulations of the Delhi Technological University, Delhi.
The research work presented and reported in the thesis has not been submitted either in part or full to any other university or institute for the award of any other degree or diploma.

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This is to certify that the thesis entitled "**STUDY OF SELECT ISSUES IN CONTEXT TO SUSTAINABLE MANUFACTURING SYSTEMS**" submitted by **Mr. Deepak Sharma,** Roll No. 2K16/PhD/ME/14 to the Delhi Technological University (Formerly known as Delhi College of Engineering), Delhi, for the award of the degree of **Doctor of Philosophy** is a bona fide record of original research work carried out by him under our supervision in accordance with the rules and regulations of the institute. The results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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To my parents

Mr. B.P Sharma & Mrs. Chhaya Sharma

&

Mr. Jai Parkash Sharma & Mrs. Shanti Devi

&

To my loving and supportive wife Bindu

The love, encouragement, and support of my parents

and wife have been exemplary.

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ABSTRACT

In the era of global competition, we find ourselves facing constraints imposed by a world with finite resources, increasing population, and diminishing non-renewable energy sources. The manufacturing sector has been acknowledged for its extensive use of renewable raw materials and energy. This sector is recognized as a significant contributor to pollutants giving rise to various environmental problems and health risks to communities. Traditional manufacturing system leads to the rapid depletion of natural resources, contributes to global warming, and a decline in biodiversity. However, the growth of manufacturing is essential for the improvement of societal living standards, particularly in context to developing and underdeveloped nations. The solution lies in the adoption of sustainable-centric practices within manufacturing organizations. Sustainable manufacturing is a necessary prerequisite for conserving natural resources, mitigating adverse impacts on the environment, global economy, and society.

The present study has explored the status of sustainable manufacturing practices around the world through an extensive literature review using bibliometric analysis. The detailed study of the literature assists in the identification of research gaps to formulate the objectives of the study. In addition, insights about existing sustainability metrics with the inclusion of environmental, economic, and social aspects of sustainability have also been explored.

Based on the literature, it has been found that in transitional attempts for the integration of sustainability in organizations, more emphasis is given to economic and environmental dimensions, but the social aspect is usually overlooked. In this research work, all the major factors that could induce social sustainability (SS) within the system are explored and examined through a comprehensive literature review and underlying hypothesis. The structural equation modelling (SEM) approach has been utilized in building a socially sustainable model for the business organization. The proposed formulated model, along with the factors can suitably be

used for the assessment of social sustainability, and its adoption by different organizations in this business world.

The synergy of sustainable manufacturing with Industry 4.0 technologies and circular economy practices can induce flexibility in a business organization, build up capabilities for improving sustainable performance, navigate existing sustainability challenges, and pave the way toward the United Nations' (UN)' sustainable development goals (SDGs). Based on the extant literature review on the realm of digital technologies, circular economy practices, and SDGs, hypotheses are underpinned and later validated. A quantitative questionnaire-based survey method has been used for data collection across Indian manufacturing organizations, analyzed by partial least square structural equation modelling (PLS-SEM). This research study contributes various implications to researchers and practitioners for accelerating the transition from a linear economy to a sustainable economy.

The current study has proposed a framework to evaluate the sustainability index of a manufacturing system. The realistic set of sustainability indicators considering all dimensions of the triple-bottom line has been explored and validated through a questionnaire survey. Furthermore, the depicted indicators are prioritized and indexed using the Delphi method and Graph Theory Matrix Approach (GTMA). Its application is illustrated in the context of an Indian manufacturing organization. This study will assist the concerned professionals in gauging their industrial sustainability performance.

The novelty of this research study is to explore a realistic set of sustainability indicators that will assist industry professionals and practitioners in putting efforts on the right path for achieving sustainability in their organizations and developing necessary strategies correspondingly. The framework and sustainability indicators proposed within this study can serve as a benchmark to excel in the adoption of sustainability in manufacturing organizations with the creation of more values and satisfaction among the stakeholders, society, and industries while diminishing the environmental effects. The result outcomes significantly assist in achieving business sustainability and targets of Sustainable Development Goals, which are optimal units for gauging and evaluating the progress of sustainable development across all levels.

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LIST OF ABBREVIATIONS

AIML	Artificial Intelligence and Machine Learning
AM	Additive Manufacturing
AMOS	Analysis of Moment Structures
AR-VR	Augmented reality and Virtual reality
AVE	Average Variance Extracted
BA	Bibliometrics Analysis
BDA	Big Data Analytics
CE	Circular Economy
CEP	Circular Economy Practices
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CI	Community Interrelations
CO	Community
CP	Consumer Protection
CR	Composite Reliability
CSR	Corporate Social Responsibility
CU	Customers
DCT	Dynamic Capability Theory
DF	Degree of Freedom
DTs	Digital Technologies
EC	Economic
EF	Environmental Factors
EFA	Exploratory Factor Analysis
EM	Employee
EN	Environmental
GCC	Global Certification and Control
GFI	Goodness of Fit Index
GHG	Greenhouse Gas Emissions
GTMA	Graph Theory Matrix Approach
I4.0	Industry 4.0
IAE	Indirectly-Associated Expenses
IIOC	Initial Investment & Operating Cost
IoT	Internet of Things
IPM	Indicators Permanent Matrix
IT	Institutional Theory
JC	Job Characteristics
KMO	Kaiser-Meyer-Olkin

MEC	Materials and Energy Consumption
MSV	Maximum shared Variance
NGOs	Non-Governmental Organizations
OHS	Occupational Health & safety
PCFI	Parsimony Comparative Fit Index
PGFI	Parsimony Goodness of Fit Index
PLS	Partial Least Squares
PNFI	Parsimony Normed Fit Index
3R	Reduce, reuse, and recycle
RBT	Resource-based Theory
RMSEA	Root Mean Squared Error of Approximation
RMR	Root Mean Residual
SC	Social
SDGs	Sustainable Development Goals
SE	Stakeholder Engagement
SEM	Structural equation modelling
SI	Sustainability Indicators
SM	Sustainable Manufacturing
SMEs	Small and Medium-Sized Enterprises
SPO	Sustainable Performance of the Organization
SPSS	Statistical Package for Social Science
SS	Social Sustainability
ST	Stakeholder`s Theory
TBL	Triple Bottom Line
UN	United Nations
VC	Value Creation
WC	Water Consumption
WoS	Web of Science

Chapter 1

INTRODUCTION

1.1 Background

Global competitive scenario and industrial growth are pushing manufacturing organizations to transform the system from conventional towards sustainable viable manufacturing. Since 1970, governments, non-government organizations (NGOs), industrialists, and academicians recognized the unsustainability development model as the main problem of society. The rise in Industrial growth, pollution, and population has impacted the relentless increase in natural resource consumption, and shifted the focused attention towards global resource shortage (Sartal et al., 2020). The rapidly increasing deforestation and the use of natural resources have given rise to significant environmental issues, that have led to the need for sustainability viz. fulfilling the needs of the current without jeopardizing the capacity of future generations to fulfill their own needs (Sala, 2019). The manufacturing sector is facing a few sustainability challenges like greenhouse gas emissions, global warming, and a decline in biodiversity (Aktaş and Demirel, 2021). The manufacturing industries are not limited to only production but they involve a series of various processes from procurement of raw material, consumption, supply chain, and ends to disposal. The waste generation during the processing process, product use, and after the end of the product life is responsible for environmental degradation. Thus, it becomes important to mitigate resource use and reduce the environmental effects of production processes (Behrisch et al., 2011a; Bereketli and Erol Genevois, 2013; Pereira et al., 2019). United Nations (UN) estimated that almost three planets' natural resources will be required to sustain human life of up to ~9.6 billion by 2050 (Haleem et al., 2021).

The responsive solution to such endangering population growth, environmental deterioration, societal, and technological imbalance lies with sustainable practices for overall development

(Mathiyazhagan et al., 2018). In this era of competitive dynamic technology, sustainable manufacturing (SM) practices have become a meaningful alternate approach with optimized economic concurrence and balanced societal aspects along with a healthy environment (Mishra et al., 2019). SM is an eco-friendly concept, inclined towards efficiently designed products with economic benefits, and better quality (Gouda and Saranga, 2020). Manufacturing industries will have to transform their traditional manufacturing practices into SM practices considering all facets of the triple bottom line (TBL), i.e., environmental, social, and economic (Singh et al., 2019; Mengistu and Panizzolo, 2022). SM is a necessary prerequisite to conserve natural resources and mitigate the adverse impacts on the environment, global economy, and society.

1.2 Evolution of manufacturing concepts

Manufacturing activities have concentrated for many years primarily on meeting or generating demands with a competitive approach toward creativity, market suitability, and product efficiency (Garetti and Taisch, 2012; Shojaeipour, 2015a). It is an integral part of human life as well as the global economy and has evolved through various generations including traditional manufacturing, lean manufacturing, green manufacturing, and sustainable manufacturing as shown in Figure 1.1 (Badurdeen et al., 2009).

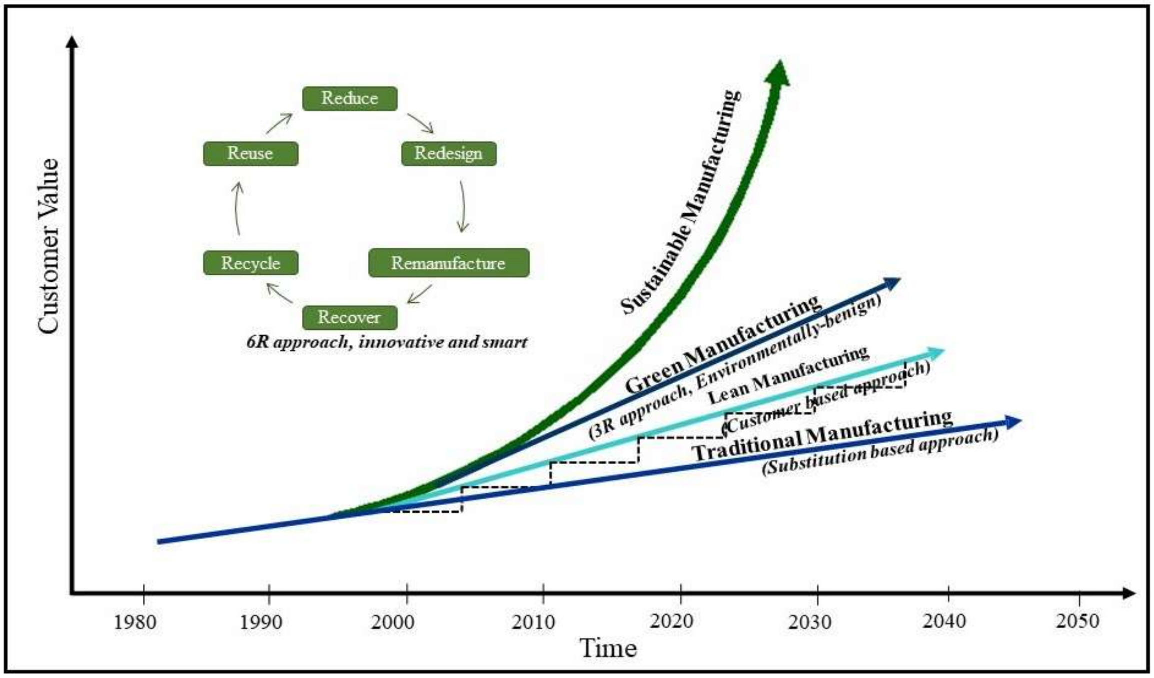

Figure 1.1: Various Generations of Manufacturing

Traditional manufacturing is primarily oriented toward functionality, production time, cost, and performance of products. The approach is mainly concerned with manufacturing economically-viable products to sustain a competitive market with no integration of environmental and social aspects (Boulanger, 2008; Pereira et al., 2019). Lean manufacturing was first adopted by the Toyota company, an automobile sector in Japan in the 1930s (Bortolotti et al., 2015). The term was broadly by James Womack and Daniel Jones with the inclusion of five key principles namely specification of the product value, identification of the product value stream, making continuous product value flow, pulling product value from the producer, and perfection pursual' (Illich, 1987a). The concept has been broadly recognized as one of the most important production countermeasures by the manufacturing sector.

Lean Manufacturing uses consumer-based strategic tools to reduce resource usage by waste reduction with improved efficiency, reliability, consistency, product quality, and customer loyalty (Ghobadian et al., 2020; Hibadullah et al., 2013). However, the improved living conditions have led to rising demand for products, confronted with massive quantities of manufactured goods, resulting in an ever-growing generation of waste and emissions (Abualfaraa et al., 2020). The issue of waste minimization has been dealt with by using an environmentally benign concept of green manufacturing based on the 3R approach involving reduce, reuse, and recycling (Kishawy et al., 2018).

Literature reports lean and green manufacturing as synonym terms with some distinctions and contrasts (Govindan et al., 2014). Both Lean and green manufacturing are aimed at customer participation and waste minimization through process efficiency enhancement strategies but deal with varying implementation techniques (Garza-Reyes, 2015). Esmaeilian et al., (2016) in their study distinguished between various manufacturing approaches, like green manufacturing, lean manufacturing, mass manufacturing, and sustainable manufacturing using the concept of TBL. Green manufacturing focuses exclusively on the environmental and social aspects, while lean manufacturing addresses solely the environmental dimension, mass manufacturing caters to the social and economic dimensions, and only SM meets the requirement of all three aspects of TBL.

Hence, sustainable manufacturing has emerged as an inclusive approach that combines elements of lean and green manufacturing while giving due consideration to society, the economy, and the environment (Stark et al., 2014). Considering the significant impact of manufacturing on energy consumption and its global socio-economic importance, SM has emerged as a critical aspect in the pursuit of achieving a broader image of sustainability.

1.3 Sustainable manufacturing: TBL Concept

Elkington, (1994) established the concept of TBL in 1994. The concept comprises, that the commitment goal of the business organization from the perceptive of stakeholders, consumers, and community should be to achieve sustainability from the aspect of all three dimensions named as environmental, economic, and social sustainability. Every aspect of TBL is gauged based on the impacts on keen 3Ps` (people, profit, and planet).

The concept of SM is based on the seven "E-paradigm" (Environment, Ecology, Energy, Economy, Empowerment, Employment, and Education). It involves the design and control of sustainable processes, systems, and products through efficient research, development, and commercialization. The sustainable process involves designing of technological methodology for the reduction in energy consumption, feedstock usage, and waste generation along with minimum exposure to hazards (Bereketli and Erol Genevois, 2013; Jawahir et al., 2013). The sustainable system involves consideration of the life cycle stages of products involving pre-production, production, usage, and post-usage through efficient supply chain management (Casamayor and Su, 2013; Jayal et al., 2010). In SM, the products are designed based on an innovative 6R approach involving reduce, redesign, reuse, recover, remanufacture and recycle (Badurdeen et al., 2009). The terms are defined as discussed ahead.

- Reduce: It refers to reducing resource utilization and energy usage during production, resulting in reduced pollution during use (Badurdeen et al., 2009).
- Redesign: It consists of the use of innovative tools to produce sustainable products with ease of manufacturing process and capacity (Peralta Álvarez et al., 2017a).
- Reuse: It refers to the reuse of the parts or entire components of the products already generated during their first life cycle, which leads to minimizing the consumption of resources (Casamayor and Su, 2013).
- Recovery: It is the method of restoring all units or pieces from former users (Rosen and Kishawy, 2012).
- Remanufacture: It involves the replacement of a previously used commodity, which is returned to an original state or new form by recycling as many components as practicable without loss of operation. This step brings a new life to most component

pieces, with little energy and material input (Deutz et al., 2013a; Pigosso et al., 2010).

- Recycle: It involves the recycled process of existing materials which is commonly known as converting waste from the first life cycle of products into new materials or goods (Ahmad et al., 2018; Rosen and Kishawy, 2012).

The implementation of the 6R approach induces a closed loop for the products, i.e., recovery of end-of-use/end-of-life and total lifecycle resource flow for advancing SM (Enyoghasi and Badurdeen, 2021). Hence, the 6R approach is aimed to attain three-dimensional synchronization of the environmental, social, and economic controls termed TBL (Badurdeen et al., 2009). The economic gain is not the only viewpoint to be optimized in manufacturing processes for sustainability but it also takes account of environmental and social issues (Boulanger, 2008; Cobut et al., 2015a). Due to the increasing awareness and desire for sustainability, the key industries are considering a blend of lean and green alternatives that not only mitigate waste but also eliminate the environmental and social detrimental consequences of commonly used manufacturing processes through the extension, adjustment, and upgradation of existing used methods (Stoycheva et al., 2018). TBL approach is thus oriented towards meeting the greener needs of the environment by applying the "waste reduce, reuse and recycle" concept to achieve economic gain through minimization of raw material and energy use by redesigning, remanufacturing, and recovery resulting in social benefits in terms of reduced emissions of toxic pollutants, and mitigating health risks in the entire manufacturing process (Behrisch et al., 2011a; Gardan and Schneider, 2015; Sala, 2019).

1.4 The synergy between Sustainable Manufacturing, Industry 4.0, and Circular Economy

The unsustainable production, consumption, and growing population will cause serious socio-economic crises and threats to life expectancy around the planet. It is estimated that the population around the world will be going to rise to 9.5 billion by 2050 (UNIDO, 2017). This resulted in an increase in consumers and their demand for more manufacturing goods and businesses. This type of formulated system can disturb the ecological balance, leading to more use of non-renewable resources, consumption at a faster rate, increased emissions, and improper disposing of the product. The only solution to these problems lies in the path of sustainable development (Bag and Pretorius, 2022).

SM, Circular economy (CE), and Industry 4.0 (I4.0) are the new essential paradigms to be adopted by manufacturing organizations for achieving sustainable development goals (SDGs). Previous research confirmed that I4.0 can unlock the potential of SM (de Sousa Jabbour et al., 2018; Machado et al., 2020). Advanced and Digital Manufacturing technologies (ADMTs) have revolutionized the SM arena by upgrading the research and development capabilities and enabling innovation collaboration in the organization (Szalavetz, 2019). SM develops circularity capabilities by advancing and activating the ten similar CE strategies like reuse, reduce, recycling, recovery, remanufacturing, refurbish, repurpose, repair, refuse, and rethink (Morseletto, 2020). Zeng et al., (2017) confirmed the strong and positive bond between SM and CE. Lopes de Sousa Jabbour et al., (2018) emphasized in their study that the concept of I4.0 technologies can strengthen CE strategies. Nascimento et al., (2019) indicated that I4.0 can assist in the circularity of reusable scrap electronic items. Rajput and Singh, (2021) suggested that artificial intelligence (AI), policy and service structure, and CE are the leading drivers for bonding I4.0 and CE. Bag and Pretorius, (2022) imply that every developing country must focus on I4.0 technologies, institutional forces on resource optimization, and adoption of data-driven SM and CE capabilities.

Hence, the amalgamation of SM, I4.0 technologies, and CE concepts is essential for achieving sustainable development in the organization and is still under-researched which ignites the spark of motivation for the researcher to do this study.

1.5 Research Motivation

Manufacturing industry operations have significantly aided the economic development of developing countries, and they play a crucial role in global economy by supplying goods and services. In India, manufacturing sector contributes 14 to 18 % to its gross domestic product (Kapoor, 2015), but after the government initiative of "Make in India" program, it may rise to 25 % by 2025 (Soda et al., 2015). This shows that the manufacturing industry is propitious and will strengthen the nation's development (Islam and Karim, 2011). However, in the absence of constructive environmental measures, manufacturing activities will result in the development of massive amounts of waste, exploitation of natural resources, and excessive energy consumption. According to reports published in 2011, the manufacturing industry is responsible for 20% of worldwide carbon dioxide emissions (UNEP, 2011). World Health Organization (WHO) reports that air pollution killed around 3.7 million persons under the age of 60 years in India alone. On the one hand manufacturing industries are found to play an important role in increasing national GDP, but they are also a key source of air pollution, which has an adverse impact and causes respiratory and cardiovascular ailments (Virmani et al., 2021a). These alarming reports and the rise in environmental awareness brings more attention to the concept of SM adoption in organizations. SM focus is not only on environmentally conscious issues, but it is broader than the approach of green manufacturing (Chan et al., 2017). SM combines all the important three aspects viz. economic, social, and environmental, defined as three pillars of SM. Business and operational activities, that can achieve economic benefits without ignoring environmental integrity, and provides quality of life to all stakeholders, are referred to as SM practices (Hami et al., 2015). Organizations that are high on SM practices not only derive sustainability benefits but also reduce costs and enhance quality in many ways (Gouda and Saranga 2020).

Rusinko, (2007) investigated SM practices and their link to competitive manufacturing outcomes, finding that pollution prevention strategies are associated with lower manufacturing costs. SM technologies are the most cost-effective strategy to reduce environmental consequences without jeopardizing economic competitiveness (Costantini et al., 2017). Adoption of SM activities can avoid environmental hazards like greenhouse gas emissions, pollutant creation, and residue filling the land (Duflou et al., 2012). Sengupta et al., (2019) highlight that environmental regulations are less harsh in developing countries with cheap labor resources, and on the other hand, strict environmental regulations become costly for businesses due to the costs associated with meeting the standards. Sustainable activities in a business organization convert the resource into consumer value (Evans et al., 2017). Business organization performance is judged not only by its financial condition but also by its ability to attract additional business while adhering to regulations that promote sustainable production and environmental protection (Gopalakrishnan et al., 2012). In developing countries there is a need for the identification of SM enablers, that can ease the adoption of SM in manufacturing organizations.

In developing nations, the diffusion of SM practices is relatively low despite the high potential in world economics and workforce deployment (Ngan et al., 2019). SM adoption in manufacturing organizations of developing countries is getting set back issues due to improper performance measurement framework and unavailability of consistent, quantified, and practically applicable sustainability indicators (SI) (Jamwal et al., 2021). SI assists in managing the processes of industrial operations avoiding the damages to its TBL aspects for an organizational transition towards sustainability. It also helps to anticipate the possible conditions, trends, occurrences, and situations (Feil et al., 2019). Sartal et al., (2020) emphasized the unavailability of accepted standards and assessment procedures to measure organizational sustainability. Some companies have been pursuing sustainability with unclear strategies and policies (Ihlen and Roper, 2014). Elkington with his team conducted a research study in North America and Europe, which concluded that companies had to face a high possibility of medium and long-term losses if they don`t pay equal attention to environmental and social aspects with economic (Henao and Sarache, 2022). Some researchers highlighted that stakeholder pressure can affect the behavior of SMEs by encouraging environmental commitment (Nguyen and Adomako, 2022). Moldavska and Welo (2019) found the absence of suitable assessment frameworks and indicators as decision-making tools for SM. Danese et al., (2019) found that customers presume enhanced environmental and social commitment from the industry, and they can even pay more for their products, resultantly improving financial and operational performance. Swarnakar et al., (2021) highlighted the absence of environmental and social SI, giving the primal need for the identification of a structured set of SI from a TBL perspective. The present study depicted the potential indicators for achieving sustainability in manufacturing organizations. The relative importance of these indicators has been evaluated, performance framework is developed and tested through a case analysis for assessing the sustainability index in manufacturing organizations.

Sustainable development is explained using three pillars of sustainability named as environmental sustainability, social sustainability (SS), and economic sustainability. The policymakers concentrated on economic factors in the "profit maximization" tradition without consideration of environmental and social well-being issues. Although, with growing awareness among stakeholders (including employees, consumers, and communities), government and non-governmental organizations (NGOs) have started advocating for socially inclusive and environmentally ethical means in a manufacturing organizations (Madan et al. 2017). Globalization has resulted in a competitive market scenario between countries with weak regulations and those with strong environmental concerns and well-derived social principles, forcing the former to exit the markets (Abualfaraa et al., 2020). UN has defined 17 sustainable development goals (SDGs) with 169 connected targets (United Nations, 2015). Schroeder et al. (2019) showed that out of 17 SDGs, 11 SDGs are related to the social dimension. Thus, SS notably contributes to the United Nation's SDGs. A SS perspective of an organization is described as the capability of the manufacturing unit/industries to consider the social well-being, education, and financial and personal security of the society and the people who work within it with due consideration of demographic and economic equity (Lami and Mecca, 2021). SS dimension is vast, and its explained definitions are nebulous compared to the remaining dimensions, making its accomplishment a challenge for distinct sectors (Afshari et al., 2022). Selection of suitable indicators, and achieving social impact objectives are significant challenges for manufacturers. The present study provides a suitable framework for assessing SS with priority inclusiveness.

The adoption of a Circular Economy (CE) and sustainable practices in manufacturing organizations helps in diminishing the ecological risks, accelerating the reduction in waste byproducts and optimal resource utilization (Moktadir et al., 2018). The implementation of the circularity concept in business operations is a notable practice for bringing sustainability and achieving SDGs, established by the UN (Nayal et al., 2022). The purpose of CE in business organizations remained an arduous project, which can easily be paved from linear to CE by inducing technological advancements (Khan et al., 2021). The application of Digital Technologies (DTs) using Cloud Computing, Internet of things (IoT), Augmented reality and Virtual reality (AR-VR), Artificial Intelligence and Machine Learning (AIML), Big Data Analytics (BDA), and Blockchain for managing the absolute supply chain process from procurement of raw materials, designing, manufacturing, logistics, and dispatching is referred as the fourth industrial revolution. The industry 4.0 (I4.0) revolution is to automate the traditional manufacturing system and industrial processes using DTs influencing the capabilities of SM and CE. Organizations must give more emphasis on SM for succeeding in

CE competence. Digitalization is proclaimed as the most prominent evolution for sustainability and paving the way toward SDGs (Sachs et al., 2019; Walker et al., 2019). The current study integrates the combination of I4.0 technologies and CE philosophy for enhancing the sustainable performance of an organization and meet SDGs.

1.6 Research Objectives

Based on a detailed literature review (discussed in Chapter 2), the following research objectives (ROs) have been formulated:

RO 1: To study the status of sustainable manufacturing practices in India.

RO 2: To develop a performance framework for a sustainable manufacturing system.

RO 3: To analyze the antecedents for the performance of sustainable manufacturing system.

1.7 Contribution of the Study

The study focus is on finding the current status and vital indicators influencing the sustainability of manufacturing sector, developing a performance framework, and to analyze the synergistic effect of antecedents on the performance of a sustainable manufacturing system. The distinct and significant contributions of the study in sync with the objectives are summarized below:

i. The extensive literature review to depict the status of sustainable manufacturing practices around the globe as well as in India has been done using bibliometric analysis. The detailed literature review helps in the identification of various research gaps that need to be addressed in this study.

ii. In this research work, SM has been described in terms of principles, implementation measures, and indicators of sustainability assessment. The various sustainability indicators have been explored and documented to provide an overview of the sustainability assessment framework.

iii. The present study has proposed a framework for evaluating the sustainability index and gauging industrial sustainability performance. Based on the integrated concept of stakeholder, resource-based, and institutional theories, sustainability indicators were depicted. The explored indicators of TBL were rated on a five-point rating scale by respondents through a questionnaire survey and confirmed using structural equation modelling (SEM). The prioritization and sustainability index is produced using Delphi method and Graph Theory Matrix Approach (GTMA) to measure the sustainability of manufacturing organizations.

iv. The current study examined how organizations could induce social sustainability (SS), usually the overlooked dimension of sustainability within the system through a comprehensive literature review and underlying hypothesis. The structural equation modelling (SEM) approach has been applied in building a socially sustainable model for the business organization. The proposed model, along with the factors can be suitably used for the SS assessment and adoption by different organizations in this business world.

v. The present study analyzed the synergistic effect of industry 4.0 technologies and circular economy practices through the lens of management theories (complementary resource-based view theory, stakeholder`s theory, and dynamic capability theory) to enhance the sustainable performance of the firm that can compel them to achieve SDGs. A survey was conducted among manufacturing industries operating in India to identify the individual and combined effects of I4.0 technologies and CE practices based on sustainable performance and realization of SDGs using PLS-SEM.

1.8 Organization of the Thesis

The current research work is divided into eight chapters to structure the thesis effectively, shown in Figure 1.2. A concise summary of each chapter is given below:

Chapter 1 (Introduction): This chapter provides an overview of the research study through various sections. It comprises the background of the study, sustainable manufacturing and TBL concept, synergy between sustainable manufacturing, industry 4.0, and circular economy, motivation of the research, research objectives, contributions of the study, and research flow chart.

Chapter 2 (Literature Review): The detailed literature review with the help of Web of Science database has been carried out to explain the status of sustainable manufacturing practices and triple bottom line across the world. In total, 996 articles were selected for the study by utilizing a four-stage methodological bibliometric analysis. The systematic classification of selected articles led to the depiction of research gaps, which further assisted in the formulation of the objectives for the current study.

Chapter 3 (Research Methodology): The methodical and theoretical approach to research has been presented in this chapter. It also explains the research approach, the research strategy, data collection, and analysis methods.

Chapter 4 (Questionnaire Administration and Descriptive Statistics): This chapter covers the development of a questionnaire and its administration across distinct manufacturing sectors. Descriptive statistics have been employed to analyze the data, and the resulting insights are illustrated in the form of a bar chart. In the succeeding Chapter 5, the hypotheses testing is done on the collected responses.

Chapter 5 (Hypotheses Testing: Results and Analysis): This chapter explains the hypotheses testing and the analysis of their results using various statistical tools in SPSS and structural equation modelling using AMOS and PLS.

Chapter 6 (Framework for the evaluation of the sustainability index of a manufacturing system): Within this chapter a novel framework is presented for evaluating the sustainability index of a manufacturing system, utilizing a case study as a basis. This framework is built upon sustainable manufacturing indicators, which were identified through an extensive review of literature, and modelled using Graph Theory Matrix Approach (GTMA).

Chapter 7 (Results and Discussion): This chapter summarizes the study`s important outcomes with discussion and conclusion.

Chapter 8 (Summary, Implications, and Conclusion): This chapter represents the summary of the work done and the research findings of the study. It also explains the theoretical and practical implications, followed by limitations, future research directions, and concluding remarks of the present study.

1.9 Conclusion

This chapter introduces the background for the research study on the select issues of sustainable manufacturing systems in Indian context. The overview is provided regarding the evolution of the manufacturing concepts, sustainable manufacturing, and triple bottom line. The manufacturing industries have reached the fourth industrial revolution, where there is an urgent need for synergy between Industry 4.0, sustainable manufacturing, and circular economy for achieving sustainable development and advancing SDGs. The motivation of the study's formulated objectives and research contributions have been explained in the following section of this chapter.

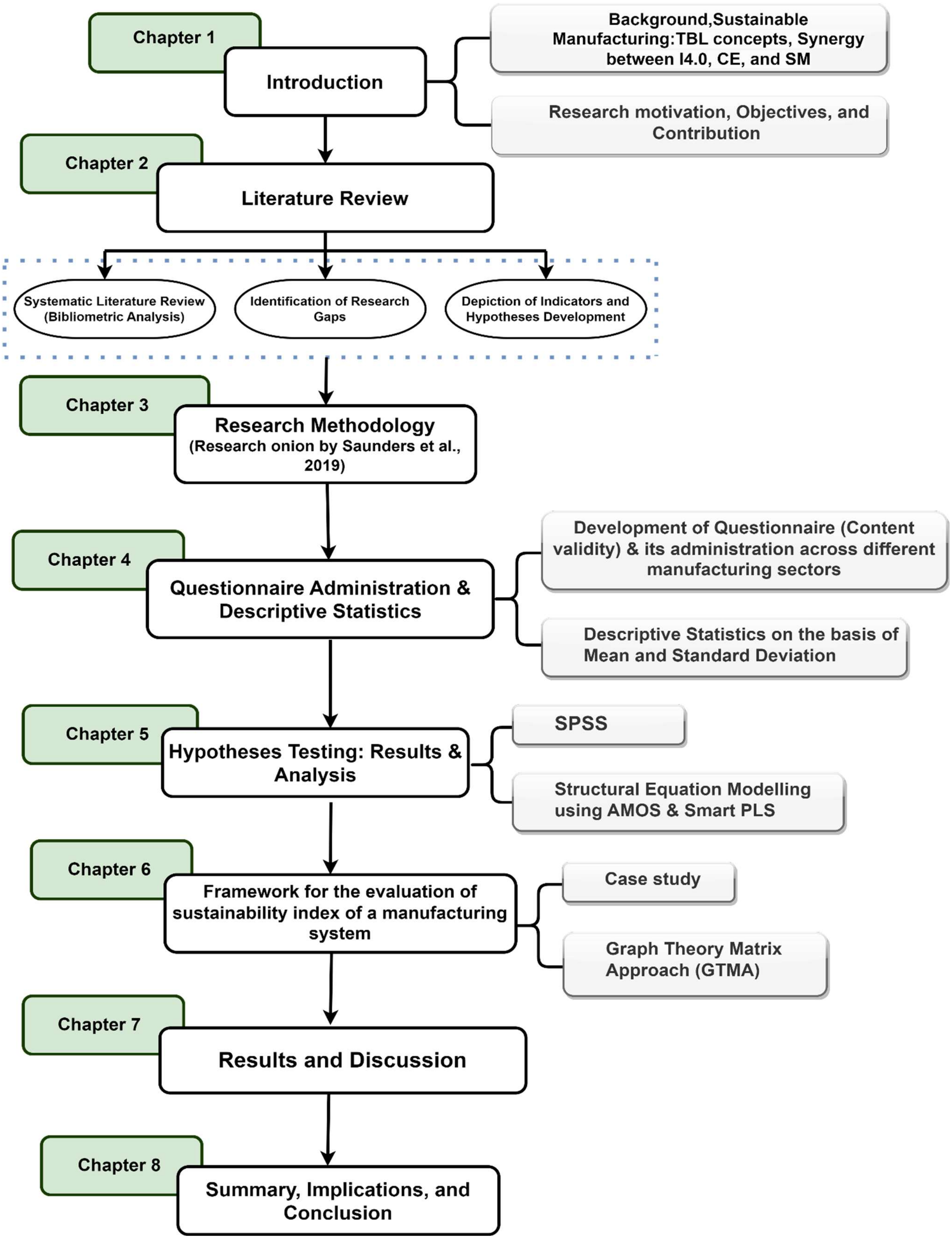

Figure 1.2: Flowchart showing the organization of a thesis

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The foundation of any research study relies on a robust literature review. Based on this perception, a critical analysis of the literature was done for the identification of various research gaps and future study directions. This chapter provides detailed insights of the status of sustainable manufacturing (SM) practices and TBL concepts around the world. The SM indicators for all three dimensions are critically reviewed, to form a basis for the development of a framework for a sustainable manufacturing system. The interconnection and need for the combination of Industry 4.0, SM, and CE are explained in past literature. The underlying hypotheses with the conceptual framework are formulated based on research gaps and objectives of the study.

2.2 Status of Sustainable Manufacturing Practices in India

SM is gaining high attention among environmentally conscious industries uncovering its high prospects in cost minimization along with boosting organizational performance with quality products (Nidumolu et al., 2015). A study done in 60 economies with 30,000 participants, suggested that millennials are willing to pay more for the products and services of the companies inclined towards sustainability concerns (Bhatt et al., 2020). SM accords with developing environmentally friendly products with desired quality, concerning the safety and wellness of all stakeholders with the conservation of energy, materials, and natural resources (Akbar and Irohara, 2018).

This section focuses on the current adoption level of SM around the world and the identification of previous efforts done by other researchers in this domain for the last ten years. The period selected for the assessment is 2012-2022. A detailed review with bibliometrics analysis (BA) has been used in the current study to evaluate the year-wise publication trend of articles, year-wise citation structure, country`s wise, author-wise, journal-wise assessment of work, source-wise citation structure, most used keywords, and network analysis of the research publications. Presently, BA is a popular research review method for assisting scholars in evaluating past and future trends of the work (Di Stefano et al., 2010). BA was carried out on an R-language-based Bibliometrix-Biblioshiny package and VOS viewer for network analysis. This package was initiated with the help of R-studio, then a raw data file in the BibTeX extension format is imported for scientometrics and cluster analysis.

The structured review of past literature with appropriate search keywords, properly selected databases, filtering the search database, and building a bibliography is named scientometric analysis (Muhuri et al., 2019). This research work follows a four-stage process for the collection of data and thematic evaluation focused on depicting concerned published papers, and segregation for identifying the most cited works/countries/authors, etc. The four-stage methodological BA has been utilized by many research studies (Bartolacci et al., 2020; Goyal and Kumar, 2021). The detailed article segregation process flowchart is shown in Figure 2.1.

In the first stage, the articles were searched on the Web of Science (WOS) database with relevant keywords. The WOS database is the most prestigious database for the journals indexed in SCI, SSCI, SCI-E, and ESCI. As an initial move, the keywords search was "Sustainable Manufacturing" OR "Triple Bottom Line " AND "Sustainability", which resulted in a total of 4,126 documents comprised of book reviews and book chapters. The second stage was done with more specific keywords for more refinement, resulting in a total of 1,876 documents. The keywords search syntax used was "Sustainable Manufacturing” AND “Triple Bottom Line” OR " Sustainability Assessment" OR "Sustainable Manufacturing Indicators" OR "Sustainable Manufacturing System" OR " Sustainable Production & Consumption" OR "Sustainable performance" OR " Sustainable Development in Manufacturing" OR "Industry 4.0 in Manufacturing" OR " Circular Economy Practices in Manufacturing" OR "Sustainable performance framework" OR "Sustainable Manufacturing Practices". The refinement in the third stage was done based on “language”, “document types”, and “citation topics meso”, and resulted in 1,320 documents. In the last fourth stage, refinement was done on “citation topics micro” and “WOS index”. The indexing selected was SCI, SSCI, SCI-E, and ESCI. After these four stages and search query strings, the documents selected were 996, taken further for BA analysis.

The summary of the bibliographic data analyzed using the Bibliometrix-Biblioshiny package is presented in Table 2.1, showing the main information, document type, author information, and bibliographic information.

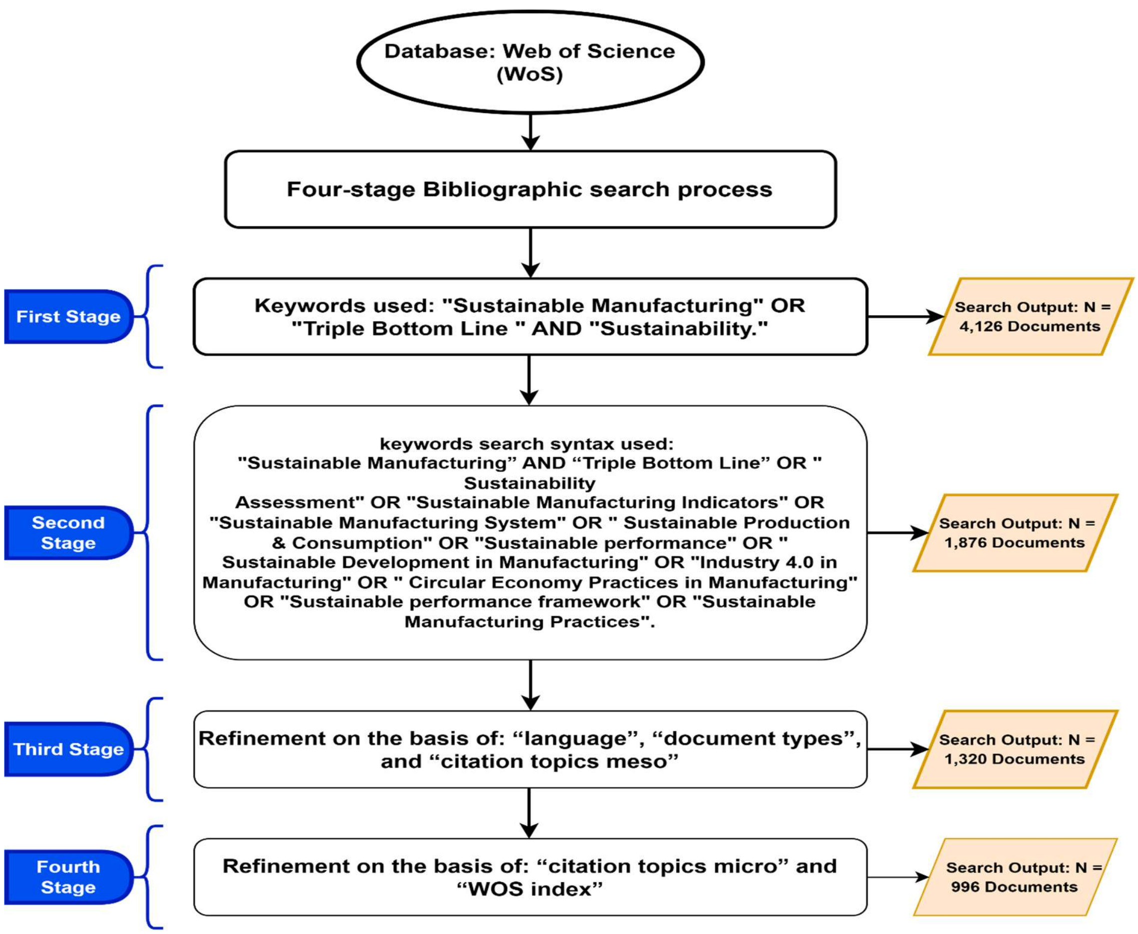

Figure 2.1: Article segregation process flowchart

Table 2.1: Summary of the Data

Primary Data Information	
Time-period	2012:2023
Total Documents Count	996
Keywords Plus (ID)	1820
Authors	2734
Single-authored document	46
Average citations per doc	29.48
Annual Growth Rate %	6.73
Average Age of Document	4.4
Co-Authors per Doc	3.51
International co-authorships %	39.66
Article	854
Early access (article)	17
Review	119
Early access (review)	6
References	51545

2.2.1 Research articles published (year-wise)

The pattern of research articles in SM for the last 11 years is shown in Figure 2.2. The number of publications in the domain of sustainability in manufacturing takes a steeper rise from 2016 onwards. In 2016, the publications were 52 which rises to 150 in 2019. After that, it starts declining at a smaller rate due to arisen of Industry 4.0 technologies, Circular Economy strategies, and net-zero philosophy. This suggests that the field of sustainability needs to be integrated with digital technologies and CE philosophy for achieving sustainable development goals.

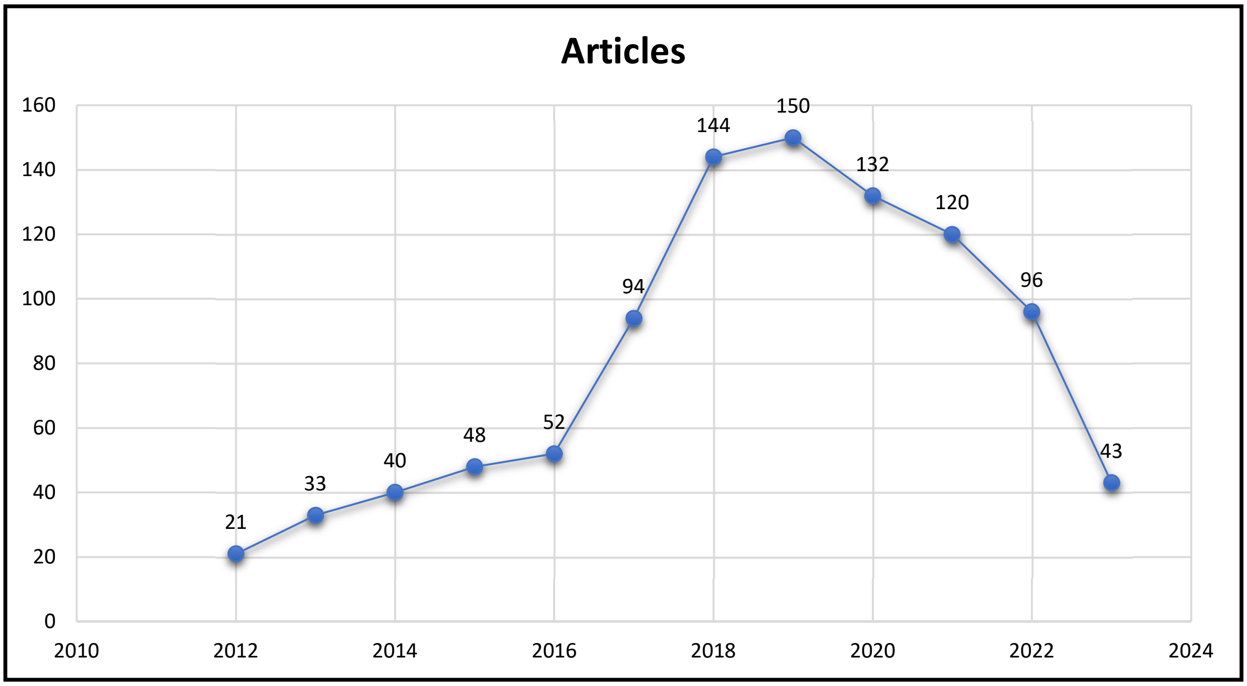

Figure 2.2: Year-wise research publications

2.2.2 Prominent authors with their publications and citations

This sub-section summarizes the most cited documents, prominent authors, and citations in the domain of SM for the last 11 years. Table 2.2 presents the details of the top 20 most cited SM publications. Gimenez and Tachizawa, (2012) work remains the most cited with 420, published in 2012. The normalization of total citations is used for benchmarking and comparison of documents (Adekunle et al., 2021).

Table 2.2: Most cited documents on SM.

Reference	**Publication Source**	**Title**	**TC**	**TC/Year**	**Normalized TC**
Gimenez and Tachizawa, (2012)	*Supply Chain Management: An International Journal*	Extending sustainability to suppliers: a systematic literature review	420	35.00	5.14
Santoyo-Castelazo and Azapagic, (2014)	*Journal of Cleaner Production*	Sustainability assessment of energy systems: integrating environmental, economic and social aspects	341	34.10	4.06
Sharifi and Murayama, (2013)	*Environmental Impact Assessment Review*	A critical review of seven selected neighborhood sustainability assessment tools	309	28.09	4.78

Beske and Seuring, (2014)	*Supply Chain Management: An International Journal*	Putting sustainability into supply chain management	265	26.50	3.16
Zaid et al., (2018)	*Journal of Cleaner Production*	The impact of green human resource management and green supply chain management practices on sustainable performance: An empirical study	239	39.83	7.31
Fernando et al., (2019)	*Resources, Conservation and Recycling*	Pursuing green growth in technology firms through the connections between environmental innovation and sustainable business performance: Does service capability matter?	239	47.80	7.48
Waas et al., (2014)	*Sustainability*	Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development	229	22.90	2.73
Mi et al., (2019)	*Omega*	The state-of-the-art survey on integrations and applications of the best worst method in decision making: Why, what, what for and what's next?	224	44.80	7.01
Faulkner and Badurdeen, (2014)	*Journal of Cleaner Production*	Sustainable Value Stream Mapping (Sus-VSM): methodology to visualize and assess manufacturing sustainability performance	223	22.30	2.66
(Sala et al., 2013)	*The International Journal of Life Cycle Assessment*	Life cycle sustainability assessment in the context of sustainability science progress (part 2)	207	18.82	3.20
(Zailani et al., 2015)	*Journal of Cleaner Production*	Green innovation adoption in automotive supply chain: the Malaysian case	207	23.00	3.57
(Varsei et al., 2014)	*Supply Chain Management: An International Journal*	Framing sustainability performance of supply chains with multidimensional indicators	198	19.80	2.36
Moktadir et al., (2018)	*Journal of Cleaner Production*	Drivers to sustainable manufacturing practices and circular economy: A perspective of leather industries in Bangladesh	196	32.67	6.00
Abdul-Rashid et al., (2017)	*International Journal of Operations & Production Management*	The impact of sustainable manufacturing practices on sustainability performance: Empirical evidence from Malaysia	183	26.14	5.51
Hoogmartens et al., (2014)	*Environmental Impact Assessment Review*	Bridging the gap between LCA, LCC and CBA as sustainability assessment tools	171	17.10	2.04
Singh and El-Kassar, (2019)	*Journal of Cleaner Production*	Role of big data analytics in developing sustainable capabilities	170	34.00	5.32
Ceulemans et al., (2015)	*Journal of Cleaner Production*	Sustainability reporting in higher education: a comprehensive review of the recent literature and paths for further research	169	18.78	2.91

Bhattacharya et al., (2014)	*Production Planning & Control*	Green supply chain performance measurement using fuzzy ANP-based balanced scorecard: a collaborative decision-making approach	169	16.90	2.01
Chardine-Baumann and Botta-Genoulaz, (2014)	*Computers & Industrial Engineering*	A framework for sustainable performance assessment of supply chain management practices	164	16.40	1.95
Disterheft et al., (2015)	*Journal of Cleaner Production*	Sustainable universities – a study of critical success factors for participatory approaches	158	17.56	2.72

2.2.3 Country and Institute wise statistics

The most contributing countries and Institutes (Affiliations) were extracted using R studio, as shown in Figures 2.3 & 2.4. Among the most contributing countries in the domain of SM and sustainability, China has been at the top with 128 publications, followed by Italy with 64, and Spain with 62 publications. In the list of top 20 only India, China, and Brazil were the developing countries putting efforts in the area of sustainability implementation. Yadav et al., (2020) highlighted that due to cheap labour costs in developing countries, MNCs are investing in manufacturing sustainability using Industry 4.0 technologies. Thus, developing nations are looking forward, and working in the area of sustainable development, circular economy, and industry 4.0. In the list of most relevant institutes, Hong Kong Polytech University has the highest number of articles in SM with 46, followed by Universiti Teknologi, Malaysia with 32, and the University of Manchester with 29 publications respectively.

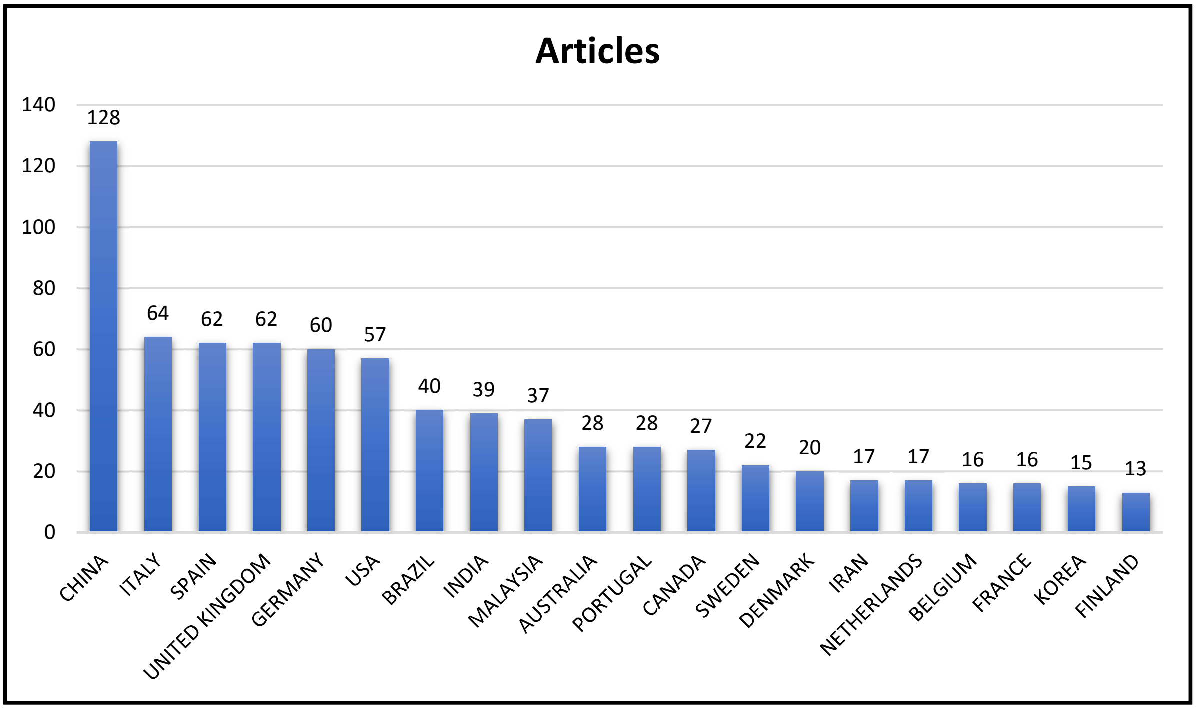

Figure 2.3: Country-wise publications in the area of SM

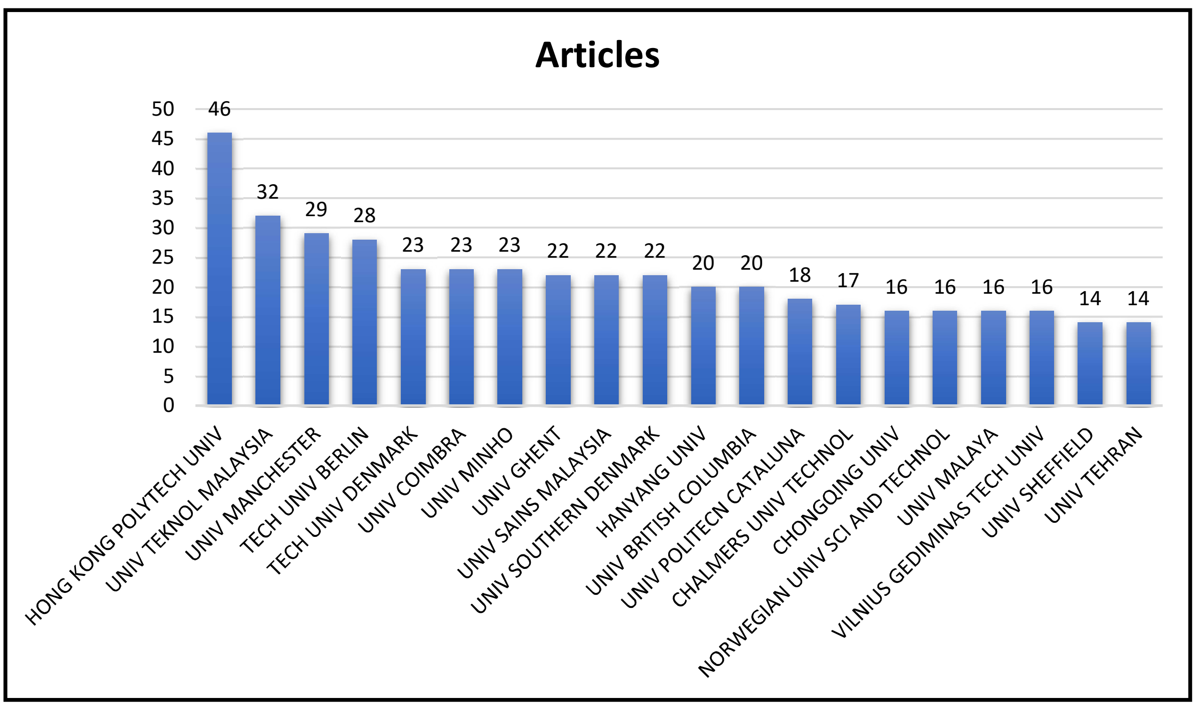

Figure 2.4: Affiliations-wise statistics

2.2.4 Top reputed journals in SM research

The top three journals which remain productive in the domain of sustainability from 2012 are; the Journal of Cleaner Production, Sustainability, and the International Journal of Life Cycle Assessment. The purpose of this analysis was to identify the most popular journals in this field. Journal of Cleaner Production (n = 271), Sustainability (n = 235), and International Journal of Life Cycle Assessment (n = 84) are the top three journals that have published the highest number of publications, shown in Figure 2.5.

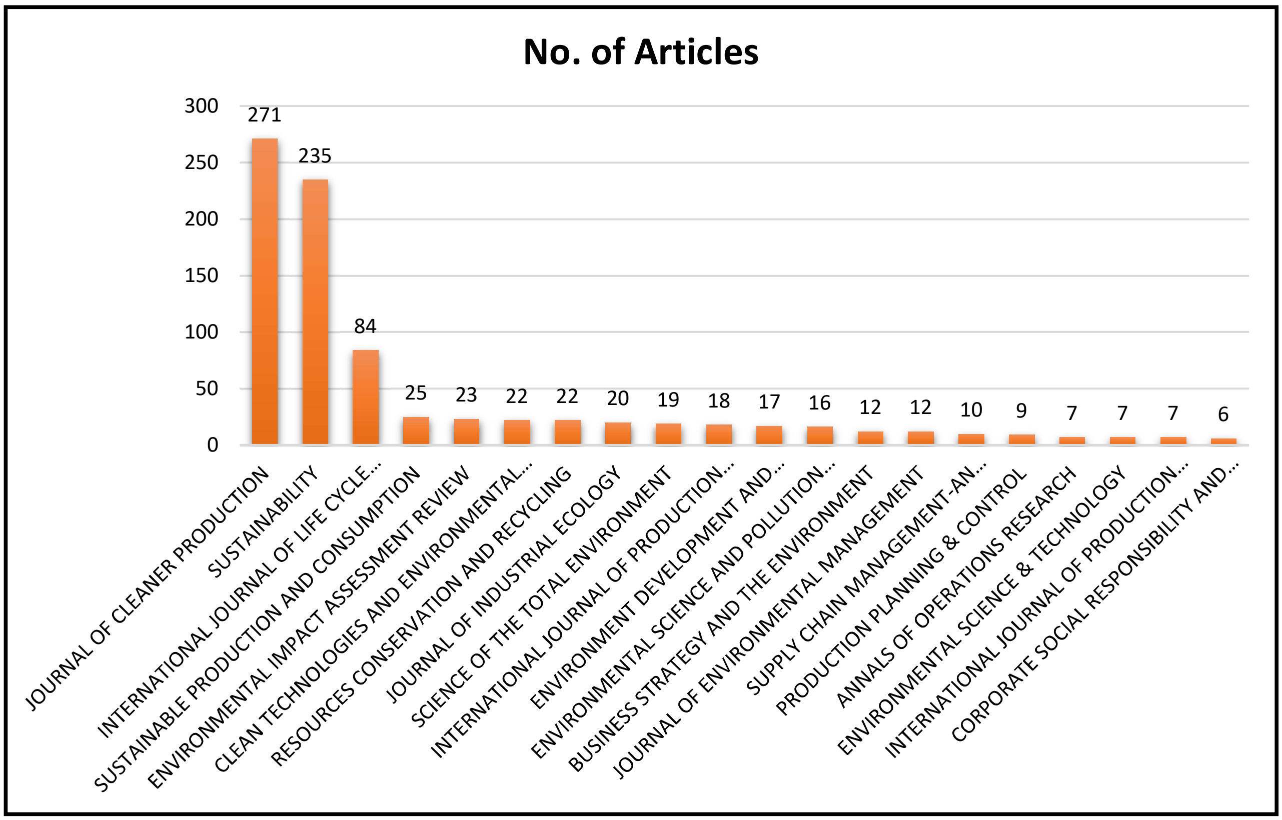

Figure 2.5: Top publishers in the SM domain

2.2.5 Co-occurrence of Keywords Analysis

The frequency of the most used keywords by the researchers for the period of 2012-2022 is shown in Table 2.3. It shows that "Sustainability Assessment" is the most used keyword by the researchers with an occurrence of 321, preceded by "Framework" and "Sustainability". Further, the VOS viewer is used to do the network analysis for the co-occurrence of keywords, shown in Figure 2.6. It can be seen that "Sustainable Development", "Life-Cycle-Assessment", and "Indicators" are the most adopted keywords with the highest node strength. The other keywords “Innovation” and “Recycling Systems” are establishing a link with “Sustainable Development” and “Sustainability”, showing that new prospects will be in the domain of CE and I4.0. The most relevant word cloud for this study of SM has been shown in Figure 2.7.

Table 2.3: Most used keywords

Keywords	*Frequency*
Sustainability Assessment	321
Framework	200
Sustainability	208
Life-cycle-assessment	148
Performance	146
Indicators	137
Sustainable Development	77
Sustainable Performance	72
Supply chain management	70
Energy	70
Innovation	58

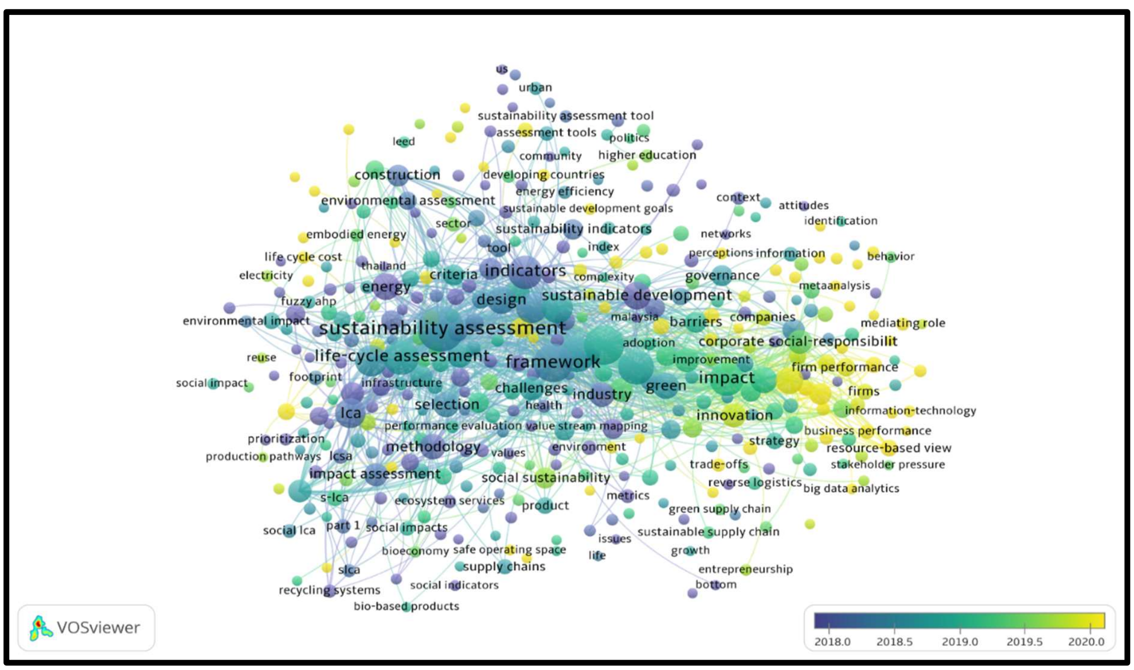

Figure 2.6: Co-occurrence of Keywords in the research domain of sustainable manufacturing

Figure 2.7: Word cloud of keywords

2.3 Theoretical Foundation of the research study

This research study applied the concept of Stakeholder Theory (ST), Resource-based theory (RBT), Institutional theory (IT), and Dynamic capability theory (DCT) as anchors for the achievement of sustainable development, and to build the theoretical basis for proposed real-world research model generated through empirical observations. These theories state that effective utilization of resources, and assets assist the firm ability to be adaptable in the competitive market scenario, and derives the smooth transition towards sustainability and CE by creating more value for the stakeholders.

2.3.1 Stakeholder`s Theory (ST)

The ST is most popular among sustainability researchers because it widens the perspective of business from the firm, itself, to a larger society and environment with an objective 'creation of value for all stakeholders' (Freeman, 2010). The encouragement of sustainable development by harnessing the synergies among stakeholders is the fundamental step to achieving sustainability on both local and global scales (Beck and Ferasso 2023). The stakeholder constitutes customers, regulators, governments, NGOs, media, etc. The rationale is that a lacking of meeting the requirements of stakeholders can lead to economic and reputation loss (Hermundsdottir and Aspelund, 2022) while meeting their needs can induce an increase in reputation, customer satisfaction, economic gains, and increase in market share (Liao, 2018). ST also explains, how firms can implement sustainability innovations, can enhance market goodwill, and diminish business risk (Hermundsdottir and Aspelund, 2022). Previous studies have found that stakeholder pressure significantly leads the top management to establish sustainable operations and steers organizational intentions toward green innovation within the manufacturing context (Shahzad et al. 2023). The engaged participation of stakeholders within the organization can enhance operational efficiencies by embracing environmentally conscious and sustainable practices. ST states that business in the organizations can be viewed as a combined effect of different groups holding stakes in the activities of that business. ST constitutes consumers, shareholders, communities, employees, financiers, and government in jointly creating trade values for the business organization (Sarkis et al., 2010). ST is considered relevant when an organization is transforming from a linear to a circular model (Gandolfo and Lupi, 2021) since a well-structured business model can induce more value for its unit, customers, and stakeholders (Moggi and Dameri, 2021). In an emerging market, stakeholders' interest in the context of CE is rising, affecting an organization's performance significantly (Chiappetta Jabbour et al., 2020; Li et al., 2019). Presently, stakeholders are aware and knowledgeable regarding digitalization and sustainable development in the firms. The industries need to push for the restructuring of the life cycle of a product from sourcing, production, consumption, disposal, and value recovery. The stakeholders` concern plays a keen role in the transition from traditional new product development to circular, required transformation from production to consumption (Modgil et al., 2021).

2.3.2 Resource-based theory (RBT)

RBT visualizes the organization as an array of resources and capabilities that develop a basis for the incorporation of sustainability (Barney, 1991). Resources mean the assets that an organization embraced, i.e., employees, financial equity, skills, and organizational (social) processes (Ramadani et al., 2022). Analogously, RBT is an inside-out frame of approach, which means that the firm available resources utilization approach, routines, and policies can yield desired outcomes. The organization's production system is a well-thought example of internal resources with inference for economic, and environmental performance. The logical thought is that waste generation, emissions, and other environmental impacts are simply indications of inefficient production systems. The firm can reduce the cost by diminishing those environmental footprints. RBT assists in understanding the effective use of resources and builds harmony between I4.0 and CE for better efficiency amid competitors (Hitt et al., 2016). The complementary combination of distinct practices acts as a driver for others` in boosting performance and meeting desired goals (Lopes de Sousa Jabbour et al., 2022). Buer et al. (2021) discussed a collective adoption of I4.0 technologies and lean manufacturing practices in an organization enhancing performance level. Identification and utilization of organizational resources can facilitate the implementation of circular strategies across the supply chain networks (Nandi et al., 2020). The resources and competencies based on the realm of RBVT exist within the organizational boundary, such as raw materials, final products/services, machinery, facilities, infrastructure, knowledge, skills of business processes, and coordination of CE configurations. Previous studies in the domain of operation management for sustainability have applied the complementary aspect for the improvement of organization performance (Hong et al., 2019; Yang et al., 2019).

2.3.3 Institutional Theory (IT)

Institutional theory, also referred as regulatory pressure, can drive the adoption of sustainable practices within the organization. IT has been used primarily in many studies as a theoretical framework to elaborate on how pressure can change the implementation of green practices in the supply chain of manufacturing organizations (Fontana et al., 2022). From an institutional perspective, stakeholders can exert coercive, normative, or mimetic pressure on organizations to promote sustainability (Yuen et al., 2017). Coercive pressures emerge from governmental agencies, industry associations, and departmental trade and industry policies, while normative pressure arises from professionalization, and mimetic pressure reflects the tendency of firms to imitate others (Dubey et al. 2019). These pressures exhibit a significant and positive correlation with tangible resources and the development of workforce skills (Bag and Pretorius 2022). The institutional perspective can induce motivation in the firm to practice sustainability, as evident in numerous sustainability studies that have employed institutional theory as a precursor (Khurshid et al., 2021; León-Bravo et al., 2019).

2.3.4 Dynamic Capability Theory (DCT)

DCT describes an organization's ability to navigate a competitive and uncertain environment by effectively organizing its resources (Teece et al., 1997). DCT involves a process of learning and developing innovative capabilities for enhancing organizational performance (Gupta et al., 2019). The changing customer preferences for sustainable products and intensified competitive supply chains have forced firms to adopt digital technologies with CE. Incorporation of I4.0 with CE develops a competitive advantage in the form of smart automation, network amalgamation of production processes, material and manufacturing cost reduction, financial investment, job opportunities, and enhancing supply chain resiliency (Kamble and Gunasekaran, 2021). The deployment of I4.0 brings a strategic and operational edge to the firms among all market players. Strategic means, the creation of new business models, and bringing data-driven solutions, which are tedious to imitate (Kamble and Gunasekaran, 2021). I4.0 technologies act as a dynamic capability to adapt, integrate, and reform intrinsic and extrinsic competencies. CE turns out to be the best organizational practice and resource that provides a solution for the increasing resource depletion rate and helps in achieving UN SDGs (Jakhar et al., 2019). Nirmal et al., (2023) observed some innovative capabilities of an organization, such as a skilled workforce, effective knowledge management, and advanced technological capabilities aid organizations in integrating supply chains, minimizing waste, and enhancing sustainable performance, leading to increased profitability. The integrated theoretical framework based on the application of ST, RBT, and IT is shown in Figure 2.8.

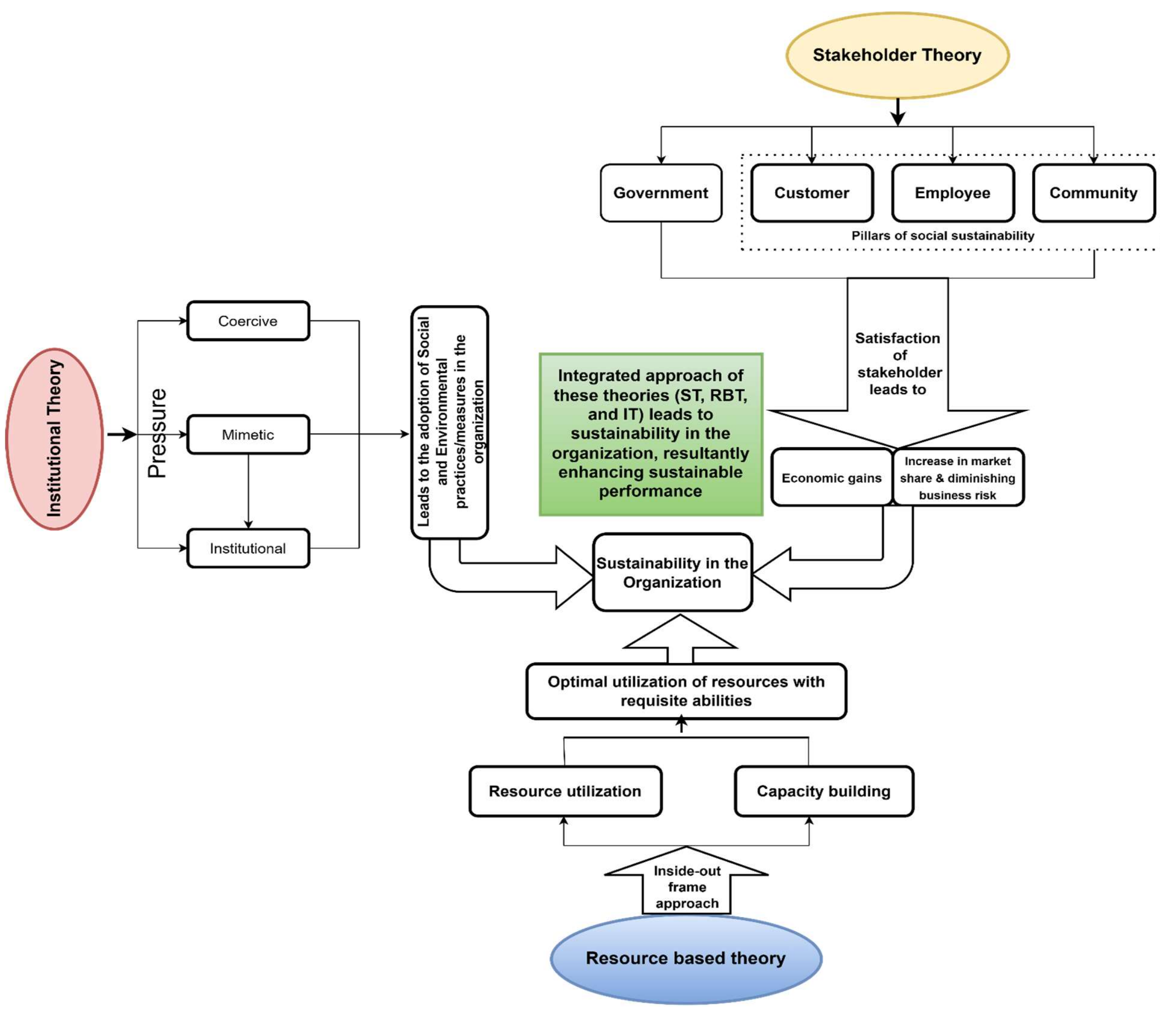

Figure 2.8: The integrated theoretical framework based on the application of ST, RBT, and IT

2.4 Sustainable Manufacturing Indicators

In view of organizations` quest for sustainable development, the prominent role of manufacturing is extensively accepted. In recent years, the manufacturing sector has seen increasing importance towards sustainability. For effective adoption of sustainability, manufacturers encourage SM practices for maintaining economic advantage with minimal impact on the environment and society (Huang and Badurdeen, 2017). Sarkis et al., (2010) specified in their study that organizational stakeholder pressures, which notably pushes firm for the adoption, and implementation of green proactive production practices emerge from customers, employees, suppliers, and shareholders.

Limited literature reports on the assessment and determination of the environmental and social impacts of production (Ahmad et al., 2019; Wu and Su, 2020). Although, the taxonomy of sustainability metrics and industrial units is not uniform. It necessitates the adoption of relevant measures and indicators for achieving the objectives of sustainable production processes and products (Chaim et al., 2018).

From a big pool of indicators, it becomes tedious to define and implement comprehensive, standardized, and usable SM indicators (Singh et al., 2007). For modelling manufacturing sustainability, identification, categorization, and assessment of an exhaustive list of indicators are highly desirable (Bui et al., 2017). An in-depth review of the literature revealed that the sustainability aspects of manufacturing systems are mostly assessed by three main indicators, which are termed environmental, social, and economic indicators (Akbar and Irohara, 2018).

2.4.1 Environmental Sustainability Indicators

The environmental dimension of sustainability focuses on the ecosystem in terms of total energy consumption, exploitation of natural resources, and self-restoration limits. Environmental assessment of manufacturing organizations is measured in terms of the use of green material (Di Foggia, 2018), energy consumption (Feil et al., 2019), and optimal water utilization throughout the product life cycle (Eslami et al., 2019). Ogunmakinde (2019) acknowledged ‘buy green’ and ‘act green’ as effective acquisition strategies for waste minimization. The organization should be capable to integrate, build, and reconfigure resources to embed environmental sustainability into new product development as per the market requirements. The Resource-based view derives two SM capabilities named "product stewardship", and “pollution prevention” as vital strategies for the company (Barletta et al. 2021).

A well-maintained and self-sustained ecosystem requires a dynamic equilibrium to prevent environmental degradation such as air pollution, global warming, climate change, water pollution, land contamination, etc. (Bereketli and Erol Genevois, 2013). Gedam et al. (2021) emphasized carbon footprints, green production practices, green logistics, green packaging, and green accounting for building a sustainable ecosystem in supply chain networks. The prime focus lies on the consumption of materials, energy, water, and biomass, in addition to their environmental impacts involved in logistics (packaging, storage & transportation), and certification (environmental laws & regulations) of the process (Bonvoisin et al., 2014; Ogunmakinde et al., 2022). To counter the hazardous effects of manufacturing activities on the environment, the World Economic Forum (WEF) promoted the circular economy to imply the reuse/recycling of products without affecting biodiversity. Khan and Haleem (2021) recommended the optimized reuse of products, parts, and materials leading to increased profit and reduced environmental distraction. Environmental sustainability can also be achieved through energy consumption, emissions, waste, water, and carbon footprint (Mani et al. 2014). Bhutta et al. (2021) reviewed green packaging, distribution, and inculcation of environmental standards (ISO 14000-14001), and observed that sustainable procurement strategies are the prominent areas of environmental sustainability practices with enhanced financial performance (Wang and Mao 2020). Table 2.4 shows the list of various references cited for these indicators.

2.4.2 Economic Sustainability Indicators

The assessment of economic performance stands as a key factor in gauging the financial prosperity of any manufacturing unit (Borchardt et al. 2011). The economic attributes for any manufacturing organization lie in its capacity to deliver superior value to customers rather than competitors. Within the economic context, the emphasis rests on identifying indicators that can effectively gauge progress in acquiring financial gains for the organization (Mengistu and Panizzolo 2022). It is noteworthy that many manufacturing organizations often lack a well-defined and comprehensive set of mature indicators when it comes to evaluating financial activities (Swarnakar et al. 2021). The economic facet of sustainability encompasses its effects on the economic health of stakeholders, local communities, and national economic systems (Butnariu and Avasilcai 2015). It considers the generation and dissemination of direct economic benefits, including operational costs, sales, administrative expenses, employee remuneration, contributions, as well as investments incurred in the safety, stakeholders` health, net profits, expenditure on various sanctions, approvals, and fines. The financial risks and implications due to the value depreciation of the products, repair, and maintenance are also assessed.

Furthermore, the assessment also takes into account substantial financial aid or subsidies obtained for the industrial setup and distribution of manufactured goods (Riayatsyah et al. 2017). The competitive strategies, recruiting procedures, and amount of expenditure on local vendors and senior-level management at significant operational sites are considered to assess the financial position and stability of the unit (Wu and Su 2020). Xu et al. (2017) indicated that taxation over carbon emissions is one of the followed global initiatives for reducing GHG emissions in developing and developed nations, highlighting the significance of economic indicators designed to analyze industrial operations and their influence on a wide variety of stakeholders. Table 2.5 shows the considered economic sustainability indicators with their references.

2.4.3 Social Sustainability Indicators

Social sustainability (SS) is considered the least explained and inscribed pillar of sustainable development compared to the remaining two pillars i.e., environment & economic (Torkayesh et al., 2021). The sustainable socio-economic development of a country is strongly dependent upon the social well-being of its people engaged in various sectors. Earlier, Holahan and Moos, (1986) stressed the role of individual characteristics on job-related issues. During the 21^{st} century, the ever-increasing trend of urbanization and awareness about climate change started highlighting the adverse social implications, including occupational health and safety of workers, shifting demographic pools, intensifying poverty, food scarcity, lack of educational facilities, and disparity in various working sectors (Figueroa-García et al., 2018; Khalid et al., 2018; Moreira et al., 2018; Razmjoo et al., 2020a).

Generally, there is a direct relationship between the personal characteristics of the employees, such as skills, experience, and proficiency, and the various benefits availed by the organization. Tafere et al., (2020) have reported the impact of the relationships between the personal characteristics of workers and their social and psychological conditions that may lead to triggering a disaster. However, depending upon the nature of employment, employees are categorized into full-time, contractual, and part-time employees, and accordingly, the financial, well-being, and development benefits differ. In many organizations, the demographic disparity is also a discriminating factor. It generally leads to job stress, insecurity, dissatisfaction, self-perceived fatigue, lack of motivation, and incompetence among the employees, resulting in a negative impact on the organization's performance and outcomes (Golinska et al., 2015a). In addition, the lack of suitable jobs, increasing job stress, inequities in wages, and gender ratio further intensify the social imbalance (Seo et al., 2015). Likewise, Jung et al. (2018) stated that irresponsible attitudes and physical fatigue can negatively impact the performance of the workforce, thereby affecting the organization's overall performance.

Zhang & Mohandes, (2020) pointed out that it's the corporate responsibility to ensure its workforce's occupational health and safety and provide equitable job and promotion opportunities. Zu et al. (2014) reported that any organization is bound not only on an economic basis but also legally, ethically, and morally to its stakeholders and community. Wu & Su, (2020) emphasized that the stakeholders get involved in the organization's financial aspects and get returns in terms of shares while the community gets benefitted in terms of infrastructural and technological development. Zohar, (2000) recognized the impact of organizational policies and training programs on developing the atmosphere of safety and societal well-being. In any occupational accident, the direct and indirect costs involved medical assistance, rehabilitation, and disability compensation, as well as time loss for both the employee and the organization (Liesivuori et al., 2002). Thus, training on the prevention of occupational safety and accidents must be prioritized regularly in the organization.

Hutchins & Sutherland, (2008) showed the interdependence of organization and their stakeholder. They mentioned that creating transparent policies for the promotion, increments, healthcare support, education, and family security of the employee boosts the organization's performance. Karji et al. (2019) concluded that developing safe work culture in the organization contributes to creating a socially sustainable community with the prediction of possible risks, leading to a productive work environment.

The prior research has yet to empirically differentiate and fragment amid the external stakeholders' (consumers, communities, investors), and internal stakeholders (employees) orientation toward SS (Chatzopoulou et al., 2022). The degree of organizational SS depends upon the quality of people's relationships (Prieto et al., 2022).

The National Institute of Standards and Technology (NIST) observed that manufacturing activities and products are hindering the social dimension of sustainability (employee, customer, and community well-being) (Kibira et al., 2018). The social indicators (e.g. health & safety of employees and customers) have been used to understand the social effect of different manufacturing processes, and products (Chaim et al., 2018). SM expects a sustainable workplace, an empowered, informed, and willing workforce despite their age, gender, abilities, and respective personal growth in light of the diminishing recruiting pool (Gebisa and Lemu, 2017). The concepts of equality, empowerment, inclusion, engagement, sharing, cultural identity, and institutional cohesion are the foundation of SS (Henao et al., 2017). It emphasizes society's solidarity and its ability to work towards shared objectives while addressing the health and well-being, nutrition, housing, education, and cultural expression of an individual (Holm, 2018). These proactive visions are vital to the potential growth of the industries, not only to ensure demographic continuity and employee requirements but also to promote work-life balance, and the welfare of all stakeholders. It also relies on improving customer satisfaction and community relations through feedback mechanisms (Zhou et al., 2016). Manufacturing industries become more productive and sustainable and gain a competitive edge by including human resource management aspects like training, employee engagement, skill set development, rewards and incentives, and commitment (Muduli et al., 2020).

A healthy workplace, proper training, risk identification, proper feedback mechanism, financial support, suitable working hours, and medico-legal benefits promote the satisfaction and working ability of an employee (Reiman and Pietikäinen, 2010). Employee satisfaction plays a key role in enhancing the productivity of manufacturing organizations considering organizational culture, working environment, equality policies, facility of rewards, and incentives among others (Lee et al., 2014; Swarnakar et al., 2020). Transparent, confidential, and proactive feedback mechanisms involving various stakeholders (employees, customers, and community) act as a guiding source for the growth of a company (Moreira et al., 2018), Generally, the stakeholders like customers, employees, public, suppliers, and shareholders can apply mimetic, coercive, and normative pressure to influence firms for the adoption of sustainable practices. The various literature reports showcasing these indicators have been listed in Table 2.6.

Table 2.4: Depicted Environmental Sustainability Indicators

S. No.	*Indicator*	*Acronym*	References																																		
			Sala (2020)	Jayal et al. (2010)	Borchardt et al. (2011)	Beng and Omar (2014)	(Badurdeen et al., 2009)	Cobut et al. (2015)	Yuan et al. (2012)	Bonvoisin et al. (2014)	Behrisch et al. (2011)	Bereketli and Erol Genevois (2013)	Akbar and Irohara (2018)	Bracke et al. (2017)	Shojaeipour (2015)	Eastwood and Haapala (2015)	Pigosso et al. (2010)	Boks (2006)	Deutz et al. (2013)	Ghobadian et al. (2020)	Peralta Álvarez et al. (2017)	Golinska et al. (2015)	Jin et al. (2017)	Talens Peiró et al. (2010)	Joung et al. (2013)	Chaim et al. (2018)	Cor et al. (2014)	Krajnc and Glavič (2005)	Razmjoo et al. (2020)	Pinto et al. (2020)	Badurdeen and Jawahir (2017)	Moktadir et al. (2018)	Keeble et al. (2003)	*Sharma (2021)*	Feil et al. (2019)	Ahmad et al. (2019)	Sangwan et al. (2018)
1	Recycling of used materials	EN1	√	√		√				√		√		√				√	√						√		√			√	√						√
2	Consumption of recycled/refurbished materials/components	EN2	√						√	√	√	√									√			√										√	√		
3	Non-Hazardous materials consumption	EN3	√				√			√						√																			√	√	
4	Economic water consumption	EN4	√					√			√		√			√						√			√	√	√		√					√	√	√	√
5	Green packaging materials	EN5			√						√	√											√														

6	Green transportation/ fuel economy and emission control	EN6						√			√	√							√								√				√				√		√
7	Reuse and recycling of wastewater	EN7	√													√									√				√	√				√	√		√
8	Renewable energy Consumption	EN8	√					√	√				√						√					√	√			√						√	√	√	√
9	Elimination of Landfill & contamination	EN9	√																					√	√	√		√		√					√		√
10	Water Contaminatio n	EN10	√										√		√	√									√				√							√	√
11	Prevention of water pollution	EN11	√	√				√	√				√	√	√		√						√	√	√			√	√	√			√		√	√	
12	Green Initiatives	EN12		√										√			√	√														√	√				
13	Emission control	EN13	√		√	√				√	√	√	√		√	√	√		√		√	√		√	√		√	√		√			√	√	√	√	
14	Labels and certificates (ISO 14001 & ISO 9001)	EN14			√	√					√	√				√	√		√	√		√				√	√				√		√	√	√		
15	Quality control	EN15				√				√	√							√	√								√					√	√				

Table 2.5: Depicted Economic Sustainability Indicators

S.No.	*Indicator*	*Acronym*	References																												
			Badurdee n and	Boks	Bonvoisin	Borchardt	Boulanger	Bourell et	Bracke et	Chong et	Cobut et	Deutz et	Frazier	Ghobadia	Golinska	Jayal et	Jin et al.	Lee et al.	Moktadir	Pigosso et al. (2010)	Singh et	Bui et al.	Illich	Butnariu	Ocampo	Lu et al. (2011)	Schau et al. (2011)	Kim et al. (2013)	Feil et al. (2010)	Ahmad et al. (2019)	Sharma (2021)
1	Wages and operating cost	EC1	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√			√		√	√	√	√	√	√	√
2	Pollution control cost	EC2																										√	√	√	
3	Environmental treatment cost	EC3																								√		√	√	√	
4	Expenses on corporate social responsibility (CSR)	EC4	√	√		√													√						√						√
5	Sales promotion	EC5		√		√																							√	√	
6	Facility expansion	EC6	√																						√					√	
7	Revenue generation	EC7	√				√									√			√			√	√		√	√			√	√	√
8	Investment in research and development	EC8																						√	√				√	√	
9	Profit earned	EC9																						√	√				√	√	
10	Annual Productivity	EC10																											√		
11	New Product Design and Development	EC11																						√						√	
12	Market share	EC12		√		√																							√		
13	Liability and Debt payment	EC13																			√										√
14	Depreciation	EC14																									√		√	√	
15	Maintenance	EC15																								√		√		√	
16	Prevention of scrap production	EC16																								√	√	√		√	

Table 2.6: Depicted Social Sustainability Indicators

S.No.	*Indicator*	*Acronym*	References																											
			Badurdeen and Jawahir (2017)	Bortolotti et al. (2015)	Beng and Omar (2014)	Chaim et al. (2018)	Cor et al. (2014)	Gebisa and Lemu (2017)	Holm (2018)	Joung et al. (2013)	Peralta Álvarez et al.	Moreira et al. (2018)	Bereketli and Erol	Borchardt et al. (2011)	Bracke et al. (2017)	Casamayor and Su	Ceschin and Gaziulusoy	Cobut et al. (2015)	Deutz et al. (2013)	Ghobadian et al. (2020)	Jayal et al. (2010)	Bonvoisin et al. (2014)	Moktadir et al. (2018)	Butnariu and Avasilcai	Ocampo et al. (2016)	Lu et al. (2011)	Feil et al. (2019)	Ahmad et al. (2019)	Peruzzini et al. (2017)	Manik et al. (2013)	Sharma (2021)
1	Job security and Employee retention	SC1				√		√																				√		√	√
2	Health and Safety	SC2																							√	√	√	√	√	√	
3	Human rights protection	SC3				√	√		√	√	√				√	√	√		√			√						√	√		√
4	Employee performance	SC4		√					√																						√
5	Employee satisfaction	SC5																							√		√	√			
6	Training and Development	SC6	√	√		√		√	√															√	√		√	√			√
7	Risk identification and employee feedback management	SC7	√		√	√	√					√												√		√	√				
8	Customer satisfaction and relationship	SC8											√	√				√		√	√				√	√	√	√			√
9	Product Quality	SC9				√											√		√				√								√
10	Trust development	SC10						√																				√			
11	Customer feedback	SC11				√		√			√																	√	√		√
12	Community feedback	SC12				√		√			√																				√
13	Social and political aspects	SC13				√	√		√	√	√				√	√	√		√			√								√	
14	Technology development and support	SC14		√		√		√																	√			√	√		√

2.5 Industry 4.0 and Sustainable Manufacturing

The manufacturing industry has greatly benefited from the industrial revolutions, which have increased output and productivity. The first three revolutions were driven by mechanization, the introduction of electricity, and advances in information technology. The fourth Industrial revolution (I4.0) and its associated technologies have a significant potential in advancing manufacturing competitiveness (Enyoghasi and Badurdeen, 2021). Rüßmann et al., (2015) depicted and concluded the association of nine technologies with I4.0 that will have a crucial impact on the future of manufacturing, shown in Figure 2.9. Mckinsey & Company suggested that adoption of the I4.0 allied technologies can generate benefits across concerned manufacturing domains.

Industry 4.0 technologies can unlatch the circularity of resources within the supply chain process (Lopes de Sousa Jabbour et al., 2018). The deployment of I4.0 fosters a clean environment, enhanced productivity, efficiency, and sustainability, and resultantly supports the rise of urban-friendly societies. Digital technologies can leverage sustainability, and assist in addressing several SDGs (Dantas et al., 2021). The adoption of Internet of Things (IoT) in the organization assists in real-time data collection from production processes (Rusch et al., 2022). The Augmented and Virtual Reality setup improves visibility and real-time access by increasing the capability of equipment monitoring, problem evaluation, and repairs, and resultantly enhancing productivity (Wee et al., 2015). The implementation of Additive manufacturing (AM) technology assists in waste management and renewable & sustainable production. Owing to Big data analytics (BDA) helps in new product development, supply/demand forecasting, and supply chain traceability. The implementation of these technologies can be facilitated by six design I4.0 principles, shown in Figure 2.10 (Hermann et al., 2016).

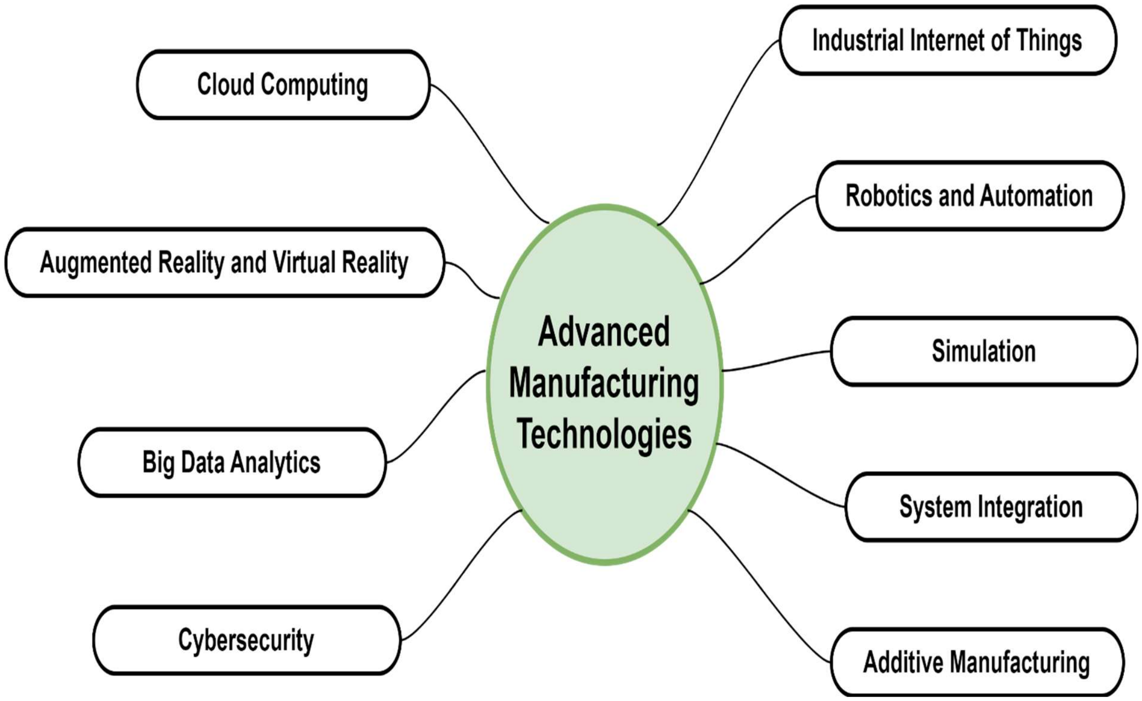

Figure 2.9: Industry 4.0 allied manufacturing technologies

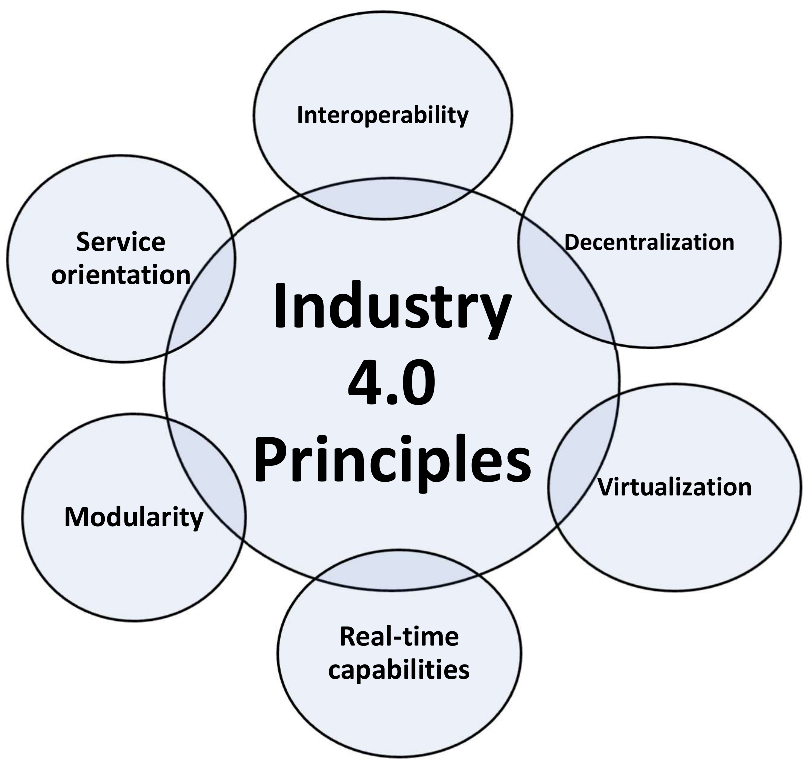

Figure 2.10: Industry 4.0 principles

The integration of I4.0 principles and technologies helps in addressing the challenges and to advance sustainable manufacturing. Kamble et al., (2018) proposed a framework in which six I4.0 principles act as a foundation for facilitating process integration through connected technologies. The amalgamation assists in making the manufacturing system more environmentally friendly, socially responsible, and economical. Several studies discussed that I4.0 technologies create a better capability for product reuse, remanufacture, recycling, and reduction, of some of the crucial elements of 6R. Thus, it can be viewed that 'I4.0 technologies build sustainability' or they act as an enabler to advance sustainable manufacturing performance (Enyoghasi and Badurdeen, 2021; Machado et al., 2020). Jena et al., (2020) proposed an SM model based on I4.0 technologies, aimed at optimizing resource utilization, and industrial waste reduction. Several past studies also elaborated SM in I4.0 through the lens of a circular economy. Rajput and Singh, (2019) concluded that I4.0 technologies enable CE to enhance TBL sustainability through cost optimization, scrap, raw materials, and carbon footprint. The above-mentioned studies depict the need for empirical studies that can utilize the potential opportunities for SM and CE through I4.0 technologies.

2.6 Research Gaps

After going through the literature, it becomes evident that integrating sustainable practices in manufacturing organizations contributes to realizing the Triple Bottom Line (TBL) concept. However, there are still some gaps that require quantitative investigation.

Gap 1: Literature reports, that the indicators used in industries are purely generic, not viable concerning activities and size, and not so fully matured to monitor specific manufacturers. The deficit of practical application and quantifiable indicators are responsible for discouragement among practitioners for not undertaking their sustainability assessment.

Gap 2: A limited number of frameworks comprised of indicators from TBL dimensions for the evaluation of the sustainability index of an Indian manufacturing system is available.

Gap 3: Despite recent trends toward incorporating environmental and economic factors into the sustainability assessment framework, the social issues' inclusiveness was found to be under-researched.

Gap 4: The synergy of Industry 4.0 technologies, circular economy strategies, and sustainability is not clear and validated on practical ground.

Gap 5: Only limited studies on specific type of I4.0 technologies supporting the implementation of circular economy have been observed in literature.

2.7 Research Questions

Based on the aforementioned research gaps, this study addresses the following research questions (RQs):

RQ 1: What are the key indicators influencing the sustainability of a manufacturing sector?

RQ 2: How can the importance of these indicators be assessed and utilize to develop a sustainability index of an organization?

RQ 3: What are the critical social sustainability factors, and how can their inter-relationships be leveraged by industry professionals to enhance organizational performance?

RQ 4: How might I4.0 technologies, Circular Economy practices, and their linkage influence the sustainable performance of a manufacturing organization?

2.8 Hypotheses formulation

Based on the literature support, the concerned hypotheses are formulated to explain the identified research gaps (discussed above), and research objectives for achieving sustainability in the manufacturing organization. The framed hypotheses of this research study will be going to answer the three research gaps (Gap 3, Gap 4, and Gap 5) related to the Indian manufacturing scenario. In this study, two hypothetical models are proposed. First, the hypothetical model incorporating various constructs of social sustainability is shown in Figure 2.11. The second proposed conceptual model is based on the synergistic effect of industry 4.0 and circular economy for enhancing the sustainable performance of the organization and achieving SDGs, shown in Figure 2.12.

2.8.1 Interrelationship of SS critical factors

Organizations can gain more financial performance and create value for their stakeholders and shareholders in the long term if they are concerned about social performance by retaining their dedicated employees, which results in more loyal customers (Dočekalová and Kocmanová, 2016; Doloi, 2012; Goel et al., 2020; Murphy and Eadie, 2019). Various researchers have signified the interrelationship of critical factors that can be used as SS indicators. Henao et al., (2017) have highlighted the effect of job characteristics such as job availability and job security on community interrelations. Seo et al. (2015) emphasized the interdependence of job characteristics (JC) and occupational health and safety (OHS). Many researchers have highlighted the role of gaining customer satisfaction and public trust by providing product information and products with better quality by building community interrelations (CI) with the provision of technology and infrastructure development (Henao et al., 2017). Past studies has emphasized product quality, product information, and customer satisfaction's influence on stakeholder engagement (Garza-Reyes, 2015; Wu and Su, 2020; Zhou et al., 2016). Hence, based on the literature review, the factors affecting the social sustainability and their interrelationship were analyzed by formulating the following hypothesis, and modeling was carried out using AMOS software:

H1a: *There is an interrelationship between JC and OHS.*

H1b: *There is an interrelationship between JC and CI.*

H1c: *There is an interrelationship between JC and SE*

H1d: *There is an interrelationship between JC and consumer protection.*

H2a: *There is an interrelationship between OHS and consumer protection.*

H2b: *There is an interrelationship between OHS and CI.*

H2c: *There is an interrelationship between OHS and SE.*

H3a: *There is an interrelationship between consumer protection and CI.*

H3b: *There is an interrelationship between consumer protection and SE.*

H4: *There is an interrelationship between CI and SE.*

2.8.2 Job characteristics and social sustainability

The organization provides benefits to their employees under their compensational policies; these benefits and their characteristics are defined as job characteristics (Simoes et al., 2016). These characteristics are vital quantitative indicators for assessing social sustainability in an organization (Popovic et al., 2018). Organizations frequently use employee layoffs and employee turnover rates as essential tools for enhancing the company's performance. Still, a higher turnover rate can lead to more replacement costs, excess demand for training requirements, and loss of learning & experience effects (Katsikea et al., 2015). On the other hand, frequent layoffs result in declining employee morale and commitment. It will enhance working stress (Cascio, 2010). As per the literature, we hypothesize:

H5: *JC is positively related to SS***.**

2.8.3 Occupational health & safety and social sustainability

Organizations' initiatives to monitor the quality of working conditions and safety risks, enhance employee satisfaction, keep operational processes running, and positively impact the company's image and brand (Simoes et al., 2016). Consequently, the following elements are needed in the process of assessing SS. Indicators like time lost due to injury and work-related diseases, risk assessment, risk control measures, health care security policy (Podgórski, 2015), training & education (Uma, 2013), etc. are used to gauge health and safety working conditions. Wan & Ng (2018) highlighted that SS could consider issues related to stakeholders' safety and physiological and psychological requirements in housing projects. Hence, we hypothesize:

H6: *OHS is positively associated with SS.*

2.8.4 Consumer protection and social sustainability

Nowadays, consumers are becoming more aware of the impact of their purchasing intentions on the environment and social sustainability (Grunert, 2011; Mohr and Webb, 2005; Simmons and Becker-Olsen, 2006). Toussaint et al., (2021) highlighted consumers' awareness of their purchasing decision from the company's corporate social responsibility (CSR) point of view. Most aware and informed consumers would prefer to buy from a company that develops & sells sustainable and responsible products. Consumers act as keen players in the outcome of CSR as they have the potential to purchase a product. Still, they must be made aware of the conditions, quality, and information of the product they want. Ozhan et al. (2022) concluded that the amount of value given to the customers in the organization leads to business success rather than the power of production. Organizations should include the concept of consumer conception in connection with the company's social practices (Jitrawang and Krairit, 2019; Kaczorowska et al., 2019). Thus, we hypothesize:

H7: *There is a positive relationship between consumer protection and SS.*

2.8.5 Community Interrelations and social sustainability

Social sustainability combines the processes and framework for stabilizing people, the planet, and profit regarding happiness, safety, and future generational perspectives (Blanc and Raymond, 2011; Eizenberg and Jabareen, 2017). It is defined as the 'neglected element of sustainability' (Kandachar, 2014) comprised of social equity and community concerns (Bramley and Power, 2009).

Social sustainability in business can be created by adopting innovative technology, research & development (Simoes, Freitas, et al. 2016). Social innovation can be achieved by meeting social needs (Caulier-Grice et al., 2012) namely, projects on social development, local education, and focus on developing initiatives for improving social sustainability, among others. Higher values of these indicate the company's initiative in the process of creation and enhancement of social sustainable businesses. Venkataraman (2004) introduced new business organizations. The entrepreneurial ecosystem is a network of interlinked elements constituting resource providers, risk-bearers, market demand, advanced technologies, infrastructure support, culture, policies, and support services to develop a right-oriented revenue generation cycle. Community involvement is vital in developing, recommending, and implementing positive solutions to social issues (Desiana et al., 2022). Literature reports that organizations must consider the concerns of their community. Therefore, we hypothesize:

H8: *There is a positive relationship between CI and SS.*

2.8.6 Stakeholder engagement and social sustainability

Social assessment of an organization is endeavored by considering stakeholders' satisfaction (Fatourehchi and Zarghami, 2020). Companies that can communicate their sustainability can improve their stakeholder's satisfaction and firms' image (Bebbington et al., 2008; Campbell, 2000). Afshari et al. (2022) studied that internal stakeholders play an essential role in achieving

SS. Organizations would have strategic importance over their competitors if they emphasized more on their stakeholders as valuable resources (Sodhi, 2015). According to the stakeholder resource-based view (Barney, 2001), utility theory, and stakeholder theory (Freeman 2010), all stakeholders, such as suppliers, employees, and customers, must be managed equally for capitalizing their respective routines, resources, and their abilities resulting in improved performance (Gualandris et al., 2015).

Stakeholders have a crucial place on CSR's part; they can lead customers to buy distinct brands, favor few retailers, and enhance the firm's image, improving its economic performance (Luo and Bhattacharya, 2006). For Example, America's renowned coffee brand, Starbucks, earned popularity among customers due to its primary emphasis on responsible social paths of sourcing and servicing, significantly improving its retailers' image (Argenti, 2004). In this study, we tried to explore the connection between SE and SS of an organization. Thus, we hypothesize:

H9: *There is a positive relationship between SE and SS.*

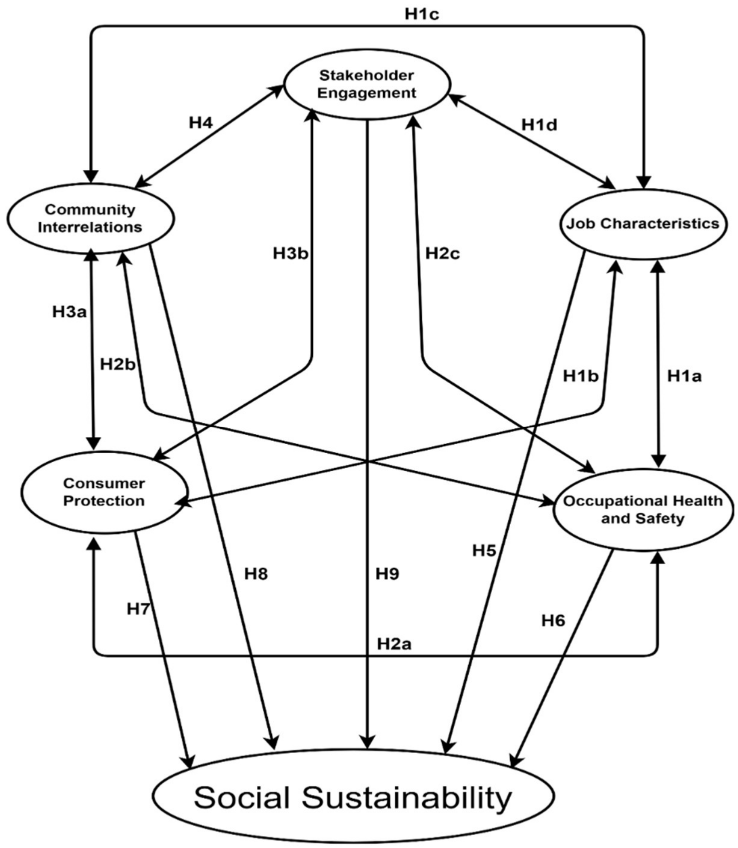

Figure 2.11: Social sustainability hypothetical model

2.8.7 Industry 4.0 and Circular economy

I4.0 technologies namely AIML, BDA, Blockchain, and IoT are pivotal in driving the transition towards a CE model (Pagoropoulos et al., 2017). The accomplishment is evident through the implementation of innovative approaches to improve and optimize product management, and performance over time (Rosa et al., 2020). The European Union CE action plan highlights that the adoption of digital technologies results in good bonding with customers, mass customization, and a collaborative economy, correspondingly leading to resource circularity, product expansion, and economy dematerialization (Rusch et al., 2022). The demand of digitalization in manufacturing organizations, driven by the concept of circularity and I4.0, is compelling them to generate information for extending product life cycle through 3R strategies- Reuse, Repair, and Recycling (Awan et al., 2021; Yang et al., 2018). I4.0 enables circularity in the business models, strengthen 3R strategies, and strategic fit among customers, community, and stakeholders (Bressanelli et al., 2018; Ranta et al., 2021). I4.0 readiness and its adoption induce multi-faceted benefits, efficient operational control, and sustainability, and lead to exponential business growth (Virmani et al., 2023). Radio Frequency Identification (RFID) and IoT assists in the traceability of the product and its spare parts (Franco, 2017). BDA helps in cleaning and deriving consequential information from the gathering to analyzing the data, which can support the concept of CE during sustainable-centric decision-making (Jabbour et al., 2019; Viles et al. 2022). Thus, the umbrella of I4.0 is expected to lead CE ecosystem (Ferreira et al., 2023). Based on the above review, hypothesis H10a can be formulated:

H10a: I4.0 leads to the adoption and implementation of CE in the organization.

2.8.8 Industry 4.0, Sustainable performance, and SDGs

I4.0 confers a competitive edge to the organization through heightened automation, responsiveness to real-time demands in a connected manufacturing system, and a unified network of products and processes (Carvalho et al., 2018; Lin et al., 2018). Digital technologies are recognized as pivotal facilitators for bringing organizational excellence, alongside a consistent elevation in efficiency and system performance (Mukhuty et al., 2022; Sharma et al., 2022). According to the European Circular Economy Research Alliance, the application of digital technologies like AIML, IoT, Blockchain, and BDA contributes to the sustainability and circular performance of the organization. Organizations can utilize I4.0 technologies to retrieve, and analyze the data on a real-time basis, leading to improvement in strategic, and operational decision-making, and flexibility in manufacturing processes (Dalenogare et al., 2018). Blockchain assures information reliability, transparency, and traceability, which may contribute the organizations for circularity of supply chains (Maranesi and De Giovanni, 2020). AM support CE initiatives by encouraging repair and refurbishment leading to potential waste reduction, material savings, and prolonging product lifecycle (Hettiarachchi et al., 2022). Furthermore, AM assists in improving circularity of materials by creating additive CE ecosystem, consequently improving sustainable business performance (Ferreira et al., 2023). Based on the discussion, hypothesis H10b and H10c can be formulated as:

H10b: I4.0 technologies positively and directly influence the sustainable performance of the organization.

H10c: I4.0 technologies lead to the achievement of SDGs.

2.8.9 Circular economy and Sustainable performance of the organization

Modernization and development in industries have produced adverse effects on the ecosystem in the form of hazardous chemical waste disposal, carbon emissions, and pollution (Yin et al., 2023). CE practices are one of the viable solutions for advancing economic development and sustainable performance of the organization (Singh and Singh, 2019). In CE, products and materials are utilized up to last limit. Additionally, waste generation and resource exploitation are minimized while keeping the resources within the economy till product life (Cao et al., 2024; Kristoffersen et al., 2021). Sardana et al. (2020) explored the benefits of CE in the organization which strengthens the waste treatment and recycling expertise, and yields cost reduction. Hence, implementation of CE practices can enhance efficiency, reduce scrap rate, distribution period, and inventory cost, resultantly improving the operational performance (Yin et al., 2023). Investment in CE practices enhance the economic performance in terms of sales, turnover, and market share (Chen et al., 2021). The absorption of CE in the firm reduces the adverse effects of manufacturing activities on the environment (Tang et al., 2022). CE relies on the concept of 3R (reduce, reuse, and recycle) which manufacturers can employ to preserve natural resources, and recycle waste products through green purchasing across the entire production cycle (Sakthivadivel et al., 2020). Hence, considering the above arguments, hypothesis H11 can be formulated as:

H11: CE has a positive and significant effect on the sustainability performance of the organization.

2.8.10 Circular economy and Sustainable Development Goals (SDGs)

In manufacturing organizations, industrial processes lead to natural resource exploitation and waste generation. The conventional economic model is proving inadequate; the need arises for a transition towards the CE. The implementation of CE practices is critical for maintaining competitive advantage, economic progress, and attaining SDGs (Fehrer and Wieland, 2021; Nujen et al., 2023). CE emphasizes mainly the use of greener energy as a source for reducing pollution, raw materials consumption, and waste generation (Khan and Kabir, 2020). Along the same line, SDG 7 is for providing affordable and renewable energy for use and production. Internationally, many organizations argue about the potential part of CE for generating millions of jobs in the coming decade (Dantas et al., 2021). Lacy and Rutqvist (2015) reported that a shift to CE offers an economic prospect of $4.5 trillion, which would decline the dependency on scarce resources and increase economic flexibility. The SDG 8 focuses on the promotion of economic growth maintaining adequate employment and fair work. CE practices include reducing, reusing, recycling, recovery, circular design, and safe waste disposal approaches, turning out as a treasured asset for achieving SDG 12 and defining sustainable production and consumption (Priyadarshini and Abhilash, 2020). The major array of problems associated with linear patterns can easily be harnessed using the synergy of CE and I4.0 technologies, contributing directly to the achievement of SDG 12 targets. Based on aforementioned literature support, hypothesis H12 can be formulated as:

H12: The implementation of CE practices leads to the accomplishment of SDGs.

2.8.11 Sustainable performance, and SDGs

The sustainability performance in firms is widely measured based on environmental, social, and governance scores (Tamimi and Sebastianelli, 2017). The firm progress towards achieving the SDGs depends on the extent to which embraced sustainable practices and activities are assisting in enhancing the corporate sustainable performance (Khaled et al., 2021). The SDGs are concerned with 5Ps, namely people, planet, prosperity, peace, and partnership (Suryanto et al., 2021). One of the keen aims of SDGs is to create an innovative and people-centric sustainable economy, confirming employment with better standard of living (Sadiq et al., 2023). UN SDGs Agenda 2030 are interlinked and are based on environmental, social, and corporate governance (Khaled et al., 2021). SDGs can be advanced through the mutual efforts of business organizations, corporations, and firms towards environmental protection, improved social well-being, health and safety, and increased sustainable performance (Vveinhardt and Sroka, 2021). Implementation of standard sustainability metrics amend the environmental, economic, and social performance of the organization, and is beneficial in gaining 17 prescribed SDGs (Hussain et al., 2021). Business organizations could pump the targets of SDGs by adopting I4.0 into their manufacturing activities (Rosati and Faria, 2019). Integration of Green innovation strategies with business strategies helps to minimize emissions, energy consumption, waste, and organizational identity among competitors, and in developing a support system for innovating products, processes, and services for an organization (Khan et al., 2022). In view of the above support statements, hypothesis H13 can be formulated as:

H13: Sustainable performance of the organization assists in achieving UN SDGs.

2.8.12 Mediating effect of CE practices and Sustainable performance of the organization

Many researchers argue that the 2030 agenda of SDGs is an ambitious and powerful attempt, however, it seems to be an oxymoron (Del Río Castro et al., 2021; Spaiser et al., 2017). Till now, the research on this domain seems to be silo-based (Bergman et al., 2018). The success and achievement involve the need for an integrated, action-oriented, and multi-disciplinary consistent approach. Building a sustainable robust system requires a synergistic linkage of I4.0 technologies with CE philosophy, responsible utilization of resources, collaboration from all the stakeholders, and technological dynamic capabilities. The adoption and inducement of I4.0 optimally combine the organization's assets, leading toward the policy of know-how. This approach is termed as 'seizing', one of the important dynamic capabilities for organizational learning (Teece, 2007).

Given the aforementioned literature support and direct associations, the current study proposes that I4.0 technologies sequentially and serially mediate the realization of SDGs.

By extending the above-proposed hypotheses H10-H13, evidence of available literature, and practical viability and conviction of the proposition, the hypotheses H14, H15, and H16 can be formulated as:

H14: CE practices mediate the relationship between I4.0 technologies and SDGs.

H15: Sustainable performance mediates the relationship between I4.0 and SDGs.

H16 (Serial Mediation): CE practices and sustainable performance mediate the linkage between I4.0 and SDGs.

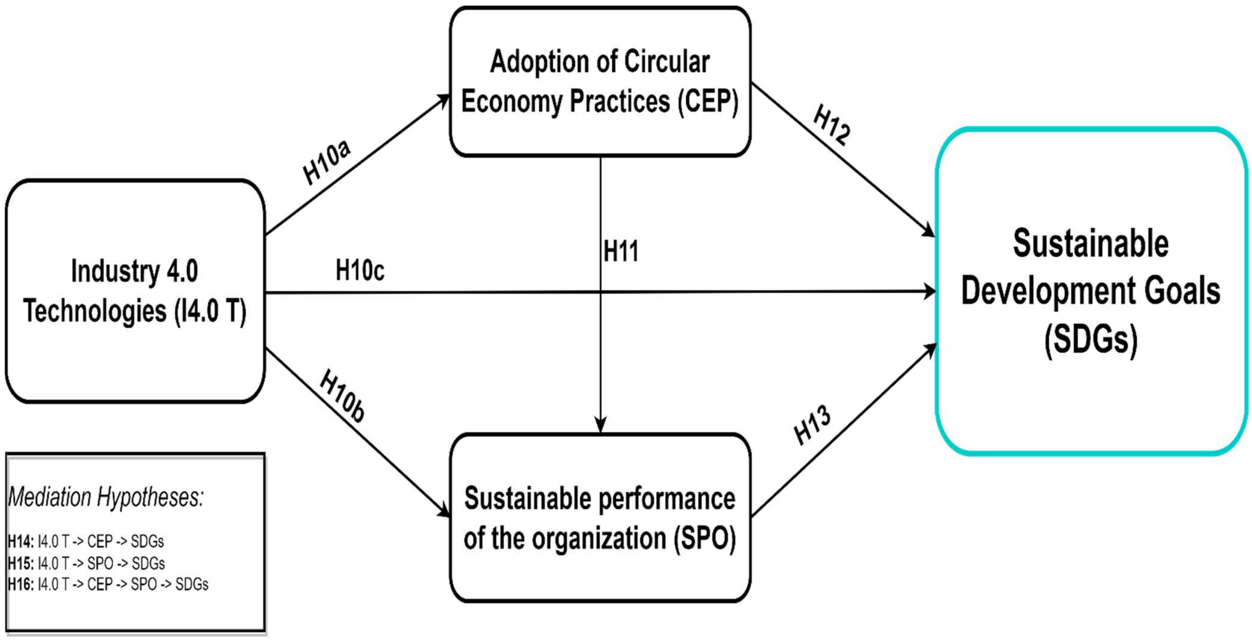

Figure 2.12. A conceptual framework based on I4.0, CE, and SDGs

2.9 Summary

This chapter explains the past research work in the domain of sustainable manufacturing and the triple bottom line across the world. The detailed review of the literature helps in the identification of research gaps and objectives of the study. The emergence of the fourth industrial revolution and its associated technologies act as antecedents for the adoption of sustainability and improvement in sustainable performance of manufacturing organizations. Prior studies show that to achieve sustainability in manufacturing systems, the integration of industry 4.0, sustainable manufacturing, and circular economy is required. In total, sixteen hypotheses have been formulated based on literature evidence in the context of social sustainability, industry 4.0 technologies, circular economy, sustainable performance, and sustainable development goals.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

In the previous chapter, a detailed literature review was done to explore the status of sustainable manufacturing practices in India and across the world. This chapter will describe the answers to the depicted research gaps and formulated objectives through a transition from theoretical research to a practical paradigm. In this chapter, sections are divided into two broad categories- firstly, the philosophical and conceptual aspects of theories are explained using the research onion, given by (Saunders et al., 2019). The research onion demonstrates the sequential steps of effective research progression passed by the researchers during the work. Secondly, the practical aspect of the research study covers an analysis of literature, questionnaire development, construct validity, semi-structured interviews, and data evaluation.

3.2 Conceptual aspect of theoretical research

The concept of research onion was given by Saunders et al., (2012) to guide researchers in developing a sound research framework having an interplay of theory and empirical method, shown in Figure 3.1. The philosophical aspects of the research are covered by outer layers and the practical aspect by inner layers.

3.2.1 Research Philosophy

Research philosophy means the development of knowledge on the system of beliefs and assumptions. A well-planned and consistent set of assumptions will form a valid research philosophy, which will act as a base for your methodological choice, research strategies, data collection and validation, and evaluation techniques. Saunders et al., (2019) defined research philosophies into three types; Ontology, Epistemology, and Axiology.

Ontology philosophy assumptions are based on the nature of reality. The ontological assumptions transform the way of seeing and studying the research objectives, leading to developing a choice of what to research for your study. Epistemology philosophy refers to developing assumptions on the extent of knowledge, what looks acceptable, defined, and legitimate (Burrell and Morgan, 2011). Axiology philosophy is based on the role of ethics and values. In this, the researcher is concerned more with their values rather than other suggestions during the process of researching. For example, collecting responses for your study in which you place more value on face-to-face interviews than responses received through anonymous questionnaires.

Bryman and Bell, (2015) concluded that in management research, mainly four philosophical positions are adopted, named as positivism, interpretivism, realism, and pragmatism. Positivism is a scientific outlook that conceives informational data interpretation through mathematical analysis, signifying that social sciences can be evaluated similarly to physical sciences. It believes, truth is always stable, and it can be represented and studied objectively. Contrary, interpretivism uses a philosophical stance and states that analysis of social science is complex and it is not possible to use theories scientifically. Golicic and Davis, (2012) stated that positivism and interpretivism are two majorly adopted philosophies in the domain of supply chain management and operations management. Realism, like positivism, is an epistemic branch that posits a scientific method to knowledge formation. This idea fosters data collection and analysis. Pragmatism is a philosophy that tries to account for lived experience in human behaviour and activity. It is a philosophical tradition that connects practice and theory.

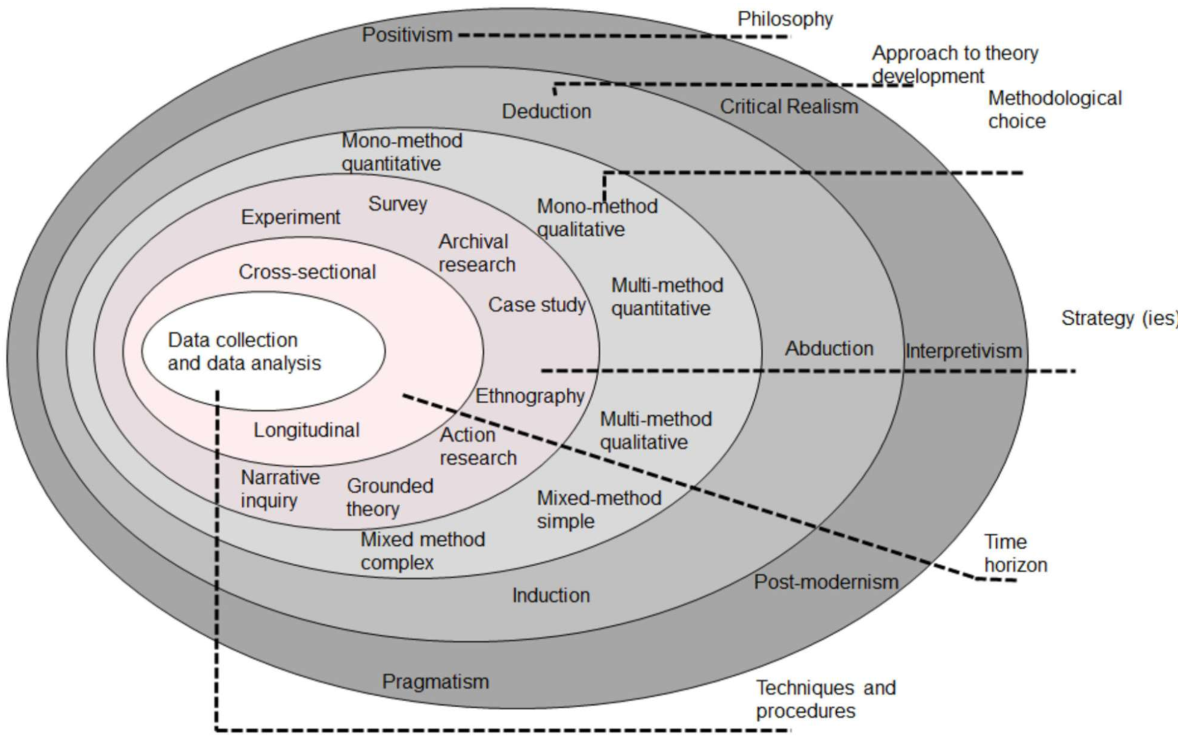

Figure 3.1: Research Onion by Saunders et al., (2012)

3.2.2 Philosophy adopted for the research study

This research study employs an empirical approach by utilizing data to replicate real-world scenarios, thereby aligning with the positivism philosophy. Positivism is a paradigm that not only advances theories through causal testing but also verifies them through empirical investigations. Saunders et al., (2012) have emphasized that positivism has a significant advantage over interpretivism as it minimizes the researcher's personal biases during the research process. Based on the aforementioned arguments, it is deemed appropriate to apply positivism to this study.

3.2.3 Research approach of the Study

The fundamental testing approaches in business and social research are categorized as inductive, deductive, and abductive shown as a second layer on the research onion (Figure 3.2).

The inductive approach involves the collection and evaluation of empirical observations to create a hypothesis and then develop a theoretical framework. While, deductive approach entails the use of a theory to develop hypotheses, followed by empirical testing. Abductive research represents a convergence of the deductive and inductive research paradigms, stemming from the recognition that certain research observations may not conform exclusively to the principles of either a pure deduction or pure induction (Kovács and Spens, 2005).

In this research study, a deductive approach was employed, wherein hypotheses were formulated based on selected theoretical concepts. A questionnaire was developed to collect data from specific industries, which was then tested using some empirical analysis. Chicksand et al., (2012) observed that all studies in supply chain management using quantitative techniques, utilized the approach of deductive in the research process.

3.2.4 Research strategy

The research strategy is influenced by a range of factors, including the study questions, objectives, established expertise, available time and resources, and intellectual underpinnings. There are seven fundamental research strategies widely accepted and adopted in business and management research, namely; experiment, survey, case study, action analysis, grounded theory, and ethnography. It is noteworthy that these strategies are not mutually exclusive, we can incorporate survey techniques with case study.

This research study employed surveys and case studies methods as a research strategy, which enables researchers to gather data about specific practices, situations, or views at a given point in time through questionnaires or interviews for a specific industry. Once data is collected, both quantitative and qualitative analytical techniques can be applied to infer existing relationships. However, data collection using the survey method has a few limitations, vagueness, and difficulty in explaining the underlying causes of the measured phenomena. Apart from this, several chances of biases, like the self-selecting nature of respondents, period selection of the survey, and the design of the survey by the researchers may exist.

Case studies are a methodical approach to elucidate real-world interactions, typically within a singular organization. This research tool is particularly valuable for investigating practice-based issues when the actors' expertise is significant and the context of action is crucial. Cepeda and Martin, (2005) stated that the case study technique is highly adept for gathering practitioner knowledge and documenting practice experience. However, case studies have limitations due to their confinement to a single entity, which makes it arduous to draw generalized conclusions. Additionally, diverse researchers may interpret identical or similar data differently, resulting in a potential study bias.

3.2.5 Research method design

Research method choices pertain to the utilization of either quantitative or qualitative research methods or a combination of both in either simple or complex ways or even the use of mono-methods. Quantitative research methods entail the use of numbers and mathematical operations, while qualitative methods are primarily associated with descriptive data and interviews. There are three main methodologies available for gathering data: mono-methods, mixed methods, and multiple methods. Mono-method is employed when research is focused either on quantitative or qualitative techniques. Mixed methods combine both qualitative and quantitative data-gathering techniques and analyze the procedures either simultaneously or sequentially, without necessarily combining the two. This approach allows researchers to convert qualitative data to numerical codes or take quantitative data and add qualitative interpretation, enabling statistical analysis. Multiple methods are utilized when more than one data collection tool is used with related research procedures but within the context of either a quantitative or qualitative worldview (Aleksandras Melnikovas, 2018).

In this study, a mixed model research approach was utilized, where data was initially collected through the questionnaire in a qualitative format before being converted into numerical codes for statistical analysis. The quantitative approach was used in the development of a framework for measuring the sustainability index of a manufacturing system using the Graph theory matrix approach (GTMA), and Structural equation modelling (SEM) was used for testing the formulated hypotheses.

3.2.6 Time Horizon

The time horizon for business research can be broadly classified into two types, namely cross-sectional and longitudinal. The cross-sectional approach involves studying a phenomenon at a particular moment in time, while longitudinal research aims to examine the same concept at multiple time points. The cross-sectional approach is often associated with the positivist perspective, wherein researchers maintain an objective, impartial view of the phenomenon under study. Cross-sectional studies typically employ survey strategies, as evidenced by Saunders et al., (2012). These studies can be used to describe the occurrence of a particular phenomenon or explain the relationships among factors within an organization. Alternatively, they may utilize qualitative methods, such as case studies that are based on interviews conducted within a brief period.

Conversely, longitudinal studies require the researcher to observe an event or phenomenon over an extended period. Adams and Schvaneveldt, (1991) suggest that longitudinal research enables the researcher to maintain some control over the variables studied, as long as the data collection process does not impact the variables under investigation. In the present study, the cross-sectional viewpoint has been adopted, primarily because the study focuses on investigating the indicators of SM at a specific point in time to develop a performance framework, without any intention to map the changes in sustainable manufacturing practices or their impact over time.

3.2.7 Data collection approach

The data for this study were collected from both primary and secondary sources. To gather primary data, semi-structured interviews and questionnaire surveys were conducted with relevant respondents of the manufacturing organizations. A questionnaire is an instrument used to collect data wherein each respondent answers the same sequence of questions in a pre-decided order on a measuring scale. The questionnaire was designed as close-ended for lesser time and effort needed to answer the set of questions asked in the questionnaire. The questions were rated on five Point Likert scale. Additionally, to minimize the vagueness and to confirm the collected responses, secondary data was obtained from publicly available sources and websites.

The case studies were developed using a variety of resources, including current manufacturing scenario updates, annual reports, business publications, and corporate magazines, as well as materials accessible on the website, and the internet. Both questionnaire surveys and semi-structured interviews were utilized to gather primary data and information from the relevant respondents in the organizations.

3.2.8 Data analysis approach

Based on the identified research gaps and formulated objectives, multiple relationships exist amid the depicted indicators of SM and sustainable practices, leading to multivariate analysis. Hair, (2014) stated that SEM and multiple regression are the most commonly applied methods for multivariate analysis. SEM has few advantages over multiple regression in the estimation of multiple causal relationships simultaneously in a single round, whereas regression is limited to analyzing the relationship between two variables at a time (Bagozzi and Yi, 2012).

Furthermore, SEM has the potential to identify new relationships and recommend potential ones. There are two distinct approaches to SEM: Covariance-based SEM (CB-SEM) and Partial Least Squares (PLS-SEM). CB-SEM is utilized to confirm theories by assessing the robustness of a model by estimating a covariance matrix for the sample data, whereas PLS-SEM operates similarly to multiple regression analysis. These features make PLS-SEM highly valuable for exploratory research (i.e., theory building and development), while CB-SEM is better suited for theory testing and confirmation. Thus, CB-SEM has been adopted with a deductive approach for the research study.

3.3 Roadmap of the research study

The outline of the research study is divided into three phases. Firstly, the most adequate, and leading indicators of SM were explored and incorporated through an exhaustive literature review that assist in achieving sustainability and enhancing the performance of the manufacturing organizations. The underlying hypotheses and conceptual model were formulated based on the literature and experts' advice. The depicted indicators and hypotheses were then assessed through the administration of a questionnaire, whose content was validated by academic and industrial experts. The collected response data was initially scrutinized based on mean values, due to a large number of indicators, only those factors are considered for the next phase, whose mean values are greater than 3. In the second phase, the reliability of the collected data and subgrouping of the dimensions was done using exploratory factor analysis (EFA), and its validity testing is carried out by confirmatory factor analysis (CFA). Before the SEM analysis, the raw data was filtered and checked for missing values. The third phase involves the evaluation of indicators using GTMA and hypotheses testing using path analysis in SEM via AMOS and PLS. In a detailed discussion with the experts' panel using the Delphi technique, a sustainability index is produced for manufacturing organizations using GTMA. The validity of the constructs was confirmed quantitatively to reach statistical significance.

Thus, all the constructs were found significant that can be used to assess social sustainability, enhance sustainable performance, and achieve sustainable development goals of the various organizations and manufacturing units. The roadmap of the research methodology is shown in Figure 3.2.

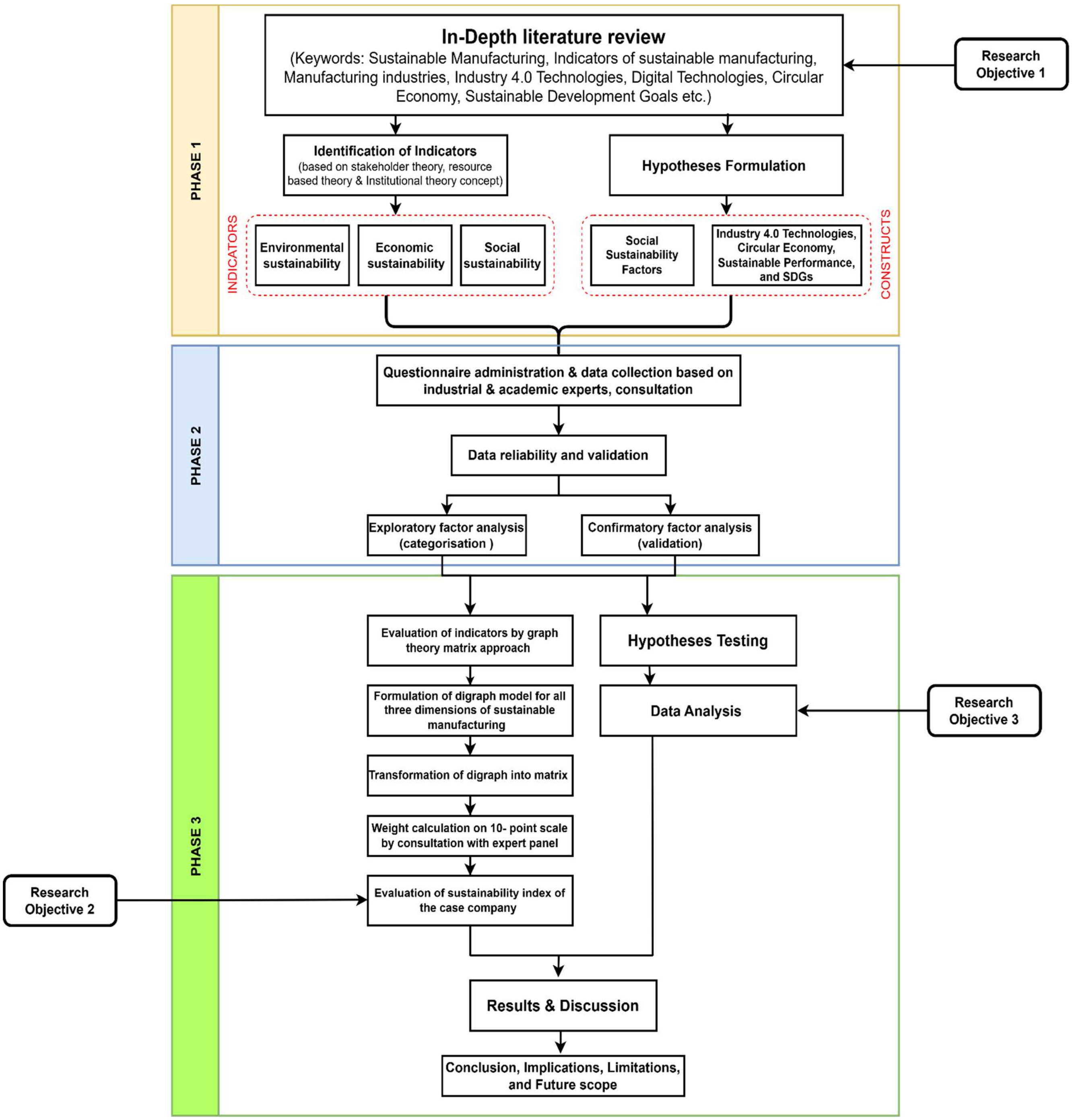

Figure 3.2: Roadmap of the research methodology

3.4 Conclusion

In the preceding chapter, an in-depth literature review was done, research gaps were depicted, and hypotheses were formulated to be tested, along with the development of a conceptual model. This chapter showcases a methodical and theoretical approach to research by utilizing the research onion, as advocated by Saunders et al., (2012), to comprehend the research paradigm and philosophy, the research approach, the research strategy, data collection, and analysis methods. As the study was explanatory, a positivist philosophy stance was taken, in conjunction with the deductive research approach, which forms the outer layers of the research onion. This research study employed surveys and case studies, using a mixed method, and a cross-sectional time horizon; data was obtained using a questionnaire, and SEM was employed for analysis purposes.

Chapter 4

QUESTIONNAIRE ADMINISTRATION, AND DESCRIPTIVE STATISTICS

4.1 Introduction

This chapter covers the systematic evaluation of the literature on sustainable manufacturing practices and formulated hypotheses. The questionnaire has been developed based on an extensive literature review and experts` opinions and circulated among the concerned manufacturing organizations to gather the required information. The standardized set of questions included in the questionnaire was based on research gaps (Gap 1 to Gap 5), depicted in Chapter 2. The organizations investigated for this study were Automobile, Iron & Steel, Sheet metal processing, Chemical and Industrial fertilizer, home appliance industries, Textile industries, and Electrical and electronics. The data collected through the questionnaire survey was initially analyzed based on mean values, then for reliability and validity through structural equation modelling (SEM) using AMOS and PLS. In the end, Graph Theory Matrix Approach (GTMA) has been applied to evaluate the sustainability index of the manufacturing case organization.

4.2 Questionnaire Designing

In order to ensure effective research, several key requirements must be met. The foremost requirement is to convert the stated research objectives into clear and concise questions that are capable of eliciting informative responses from participants. The second requirement is to design the questions in a way that engages respondents and motivates them to provide thoughtful and meaningful responses. This can be achieved by creating non-threatening questions that are easy to understand and that encourage participation. It is important to keep in mind that the instrument will be administered to a large sample size, and as such, the questions should be clear and interesting to maintain participant engagement. Finally, the questions should be self-explanatory and unambiguous to avoid any confusion that may lead to inaccurate or unusable data. By following these guidelines, researchers can ensure that their studies yield reliable and informative results.

4.3 Questionnaire administration and Data collection

In the present study, the quantitative survey method approach has been utilized. The constructs and variables were selected based on prior validated measure of the research articles. The adoption of validated measures enhances the research accuracy in comparison of untested (Lopes de Sousa Jabbour et al., 2022). The identified items were affirmed with the help of experts' opinions. A questionnaire was prepared in consultation with academic experts and professionals/practitioners from manufacturing industries and service organizations for data collection. To assess the theoretical constructs related to the integration of sustainable-centric innovative practices in Indian manufacturing organizations, a twelve-page questionnaire was developed and administered. The questionnaire comprised of five sections; first section includes the basic information about the respondent and organization, second section consists of 35 items utilized to measure the synergistic effect of I4.0 technologies and CE practices on the sustainable performance and sustainable development goals in manufacturing industries, third section comprised 25 factors focused on social sustainability needed to enhance the socially inclusive sustainability and organizational performance, fourth section encompass 15 indicators of environmental sustainability, 16 indicators of economic sustainability, and 14 indicators of social sustainability, explored and finalized through an exhaustive literature review, and in last fifth section, 45 indicators of sustainability were analyzed by the experts` panel using Delphi technique through pairwise comparison for developing a framework for evaluating sustainability index of a manufacturing system.

The professionals were selected from all hierarchy levels of the Organization (Lower, Middle, and Higher). The questionnaire has been developed based on an extensive literature review. It uses a five-point Likert scale to measure items of all the constructs, where five means "Most Important", four means "Very Important," three means "Important", two means "Less Important," and one means "Least Important." The questionnaire was finalized after interacting with experts from manufacturing & service organizations and academia. The questionnaires administered during the research study have been added in the Appendix section. The whole-sole purpose of the survey was primarily notified using a detailed cover letter sent via email. The geographical region selected for this study was Delhi NCR. The Delhi and NCR regions remain in the report for its worst air quality index in the world, as per a WHO survey of around 1,650 cities. The rising air pollution endangers more lives, loss to biodiversity and responsible to climate change. Thus, it becomes of utmost need to integrate circularity and I4.0 technologies into the manufacturing industries.

The questionnaire survey was done to answer two main objectives; firstly, to analyze the antecedents for the performance of sustainable manufacturing system by combining the synergy of digital technologies and CE practices for tailoring sustainable performance of the organization and linking them with SDGs. Secondly, evaluation of social-centric, environmental, and economic indicators and their relationships to achieve sustainability in the manufacturing organization.

Based on a detailed literature review, significant indicators of SM comprised of all dimensions of TBL were discussed with the experts` panel using the Delphi Technique, and a performance framework for measuring the sustainability index of a manufacturing case organization has been accomplished by GTMA, discussed in chapter 6.

4.4 Survey responses and Characteristics of the respondents

In total 842 professionals engaged in manufacturing from 262 Indian manufacturers, were carefully chosen from the Centre of Monitoring Indian Economy (CMIE) database to participate in our questionnaire survey. We ensured that the individuals surveyed were affiliated with globally certified ISO-14001 (Environmental Management) and ISO-9001 (Quality Management) organizations. Out of the 842 professionals approached, 426 responded, which is almost 50.6 %, higher than the accepted threshold response rate (Malhotra and Grover, 1998). Table 4.1 presents the detailing of respondents' profile, revealing that the majority are affiliated with industries such as automobile, iron and steel, computer and electronics, and home appliances. These professionals possess an average industrial experience of more than 10 years.

Table 4.1: Respondents' profile

Category	*Item*	*Frequency*	*Percentage*
Gender	Male	342	80.28
	Female	84	19.7
	Aggregate	**426**	**100**
Age (in years)	≤30	87	20.42
	31-40	147	34.51
	41-50	113	26.53
	51-59	47	11.03
	≥60	32	7.51
	Aggregate	**426**	**100**
Experience (in years)	<1	24	5.63
	1–5	81	19.01
	5–10	113	26.53
	10–15	76	17.84
	15–20	83	19.48
	≥ 20	49	11.5
	Aggregate	**426**	**100**
Manufacturing Organization classification	Automobile manufacturing	119	27.93
	Home appliance Industries	43	10.1
	Iron and Steel	78	18.31
	Chemical and industrial fertilizer	27	6.34
	Computer and electronics	49	11.5
	Textile Industries	37	8.69
	Electronics hardware and component manufacturing	27	6.34
	Others (pharmaceutical, refrigeration and air conditioning, cement, plastic, rubber, etc.)	46	10.8
	Aggregate	**426**	**100**
	Junior/Senior (Engineer)	152	35.68
	Assistant/Deputy/Senior (Manager)	181	42.49

Respondents job designation	Assistant GM/Deputy GM/GM	76	17.84
	CEO/COO/CTO/President/Vice President	17	3.9
	Aggregate	**426**	**100**
Education	Graduate	223	52.35
	Post Graduate	159	37.32
	Doctorate	44	10.33
	Aggregate	**426**	**100**
Employees in the organization (in number)	≤ 1000	126	29.57
	1000-2500	97	22.77
	2500-5000	117	27.46
	≥ 5000	86	20.18
	Aggregate	**426**	**100**

4.5 Content and Construct validity

The quality of collected responses is evaluated by assessing their reliability and validity (Nayal et al., 2022), and tested using SPSS software. The computed Cronbach`s alpha (α) value should be ≥ 0.7 in exploratory research analysis for reliability confirmation (Vinodh and Joy, 2012a). The selected constructs of this study have Cronbach`s α value of more than 0.7, showing their suitability and confirmation for further evaluation.

Validity evaluation is achieved using two steps, first, the content validity of the measurement model, and second, the construct validity using confirmatory factor analysis (CFA). Content validity measures the adequacy of the samples collected from the specified domain, and indicates to what extent elements of an evaluation instrument are significant and representative of the targeted construct for a specific evaluation purpose. As content validity is subjective and varies from person to person, it cannot be conclusively determined numerically. The experts' team validated the depicted items and developed a questionnaire. Then, the construct validity was confirmed by applying convergent and discriminant validity executed using structural equation modelling (SEM)- AMOS. The reliability test (Cronbach alpha) was used to check the internal consistency of the data set. Cronbach Alpha calculates the closeness of item relationship within a group, its value ≥ 0.7 is taken as a good indicator of high reliability (Agrawal et al., 2017). The fit indices used for the confirmation are; factor loadings greater than 0.6, composite reliability (CR) ≥ 0.7, and average variance extracted (AVE) ≥ 0.50 (Hair, 2017). Data analysis shows that standardized factor loading for each item is ≥ 0.6, CR ≥ 0.7, and AVE ≥ 0.5, discussed in Chapter 5. To evaluate the discriminant validity of the constructs, Fornell and Larcker`s (1981) standards have been used (Fornell and Larcker, 1981).

4.6 Reliability of the constructs

To assess the reliability of survey questions, researchers often examine the internal consistency of responses from individuals who completed the questionnaire. Internal consistency is typically measured using composite reliability, which can be calculated using Cronbach's α. It is generally recommended that Cronbach's α values fall within the range of 0.6 to 0.9 for adequate internal consistency (Bagozzi and Yi, 1988). Mathematically,

Cronbach's α $=\left(\frac{R}{R-1}\right)\left(1-\frac{\sum_{i=1}^{R} S_i^2}{S_i^2}\right)$, where s_i^2 shows the variance of the '*I*' indicators of specific constructs measured by R indicators (I = 1, ---------, R).

During an evaluation of the data set, it was found that the value of Cronbach's α exceeded 0.6, shown in Table 4.2, which provides evidence for the reliability of the survey questions used in the study.

Table 4.2: Construct Reliability

Sustainable-centric Dimension	*No. of Items*	*Cronbach`s α*
Industry 4.0 Technologies (I4.0 T)	6	0.869
Circular Economy practices (CEP)	8	0.928
Sustainable performance of the organization (SPO)	11	0.911
Sustainable Development Goals (SDGs)	10	0.926
Job characteristics (JC)	5	0.884
Occupational Health and Safety (OHS)	6	0.920
Consumer protection (CP)	4	0.872

Community Interrelations (CI)	4	0.882
Stakeholder engagement (SE)	3	0.868
Social Sustainability (SS)	3	0.873
Materials and Energy consumption (MEC)	6	0.858
Water consumption (WC)	3	0.913
Environmental Factors (EF)	3	0.854
Global Certification and Control (GCC)	3	0.793
Initial Investment & Operating Cost (IIOC)	5	0.831
Value Creation (VC)	6	0.916
Indirectly-Associated Expenses (IAE)	5	0.860

4.7 Descriptive statistics of the dimensions

This section entails a statistical evaluation of the SM dimensions, which is carried out through an analysis of the mean and standard deviation of the collected responses using SPSS. Descriptive statistics are utilized to summarize and present the received data clearly and concisely, thus facilitating a better understanding and interpretation of the underlying patterns and significance.

4.7.1 Significant Indicators/items of I4.0 technologies dimension

In industry 4.0 dimension, six keen digital technologies which assist and improve sustainable performance in the organization were selected. The respondents were asked to assign a rating on a 5-point rating scale on their importance in manufacturing-related activities. Based on the statistical evaluation, it has been found that, among DTs, the adoption of additive manufacturing has a crucial effect on manufacturing organizations, followed by big data analytics, and augmented reality & virtual reality, shown in Figure 4.1.

These technologies assist in new product development, renewable and sustainable production, enhancement of productivity, waste management, supply chain traceability, and enhancing industrial processes before their implementation.

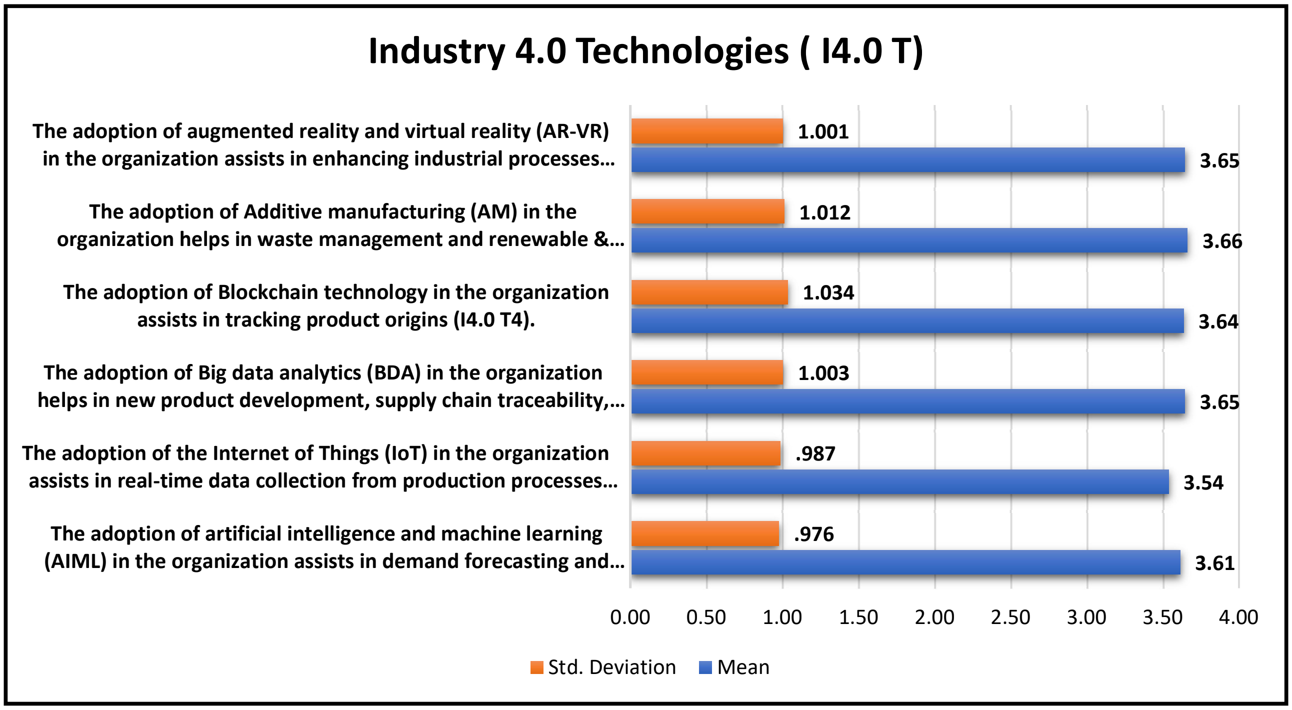

Figure 4.1: Significant Indicators/items of I4.0 technologies dimension

4.7.2 Significant Indicators/items of CEP dimension

The concept of CE and SM are interconnected that aims to develop a more environmentally, economically, and socially responsible approach to production and consumption. The existing body of literature has identified numerous CE practices that exert a positive influence on the creation of a sustainable-centric ecosystem in manufacturing organizations. This study undertook a review of crucial CE practices and sought the opinions of respondents regarding their relative importance, using a 5-point rating scale. The findings, as depicted in Figure 4.2, reveal that remanufacturing of the product, followed by cleaner production, and reuse are the three most crucial CE practices for minimizing waste generation and maximizing resource efficiency in manufacturing organizations.

By embracing a circular economy and sustainable manufacturing, business organizations can contribute to the conservation of resources, reduction of greenhouse gas emissions, and preservation of ecosystems. These approaches also provide economic benefits by fostering innovation, generating new ample business opportunities, and enhancing resource efficiency, leading to cost reduction and increased market competitiveness. Additionally, they assist in creating a more equitable and sustainable society by considering the aspects of the well-being of workers, local communities, customers, stakeholders, and future generations.

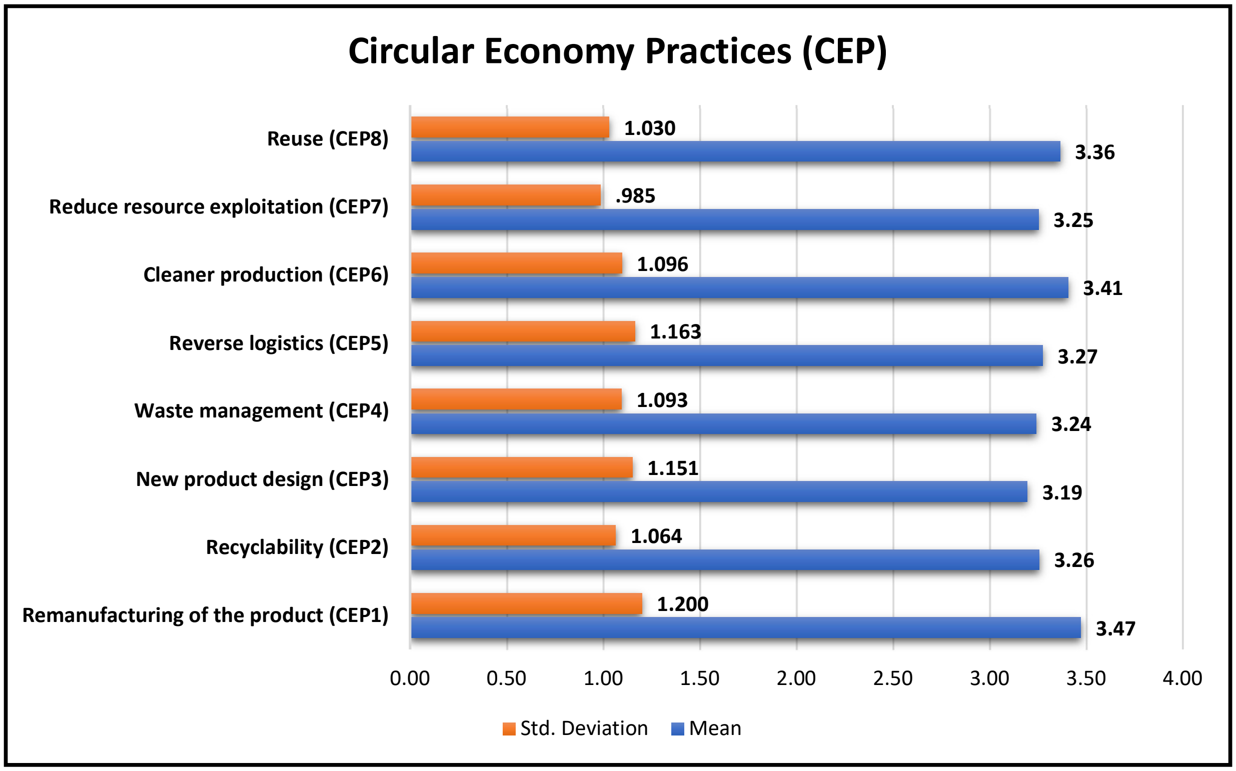

Figure 4.2: Significant practices of Circular economy

4.7.3 Crucial factors influencing sustainable performance

The sustainable performance of a manufacturing organization refers to its ability to integrate the three dimensions in a manner that balances economic growth with social responsibility and environmental stewardship. In this study, eleven crucial factors were selected that can compel organizations to improve their sustainable performance. It has been observed that reduction in plant rejections, followed by renewable energy consumption, eco-friendly product design, reduction in greenhouse gas emissions and hazardous waste, and compliance with government labels and certificates are the five most important factors for achieving and gauzing sustainable performance in the organization, shown in Figure 4.3.

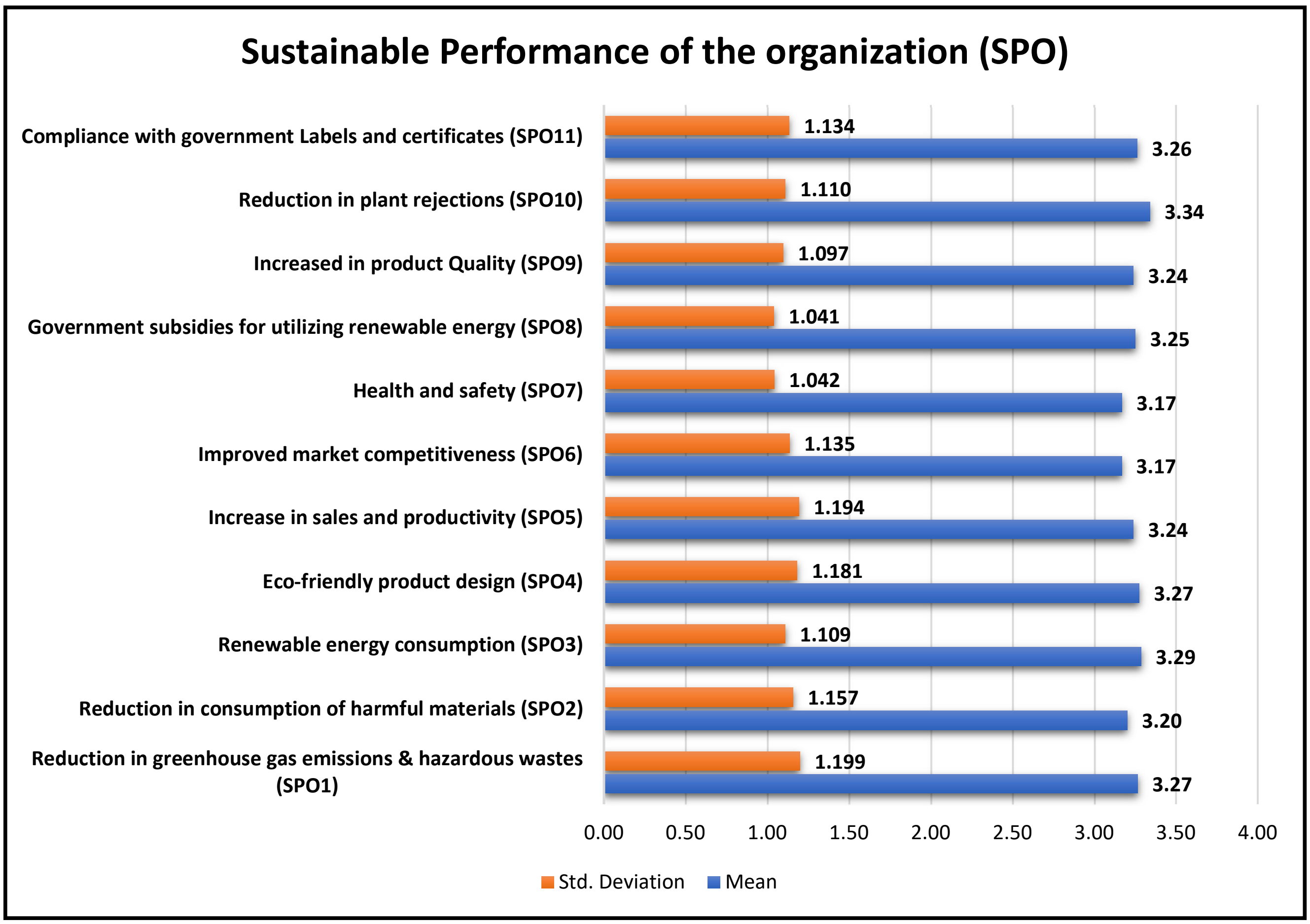

Figure 4.3: Crucial factors influencing sustainable performance

The strategic inclination of an organization towards reduction in plant rejections would improve the economic performance. The integration of eco-friendly product design with renewable energy consumption can significantly enhance sustainable performance, reduce environmental impact, and pave the way towards a sustainable and low-carbon economy. The mitigation of greenhouse gas emissions and hazardous wastes will yield a tangible decrease in costs related to waste disposal. Augmenting environmental and social performance has become imperative for organizations to ensure compliance with government labels and certificates. Non-compliance with these regulations can lead to financial penalties, detriment to reputation, and a loss of competitive prowess within the market.

4.7.4 Important Sustainable Development Goals (SDGs)

The 17 SDGs constitute an interconnected and cohesive framework specifically designed to foster sustainable practices and implement solutions that address the primary challenges confronting our society. In total 10 SDGs were selected that have direct and indirect relation with the combination of CE practices and I4.0 technologies. The respondents were asked to rate the importance of these SDGs on a 5-point rating scale.

Statistical findings show that SDG 15 (Life on land), SDG 1 (No poverty), SDG 2 (Zero hunger), SDG 14 (Life below water), and SDG 12 (Sustainable production and consumption) are the important five SDGs benefitted by sustainable CE and I4.0 nexus, shown in figure 4.4.

Anthropogenic factors like the disposal of wastes may create issues like marine pollution that may directly affect the life below water. The environmentally sustainable production, consumption, waste minimization and management, and natural re-storage of the systems advocated by the CE practices and I4.0 can assist in contributing to the biosphere-related SDG 15 and 14.

Within the societal and economic sectors, the nexus between CE and I4.0 holds the potential to exert a positive influence on the prevailing global contexts addressed by SDG 1, SDG 2, and SDG 10. The interconnectedness of these concepts can facilitate the job creation and redistribution of employment opportunities on a broad scale worldwide. This will lead to reducing inequalities, poverty, and issues related to hunger within a sustainability-driven work environment.

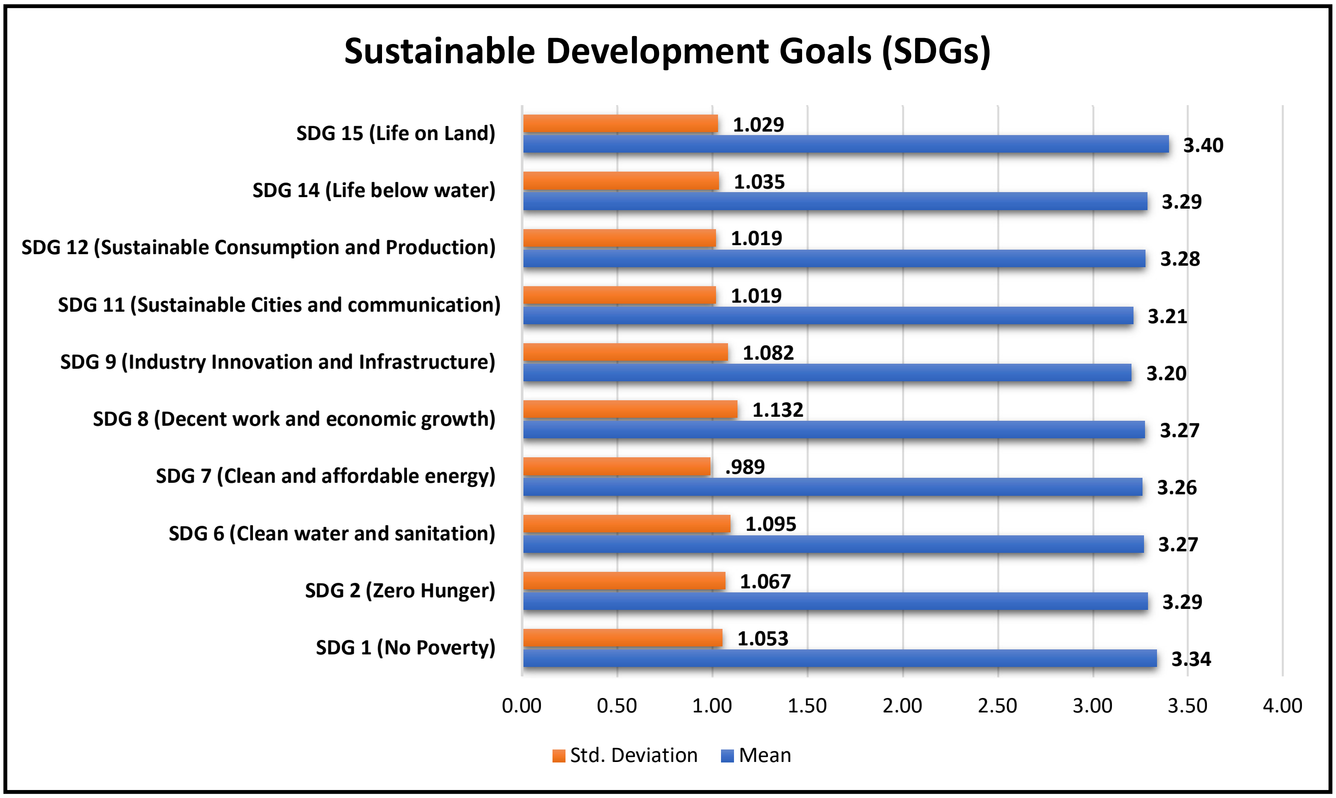

Figure 4.4: Important SDGs

4.7.5 Important factors of Job characteristics for achieving social sustainability

The organization's social sustainability is influenced by the several benefits and formulated policies for the employees. These include *job security, job availability, turnover rates, employee performance, and absentee rate*. To assess the importance of these factors, a questionnaire was administered and respondents were requested to rate them on a 5-point scale.

It has been found that Job security (Mean = 3.85, Std. Dev. = 1.266) and Job availability (Mean = 3.70, Std. Dev. = 1.232) are the two most important factors of job characteristics that help in achieving SS in the organization.

Job characteristics play a crucial role in promoting social sustainability within organizations and communities. Social sustainability refers to the ability of individuals, groups, and societies to meet their needs, maintain their well-being, and live harmoniously within their social and cultural contexts. The other factors' priority based on mean values and standard deviation is shown in Figure 4.5.

Job security and job availability are crucial factors for achieving social sustainability. These factors contribute significantly by providing economic stability, enhancing psychological well-being, fostering social cohesion, reducing dependence on social welfare, and facilitating long-term planning and investment. Additionally, high employee performance enhances productivity, innovation, and the overall work culture, while managing the turnover rate promotes employee well-being, and retention of knowledge, and reduces social costs. Hence, it becomes imperative for organizations, governments, and policymakers to assume a pivotal role in creating an environment that upholds these factors for the attainment of a sustainable and inclusive society.

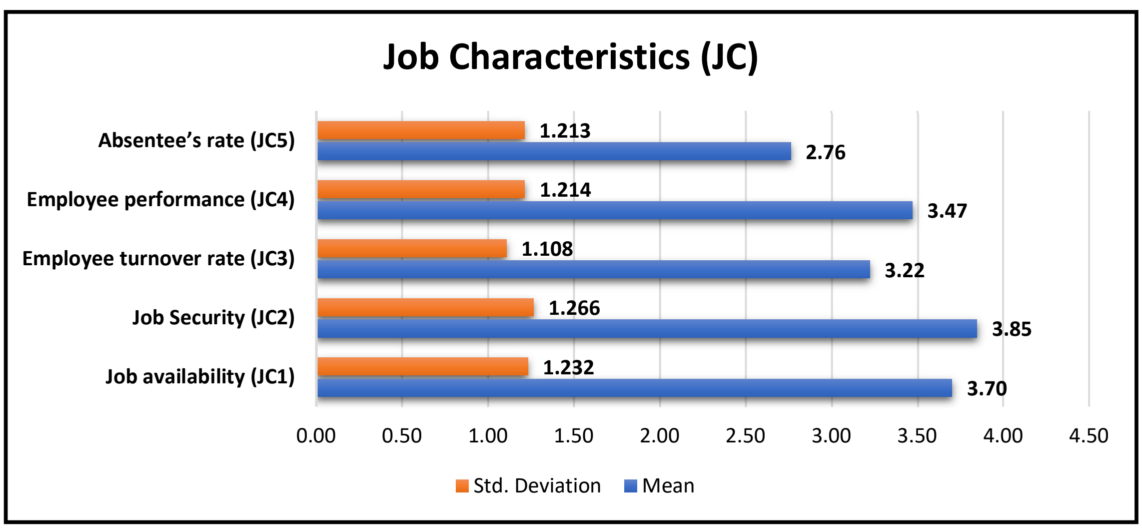

Figure 4.5: Important factors of Job characteristics for achieving social sustainability

4.7.6 Important factors of Occupational health & safety for achieving social sustainability

Occupational health and safety (OHS) refers to the initiatives and practices aimed at monitoring the physical, mental, and social well-being of employees in the workplace. It encompasses the following factors namely: *Equality policy/equity; training and development; legal benefits, occupational risk prevention and management; psychological risks; and career advancement*. The respondents were asked to rate them as per their perception on a scale of five points.

The findings reveal that equality policy/equity (Mean = 3.31, Std. Dev. = 1.207), training and development (Mean = 3.17, Std. Dev. = 1.238), and legal benefits (Mean = 3.17, Std. Dev. = 1.288) are the most significant factors of OHS dimension for achieving social sustainability in the organization. The observed ratings of all OHS factors are shown in Figure 4.6.

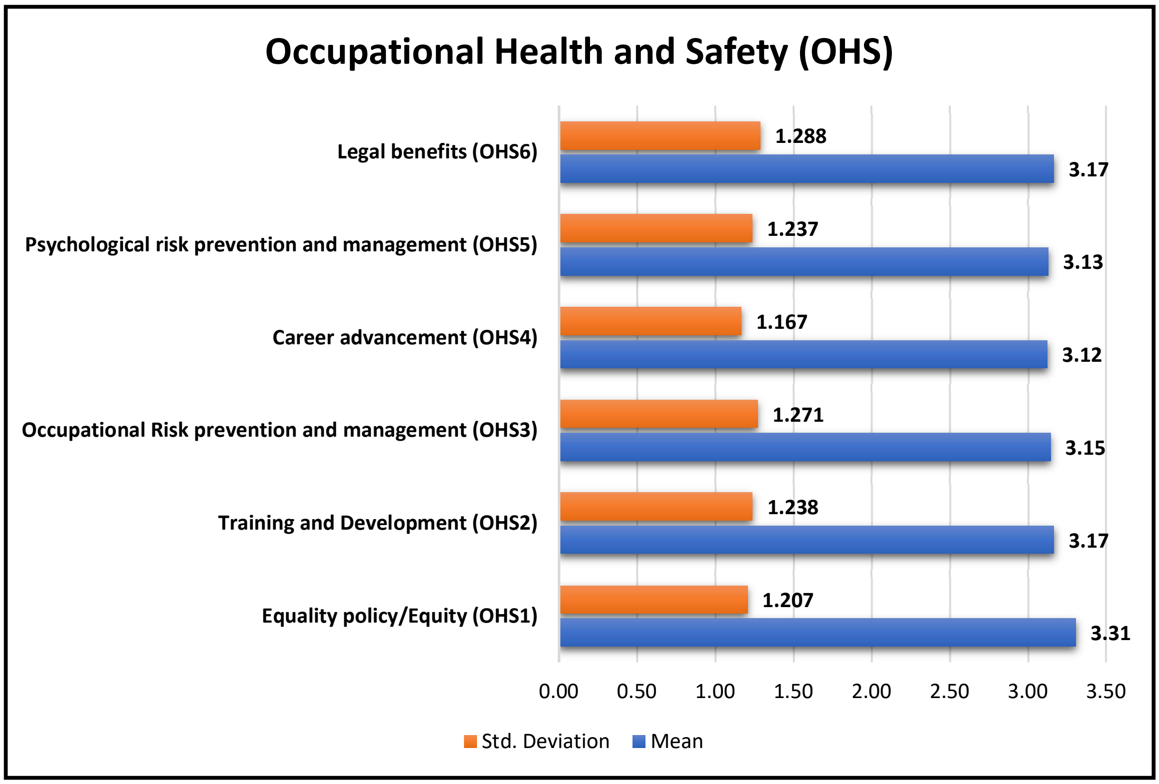

Figure 4.6: Important Factors of Occupational Health & Safety for achieving social sustainability

Social sustainability encompasses various factors that contribute to creating an inclusive and equitable society. Within this context, equality policy/equity, training and development, and legal benefits play crucial roles in improving the social fabric and ties in the community. These factors when working together promote social sustainability by fostering an environment of equal opportunities, inclusivity, and social justice.

4.7.7 Important factors of Consumer protection dimension

Consumer protection is an important dimension of SS which refers to the measures and policies formulated by organizations to create a fair, transparent, and inclusive marketplace for customers. In this study, four important factors namely: *public trust, product information, customer satisfaction, and product quality* are taken in the dimension of consumer protection. The survey participants were specifically instructed to assign relative weights on a scale of five points to gauge the importance of selected factors.

It has been observed that majorly respondents have given a high rating to product information (Mean = 3.40, Std. Dev. = 1.087) and customer satisfaction (Mean = 3.39, Std. Dev. = 1.179) over the other two aspects of consumer protection, illustrated in Figure 4.7.

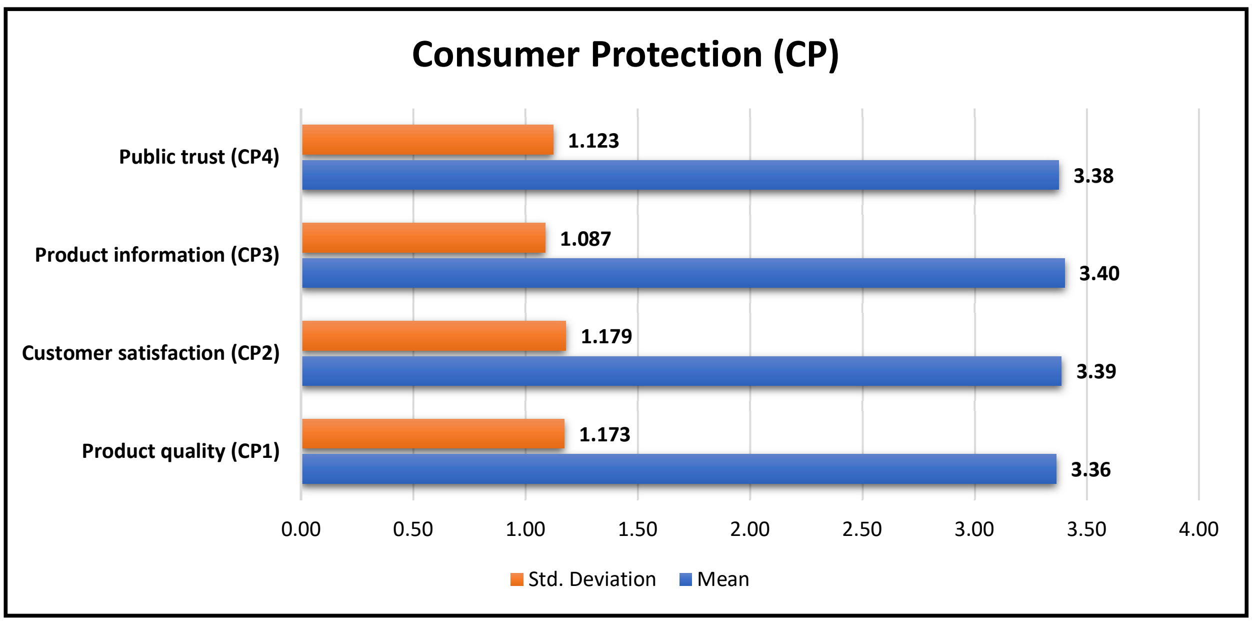

Figure 4.7: Important Factors of Consumer Protection

The valuable and needed product information indicator includes product type, contents, disposal methods, emissions, and recycling. By providing comprehensive, transparent, and detailed product information, businesses can enhance customer satisfaction, enable informed decision-making, foster trust, and bring long-term success.

4.7.8 Important factors of Community interrelations dimension

The community interrelations dimension is influenced by various factors. These factors encompass *infrastructure development, technology development, human rights protection, and demographic aspect*. Significantly, research findings emphasize that technology development is the most crucial factor of community interrelations for achieving social sustainability in the organization, as indicated by a Mean of 3.37 and a Standard Deviation of 1.114. It is closely followed by three other significant factors, namely demographic aspect (Mean = 3.36, Standard Deviation = 1.089), human rights protection (Mean = 3.35, Standard Deviation = 0.953), and infrastructure development (Mean = 3.33, Standard Deviation = 1.136), as illustrated in Figure 4.8.

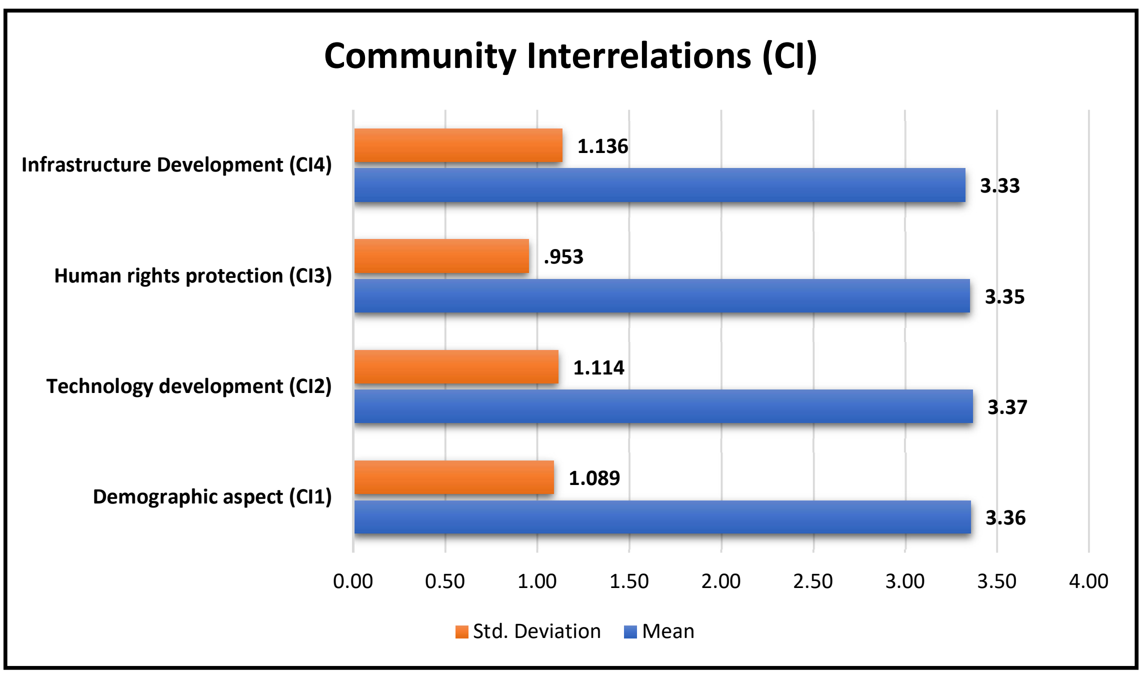

Figure 4.8: Important Factors of Community Interrelations

Generally, people exhibit a positive attitude towards the adoption of new technologies as they bring more job opportunities to the communities and support cleaner and more efficient initiatives. Technological development plays a significant role in shaping and enhancing communication, collaboration, development and empowerment, and overall connectivity within communities.

4.7.9 Important factors of the Stakeholder engagement dimension

A comprehensive social assessment of an organization remains incomplete without the evaluation of stakeholder satisfaction. Stakeholders play a pivotal role in strengthening the corporate image and attaining competitiveness in the market. This study includes three important factors of stakeholder engagement named as *community feedback, customer feedback, and employee feedback*. The respondents were asked to rate them on a five-point scale as per their perception.

It has been found that customer feedback (Mean = 3.81, Standard Deviation = 1.203) is the most important factor to be considered by the organization for achieving social sustainability followed by other two factors community feedback (Mean = 3.46, Standard Deviation = 1.091), and employee feedback (Mean = 3.39, Standard Deviation = 1.095), as shown in figure 4.9.

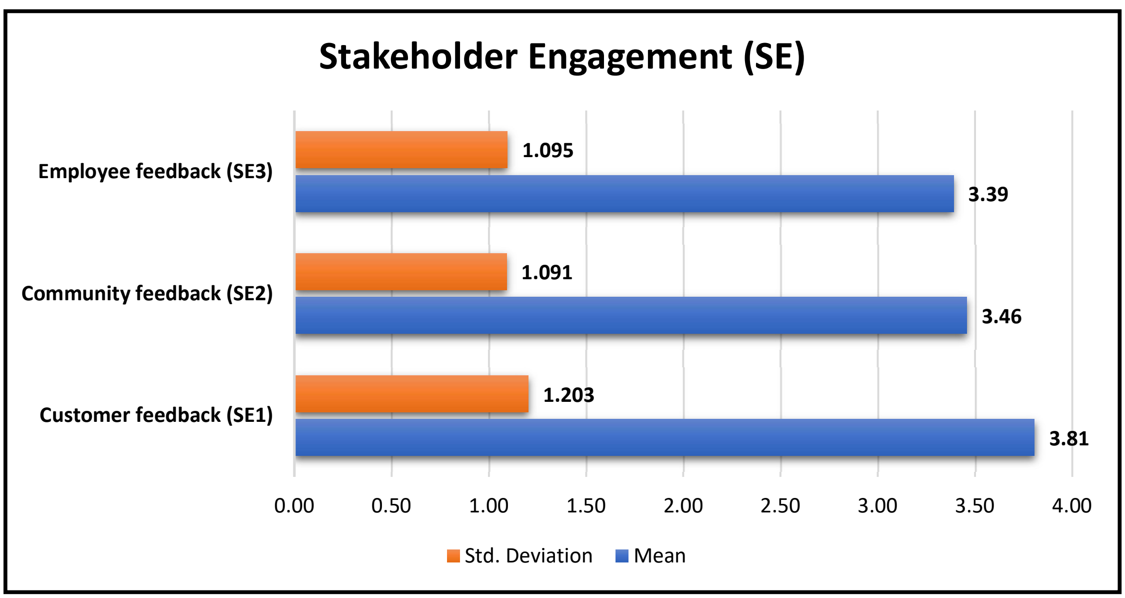

Figure 4.9: Important Factors of Stakeholders' Engagement

Customers are the crucial aspect and concern of stakeholders which significantly influence the implementation of social sustainability in the organization. Businesses can enhance social performance and product innovation by actively responding to customer feedback and aligning their practices with the values and expectations of the customers.

4.7.10 Important dimensions of social sustainability

The social sustainability of an organization depends upon three broad dimensions, namely *social well-being, security assurance, and quality of life*. These dimensions collectively contribute to the adoption of social sustainability. The respondents were asked to rate on a five-point Likert scale, where five means "Most Important", four means "Very Important," three means "Important", two means "Less Important," and one means "Least Important.

The evaluation of responses based on statistics reveals a quality of life (Mean = 3.61, Standard Deviation = 1.176) as the most important dimension to be concerned for achieving SS in the organization. The other two dimensions, security assurance have a Mean = 3.33 and Standard Deviation = 1.042 followed by social well-being (Mean = 3.30, Standard Deviation = 1.151), shown in Figure 4.10.

Quality of life is integral to social sustainability as it focuses on the well-being, equity, and long-term development of individuals and communities. By prioritizing the quality of life, social sustainability aims to create inclusive and resilient societies that provide equal opportunities, protect human rights, and ensure a high standard of living for all.

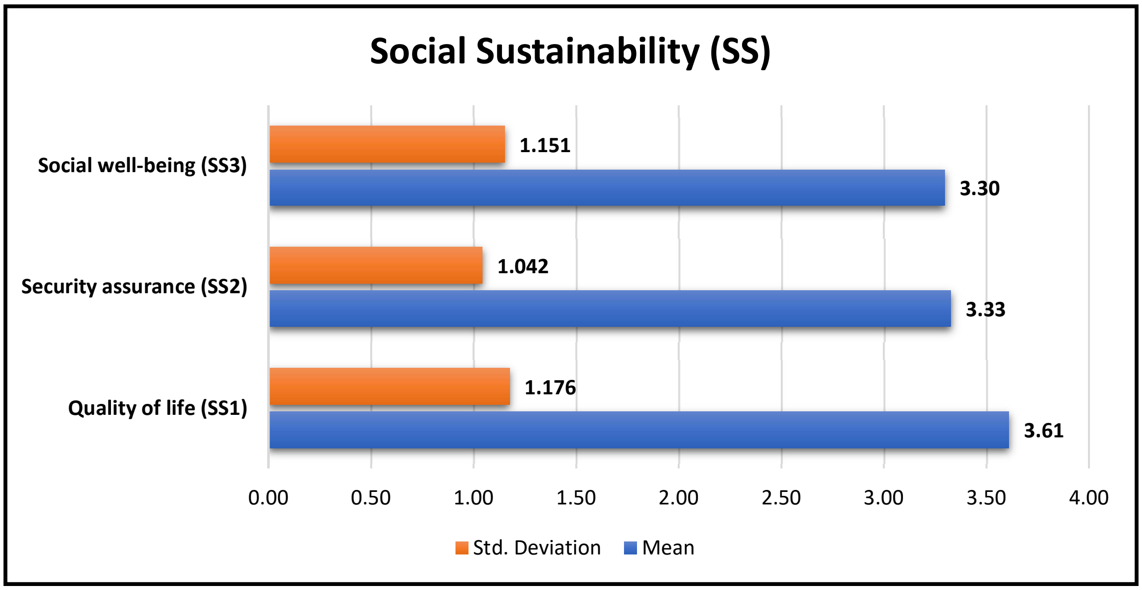

Figure 4.10: Important dimensions of social sustainability

4.7.11 Important Indicators of Materials and Energy Consumption (MEC) dimension for achieving Environmental Sustainability

The increase in greenhouse gas emissions, climate change, and global energy shortage are the significant challenges faced by the international community while achieving sustainable development. The Materials and energy consumption aspect focuses on the responsible utilization of materials and energy resources to minimize the negative impacts on the environment. This study includes six important indicators of MEC named *Recycling of used materials; Consumption of recycled/refurbished materials/components; Non-hazardous materials consumption; Green packaging materials; Green transportation/fuel economy and emission control; and Renewable energy consumption.* The respondents were asked to rate them on a five-point scale as per their perception.

It has been found that green transportation/fuel economy and emission control (Mean = 3.74, Standard Deviation = 0.96) is the most important indicator, closely followed by two other significant indicators, namely non-hazardous materials consumption (Mean = 3.73, Standard

Deviation = 0.96) and green packaging materials (Mean = 3.73, Standard Deviation = 0.992), to be considered by the organization for achieving environmental sustainability, as illustrated in Figure 4.11.

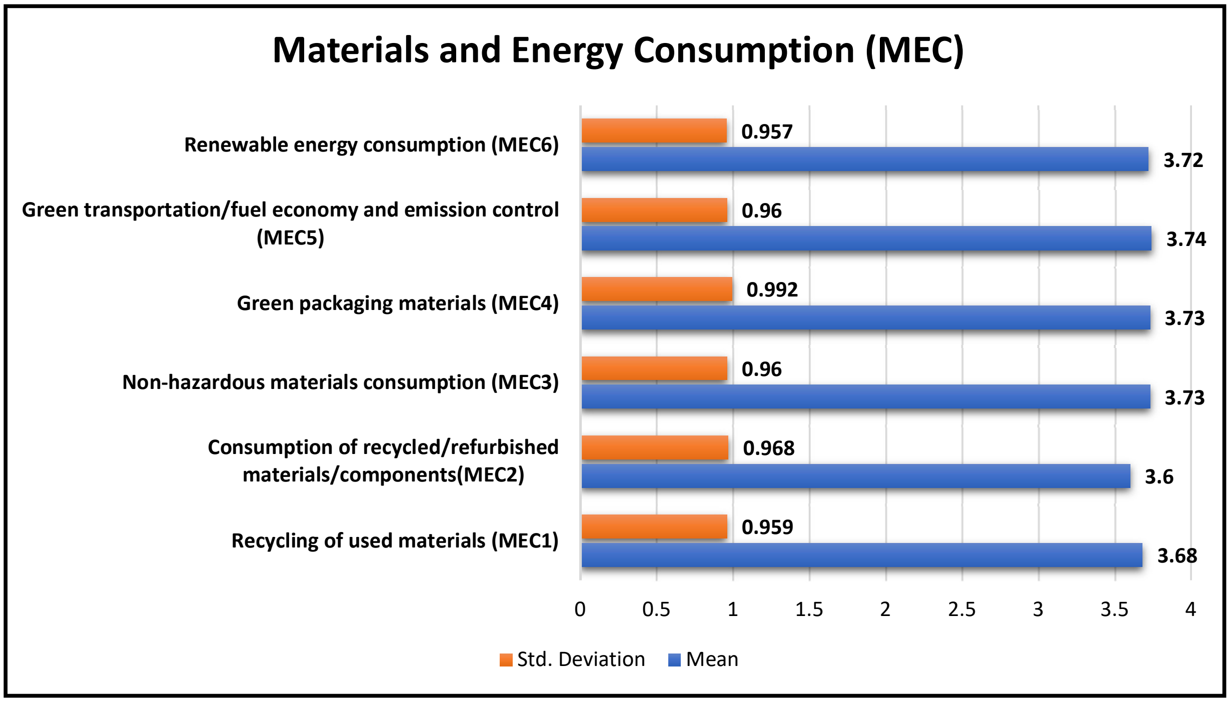

Figure 4.11: Important Indicators of Materials and Energy Consumption

Sustainable transport policy encompasses various aspects like climate, security, air quality, and health. Globally, the transport sector shares thirteen percent of total GHG emissions which expected to be double in 2050, if not any measures are taken (Eliasson and Proost, 2015). Thus, it becomes important for the manufacturing sector to focus on green transportation/ fuel economy and emission control by promoting the use of cleaner fuel, adoption of advanced vehicle technologies, electrification, and improving maintenance and inspection policies.

4.7.12 Important Indicators of Water Consumption (WC) dimension for achieving Environmental Sustainability

The industrial sector globally accounts for over 30% of GHG emissions and nearly 20% of water withdrawals (Liu et al., 2022). Industries have a significant role in addressing water challenges and achieving environmental sustainability. By ensuring responsible water consumption practices, industrial organizations can contribute to sustainable water management. Two of the 17 SDGs, namely SDG 13 (mitigating climate change) and SDG 6 (addressing water scarcity), focus on the world`s most critical global challenges. The present work includes three main indicators of water consumption named as *economic water consumption, reuse and recycling of wastewater, and water contamination*.

The respondents rank the indicators on a five-point rating scale. The findings reveal that economic water consumption is the most important indicator (Mean = 3.35, Standard Deviation = 1.219), followed by reuse and recycling of wastewater (Mean = 3.25, Standard Deviation = 1.311), and water contamination (Mean = 3.22, Standard Deviation = 1.191), shown in Figure 4.12.

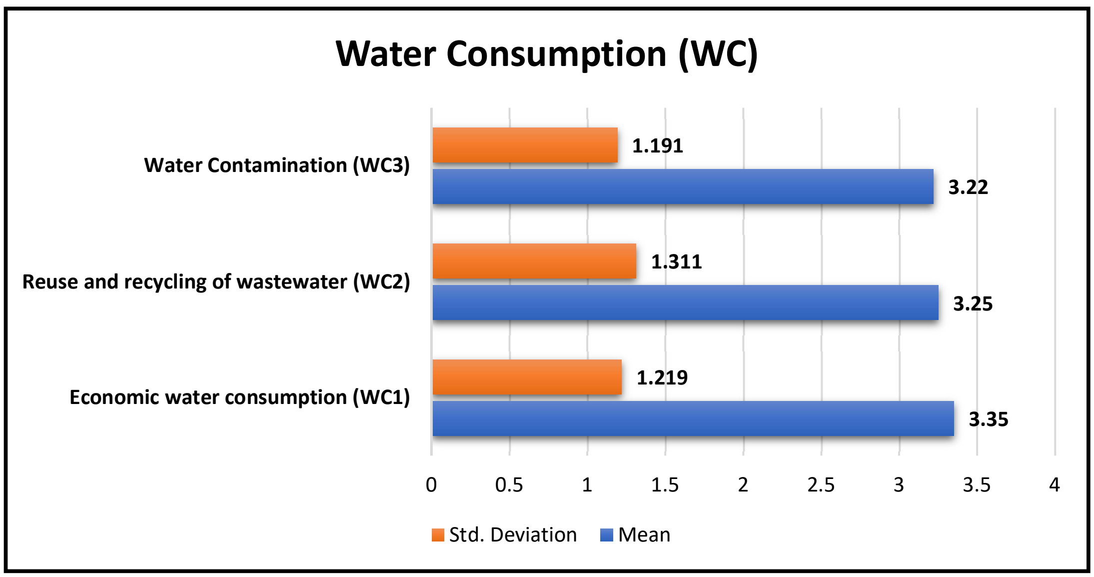

Figure 4.12: Important Indicators of Water Consumption

In developing countries, there is significant growth in manufacturing activities, resultantly increasing water consumption by a factor of more than 5 by 2050, from 245 to 1552 billion m^3 (Sachidananda et al., 2016). Hence, it is needed that manufacturing companies should proactively enhance their water management practices. This includes monitoring fresh water consumption in production processes, implementing water reuse and recycling initiatives, and reducing water contamination.

4.7.13 Important Indicators of Environmental Factor (EF) dimension for achieving Environmental Sustainability

Environmental factor dimension comprised of three crucial indicators namely: *prevention of water pollution, elimination of landfill & contamination, and emission control*. The respondents were asked to assign the weights to various indicators of environmental factors. It has been observed that emission control is the most important indicator (Mean = 3.17, Standard Deviation = 1.128), followed by prevention of water pollution (Mean = 3.12, Standard Deviation = 1.211), and elimination of landfill and contamination (Mean = 3.12, Standard Deviation = 1.083) as illustrated in Figure 4.13.

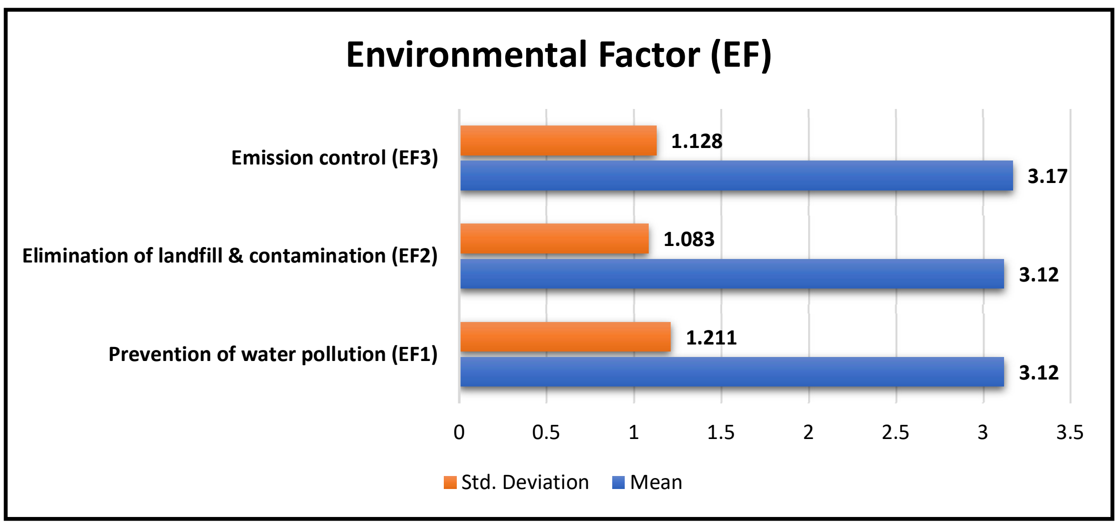

Figure 4.13: Important Indicators of Environmental Factor

The manufacturing sector is one of the major contributors to emissions. Emission control is vital for protecting the air quality index, mitigating climate change, reduction of carbon emissions, preserving the environment, and promoting technological innovation. During manufacturing processes, various types of unused raw materials, scrap parts, and hazardous and non-hazardous solid/liquid are dumped into nearby lands as landfills. The harmful substances from landfills can leach into groundwater, leading to water pollution and posing a risk to human health. Thus, industries should ensure the elimination of landfill and contamination.

4.7.14 Important Indicators of Global Certification and Control (GCC) dimension for achieving Environmental Sustainability

Governance institutions play a pivotal role in the development of laws and policies that apply to all industries within a country. They hold direct responsibility for overseeing natural resource exploration, tracking environmental issues, ensuring environmental protection, and moving toward sustainable development. Global certification and control are important to establish and maintain all the processes that industries utilize to develop products and services. It includes three needed indicators like *labels and certificates (ISO 14001 & ISO 9001), green initiatives, and quality control*. The respondents rate these indicators in the context of the manufacturing sector on a scale of five points.

The result shows that quality control is the crucial indicator (Mean = 3.53, Standard Deviation = 1.156), followed by two other important indicators namely: green initiatives (Mean = 3.42, Standard Deviation = 1.178), and labels and certificates (ISO 14001 & ISO 9001) (Mean = 3.41, Standard Deviation = 1.242) as shown in Figure 4.14.

Quality control measures ensure that products or services not only meet quality requirements but also comply with environmental regulations, and promote sustainable manufacturing, and environmental performance. The ISO 9000, ISO 14000 series, and OHSAS 18000 series are the certifications for organizations to align them towards standardized processes and quality to meet environmental standards.

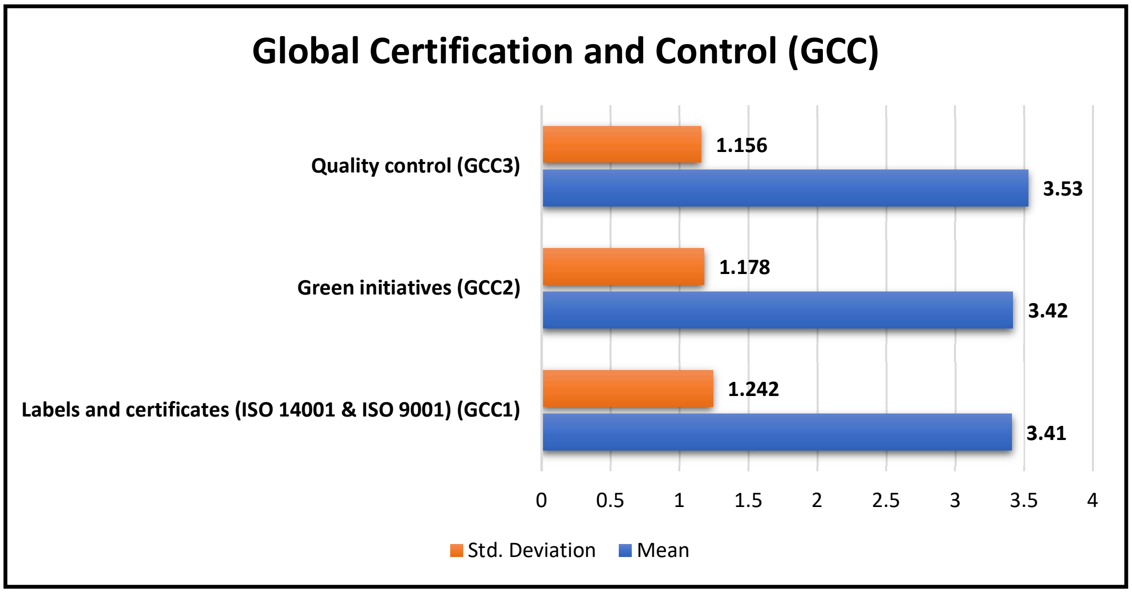

Figure 4.14: Important Indicators of Global Certification and Control

4.7.15 Important Indicators of Initial Investment and Operating Cost (IIOC) dimension for achieving Economic Sustainability

In developing countries like India, manufacturing organizations place great emphasis on economic aspects over environmental and social sustainability. With an increase in price competition and technological revolution, industries focus remains on the quality issue and profit, diverting them from integrating sustainable-centric practices. Thus, it becomes vital for manufacturers to find a real set of effective sustainability indicators to access the sustainability of their business model. In this study, five important indicators of initial investment and operating cost are considered namely: *Wages and operating cost; Liability and debt payment; Environmental treatment cost; Expenses on corporate social sustainability (CSR); and Sales promotion.* The respondents were asked to prioritize them based on their importance in the organization.

The findings reveal that environmental treatment cost (Mean = 3.26, Standard Deviation = 1.148) and expenses on corporate social responsibility (Mean = 3.26, Standard Deviation =

1.222) are the important indicators, succeeded by sales promotion (Mean = 3.2, Standard Deviation = 1.25), wages and operating cost (Mean = 3.19, Standard Deviation = 1.261), and liability and debt payment (Mean = 3.13, Standard Deviation = 1.192), illustrated in Figure 4.15.

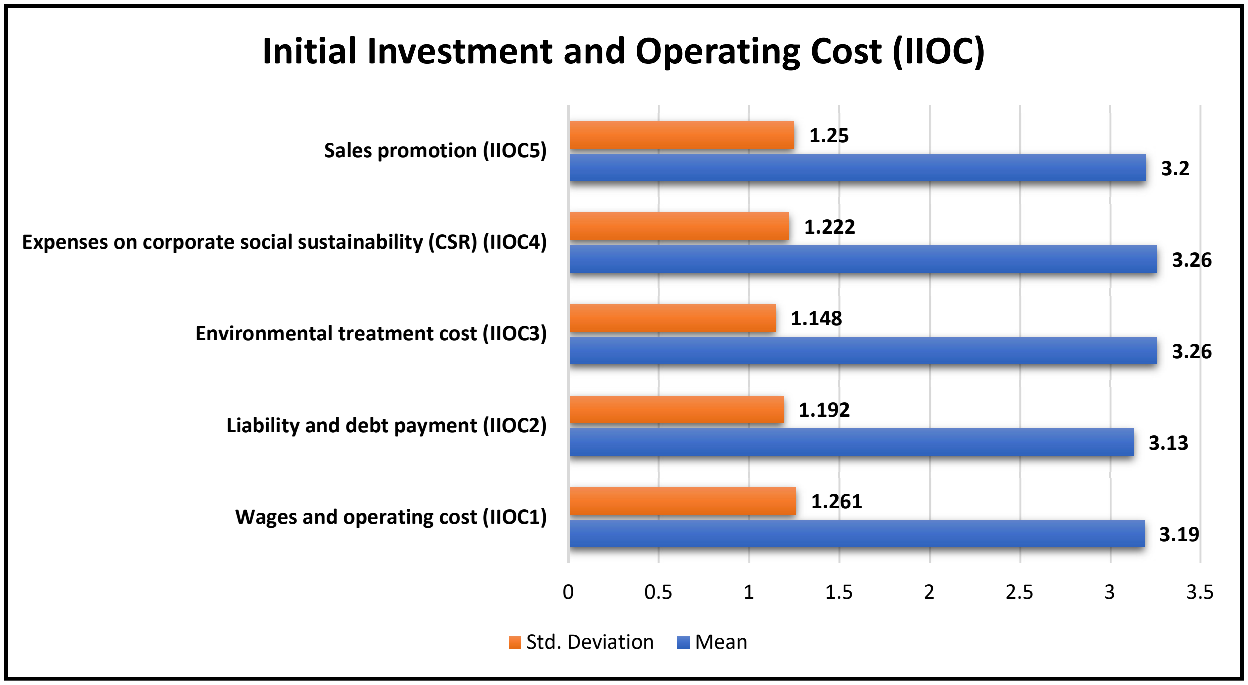

Figure 4.15: Important Indicators of Initial Investment and Operating Cost

The environmental treatment cost is significantly influenced by the type of wastewater treated and the specific process utilized. This cost includes various elements such as planning, infrastructure, machinery and equipment, automation, electrification, spare parts inventory, training and development, costs reserve, etc. (Popovic et al., 2013). The availability of affordable treatment plants, an ample number of monitoring facilities, exchange of technologies and knowledge with other countries will give an opportunity to not only address pollution effectively but also to manage costs efficiently. Thus, this harmonious balance between economic and environmental growth will pave the way for India toward sustainable development.

4.7.16 Important Indicators of Value Creation (VC) dimension for achieving Economic Sustainability

Value creation is the benefits the organization could have after the adoption of sustainable-centric practices. VC encompasses the following important indicators such as: *Revenue generation; Profit earned; Annual productivity; New product design and development; Market share; and Facility expansion.* The respondents were asked to assign the weight to these indicators. It has been observed that revenue generation (Mean = 3.29, Standard Deviation = 1.239) is the most vital indicator of value creation followed by other five indicators: profit earned (Mean = 3.16, Standard Deviation = 1.235), new product design and development (Mean = 3.15, Standard Deviation = 1.175), annual productivity (Mean = 3.14, Standard Deviation = 1.278), market share (Mean = 3.13, Standard Deviation = 1.226), and facility expansion (Mean = 3.13, Standard Deviation = 1.267) as shown in Figure 4.16.

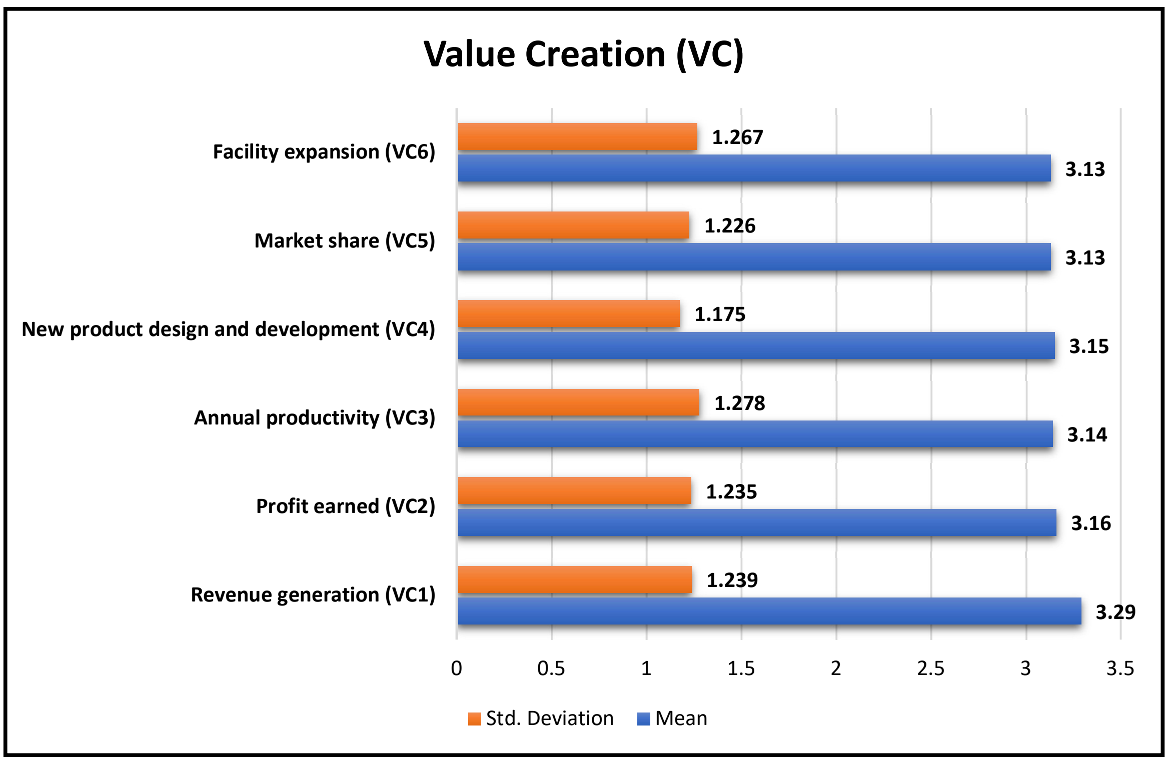

Figure 4.16: Important Indicators of Value creation

The primary objective of value creation is to develop a product that exhibits good functionality with high quality at minimal input cost. Due to unforeseen, unpredictable circumstances like pandemics, natural calamities, and competitive scenarios, organizations strive to employ indicators that can enhance their revenue generation, annual productivity, and market share.

4.7.17 Important Indicators of Indirectly Associated Expenses (IAE) dimension for achieving Economic Sustainability

The category of indirectly associated expenses comprises indicators that higher management of the industries considers before doing any changes to manufacturing processes and policies. This includes five indicators namely: *Depreciation; Maintenance; Pollution control cost; Investment in research and development; and Prevention of scrap production.* The prioritization of these indicators is done based on respondents rating on a scale of 5-point as shown in Figure 4.17.

The descriptive statistics reveal that investment in research and development (Mean = 3.43, Standard Deviation = 1.163) is the most important indicator as per respondent's weightage, followed by the remaining four indicators: prevention of scrap production (Mean = 3.37, Standard Deviation = 1.143), pollution control cost (Mean = 3.33, Standard Deviation = 1.097), maintenance (Mean = 3.32, Standard Deviation = 1.08), and depreciation (Mean = 3.14, Standard Deviation = 1.059).

The manufacturing sector has evolved towards Industry 4.0, where the role of advanced and digital manufacturing technologies is at the forefront. The organization's investment in research and development initiatives is essential to achieve sustainable economic development. The prevention of scrap production leads to cost savings, improved efficiency, higher product quality, and a competitive edge in the market.

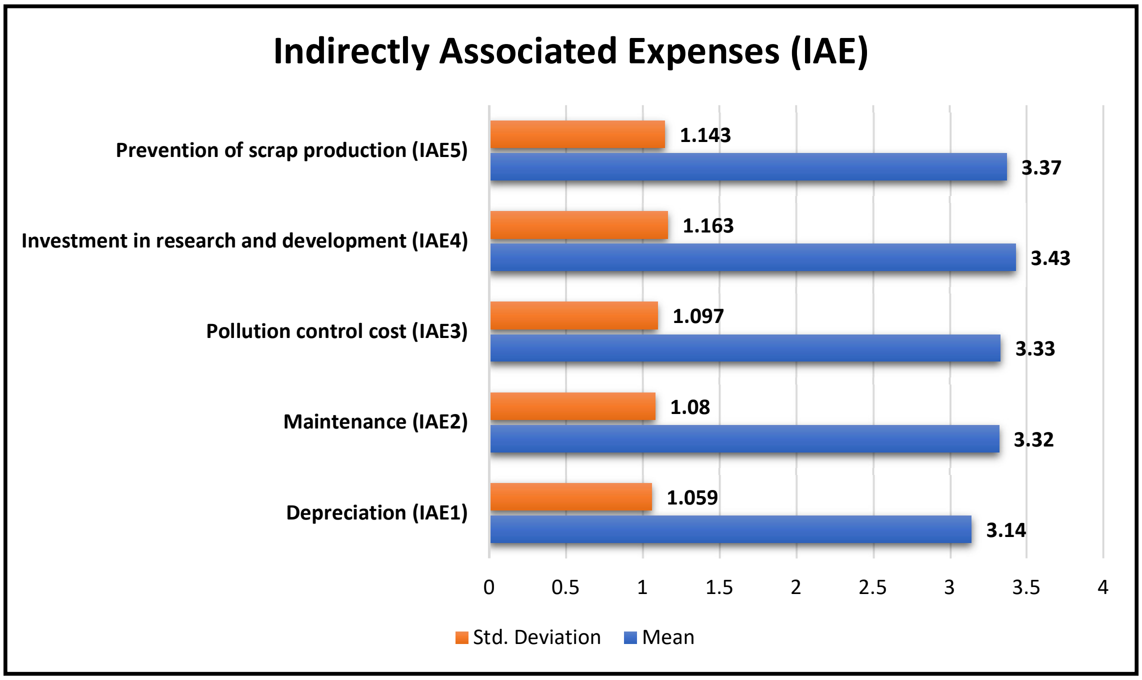

Figure 4.17: Important Indicators of Indirectly Associated Expenses

4.8 Conclusion

This chapter discusses the outcomes obtained from the questionnaire survey performed among the employees of distinct manufacturing sectors like automobile, iron and steel, electrical and electronics, chemical and industrial fertilizer, home appliance industries, textile industries, and others (pharmaceutical, refrigeration, and air conditioning, cement, plastic, and rubber, etc.). Descriptive statistics have been employed to analyze the data, and the resulting insights are illustrated in the form of a bar chart. In the succeeding Chapter 5, the hypotheses testing is done on the collected responses.

Chapter 5

HYPOTHESES TESTING: RESULTS AND ANALYSIS

5.1 Introduction

This chapter focuses on the analysis and validation of formulated hypotheses, discussed in chapter 2. The proposed hypotheses were tested in two distinct and connected reference. Firstly, the hypothetical model incorporating various constructs of social sustainability were tested and validated for the business organizations. Secondly, the proposed conceptual model incorporating the antecedents of sustainability for achieving sustainable performance in context of manufacturing organizations has been analyzed. The selected antecedents for this study are digital technologies and circular economy practices. Both these hypothetical models were tested in reference of developing economies like India. To test these hypotheses, structural equation modeling (SEM) approach has been employed. Structural equation modelling (SEM) is known for its use as regression analysis to a collection of variables defined by the researchers (Jenatabadi, 2015). SEM is a powerful tool used in multivariate analysis for framing exogenous and endogenous variables. It has a wide range of applications and is a rapidly evolving solution for most research problems requiring statistical analysis.

5.2 Hypotheses Testing

This section of the study investigates the formulated hypotheses in light of the gathered data. SEM with the aid of Analysis of Moment Structures (AMOS) and Smart PLS has been employed to establish relationships among the latent constructs and to test the proposed hypotheses. SEM assist to understand the interrelationships between the chosen constructs, based on correlations, covariances, regression weights, and statistical significance. The analyzed results provide insights into the goodness-of-fit of the model. The subsequent sections comprehensively elucidate the detailed findings with analysis.

5.3 Evaluation of social sustainability factors

The following are the proposed research hypotheses with the factors to be adopted by distinct business organizations for the assessment of social sustainability.

H1a: *There is an interrelationship between JC and OHS.*

H1b: *There is an interrelationship between JC and CI.*

H1c: *There is an interrelationship between JC and SE*

H1d: *There is an interrelationship between JC and consumer protection.*

H2a: *There is an interrelationship between OHS and consumer protection.*

H2b: *There is an interrelationship between OHS and CI.*

H2c: *There is an interrelationship between OHS and SE.*

H3a: *There is an interrelationship between consumer protection and CI.*

H3b: *There is an interrelationship between consumer protection and SE.*

H4: *There is an interrelationship between CI and SE.*

H5: *JC is positively related to SS**.***

H6: *OHS is positively associated with SS.*

H7: *There is a positive relationship between consumer protection and SS.*

H8: *There is a positive relationship between CI and SS.*

H9: *There is a positive relationship between SE and SS.*

5.3.1 Result analysis

5.3.1.1 Exploratory factor analysis (EFA)

This study uses exploratory factor analysis (EFA) to estimate the dimensionality of twenty-five social sustainability factors and develop a factorial structure. The accuracy with which the constructs repeatedly measure the same phenomenon within allowable variation is referred as the constructs' reliability. The responses collected from the questionnaire were transformed into data and verified for reliability using Cronbach's alpha in SPSS. Any construct with a Cronbach's alpha value greater than 0.7 is considered reliable (Vinodh and Joy, 2012b). All the constructs were found reliable with Cronbach's alpha value (>0.7) as listed in Table 5.1. A significant positive correlation existed between the constructs in Pearson's coefficient two-tailed test with $p<0.01$ and $r(298) > 0.148$. KMO and Bartlett's test for the constructs reported adequacy of sampling as 0.877 and Bartlett's test of sphericity significance ($p<0.01$) indicated a significant correlation (Lučić, 2020).

Table 5.1. KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		*.877*
Bartlett's Test of Sphericity	Approx. Chi-Square	6784.389
	df	300
	Sig.	0.000
Construct validity	Latent Variables	Cronbach's Alpha
	JC	0.884
	OHS	0.920
	CP	0.861
	CI	0.871
	SE	0.861
	SS	0.874

5.3.1.2 Confirmatory factor analysis (CFA)

In this section, the factorial validity of the five-dimensions comprised of twenty-five (25) indicators of social sustainability was evaluated using confirmatory factor analysis (CFA). The compatibility of the developed model has been assessed through basic goodness-of-fit measures namely: Chi-square ($\chi2$), Normal Chi-square ($\chi2$ /df), Root mean residual (RMR), Goodness-of-fit index (GFI), Adjusted goodness-of-fit index (AGFI), Normed fit index (NFI), Relative fit index (RFI), Comparative Fit Index (CFI), Tucker Lewis Index (TLI), parsimony comparative fit index (PCFI) and Root Mean Square Error Approximation (RMSEA). A model with $\chi2$ /df value close to 2, RMR and RMSEA value < 0.1, and the values of remaining goodness-of-fit measures <0.9 is considered a good fit (Rai et al., 2021). The developed model (Fig. 5.1) was found to have excellent fit outcomes with χ^2 value as 495.498 (dF= 260, $p<0.001$), χ^2/dF value as 1.906, GFI=0.913, AGFI= 0.891, RMR= 0.054, NFI=0.25, RFI=0.914, TLI= 0.964, CFI= 0.965, PCFI=0.837, FMIN=1.195 and RMSEA = 0.046. Hence, the model was found valid with model fit measures shown in Table 5.2.

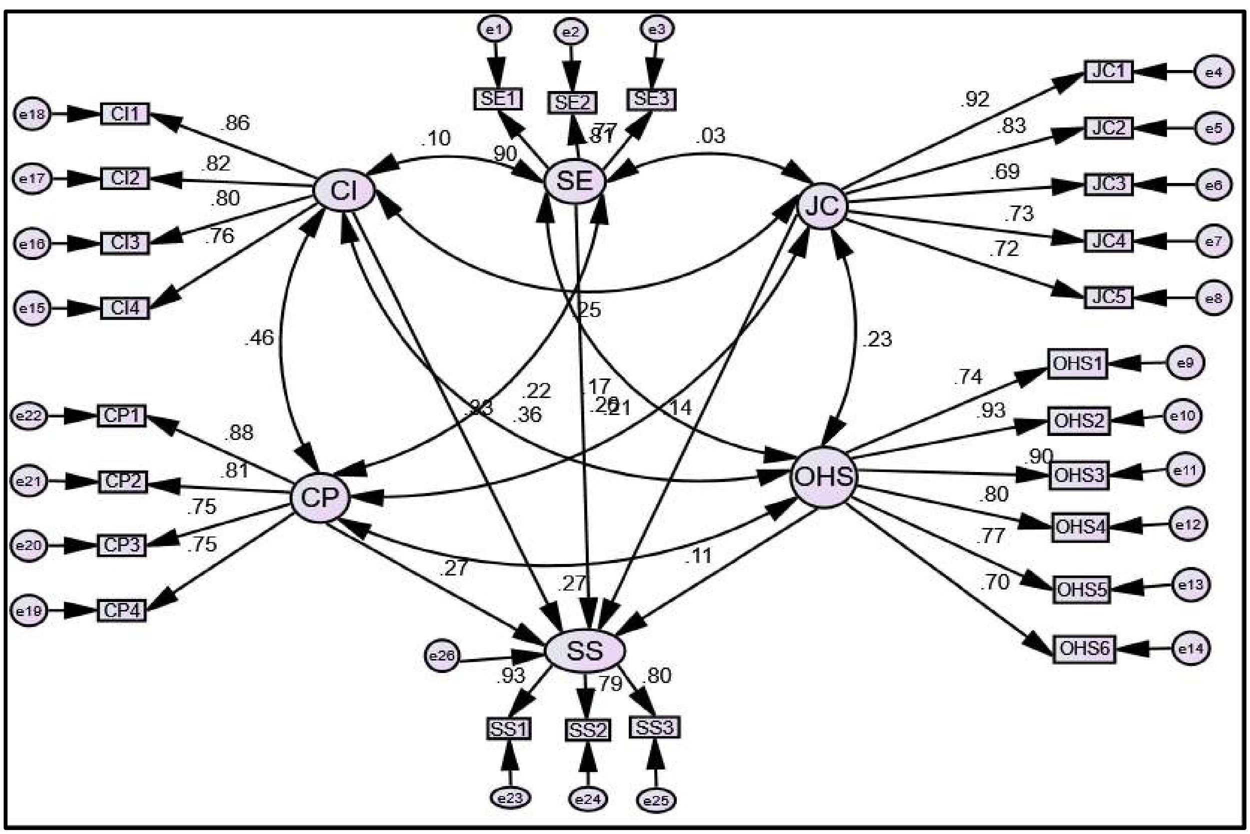

Fig. 5.1. Structural model for social sustainability Indicators

Table 5.2: Model fit measures for the developed model

Measure	Estimate	Threshold	Explanation
CMIN	495.498	--	--
DF	260	--	--
CMIN/DF	1.906	Between 1 and 3	Excellent
CFI	0.965	>0.95	Excellent
SRMR	0.039	<0.08	Excellent
RMSEA	0.046	<0.06	Excellent
PClose	0.844	>0.05	Excellent

The validity of the constructs was confirmed quantitatively by standardized factor loadings (FL) and Average variance extracted (AVE) values >0.5, Maximum shared variance (MSV), maximum reliability (MaxR) (H), square root of AVE (†) and construct reliability (CR) value >0.7 to reach statistical significance as shown in Table 5.3. All the constructs were found to exhibit AVE values above 0.5 and were integrated into the model using AMOS (Mani et al., 2020).

Table 5.3**:** Construct validity and Discriminant validity for the constructs used in the model.

Construct	**Construct validity**				**Discriminant validity**				
	CR	**AVE**	**MSV**	**MaxR(H)**	**SE**	**CI**	**CP**	**OHS**	**JC**
SE	0.802	0.535	0.048	0.886	**0.731**				
CI	0.849	0.547	0.209	0.890	0.102	**0.739**			
CP	0.834	0.524	0.209	0.888	0.219	0.457	**0.724**		
OHS	0.889	0.565	0.133	0.942	0.170	0.365	0.268	**0.752**	
JC	0.847	0.512	0.061	0.913	0.027	0.246	0.205	0.230	**0.716**

Nomological validity was found significant and acceptable with all significant p-values and positive values of the correlation estimates. Thus, all the constructs were significant and can be used to assess the social sustainability of the various organizations and manufacturing units (Lučić, 2020).

Fig. 5.2 shows the relative importance of selected dimensions to assess social sustainability based on descriptive statistics. It indicates that stakeholder engagement is the most important dimension followed by job characteristics and occupational health & safety as the least important dimension. Many authors confirmed that enhancing corporate reputation among the stakeholders positively impacts organizational performance (Greening and Turban, 2000; Singh and Misra, 2021).

Table 5.4 illustrates the direct and total effects of exogenous variables on observed endogenous variables. Factors with a factor loading below 0.6 were excluded from the analysis. The findings reveal minimal indirect effects on social sustainability indicators SS1, SS2, and SS3, while demonstrating substantial direct effects, underscoring the importance of the selected constructs. Regarding job characteristics dimension, the most significant impact came from job availability, followed by job security and absentee rate, while the employee turnover rate exhibited the least effect. In the case of occupational health and safety dimension, training and development demonstrated the maximum effect, followed by occupational risk prevention and management, and career advancement. Conversely, legal benefits and equity policy displayed comparatively lesser effects, indicating a need for more awareness among stakeholders to enhance social sustainability in the organization. In context of consumer protection, the maximum effect was observed for product quality, followed by customer satisfaction and product information. However, a lesser effect was observed for public trust. Community interrelations showcased a strong effect from demographic aspects, followed by technology development and human rights protection. In the case of stakeholder engagement, customer feedback showed maximum effect followed by community feedback while employee feedback had the minimal effect. Findings revealed maximum effect for quality of life, followed by social well-being and security assurance for social sustainability dimension. In summary, the final results underscored the elevated effects of community interrelations, consumer protection, and stakeholder engagement on social sustainability compared to job characteristics and occupational health and safety.

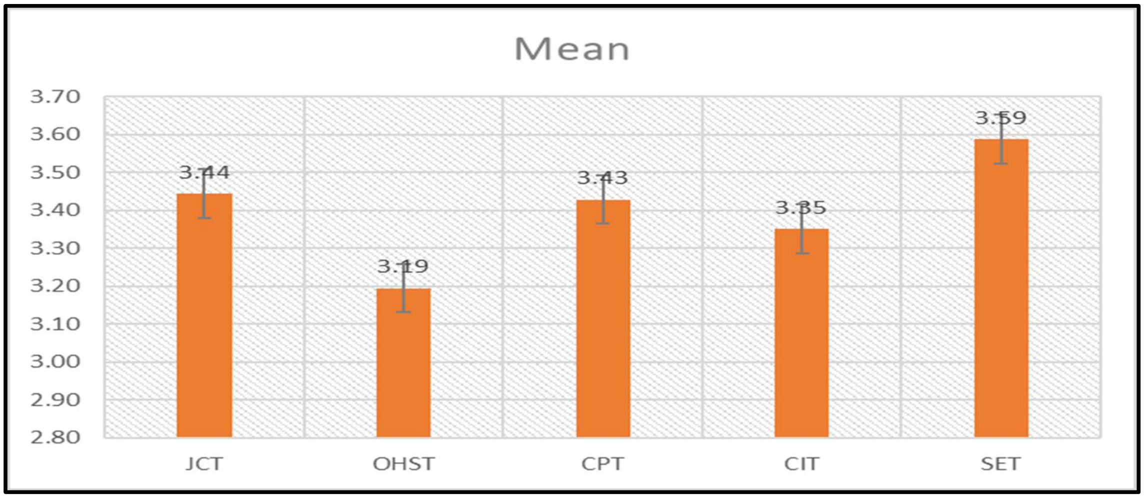

Figure 5.2: Relative importance of social sustainability dimensions

Table 5.4. Direct/ Total effects of endogenous and exogeneous variables (*indirect effects)

Variable	JC	OHS	CP	CI	SE	SS
JC1	0.890					
JC2	0.844					
JC3	0.774					
JC4	0.764					
JC5	0.792					
OHS1		0.793				
OHS2		0.891				
OHS3		0.864				
OHS4		0.800				
OHS5		0.809				
OHS6		0.786				
CP1			0.885			
CP2			0.826			
CP3			0.771			
CP4			0.743			
CI1				0.865		
CI2				0.812		
CI3				0.806		
CI4				0.776		
SE1					0.889	
SE2					0.871	
SE3					0.863	
SS	0.147	0.11	0.287	0.283	0.288	
SS1	0.184*	0.104*	0.307*	0.336*	0.297*	0.793
SS2	0.137*	0.078*	0.229*	0.25*	0.221*	0.808
SS3	0.156*	0.088*	0.261*	0.285*	0.252*	0.748

Path analysis and regression analysis were carried out to estimate regression weights for the proposed model, with results shown in Table 5.5. The results of the Correlation analysis for testing the hypothesis are shown in Table 5.6.

Table 5.5. Estimates for regression weights for the proposed model

	Estimate	S.E.	C.R.	P
JC1←JC	1.000			
JC2 ← JC	.931	.041	22.563	***
JC3 ← JC	.675	.041	16.613	***
JC4 ← JC	.786	.043	18.261	***
JC5 ← JC	.779	.043	18.026	***
OHS1 ← OHS	.778	.041	19.219	***
OHS2 ← OHS	0.987	0.033	29.676	***
OHS3 ← OHS	1.000			
OHS4 ← OHS	.811	.037	21.928	***
OHS5 ← OHS	.830	.040	20.557	***
OHS6 ← OHS	.791	.045	17.730	***
CI1 ← CI	1.000			
CI2 ← CI	.957	.048	19.782	***
CI3 ← CI	.814	.042	19.315	***
CI4 ← CI	.900	.050	17.861	***
CP1 ← CP	1.000			
CP2 ← CP	.921	.047	19.655	***
CP3 ← CP	.787	.045	17.657	***
CP4 ← CP	.818	.046	17.814	***
SE1 ← SE	1.000			
SE2 ← SE	.821	.043	18.943	***
SE3 ← SE	.782	.044	17.923	***
SS1 ← SS	1.000			
SS2 ← SS	.750	.037	20.333	***
SS3 ← SS	.839	.040	20.781	***

*S.E.- Approximate standard error, C.R.- Critical ratio

Table 5.6. Summary of Hypotheses results

Hypotheses	*Constructs*	*Estimate*	*S.E.*	*C.R.*	*P*	*Conclusion*
H1a	OHS ↔JC	.297	.069	4.276	***	Validated & Significant
H1b	JC ↔ CI	.269	.061	4.422	***	Validated & Significant
H1c	JC ↔ SE	.033	.066	.500	.617	Invalidated & Non-significant
H1d	JC ↔ CP	.238	.064	3.721	***	Validated & Significant
H2a	OHS ↔ CP	.316	.065	4.846	***	Validated & Significant
H2b	OHS ↔ CI	.404	.063	6.366	***	Validated & Significant
H2c	OHS ↔ SE	.210	.067	3.143	.002	Validated & Significant
H3a	CP ↔ CI	.456	.061	7.478	***	Validated & Significant
H3b	CP ↔ SE	.244	.063	3.905	***	Validated & Significant
H4	CI ↔ SE	.106	.058	1.845	.065	Invalidated & Non-significant
H5	JC ⟶SS	.135	.041	3.248	.001	Validated & Significant

H6	OHS ⟶ SS	.106	.042	2.496	.013	Validated & Significant
H7	CP ⟶ SS	.290	.053	5.513	***	Validated & Significant
H8	CI ⟶ SS	.368	.058	6.372	***	Validated & Significant
H9	SE ⟶ SS	.261	.044	5.963	***	Validated & Significant

*S.E.- Approximate standard error, C.R.- Critical ratio

H1a states that there is an interrelationship between JC and OHS. The correlational results validate the hypothesis (β =0.297, p<0.001) and is consistent with the literature. H1b hypothesizes that there is an interrelationship between JC and CI. This hypothesis was also validated with the positive and significant correlation (β =0.269, p<0.001). However, the hypothesis H1c accounting for the interrelationship between JC and SE was invalidated and non-significant (β =0.033, p>0.05). There was a positive and significant relationship between job characteristics and customer protection (β =0.238, p<0.001), and hypothesis H1d stating the interrelationship between JC and CP was supported. Similarly, hypothesis H2a stating the interrelationship between OHS and CP was valid (β =0.316, p<0.001). The hypothesis H2b was also considered valid with a positive and significant interrelationship between OHS and CI (β =0.404, p<0.001). Further, hypothesis H2c was found valid with a significant interrelationship between OHS and SE (β =0.210, p<0.01). The hypothesis H3a accounting for the interrelationship between CP and CI was significant and valid (β =0.456, p<0.001). Hypothesis H3b was also found valid with a positive and significant interrelationship between CP and SE (β =0.244, p<0.001). On the other hand, hypothesis H4 was not supported with an insignificant interrelationship between CI and SE (β =0.106, p>0.05). The result can be attributed to the lack of awareness about the human rights protection among the various stakeholders, as observed in the direct effect analysis (Henao et al., 2017). The former hypotheses discussed represent the correlation between the indicators, shown by bidirectional arrows. The hypotheses (H5-H9) illustrate the predictive relationship between the main dimensions, and social sustainability, shown by unidirectional arrows. The hypotheses (H7 to H9) strongly influence social sustainability. The H7 shows the influence of consumer protection on social sustainability, significantly validated (β =0.290, C.R.= 5.513), implying that the more the organization invests in considering consumer protection, strongly the SS is achieved. The influence of community interrelations and social sustainability is significantly positive and validated (β =0.368, C.R.= 6.372), indicating that when a community relationship with the organization has a positive relationship, they demonstrated stronger social sustainability. Thus, H8 is confirmed. The companies should be more involved and bothered about the life in the community of employees (Lin et al., 2021). The organization should have a strong social impact and commitment to the community, the requirement of 'corporative governance' (Bianchini et al., 2022). The hypothesis H9 result shows that the influence of stakeholder engagement on social sustainability is significantly positive and validated (β =0.261, C.R.= 5.963). Stakeholders are considered an important group to be sensitive and affect the sustainability of the business (Singh and Sushil, 2021). The Stakeholder theorists affirm that a business organization with a positive relationship with a series of stakeholders like customers, employees, suppliers, communities, and financiers leads to sustainable performance (Ozhan et al., 2022). Similarly, hypotheses H5, and H6, i.e., Job characteristics leads to social sustainability, and occupation health & safety leads to social sustainability are positively significant and validated (standardized β = 0.135, C.R.= 3.248; β =0.106, C.R.= 2.496). The social sustainability indicators like health, safety, child labor issues (gender discrimination, bonded labor etc.), human rights, community initiatives, and employment benefits are generally observed and accepted as sensitive areas of performance assessment that monitors social concern goals in the organization (V. Mani et al., 2014; Popovic et al., 2018).

The research findings are significant for integrating social sustainability in business organizations. This study empirically tested the various indicators (discussed above) that are important for enhancing satisfaction among employees, consumers, community, and stakeholders, leading to organizational performance improvement. Moreover, improving the conditions of employees can prevent brain drain, form a good organizational image, improve working conditions, and build satisfaction and loyalty among workers, employees, and stakeholders.

5.4 Synergistic effect of Industry 4.0 technologies and Circular Economy practices for enhancing the sustainable performance and achieving SDGs

The following are the proposed research hypotheses:

H10a: I4.0 leads to the adoption and implementation of CE in the organization.

H10b: I4.0 technologies positively and directly influence the sustainable performance of the organization.

H10c: I4.0 technologies lead to the achievement of SDGs.

H11: CE has a positive and significant effect on the sustainability performance of the organization.

H12: The implementation of CE practices leads to the accomplishment of SDGs.

H13: Sustainable performance of the organization assists in achieving UN SDGs.

H14: CE practices mediates the relationship between I4.0 technologies and SDGs.

H15: Sustainable performance of the organization mediates the relationship between I4.0 and SDGs.

H16 (Serial Mediation): CE practices and sustainable performance mediate the linkage between I4.0 and SDGs.

5.4.1 Result analysis

The interrelationships between I4.0 technologies, CE practices, sustainable performance of the organization (SPO), and SDGs are measured, and shown in the succeeding sub-sections. The factor loadings, Cronbach`s alpha, AVE, CR of the constructs, and hypotheses results were evaluated. The empirically tested and validated model is illustrated in Figure 5.3.

5.4.1.1 Reliability and validity estimation

SmartPLS 4 software has been utilized to analyze the surveyed data, develop the structural model, and to examine the causal relationships among the constructs. It is a powerful tool for executing different ways of correlations over clustering, estimating large complex systems, constructs, and indicators. We started with weighting path scheme in which maximum number of iterations was fixed at 300, and followed by bootstrapping in which settings were selected with subsamples at 5000, confidence interval method at percentile bootstrap with two tailed tests at 0.05 significance level. Before analyzing the proposed direct and mediating hypotheses, the constructs and their items were evaluated for the required reliability and validity measures. The rotated component factor loadings for all the construct items were above 0.6 as shown in Table 5.7. The Cronbach`s alpha values of the five constructs are; I4.0 T = 0.869, CE practices = 0.928, SPO = 0.911, and SDGs = 0.926. The CR measures are in the range of 0.8 to 0.93 and the AVE values are in the range of 0.53 to 0.66 as shown in Table 5.7. All the obtained values and subsequent results are consistent within the acceptable limit, as recommended by various researchers (Herrmann and Felfe, 2014; Jr. et al., 2017), indicating satisfactory internal consistency and convergent validity.

Discriminant validity shows the difference in item measures of the construct with the others (Hair 2014). It is checked for AVE and maximum shared variance (MSV). Fornell and Larcker, (1981) measurements and heterotrait - monotrait (HTMT) ratio has been utilized as a reference to check data discriminant validity. The results acquired after analysis have AVE values greater than MSV, and the squared root of AVE is higher than the correlation between associated items of the constructs, as shown in Table 5.8.

5.4.1.2 Structural model path analysis

Structural model analysis establishes a relationship between endogenous and exogenous variables. Before testing the direct and mediating effects among the constructs, we applied PLS-SEM algorithm with bootstrapping to derive the R^2 and Q^2 (predictive relevance) values for the concerned constructs as presented in Table 5.9. The obtained R^2 values are 0.122 for CE practices, 0.176 for SDGs, and 0.216 for SPO, surpass the recommended threshold of 0.1 (Hair, 2017). Moreover, Q2 values for CE practices, SDGs, and SPO are 0.12, 0.10, and 0.19 respectively, which are underscoring the model`s substantial predictive power as they are higher than zero. Subsequently, model fit indices were used to explain goodness of the structural model, yielding a standardized root mean square residual of 0.050 and a normal fit index of .82. Both of these values fall within the acceptable recommended range, indicating a good model fit.

The proposed six direct path hypotheses (H10 to H13) have been tested using bootstrapping 5000 subsamples at 95% bias confidence interval. The obtained results presented in Table 5.10 indicates that all hypotheses are significant and validated. The SEM analysis shows that I4.0 technologies significantly influence the adoption of CE practices ($\beta = 0.349$, $p = .000$), SPO ($\beta = 0.389$, $p = .000$), and SDGs ($\beta = 0.169$, $p = .002$), validating H10a, H10b, and H10c. Hypothesis H11 ($\beta = 0.154$, $p = .001$), reveals that adoption of CE practices in the organization leads to the enhancement of SPO. The obtained results were found consistent with the previous studies (Cheng et al., 2022; Skalli et al., 2023). Further, findings display a significant relationship that CE practices and sustainable performance both assist in achieving SDGs, H12 with $\beta = 0.194$, $P = .000$ and H13 with $\beta = 0.191$, $P = .000$.

In this section, we have examined the presence of mediating effects of CE and sustainable performance in relation to the exogeneous variable I4.0 and their impact on achieving SDGs.

In total, three hypothesized relationships (H14, H15, and H16) have been proposed to assess the indirect effects. The summary of these indirect effects has been displayed in Table 5.11. The outcome of H14 and H15 reveal that I4.0 T exhibit significant and indirect associations with SDGs through CE practices (indirect effect = .068, t = 3.095, P = .002) and SPO (indirect effect = .074, t = 3.375, P = .001). Additionally, a serial mediation test from I4.0 T to SDGs was executed with CE practices and sustainable performance as sequential mediators. The serial mediation effect of I4.0 T on SDGs have been found significant through CE practices and SPO (indirect effect = .010, t = 3.672, P = .000), thereby supporting H16. Considering the direct effects findings, I4.0 T shows a significant and validated relationship with SDGs, therefore, when CE practices and sustainable performance are introduced as a mediator, it can be inferred that the supported hypotheses (H14, H15, and H16) play a partial role.

Table 5.7: Evaluation of constructs' reliability & validity of Industry 4.0 and Circular economy practices

Constructs	Indicators/Items	Source (adaption)	Factor Loadings	Cronbach`s - α	CR	AVE
Industry 4.0 Technologies (I4.0T)	Adoption of artificial intelligence & Machine learning (AIML) in the organization assists in demand forecasting and predicting purchase behavior (**I4.0 T1**).	Gupta et al., (2022); Skalli et al., (2023)	0.782	0.869	0.872	0.604
	Adoption of Internet of things (IoT) in the organization assists in real-time data collection from production processes **(I4.0 T2).**		0.753			
	Adoption of Big data analytics (BDA) in the organization helps in new product development, supply chain traceability, and enhancing productivity **(I4.0 T3).**		0.753			
	Adoption of Blockchain technology in the organization assists in tracking product origins **(I4.0 T4).**		0.795			
	Adoption of Additive manufacturing (AM) in the organization helps in waste management and renewable & sustainable production **(I4.0 T5).**		0.801			
	Adoption of augmented reality and virtual reality (AR-VR) in the organization assists in enhancing industrial processes before their implementation **(I4.0 T6).**		0.779			
Circular Economy practices (CEP)	Remanufacturing of the product **(CEP1)**	Calzolari et al., (2021)	0.876	0.928	0.931	0.668
	Recyclability **(CEP2)**		0.812			
	New product design **(CEP3)**		0.806			
	Waste management **(CEP4)**		0.806			

	Reverse logistics **(CEP5)**		0.790			
	Cleaner production **(CEP6)**		0.739			
	Reduce resource exploitation **(CEP7)**		0.855			
	Reuse **(CEP8)**		0.846			
Sustainable performance of the organization (SPO)	Reduction in greenhouse gas emissions & hazardous wastes **(SPO1)**	Malek and Desai, (2022)	0.798	0.911	0.913	0.530
	Reduction in consumption of harmful materials **(SPO2)**		0.718			
	Renewable energy consumption **(SPO3)**		0.689			
	Eco-friendly product design **(SPO4)**		0.730			
	Increase in sales and productivity **(SPO5)**		0.705			
	Improved market competitiveness **(SPO6)**		0.689			
	Health and safety **(SPO7)**		0.751			
	Government subsidies for utilizing renewable energy **(SPO8)**		0.751			
	Increase in product Quality **(SPO9)**		0.754			
	Reduction in plant rejections **(SPO10)**		0.728			
	Compliance with government Labels and certificates **(SPO11)**		0.683			
Sustainable Development Goals (SDGs)	**SDG 1** (End Poverty) _Target (1.1, 1.2, 1.5 and 1. B)	Schroeder et al., (2019)	0.821	0.926	0.932	0.601
	SDG 2 (End Hunger) _Target (2.1, 2.2, and 2.3)		0.770			
	SDG 6 (Sustainable management of water and sanitation) _Target (6.1, 6.2, 6.3, and 6.4)		0.801			
	SDG 7 (Sustainable and affordable energy) _Targets (7.1, 7.2, and 7.3)		0.809			
	SDG 8 (Sustainable economic growth and productive employment) _Target (8.2 & 8.4)		0.728			

	SDG 9 (Sustainable Industrialization, Innovation and Resilient Infrastructure) _Targets (9.1, 9.2, 9.5, and 9.C)		0.756			
	SDG 11 (Resilient and Sustainable Cities and Communities) _Target (11.6 and 11. B)		0.787			
	SDG 12 (Sustainable Consumption and Production) _Target (12.2, 12.4, and 12.5)		0.801			
	SDG 14 (Life below water) _Target (14.2 and 14.3)		0.783			
	SDG 15 (Life on Land) _Targets (15.1, 15.2, and 15.3)		0.685			

Table 5.8. Correlation and discriminant validity

	CEP	I4.0 T	SDGs	SPO
Fornell-Larcker criterion				
CEP	**0.817**			
I4.0 T	0.349	**0.777**		
SDGs	0.308	0.322	**0.775**	
SPO	0.289	0.442	0.322	**0.728**
Heterotrait-monotrait ratio				
CEP				
I4.0 T	0.385			
SDGs	0.322	0.349		
SPO	0.310	0.493	0.347	

Note: Numbers in bold, shown diagonally are square roots of the AVE values.

Table 5.9. Structural model fit results

	R^2	Q^2	SRMR
CEP	0.122	0.12	0.050
I4.0 T			
SDGs	0.176	0.10	
SPO	0.216	0.19	

Table 5.10. Summary of direct path hypotheses results

Hypothesis	Path	Estimate (β)	T values	P	Conclusion
H10a	I4.0 T ⟶ CEP	.349	7.897	.000	Significant & validated
H10b	I4.0 T ⟶ SPO	.389	7.877	.000	Significant & validated
H10c	I4.0 T ⟶ SDGs	.169	3.169	.002	Significant & validated
H11	CEP ⟶ SPO	.154	3.344	.001	Significant & validated
H12	CEP ⟶ SDGs	.194	4.028	.000	Significant & validated
H13	SPO ⟶ SDGs	.191	3.878	.000	Significant & validated

Table 5.11. Summary of Hypotheses testing (Mediation analysis)

Hypotheses	Path	Indirect effect	T value	P	Conclusion
H14	I4.0 T -> CEP -> SDGs	.068	3.095	.002	Supported partial mediation
H15	I4.0 T -> SPO -> SDGs	.074	3.375	.001	Supported partial mediation
H16	I4.0 T -> CEP -> SPO -> SDGs	.010	3.672	.000	Supported, partial mediation

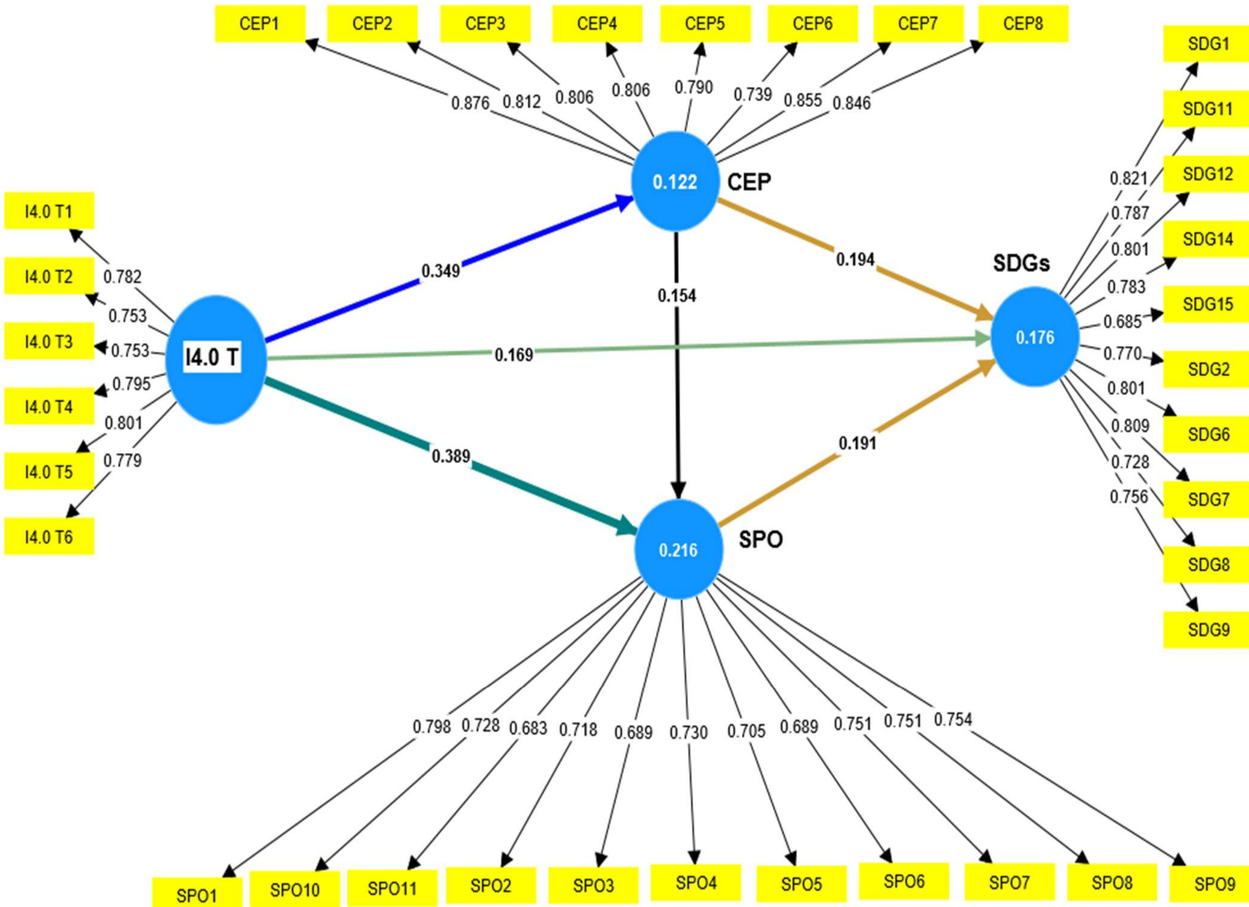

Figure 5.3. Structural model

5.5 Conclusion

This chapter explains the quantitative evaluation of proposed hypotheses and research model using various statistical tools in SPSS and structural equation modelling using AMOS and smart PLS. The study concern is to provide solution for the research gaps. In line with the formulated objectives, this research analyzes the factors responsible for attaining social sustainability within organization and the effects from the integration of I4.0 technologies with circular economy strategies on the sustainable performance. The obtained results were thoroughly examined and discussed with supported literature. It was highlighted that strengthen of community interrelation plays an important role in promoting social sustainability within the organization. Additionally, the study emphasized the benefits of the combined synergy of I4.0 technologies with circular economy practices. These includes ‘Reduction in greenhouse gas emissions’, ‘Increase in product quality’, ‘Government subsidies for utilizing renewable energy’, ‘Health and safety’, and ‘Eco-friendly product design’, resultantly enhancing the sustainable performance.

Chapter 6

FRAMEWORK FOR EVALUATING SUSTAINABILITY OF A MANUFACTURING SYSTEM

6.1 Introduction

A traditional manufacturing system leads to the rapid exploitation of natural resources, global warming, and a decline in biodiversity. Sustainable practices are essential for the conservation of natural resources and environmental protection. A reluctant attitude of manufacturing organizations towards sustainable practices has been observed due to the lack of exposure to sustainability-specific indicators and sustainability frameworks. In this chapter, Graph Theory Matrix Approach (GTMA) has been adopted to evaluate the sustainability index of a manufacturing system. The literature review assists in depicting the crucial forty-five indicators of sustainable manufacturing. A case study of an Indian manufacturing organization has been considered for which the GTMA-based framework was proposed for the evaluation of the sustainability index. The findings of the study unveiled that 'employees and customers welfare', 'material & energy consumption', and 'value creation' possess a strong contribution to the sustainable operations of an organization. The result outcomes will assist the concerned professionals in gauging their industrial sustainability performance.

6.2 Methodology (GTMA)

The identified indicators of sustainable manufacturing were discussed with the experts' panel using the Delphi technique for the pairwise comparison across all ten subgroups, leading to a sustainability index tailored for manufacturing organizations using GTMA. To ensure minimum ambiguity among opinions, the following selection criteria were considered:

- Experts should have experience in the Manufacturing industry and be concerned with the application of sustainable practices.
- Experts should be working in the field of sustainability, and CSR initiatives within their respective organizations.

The experts' panel comprised 12 members having managerial experience as Head-R&D, Head-PPC, General Manager Operations, Quality Managers, Production Managers, etc. Among these experts, 5 were from the automobile sector, 4 from the iron & steel sector, and 3 from the chemical and pharmaceutical sector. Given the constraints imposed by the COVID-19 pandemic, opinions were gathered through a series of online interactive video conferencing sessions. The consensus formed during these sessions among the indicators was incorporated within the GTMA framework.

6.3 Graph Theory Matrix Approach (GTMA)

The graph theory matrix (digraph) approach is used for evaluating the intensity of indicators for environmental, economic, and social sustainability by computing a permanent matrix. It is a systematic and powerful tool for converting qualitative preferred opinions into quantitative values by providing a single mathematical index. The other multi-criteria decision-making techniques like the best-worst method, the Analytic network process (ANP), the Analytical Hierarchical process (AHP), and the Technique for order preference by similarity to the ideal solution (TOPSIS), technically give similar results. Although, these methods lack in capturing interdependency among variables while doing pair-wise comparisons. GTMA has no such constraints, as it is based on digraphs and permanent matrix value computation which doesn't need a hypothesis formulation about interdependency (Tuljak-Suban and Bajec, 2020). GTMA can solve a few complex problems, resulting in its widespread applications in many fields of science and engineering (K. E. K. et al., 2018), such as logistics service providers (Gupta and Singh, 2020), supply chain flexibility index (Singh and Kumar, 2019), roadblocks of Industry

4.0 (Virmani et al., 2021), for evaluating the maintainability index (Singh et al., 2015). In this study, we used it to measure the sustainability index for an SM system.

GTMA methodology consists of the following steps:

- Digraph formulation between indicators based on mutual correlations.
- Matrix formulation for different groups and subgroups of indicators.
- Computation of permanent function for each sustainable dimension.
- Construct inheritance and interdependency matrix for indicators with expert's opinion based on the rating scale.
- Calculation of permanent function for an SM system.

Hence, the permanent function is calculated by formulating a permanent matrix by using a generalized equation written as:

$$
\begin{aligned}
perm\, I = {} & \prod_{i=1}^{6} F_i + \sum_{i=1}^{5} \sum_{j=i+1}^{6} \sum_{k=1}^{3} \sum_{l=k+1}^{4} \sum_{m=l+1}^{5} \sum_{n=m+1}^{6} \left(r_{ij} r_{ji}\right) I_k I_l I_m I_n \\
& + \sum_{i=1}^{4} \sum_{j=i+1}^{5} \sum_{k=j+1}^{6} \sum_{l=1}^{4} \sum_{m=l+1}^{5} \sum_{n=m+1}^{6} \left(r_{ij} r_{jk} r_{ki} + r_{ik} r_{kj} r_{ji}\right) I_l I_m I_n \\
& + \left[\begin{aligned} & \sum_{i=1}^{3} \sum_{j=i+1}^{6} \sum_{k=j+1}^{5} \sum_{l=i+2}^{6} \sum_{m=1}^{5} \sum_{n=m+1}^{6} \left(r_{ij} r_{jk}\right) \left(r_{kl} r_{lk}\right)_l I_m I_n \\ & + \sum_{i=1}^{3} \sum_{j=i+1}^{5} \sum_{k=i+1}^{6} \sum_{l=j+1}^{6} \sum_{m=1}^{5} \sum_{n=m+1}^{6} \left(r_{ij} r_{jk} r_{kl} r_{li} + r_{il} r_{kj\,ji}\right)_l I_m I_n \end{aligned} \right] \\
& + \left[\begin{aligned} & \sum_{i=1}^{4} \sum_{j=i+1}^{5} \sum_{k=j+1}^{6} \sum_{l=1}^{5} \sum_{m=l+1}^{6} \sum_{n=1}^{6} \left(r_{ij} r_{jk} r_{ki} + r_{ik} r_{kj} r_{ji}\right) \left(r_{lm} r_{ml}\right)_l I_m \\ & + \sum_{i=1}^{2} \sum_{j=i+1}^{5} \sum_{k=i+1}^{6} \sum_{l=i+1}^{6} \sum_{m=j+1}^{6} \sum_{n=1}^{6} \left(r_{ij} r_{jk} r_{kl} r_{lm} r_{mi} + r_{im} r_{ml} r_{lk} r_{kj} r_{ji}\right) I_n \end{aligned} \right] \\
& + \left[\begin{aligned} & \sum_{i=1}^{3} \sum_{j=i+1}^{5} \sum_{k=i+1}^{6} \sum_{l=i+1}^{6} \sum_{m=1}^{6} \sum_{n=m+1}^{6} \left(r_{ij} r_{jk} r_{kl} r_{li} + r_{il} r_{lk} r_{kj} r_{ji}\right) \left(r_{mn} r_{nm}\right) \\ & + \sum_{i=1}^{1} \sum_{j=i+1}^{5} \sum_{k=j+1}^{6} \sum_{l=1}^{4} \sum_{m=l+1}^{5} \sum_{n=m+1}^{6} \left(r_{ij} r_{jk} r_{ki} + r_{ik} r_{kj} r_{ji}\right) \left(r_{lm} r_{mn} r_{nl} + r_{\ln} r_{nm} r_{ml}\right) \\ & + \sum_{i=1}^{1} \sum_{j=i+1}^{6} \sum_{k=i+1}^{3} \sum_{l=i+2}^{6} \sum_{m=k+1}^{5} \sum_{n=k+2}^{6} \left(r_{ij} r_{ji}\right) \left(r_{kl} r_{lk}\right) \left(r_{mn} r_{nm}\right) \\ & + \sum_{i=1}^{1} \sum_{j=i+1}^{5} \sum_{k=i+1}^{6} \sum_{l=i+1}^{6} \sum_{m=i+1}^{6} \sum_{n=j+1}^{6} \left(r_{ij} r_{jk} r_{kl} r_{lm} r_{mn} r_{ni} + r_{in} r_{nm} r_{ml} r_{lk} r_{kj} r_{ji}\right) \end{aligned} \right]
\end{aligned}
\qquad (1)
$$

Matrices are formulated on a rating scale of 0-10, shown in Table 6.1, to define the relative importance of indicators using experts' opinions.

Table 6.1: Rating scale for Interdependency estimation of Indicators

Qualitative description	*Relative Dependence*	
	Sij	Sji = (10- Sij)
Exceptionally low influencing	0	10
Extremely low influencing	1	9
Very low influencing	2	8
Below average influencing	3	7
Average influencing	4	6
Above-average influencing	5	5
Moderate influencing	6	4
High influencing	7	3
Very high influencing	8	2
Extremely high influencing	9	1
Exceptionally high influencing	10	0

Based on the matrices', directed graphs are prepared for all the groups and subgroups of the indicators. A directed graph consists of nodes and edges. Nodes represent the SM indicators and edges represent their interconnections. I_i shows the inheritance of indicators and r_{ij} shows the influence of i_{th} indicator on j_{th} indicator.

Figure 6.1 shows a schematic representation of environmental sustainability and its sub-group indicators showing their interdependencies. The sub-group indicator includes material and energy consumption ($I1_1$), water consumption ($I1_2$), environmental factor ($I1_3$), and global certification and control ($I1_4$). The indicators permanent matrix (IPM) of environmental sustainability shown in Figure 6.1. is written as:

$$Per(Environmental) = IPM\,(Environmental) = \begin{pmatrix} I1_1 & r_{12} & r_{13} & r_{14} \\ r_{21} & I1_2 & r_{23} & r_{24} \\ r_{31} & r_{32} & I1_3 & r_{34} \\ r_{41} & r_{42} & r_{43} & I1_4 \end{pmatrix}$$

The units of the matrix obtain values from the digraph. The units shown on the diagonal constitute the nodes of the digraph, which are permanent matrix values of the sub-factors of the respective dimension of SM indicators. The non-diagonal units show the interdependencies among the indicators.

Figure 6.2 digraph represents economic sustainability and its sub-group indicators with linkages. Sub-group indicator constitutes initial investment and operating cost ($I2_1$), value creation ($I2_2$), and indirectly-associated expenses ($I2_3$). The IPM of economic sustainability shown in Figure 6.2 is written as:

$$\text{Per (Economic)= IPM (economic)} = \begin{pmatrix} I2_1 & r_{12} & r_{13} \\ r_{21} & I2_2 & r_{23} \\ r_{31} & r_{32} & I2_3 \end{pmatrix}$$

Figure 6.3 digraph shows the detailed formulation with the interrelationship of social sustainability, and its sub-group indicators. The sub-group indicator is an employee ($I3_1$), customer ($I3_2$), and community ($I3_3$). The IPM of social sustainability shown in Figure 6.3 is written as:

$$\text{Per (Social)= IPM (social)} = \begin{pmatrix} I3_1 & r_{12} & r_{13} \\ r_{21} & I3_2 & r_{23} \\ r_{31} & r_{32} & I3_3 \end{pmatrix}$$

Figure 6.4 digraph represents the overall interaction among sustainable manufacturing indicators, i.e., environmental (I1), economic (I2), and social (I3). The IPM of a sustainable manufacturing system represents the resultant value of sustainability for an organization, computed as:

$$\text{Per (IPM) [SM system]} = \begin{pmatrix} I1 & r_{12} & r_{13} \\ r_{21} & I2 & r_{23} \\ r_{31} & r_{32} & I3 \end{pmatrix}$$

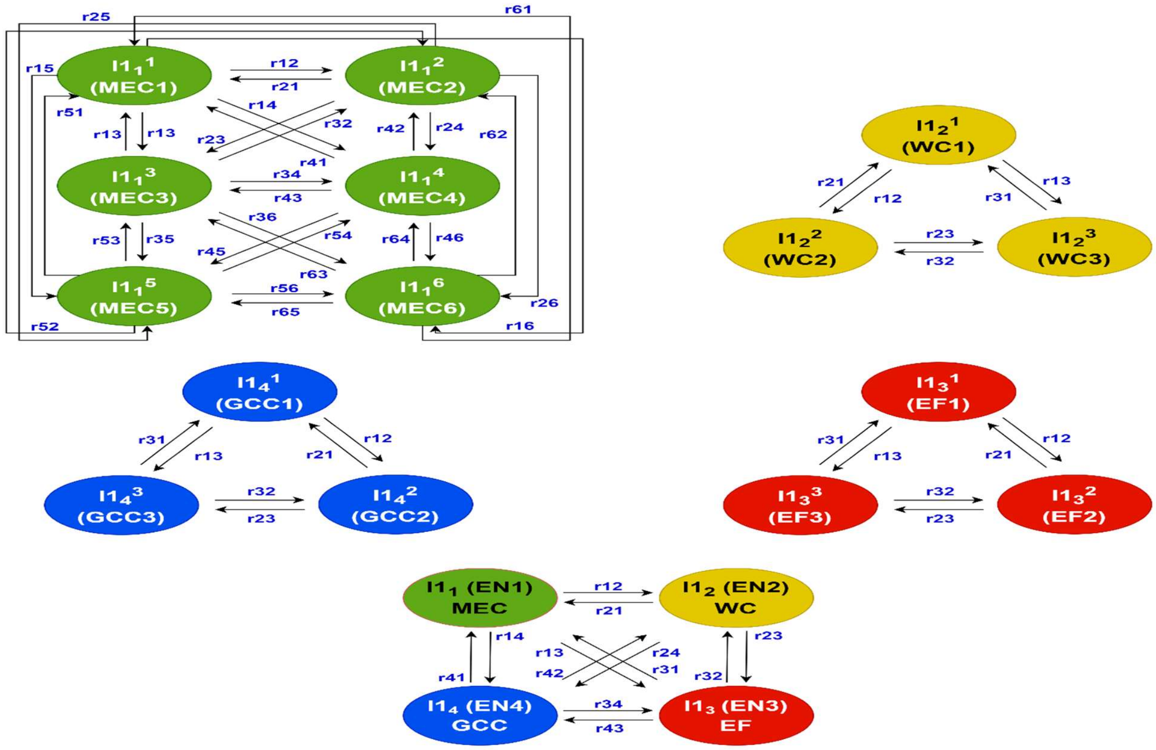

Figure 6.1. Digraph related to environmental sustainability and its sub-group indicators

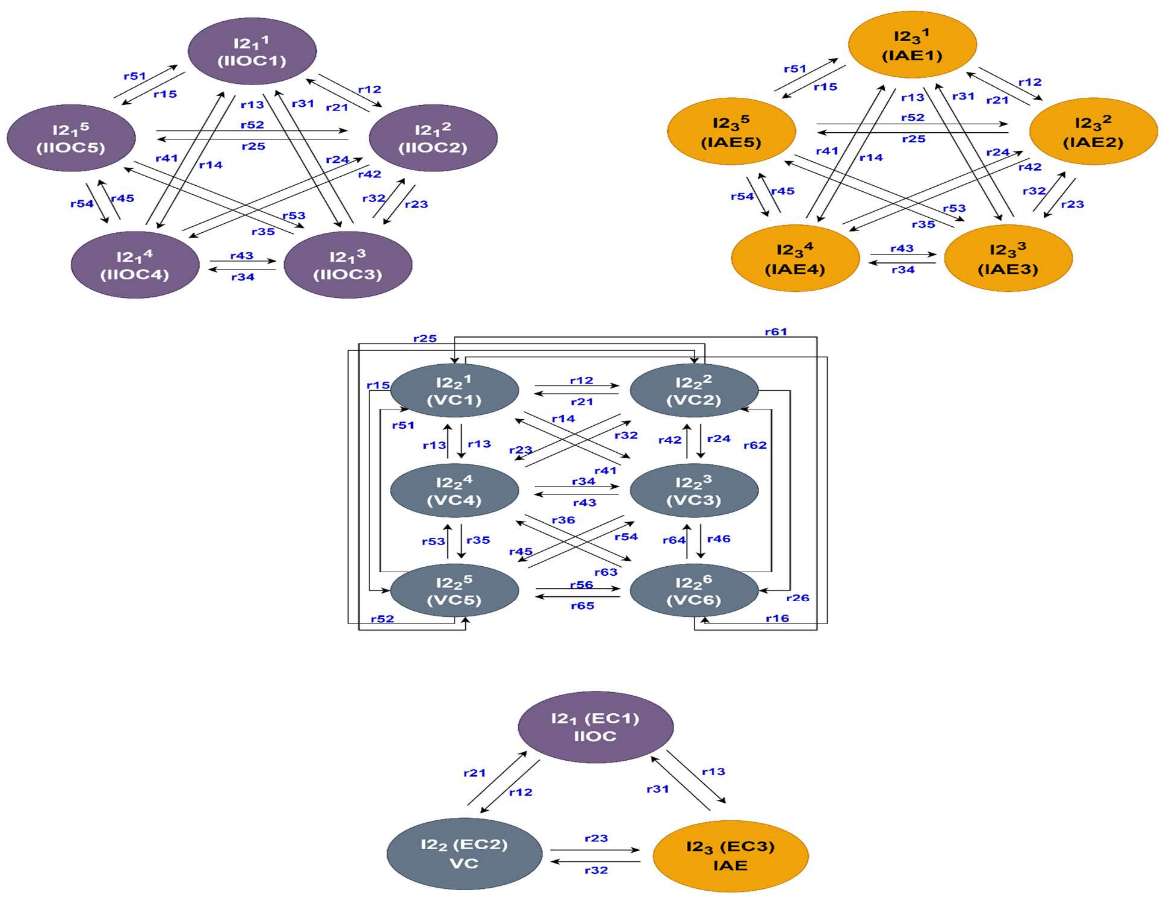

Figure 6.2. Digraph related to economic sustainability and its sub-group indicators

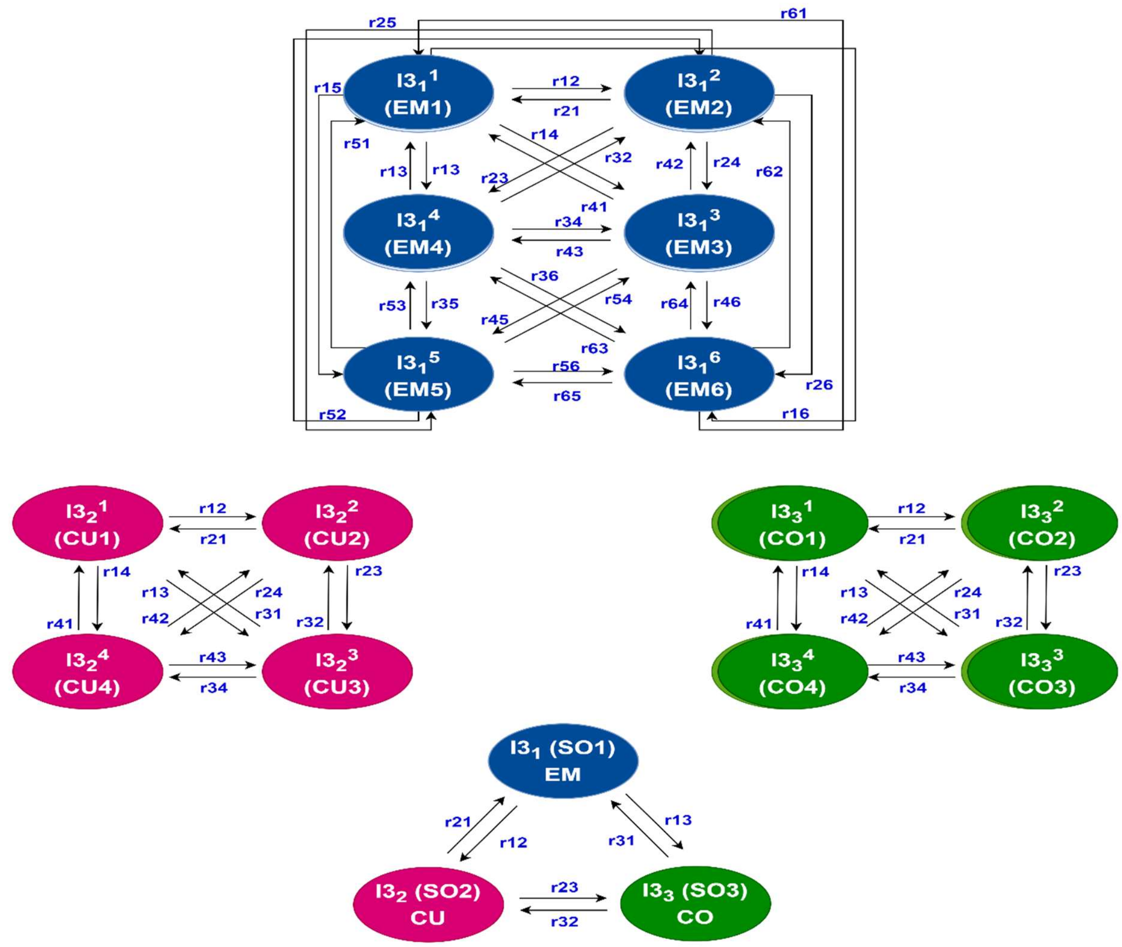

Figure 6.3. Digraph related to social sustainability and its sub-group indicators

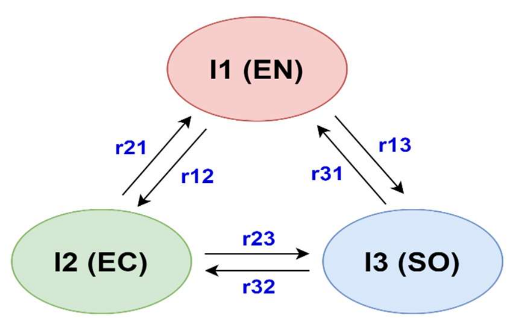

Figure 6.4. Digraph related to sustainable manufacturing dimensions

6.4 Evaluation of SM index by GTMA: Case illustration

The manufacturing sector's contribution is about 17 % of India's GDP (Virmani et al., 2021). In this study, a company having global headquarter in the National Capital Region of India is considered for the case analysis. The company is dealing with auto components & their systems, electric vehicles, charging infrastructure, and renewable energy. It supplies the components and services to all major giants of the automobile industry in India and abroad (Germany, Italy, the USA, China, and Spain). The company has a worth of $1.8 billion in 18 locations in 8 countries across the world with 21,000 global workforces. GTMA is applied to evaluate the sustainability index of this manufacturing organization. The panel of experts (details discussed in the methodology section) was consulted for data collection.

6.4.1 Indicators permanent matrix (IPM) for sustainability index evaluation

In this section, the IPM of each sub-category and major category of indicators is evaluated as per the GTMA description, given in section 6.3. Quantification of the matrix is achieved by an expert's score based on a rating scale (shown in Table 6.1). Notations used for the main categories are I1 (environmental sustainability), I2 (economic sustainability), and I3 (social sustainability). Step by step result of IPM calculation for each SM dimension is shown below by applying equations (2) to (15).

Environmental sustainability index evaluation:

$$Per[I1_1(MEC)] = \begin{pmatrix} I1_1^1 & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} \\ r_{21} & I1_1^2 & r_{23} & r_{24} & r_{25} & r_{26} \\ r_{31} & r_{32} & I1_1^3 & r_{34} & r_{35} & r_{36} \\ r_{41} & r_{42} & r_{43} & I1_1^4 & r_{45} & r_{46} \\ r_{51} & r_{52} & r_{53} & r_{54} & I1_1^5 & r_{56} \\ r_{61} & r_{62} & r_{63} & r_{64} & r_{65} & I1_1^6 \end{pmatrix} = \begin{bmatrix} 5 & 5 & 7 & 6 & 6 & 5 \\ 5 & 3 & 7 & 6 & 6 & 5 \\ 3 & 3 & 2 & 4 & 3 & 3 \\ 4 & 4 & 6 & 4 & 6 & 4 \\ 4 & 4 & 7 & 4 & 2 & 4 \\ 5 & 5 & 7 & 6 & 6 & 4 \end{bmatrix} = 6766664 \quad (2)$$

$$Per[I1_2(WC)] = \begin{bmatrix} I1_2^1 & r_{12} & r_{13} \\ r_{21} & I1_2^2 & r_{23} \\ r_{31} & r_{32} & I1_2^3 \end{bmatrix} = \begin{bmatrix} 3 & 6 & 5 \\ 4 & 2 & 4 \\ 5 & 6 & 4 \end{bmatrix} = 482 \quad (3)$$

$$Per[I1_3(EF)] = \begin{bmatrix} I1_3^1 & r_{12} & r_{13} \\ r_{21} & I1_3^2 & r_{23} \\ r_{31} & r_{32} & I1_3^3 \end{bmatrix} = \begin{bmatrix} 3 & 6 & 5 \\ 4 & 2 & 4 \\ 5 & 6 & 4 \end{bmatrix} = 482 \tag{4}$$

$$Per[I1_4(GCC)] = \begin{bmatrix} I1_4^1 & r_{12} & r_{13} \\ r_{21} & I1_4^2 & r_{23} \\ r_{31} & r_{32} & I1_4^3 \end{bmatrix} = \begin{bmatrix} 2 & 4 & 5 \\ 6 & 4 & 5 \\ 5 & 5 & 3 \end{bmatrix} = 496 \tag{5}$$

After the computation of IPM values for each subcategory, the final score of the dimension is calculated by using the above permanent values as a diagonal element, and off-diagonal elements represent interdependence values assigned by experts, as shown in equation (6).

$$\begin{aligned} Per[I1(Environmentalsustainability)] &= \begin{bmatrix} I1_1 & r_{12} & r_{13} & r_{14} \\ r_{21} & I1_2 & r_{23} & r_{24} \\ r_{31} & r_{32} & I1_3 & r_{34} \\ r_{41} & r_{42} & r_{43} & I1_4 \end{bmatrix} \\ &= \begin{bmatrix} 6766664 & 7 & 6 & 5 \\ 3 & 482 & 4 & 3 \\ 4 & 6 & 482 & 5 \\ 5 & 7 & 5 & 496 \end{bmatrix} \\ &= 77.99 \times 10^{13} \end{aligned} \tag{6}$$

Similarly, the final IPM score is calculated for economic, and social sustainability dimensions (shown by equations 7 to 15), then these scores are used to determine the sustainability index score for manufacturing organizations trying for structuring their SM system.

Economic sustainability evaluation:

Per [$I2_1$ (IIOC)] = 214097 (7)

Per [$I2_2$ (VC)] = 6708522 (8)

Per [$I2_3$ (IAE)] = 205420 (9)

$$Per[I2(Economicsustainability)] = \begin{bmatrix} 214097 & 4 & 3 \\ 6 & 6708522 & 3 \\ 7 & 7 & 205420 \end{bmatrix} = 29.5 \times 10^{16} \tag{10}$$

Social sustainability evaluation:

Per [$I3_1$ (EM)] = 7139994 (11)

Per [$I3_2$ (CU)] = 9431 (12)

Per [$I3_3$ (CO)] = 9716 (13)

$$Per[I2(Socialsustainability)] = \begin{bmatrix} 7139994 & 5 & 6 \\ 5 & 9431 & 6 \\ 4 & 4 & 9716 \end{bmatrix} = 65.42 \times 10^{13} \quad (14)$$

Overall sustainability index score (SIS) for selected manufacturing system

$$Per(SMsystem) = \begin{bmatrix} 77.99 \times 10^{13} & 5 & 6 \\ 5 & 29.5 \times 10^{16} & 6 \\ 4 & 4 & 65.42 \times 10^{13} \end{bmatrix} = 15.05 \times 10^{46} \quad (15)$$

6.4.2 Theoretical Best and worst-case values

After the calculation of SIS, we further examined the range to gain insights into hypothetical scenarios, characterized by maximum and minimum values. In the case of the maximum index value, the manufacturing organization needs to excel in all three dimensions of sustainability. Hence, in this context, the inheritance score is maintained at its maximum value, i.e. 5. Conversely, in the scenario with the minimum index value, it becomes evident that the organization has a low existence of sustainability indicators. In such cases, the inheritance value is assigned as '1'. This situation occurs in those, who have just started the implementation of SM practices. The summary of GTMA results for all dimensions of sustainability with the computed permanent values for actual, maximum, and minimum scenarios, is presented in Table 6.2. Additionally, corresponding logarithmic values for each category were also computed to facilitate an easier interpretation of the results.

Best case scenario permanent values of the SM indicators:

Per [I1(Environmental sustainability)] = 38.27×10^{14}

Per [I2(Economic sustainability)] = 93.15×10^{16}

Per [I3(Social sustainability)] = 22.42×10^{14}

Per (SM system) or SIS = 79.94×10^{47}

Worst case scenario permanent values of the SM indicators:

Per [I1(Environmental sustainability)] = 13.54×10^{13}

Per [I2(Economic sustainability)] = 76.43×10^{15}

Per [I3(Social sustainability)] = 20.13×10^{13}

Per (SM system) or SIS = 20.84×10^{44}

The existing permanent matrix values (Table 6.2) show the relative importance of the indicators category-wise as well as subcategory-wise. The ranks of the SM dimensions in descending order are prioritized as economic sustainability, environmental sustainability, and social sustainability. These rankings guide the significance of each indicator, assisting organizations in making informed decisions about their sustainability priorities. The relative scores assigned to the indicators show a clear indication of where emphasis should be placed on achieving sustainability within an organization. Consequently, the final SIS can be used to assess the sustainable development of an organization. Based on the IPM score and SIS, we can conduct valuable comparisons with other organizations and establish rankings from an SM perceptive.

Table 6.2: Permanent matrix values for the actual, best- and worst-case scenario

Dimension	Indicators	Actual Case (Permanent matrix values)	Log_{10} (Actual case)	Best case (Permanent matrix values)	Log_{10} (Best case)	Worst case (Permanent matrix values)	Log_{10} (Worst case)
Environmental	Per (MEC)	6766664	6.830	9639906	6.984	4223858	6.626
	Per (WC)	482	2.683	730	2.863	314	2.497
	Per (EF)	482	2.683	730	2.863	314	2.497
	Per (GCC)	496	2.695	745	2.872	325	2.512
Per (Environmental)		77.99×10^{13}	14.892	38.27×10^{14}	15.583	13.54×10^{13}	14.132
Economic	Per (IIOC)	214097	5.331	311955	5.494	135367	5.132
	Per (VC)	6708522	6.827	9852802	6.994	4335218	6.637
	Per (IAE)	205420	5.313	303065	5.482	130237	5.115
Per (Economic)		29.5×10^{16}	17.470	93.15×10^{16}	17.970	76.43×10^{15}	16.883
Social	Per (EM)	7139994	6.854	10375846	7.016	4605190	6.663
	Per (CU)	9431	3.974	14851	4.172	6699	3.826
	Per (CO)	9716	3.987	14550	4.163	6526	3.815
Per (Social)		65.42×10^{13}	14.816	22.42×10^{14}	15.351	20.13×10^{13}	14.304
Per (SM system)		15.05×10^{46}	47.178	79.94×10^{47}	48.903	20.84×10^{44}	45.319

6.5 GTMA results discussion

The graph theory matrix (digraph) approach leads to the estimation of intensity among the indicators of environmental, economic, and social sustainability by computing a permanent matrix. As per the results summarized in Table 6.2, the following five sub-group of sustainable manufacturing indicators, i.e., employee (6.854), materials and energy consumption (6.830), value creation (6.827), initial investment & operating cost (5.331), and indirectly associated expenses (5.313) have been observed the most vital and influential from the adoption perspective of sustainability in manufacturing organizations.

Among the social sustainability indicators, the employee (EM) factor has the highest potential in enhancing the performance of the organization as they are fully responsible for manufacturing processes, product development, and designing parts. The employee management category includes job security and employee retention, health and safety, employee performance, training and development, risk identification and employee feedback management, and employee satisfaction. Lin et al. (2020) also observed that employees are the key resources in the manufacturing process for the smooth adoption of sustainability. Manufacturing organization has to impart regular training and development for the empowerment of their employees for achieving excellence in business, goals, and sustainable competitive gains (Ghosh, 2013). In India, many enterprises are engaging heavily in delivering training programs.

The second most important indicator category is materials and energy consumption, a subcategory of environmental sustainability. It includes recycling of used materials, consumption of recycled/refurbished materials/components, non-hazardous material consumption, green packaging materials, green transportation/fuel economy and emission control, and renewable energy consumption. Legitimacy pressures from different institutions accelerate the firm actions toward environmental compliance activities which leads to Institutional theory (Gupta and Gupta, 2021). The manufacturing sector, over the years, has been the backbone of Indian GDP by creating ample opportunities for their stakeholders, at the expense of a large amount of waste generation, environmental degradation, GHG emissions, and biodiversity deterioration. Thus, it becomes imperative for industries to inculcate materials and energy consumption indicators. In most countries, the organization must get a certificate of environmental compliance from the regional environmental compliance departments, which triggers the organization for the adoption of necessary environmental measures, leading to economic benefits, enhanced employee engagement, internal production efficiencies, customer satisfaction, and branding (Govindan et al., 2015). Abbas (2020) also supported that the implementation of new technologies in synchronization with green manufacturing and total quality management enables a reduction in pollution, energy consumption, and waste generation, correspondingly amplifying the organization's performance, product quality, and services.

The third, fourth, and fifth important indicators categories are value creation (VC), initial investment and operating cost (IIOC), and indirectly associated expenses (IAE), which need to be followed by manufacturing organizations for sustainability. All the above indicators are concerned with economic sustainability. Value creation aims in designing and developing a product of good functionality, and high quality at low input cost. It comprised revenue generation, profit earned, annual productivity, new product design and development, market share, and facility expansion. In today`s competitive scenario, the organization adopts those indicators that can outreach its revenue generation, annual productivity, and market share. Disruptions like pandemics and natural calamities are unpredictable and unforeseen, but firms can minimize the effect by becoming prudent towards sustainability practices. The implementation of SM practices can ensure market competitiveness and an organization's reputation during such a critical time (Nader et al., 2022). IIOC category includes indicators carried by industries in the form of wages and operating costs, liability and debt payment, environmental treatment cost, expenses as a philanthropist on CSR activities, and sales promotion. Eslami et al. (2019) confirmed in their study that economic indicators constituted process input cost (raw materials and operating), process output cost (environmental treatment cost), and capital cost. The indirectly-associated expenses (IAE) category is composed of indicators that higher management of the organization counts before any transformation in manufacturing processes. It includes depreciation, maintenance, pollution control cost, investment in research and development, and prevention of scrap production.

Overall, it has been found that economic sustainability with an indicator permanent matrix score of 17.470 is the most important dimension, followed by environmental (14.892) and social (14.816). Hariyani and Mishra (2022) have also observed that organizations are not able to enforce SM practices due to price competition and quality standard issues. In a developing country like India, it requires a huge takeout from an individual in the form of high capital, skilled manpower, and government help for transforming the existing system. In the current business environment of economic slowdown, manufacturers are noticing waste reduction and value creation; and customers are seeking products of high quality at low cost (Kumar et al., 2021b). In the last five years, we had observed very slow growth in the economy, setting foot back of manufacturers for any new change. Thus, it can comply that acceptance of indicators for sustainability adoption in manufacturing industries will be perceived by giving an extra edge to economic in comparison to environmental, and social. Shubham et al., (2018) discussed that institutional pressure from industrial associations and regulatory bodies critically influenced organizations to adopt SM practices. Tu and Wu (2021) highlighted that pressure from stakeholders (consumers and communities), policies, and regulations have a highly positive effect on sustainability and creating enterprise competitive advantage.

6.6 Conclusion

In this chapter, a framework for evaluating the sustainability index of a manufacturing system using a case study is proposed. The sustainable manufacturing indicators comprised of all three dimensions of the triple bottom line explored through an in-depth literature review were rated based on experts` opinions using Delphi technique. The Graph Theory Matrix Approach (GTMA) was used in determining the permanent matrix values for all the dimensions, leading to the calculation of a sustainability index. This index can be utilized by other manufacturing organizations to determine sustainability and other performance-related indices.

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Introduction

The results of statistical regression analysis and mathematical modeling have been summarized in this chapter. Multivariate regression analysis has been utilized for framing exogenous and endogenous variables and to establish a link between them, while mathematical modeling has been employed to prioritize sustainability indicators and to develop a framework for gauzing sustainability index of a manufacturing system.

7.2 Structural Equation Modeling

7.2.1 Analysis of Moment Structures (AMOS)

Integrating sustainability as a core function is the most challenging task for business organizations. Organizations are forced to rethink, redesign, and redevelop their existing system from green practices to achieve sustainable development. The detailed review of literature highlights certain gaps in the transition toward achieving sustainable development in manufacturing systems. In the transitional attempts, more emphasis has been given to economic and environmental dimensions, but the social aspect is usually overlooked. This research targets to examine how organizations could induce social sustainability within the system through a comprehensive literature review and underlying hypothesis. The structural equation modelling (SEM) using AMOS has been applied in building a socially sustainable model for the business organization. Business organizations inclined towards sustainability must integrate all three dimensions: environmental, economic, and social. The inducement of social sustainability in the organization is complex, tedious, and challenging. The solution lies in developing conceptual and empirical studies. The study quantitatively evaluated the sensitive social sustainability indicators required for a business organization's employee and customer satisfaction and loyalty using structural equation modelling. A research model with hypotheses has been framed, and the social sustainability indicators have been proposed based on extensive literature review. The model has been validated using various statistical tools in SPSS and AMOS software.

The results show that community interrelations, consumer protection, stakeholder engagement, Occupational Health and Safety, Job Characteristics, and Community interrelations strongly correlate with each other. These constructs corresponding estimates (β) for achieving social sustainability are arranged in decreasing order of importance as: community interrelations (β = 0.34), consumer protection (β = 0.31), stakeholder engagement (β = 0.30), job characteristics (β = 0.18), and occupational health and safety (β = 0.10). The proposed factors related to the six constructs show a structural model linking each other with corresponding estimates. Among these factors and constructs, community interrelation is the most important for making the organization more socially sustainable. The result of the hypotheses testing is summarized in Table 7.1.

Table 7.1. Summary of Hypotheses testing

Hypothesis	Conclusion
H1a: There is an interrelationship between JC and OHS.	Accepted
H1b: There is an interrelationship between JC and CI.	Accepted
H1c: There is an interrelationship between JC and SE	Rejected
H1d: There is an interrelationship between JC and consumer protection.	Accepted
H2a: There is an interrelationship between OHS and consumer protection.	Accepted
H2b: There is an interrelationship between OHS and CI.	Accepted
H2c: There is an interrelationship between OHS and SE.	Accepted
H3a: There is an interrelationship between consumer protection and CI.	Accepted
H3b: There is an interrelationship between consumer protection and SE.	Accepted

H4: There is an interrelationship between CI and SE.	Rejected
H5: JC is positively related to SS.	Accepted
H6: OHS is positively associated with SS.	Accepted
H7: There is a positive relationship between consumer protection and SS.	Accepted
H8: There is a positive relationship between CI and SS.	Accepted
H9: There is a positive relationship between SE and SS.	Accepted

7.2.2 Partial Least Square-Structural Equation Modeling (PLS-SEM)

The manufacturing sector plays a vital role in the economic growth of developing countries. The technological revolution and global emphasis on SDGs in manufacturing sectors have motivated researchers to explore prominent strategies in all possible processes to develop a robust world-class sustainable system. In this study, SmartPLS 4 software has been utilized to analyze the survey data related to antecedents of sustainability for the performance of sustainable manufacturing system. Consequently, this study empirically investigated and addressed the synergistic effects of I4.0 and CE on the development of decision support system aimed at fostering sustainability, sustainable business performance, and the attainment of UN SDGs within manufacturing organizations. The investigated direct and indirect hypotheses reveal the key outcomes, such as the adoption of I4.0 technologies with CE philosophy could transform the manufacturing landscape, enhance the sustainability readiness, and acts as a catalyst for the pursuit of UN SDGs. Furthermore, the CE practices and sustainable performance exert substantial and indirect influence (partial mediation) on the exogenous variable (I4.0 technologies), ultimately impacting their effectiveness in achieving SDGs. The obtained results are in line with past studies in which digital technologies come as a pivotal one for enabling circular transition in industrial firms towards transparency, visibility, increase in resource utilization, servitization, and circular design (Chauhan et al., 2022; Ivanov et al., 2022; Neri et al., 2023). The transition towards a CE requires a new innovative mindset that can think beyond isolated measures (Peter et al., 2023). The conceptual framework developed demonstrates the role of enabling I4.0 technologies in making a remarkable change in the implementation of CE leading to the achievement of SDG targets. The adoption of I4.0 as the core of the system can enable and improve capabilities of waste management, re-storage of natural systems, circular design, reverse flow activities, etc.

The integrated concepts of theories (RBVT, ST, and DCT) complement each other and act as company-level drivers in developing sustainable strategies, optimal resource utilization, and strong capabilities of adaption in an evolving business environment. Yadav et al. (2023) proposed that organizations need digital technologies to manage their tangible and intangible resources, lean, and green practices to attain sustainability goals. Implementation I4.0 drivers is an organizational capability that favors product design, rapid upgrading and maintenance, and the concept of net zero emissions, leading toward the achievement of sustainable performance and SDGs (Contreras et al., 2023). Consumption and choice of resources (materials, energy, and water), product design, green purchasing, and product circularity come under environmental concise practices that enable the firm to gain a real competitive edge to preempt competition (Coppola et al., 2023). RBVT centered dynamic capabilities not only reduce resource input, waste, energy leakage, and emissions but also play a pivotal role in shaping new business practices and fostering strategic collaborations with diverse stakeholders. Moreover, they facilitate organizational restructuring and the creation of a competitive advantage, particularly when firms prioritize their commitment and capabilities towards the natural environment and sustainable development. Mishra et al. (2021) proposed a resource-based view perception as a path for CE transition. Dynamic capabilities are the first essential step for sustaining CE and achieving sustainability in the firm (Panwar and Niesten 2022). Stakeholders play an important role in organization decisions towards circular product design

(Pinheiro et al., 2022). Beck et al. (2023) concluded that stakeholder engagement, collaboration, and value creation have been crucial to reach SDGs 1,2,6,7,8,9,11, and 12.

Based on the findings, we propose a significant correlation between I4.0 technologies, CE practices, sustainable performance, and SDGs. However, it is noteworthy that standalone CE systems are not inherently the most sustainable alternative and may not necessarily result in fewer emissions as corroborated by prior research studies (Dantas et al., 2021; De Souza Junior et al., 2020). The solution lies in the use of innovative technologies like IoT, BDA, AIML, Blockchain, or AM. These technologies have the capability to optimize CE practices by efficiently utilizing available resources, thereby reducing the overall material and energy flow, and consequently, minimizing emissions. I4.0 assists organizations in achieving sustainability and boosting the efficiency and responsiveness of manufacturing systems (Sharma et al., 2023). Firms can utilize AIML and BDA in improvising manufacturing processes, and performance (Maiurova et al., 2022), enabling repairability, tracking and monitoring, assembly and disassembly, and proactive asset management (Peter et al., 2023). Implementation of BDA enables an organization to have better control over predictive maintenance, route optimization on a real-time basis, customer requirements, product utilization patterns, and reuse and recycling of materials (Cheng et al., 2022). AM/3D printing enables circular design, flexibility, enhance efficiency, and reduce waste and cost. IoT is one of the widely accepted digital technologies that can enable the organization transition towards circularity by offering interaction, collection, and exchange of information through wireless communication, resulting in reduced resource consumption (Neri et al., 2023). An amalgamation of Blockchain technology with CE improves the firm business models through 3R practices, re-manufacturing, recycling, and regenerating of resources and materials, resulting in increasing production efficacy (Tang et al., 2022). I4.0 tools can induce flexibility, sustainability, improve customer-supplier relationships, build visibility across operations, and enhance competency of the supply chain management (Mishra et al., 2023).

Findings suggest, manufacturing organizations can achieve resilience prospects through investments in I4.0 technologies, such as AM, Blockchain, and AIML with CE practices. The mediating effects of CE and sustainable performance (H14, H15, and H16) with the independent variable I4.0 have been partially supported for the achievement of SDGs within the sample analyzed. CE practices namely remanufacturing of the product, reduce resource exploitation, and reuse have been examined as the vital and influential from the perception of enhancement in sustainable performance and attainment of SDGs. The outcomes align with (Neri et al., 2023), who reported reducing resource exploitation, waste, energy consumption, and green packaging distribution bring economic advantages to the firm. Manufacturing organizations equipped with digital technologies and circular business models have an edge over their competitors in terms of long-term economic gains, market competitiveness, and attainment of enduring sustainability goals. Adoption of CE practices with green logistics enhances the social, economic, and environmental business performance of the firms (Sharma et al. 2023). CE practices can avoid fines and compliance costs from environmental concerned agencies by improving the organization's effectiveness in terms of waste treatment and recycling (Yin et al., 2023). CE bring environmentally conscious production in manufacturing organizations, boosting commercial performance and yielding intangible benefits like consumers loyalty and strengthened sellers-buyers' relationships (Baxter et al., 2018). Creation of value among stakeholders and government policies plays a keen role in responsible research innovation, industrial dynamism, modernization of urban sectors, and improved conditions for humanity and the planet. These measures deal with some pressing issues namely, climate change, poverty, unemployment, inequalities, and health promotion, contributing targets of SDG 1(Bacq and Aguilera, 2022; Beck et al., 2023). Implementation of CE practices within industries nearer to urban regions could bring numerous benefits such as improvement in water quality and enhancement in energy efficiency through utilization of green fuels in transportation and innovations in waste management systems. These initiatives improve environmental and economic sustainability, and supports SDGs 6 and 7 (Bosch et al., 2021). Integration of I4.0 technologies such as IoT and BDA and CE assist in energy optimization and development of resource consumption patterns of the population. This combined effort enhances operational and resource efficiency, usage of renewable energy, contributing towards SDG 7. Aligned with the objectives of SDG 8, the transition towards a circular system presents promising economic prospects of $ 4.5 trillion (Dantas et al., 2021). This transition not only enhance economic resilience but also diminishes reliance on scarce resources, elevating organizational competitiveness and advancements in economic development. The optimization of CE practices through Digital technologies in manufacturing organizations yields a better air quality index, and robust waste management system, and mitigates climate changes leading to a resilient and sustainable urban scenario, addressing SDG 11. Implementation of CE practices such as recycling, reuse, waste recovery and prevention, and safe disposal provides a pathway to SDG 12 (Priyadarshini and Abhilash, 2020). However, I4.0 technologies revolutionize the way industries operate in manufacturing lines by minimizing the excess use of energy and resources through data optimization and monitoring. Hence, based on a questionnaire survey and empirical investigation, we came across that CE-I4.0 nexus with the sustainable performance of the organization strongly supports SDGs 1,6,7,9,11 and 12 and least to SDGs 2,8, 14, and 15. The outcomes are in accordance with several earlier investigations (Beck et al., 2023; Fatimah et al., 2020; Rodriguez-Anton et al., 2019)

Research findings emphasize on the joint adoption of I4.0 and CE through the lens of management theories to achieve sustainable performance and SDGs in context to manufacturing organizations. The shift towards a sustainable system needs a new mindset that transcends isolated measures. The proposed conceptual framework will guide manufacturing organizations toward the path of sustainability. In developing economies, uptake of I4.0 and CE is in its early stages, hindered by various challenges like inadequate infrastructure, high investment, and shortage of skilled workforce (Ghobakhloo et al., 2022). These hurdles pose significant challenges for organizations, underscoring the importance of proactive engagement from regulatory government agencies. These agencies play an important role in supporting sustainability-focused initiatives that can motivate and propel industries toward UN SDGs.

The result outcomes shed light on several noteworthy findings. Among CE practices, ‘Remanufacturing of the product’, ‘Reduce resource exploitation’, ‘Reuse’, and ‘New product design’ emerged as the most essential. In contrast, ‘Additive manufacturing’, ‘Blockchain technology’, and ‘Artificial intelligence and Machine learning’ were identified as crucial I4.0 technologies. Furthermore, the synergy between CE-I4.0 significantly enhances the five important sustainable performance factors among eleven namely ‘Reduction in greenhouse gas emissions’, ‘Increase in product quality’, ‘Government subsidies for utilizing renewable energy’, ‘Health and safety’, and ‘Eco-friendly product design’. The result summary of formulated hypotheses is shown in Table 7.2.

Table 7.2. Summary of Hypotheses results

Hypothesis	Conclusion
H10a: I4.0 leads to the adoption and implementation of CE in the organization.	Accepted
H10b: I4.0 technologies positively and directly influence the sustainable performance of the organization.	Accepted
H10c: I4.0 technologies lead to the achievement of SDGs.	Accepted
H11: CE has a positive and significant effect on the sustainability performance of the organization.	Accepted
H12: The implementation of CE practices leads to the accomplishment of SDGs.	Accepted

H13: Sustainable performance of the organization assists in achieving UN SDGs.	Accepted
H14: CE practices mediates the relationship between I4.0 technologies and SDGs.	Accepted partial mediation
H15: Sustainable performance of the organization mediates the relationship between I4.0 and SDGs.	Accepted partial mediation
H16: CE practices and sustainable performance mediate the association between I4.0 and SDGs.	Accepted partial mediation

7.3 Graph Theory Matrix Approach

Graph theory matrix approach is a systematic method for developing framework and directional graphs for gauzing performance in terms of sustainability score for the entire system based on score card. In this study the indexing of sustainability indicators and clusters depicted and finalized through experts has been prepared using GTMA. These clusters are arranged in decreasing order of importance as: employee-related issues, material and energy consumption, value creation, initial investment and operating cost, indirectly associated expenses, community, customer, global certification and control, water consumption, and environmental factors. Among these clusters of indicators, the five most important indicators are non-hazardous materials consumption, green packaging materials, green transportation/ fuel economy & emission control, renewable energy consumption, and recycling of used materials. The demand for sustainability in manufacturing industries has been increasing promptly for a cleaner environment, low GHG emissions, and an ascent in biodiversity. The adoption of sustainable manufacturing practices will improve sustainable competitiveness. This underscores the significance of environmental sustainability as a key pillar of the triple bottom line. Appolloni et al. (2022) also highlighted that sustainability is an essential need for manufacturing companies to cope with times of economic crisis and uncertainty. It can develop a competitive edge in manufacturing. Manufacturing organizations should primarily have to empower and develop their employees to achieve sustainability, excellence in business, and economic gains. The findings offer valuable insights to manufacturers, guiding them in developing effective strategies for attaining sustainable development within their organizations. To promote sustainability, business excellence, and economic growth, manufacturing organizations must prioritize the empowerment and development of their employees. Management at higher levels should actively promote the use of recycling, non-hazardous materials, and renewable energy to assess and improve sustainability performance. In today's dynamic and competitive landscape, policymakers should focus on key indicators such as organizational value enhancement, initial investment for operations, and indirectly related expenses to drive economic growth toward sustainable development. The proposed framework may be utilized to determine sustainability and other performance-related indices. GTMA and other indexing models may be used to scale the sustainability of an organization. The theoretical maximum and minimum values of the different sustainability indicators can be used as a benchmarking of the performed values using GTMA. The researchers can also compare the sustainability performance of an organization with other organizations and improve the different sustainability parameters accordingly.

7.4 Conclusion

In this chapter, the obtained results of various statistical, regression analysis, and mathematical modeling has been discussed. The estimation was accomplished using AMOS, Smart PLS-SEM, hypotheses testing, and Graph theory matrix approach. This assessment provides major contributing action factors for sustainability improvement, sustainable performance, and achievement of SDGs. The summary, implications, limitations and future scope of the research are highlighted in Chapter 8.

CHAPTER 8

SUMMARY, IMPLICATIONS, AND CONCLUSION

8.1 Introduction

Sustainable development is the need of the hour in response to the increasing population, industrialization, environmental degradation, and social inequality. Current industrial practices pose many obstacles to manufacturing sectors meeting sustainability criteria and result in negative impacts on the environment, economy, and society. To achieve a productive and sustainable climate, awareness of needs, implementation strategies, and evaluation methods for sustainability in the manufacturing sector is essential. Sustainable manufacturing is a crucial initiative towards the achievement of sustainability goals by minimizing the harmful impact on the community and environment along with boosting the global economy. The unavailability of suitable sustainability indicators pulls the organization steps back from the incorporation of sustainable-centric practices. Thus, it becomes an utmost need to depict, define, and categorize the standardized indicators, and explain the underlying hypotheses with the development of a performance measuring framework. A more efficient and universal framework can help manufacturers, customers, and policy-makers to address environmental, economic, and social issues and steadily lead toward sustainability.

This research study aimed to examine the status of sustainable manufacturing practices in Indian manufacturing organizations through the administration of a questionnaire. The opinion of various stakeholders was taken through a qualitative approach and analyzed using statistical and decision-making techniques. This chapter summarized the work done, research findings, mapping of gaps and objectives, implications with limitations, and future scope of work.

8.2 Summary of work done

The major work done during this research is as follows:

- An extensive literature review has been done to identify the status of current research concerns and their applicability within the Indian context. The review yielded various literature gaps and valuable insights that need to be studied.
- Based on the literature review the underlying hypotheses are formulated and verified with the industrial and academic experts.
- A questionnaire was prepared in consultation with academic experts and professionals/practitioners from manufacturing industries and service organizations to assess the theoretical constructs related to the integration of sustainable-centric innovative practices in Indian manufacturing organizations.
- The inclusion of factors to achieve social sustainability was found under-researched in comparison to environmental and economic in Indian manufacturing organizations. Thus, a structural model for the assessment of social sustainability has been developed using AMOS.
- The performance framework comprised of realistic indicators of TBL dimensions for the evaluation of the sustainability index of a manufacturing system using a real case study has been done by the Graph theory matrix approach.
- A framework based on the amalgamation of Industry 4.0 technologies and Circular economy practices has been developed to enhance the sustainable performance of manufacturing organizations using PLS-SEM.

8.3 Research findings

The research findings are linked with the gaps identified during the literature review. The three objectives framed during the study are properly addressed by significant contributions as discussed below:

- The critical analysis of literary work was done to identify the status of sustainable manufacturing practices and TBL concepts around the world using bibliometric analysis. The study extensively reviewed sustainability indicators for all three dimensions: environmental, economic, and social. It has been observed that there is a plethora of studies available in the context of developed countries but in developing, majorly work is emphasized in the aspect of environmental and economic, with limited exploration of the social dimension. Based on past researchers' work, it can be understood that to achieve sustainability in manufacturing systems, the integration of Industry 4.0 technologies, sustainable manufacturing, and a circular economy are required. In total, sixteen hypotheses have been formulated based on literature evidence in the context of social sustainability, industry 4.0 technologies, circular economy, sustainable performance, and sustainable development goals.
- Empirically the factors that can induce social sustainability (SS) within the system are examined through a comprehensive literature review and underlying hypothesis. The structural equation model using AMOS has been formulated. The research analysis shows that community interrelation, stakeholder engagement, and consumer protection have a strong correlation and linear regression to achieve social sustainability, as discussed in Chapter 4. The research findings are significant for integrating social sustainability in business organizations. Moreover, improving the conditions of employees can prevent brain drain, form a good organizational image, improve working

conditions, and build satisfaction and loyalty among workers, employees, and stakeholders.

- An integrated concept of industry 4.0 technologies and circular economy practices was used to improve the sustainable performance of the manufacturing organization and their critical role in achieving UN SDGs. It was observed that I4.0 technologies come as pivotal for enabling circular transition in industrial firms towards transparency, visibility, increase in resource utilization, servitization, and circular design. The nexus of CE-I4.0 enhances the sustainable performance of the organization and strongly supports the sustainable development goals (1,6,7,9,11, and 12).
- A framework has been proposed for evaluating the sustainability index of a manufacturing system and gauging the industrial sustainability performance. The realistic set of indicators was explored from the literature and screened through the Delphi technique. Based on the experts` opinions and graph theory matrix approach a sustainability index score for a case organization was calculated. It was observed that employees (a sub-indicator of social sustainability), materials and energy consumption (sub-indicators of environmental sustainability), value creation, initial investment, and operating costs, and indirectly associated expenses (sub-indicators of economic sustainability) are the five most important indicators of sustainable manufacturing.

The mapping of gaps, objectives, hypotheses, and adopted research models is shown in Figure 8.1.

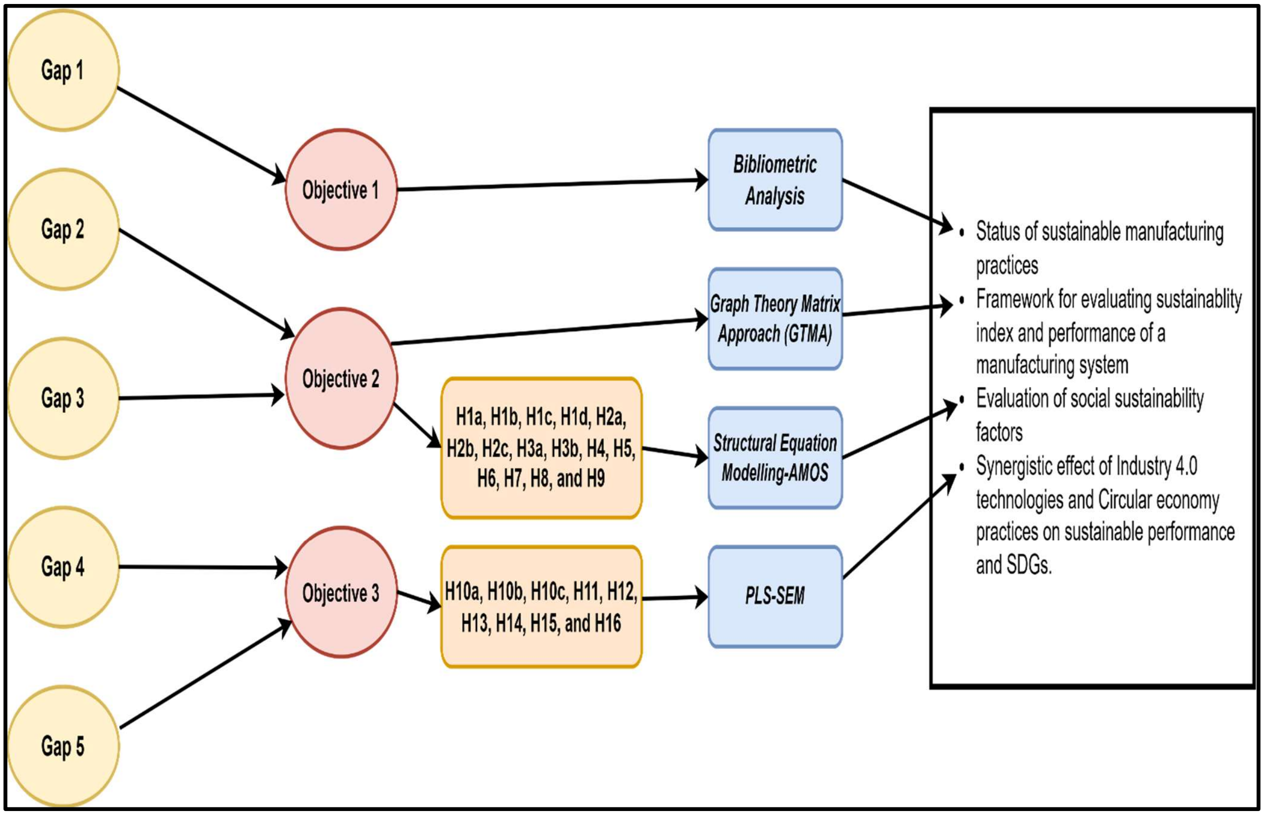

Figure 8.1: Mapping of Gaps, Objectives, and Hypotheses

8.4 Implications

This research contributes to the Indian manufacturing industry towards a better understanding of practices, indicators, and technologies for the inducement of sustainability. By the utilization of distinct research methodologies namely: questionnaire surveys; case studies; SEM-AMOS, and graph theory and matrix approach, a comprehensive set of result outcomes has been obtained from the perception of manufacturing sustainability. A framework is proposed comprised of all dimensions of the triple bottom line to gauge the sustainability index and performance of a manufacturing organization. These valuable result outcomes hold significant implications in aiding industry managers and academicians in achieving sustainability.

8.4.1 Theoretical Implications

- The questionnaire developed in this study can be utilized to conduct other empirical studies in manufacturing organizations.
- This study may lead the researchers' innovative ideas to find more unexplored areas to make the organization more socially sustainable.
- The present study analysis will assist practitioners in the adoption of industry 4.0 technologies and circular economy practices to combat the uncertainties of supply and demand and to gain market competitiveness with productivity in this technologically changing era.
- This research study will provide an opportunity for new researchers to extend the work for a peculiar digital technology and their applicability in specific firms.
- The research outcomes suggest that to gain a competitive advantage, an organization must be focused primarily on internal strengths and weaknesses, bonded by stakeholders, and motivated by legitimacy.
- This work will motivate the researchers and practitioners to explore more management theories to address sustainability indicators.
- The proposed framework can be used to determine the sustainability and other performance-related indices. GTMA and other indexing models may be applied to scale the sustainability of an organization.
- The researchers can also compare the sustainability performance of an organization with other organizations and improve the different sustainability parameters accordingly.
- The theoretical maximum and minimum values of the different sustainability indicators can be used as a benchmarking of the performed values using GTMA.

8.4.2 Managerial Implications

- The extensive literature review and its outcomes will assist the industry to find out the critical factors and their relationships to enhance the social sustainability of the organization.
- The adoption of emerging technologies like blockchain, additive manufacturing, IoT, and augmented reality & virtual reality enhances transparency, visibility, resource utilization efficiency, and organization competitiveness, and enables circular transition for industrial firms. The research outcomes will guide practitioners in choosing the best industry 4.0 technologies for their system and aligning the product in line with the concept of the circular economy.
- The identified realistic set of sustainability indicators will help managers in the decision-making process, business building, and market competitiveness, and allow them to fully commit to their use for achieving sustainability in manufacturing processes.
- The relative priority of indicators will assist industry professionals and practitioners in putting the efforts on the right path for achieving sustainability in their organizations and developing necessary strategies correspondingly.
- The use of recycling, non-hazardous materials, and renewable energy consumption should be encouraged by a higher level of management for gauging sustainability performance.
- In this dynamic competitive era, policymakers' keen aim should be on a few indicators like value enhancement for the organization, the initial investment for operations, and indirectly involved expenses for the economic growth towards sustainable development.

8.5 Limitations and Future Scope

Like any research, this study is not exempt from limitations. The limitations are mentioned in this section leading to future prospects.

- The current study relied on inputs from subjective experts. The opinions provided by the respondents may be biased or influenced by some other factors that can directly impact the final outcome of the study.
- The social sustainability factors were evaluated for a generic organization, but they may be focused on a specific industry type like construction, textile, leather, etc.
- The present study has selected six Industry 4.0 technologies (AIML, IoT, Big Data Analytics, Blockchain, Additive Manufacturing, and AR-VR) during the analysis, but a few more may also be utilized that can alter the outcomes of the study.
- The study has modelled SM indicators in the context of Indian manufacturing organizations but it may differ for other different sectors.
- The framework proposed is for a specifically selected manufacturing case organization, so it can`t be generalized for the entire manufacturing sector. Thus, a few more sectors like construction, service, textile, etc., may be considered for further analysis.
- As a part of future studies, sustainability can be also evaluated in the context of a net zero economy by considering other relevant indicators in the framework.
- Presently, the research study is focused only on the Indian manufacturing sectors, but it should be tested in the manufacturing and other sectors of developing countries like China, Thailand, Indonesia, etc.
- In this research study, a sample size of 426 responses from manufacturing organizations has been adopted. Further more extensive survey can be administered for a bigger sample size.

8.6 Conclusion

This research studied the various factors, indicators, technologies, and practices that assist in the inducement of sustainability in Indian manufacturing organizations. The demand for sustainability in manufacturing industries has been increasing promptly for a cleaner environment, low greenhouse gas emissions, and an ascent in biodiversity. The adoption of sustainable manufacturing practices will improve sustainable competitiveness. Different methodologies like structural equation modelling-analysis of moment structures (AMOS), partial least square structural equation modelling (PLS-SEM), Delphi technique, and graph theory matrix approach have been adopted to address the research gaps and formulated objectives.

The structured review of past literature with the help of the Web of Science database has been carried out to study the status and current adoption level of sustainable manufacturing in India and globally. The Bibliometrix-Biblioshiny package and VOS viewer were used to evaluate the past and future trends of SM. The review of the literature resulted in the identification of research gaps and the objectives for the present study.

Business organizations inclined towards sustainability must integrate all three dimensions: environmental, economic, and social. Based on the literature it has been found that there is a lack of social sustainability research in Indian manufacturing organization and the factors needed for the inducement of social sustainability is complex, tedious, and challenging. The present study quantitatively evaluated the sensitive social sustainability factors required for a business organization's employee and customer satisfaction and loyalty using structural equation modelling. A research model with hypotheses has been framed, and the social sustainability factors have been proposed based on an extensive literature review. The model has been validated using various statistical tools in SPSS and AMOS software. The results analysis and outcomes show that community interrelations, consumer protection, stakeholder engagement, Occupational Health and Safety, and Job Characteristics are the crucial dimensions needed to be addressed for making the organization more socially sustainable.

The technological revolution brings a lot of uncertainties in the path of organizations. The survival lies in the path of industry 4.0 technologies and the concept of circularity, bringing more flexibility, strengthening organizational capabilities, and navigating existing sustainability challenges. The present study has integrated the technologies of Industry 4.0 with practices of circular economy in improving the performance of the firm in terms of environmental, economic, and social that can compel organizations in achieving SDGs. The findings of the study will provide learning outcomes to the organizations, planning to implement digital technologies in achieving sustainability performance benefits. The research outcome also brings additional benefits, that how circular economy practices can be combined with I4.0 in achieving Agenda 2030 of UN 17 SDGs. We conclude that the nexus of I4.0 and CE holds a large number of opportunities for generating sustainable performance and contributing to SDGs.

The major contribution of the study is the development of a framework for measuring the sustainability index of the selected manufacturing case organization using the graph theory matrix approach. The realistic and critical indicators of environmental, economic, and social were identified from the literature and confirmed through experts' opinions by the Delphi technique. The result analysis shows that employees (a sub-indicator of social sustainability), materials and energy consumption (sub-indicators of environmental sustainability), value creation, initial investment, operating costs, and indirectly associated expenses (sub-indicators of economic sustainability) are the five most important indicators of sustainable manufacturing. It is observed that in developing countries like India, economic sustainability is more important than environmental and social sustainability. The difference in the importance of environmental and social sustainability is not significant.

The findings and validated model of this study can assist policymakers to enhance their understanding of sustainable manufacturing issues among Indian manufacturing organizations, leading to improved decision-making and the development of strategies for effective implementation of sustainable manufacturing practices.

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APPENDIX

QUESTIONNAIRE

Delhi Technological University, Delhi
Department of Mechanical Engineering,
Shahbad-Daulatpur, Bawana Road,
Delhi-110042

<u>Study of select issues in context to Sustainable Manufacturing System</u>

Dear Respondents,

This survey is being conducted by Deepak Sharma, Research Scholar, Delhi Technological University (DTU), Delhi, under the supervision of Dr. Pravin Kumar, Associate Professor, Department of Mechanical Engineering, DTU, Delhi and Co-supervision of Professor, Rajesh Kumar Singh, Department of Operations Management, MDI, Gurgaon.

The primary objective of this survey is to identify the importance of factors or indicators needed for the inducement of sustainability in the organization for developing a framework for sustainability assessment. Furthermore, to understand the integration of Industry 4.0 technologies and circular economy practices for the enhancement of sustainable performance and achieving sustainable development in manufacturing industries. Please provide your best opinion for all questions. Your feedback in this regard will give a significant value to this study. We request you to spare some time in responding to the enclosed questionnaire. The data will be used for statistical analysis only. It will take approximately 10 minutes to complete the survey form.
I fully understand the sacredness of the environmental topic in India and therefore assure you that the views expressed in this survey will be kept strictly confidential and will be used only for academic research.

Questionnaire is divided into following sections:

I. Demographic information
II. Industry 4.0 technologies and Circular economy practices for enhancing sustainable performance of the organization
III. Evaluation of social sustainability factors
IV. Importance of sustainable manufacturing indicators
V. Framework for evaluating sustainability index of a manufacturing system

With kind Regards

Deepak Sharma

Email: deep241087@gmail.com

SECTION I

DEMOGRAPHIC INFORMATION

Part A: Respondent information (Please Indicate)

1. Name (if you please):
2. Email address (if you please):
3. Designation:
   (a) Junior/Senior Engineer [ ]
   (b) Assistant/Deputy/Senior Manager [ ]
   (c) Assistant GM/Deputy GM/GM [ ]
   (d) CEO/COO/CTO/President/Vice President [ ]
4. Your functional area of work
   (a) Research & Development [ ]
   (b) Operations [ ]
   (c) Marketing and Sales [ ]
   (d) Finance/Purchasing [ ]
   (e) Production/Manufacturing [ ]
   (f) Logistics/Supply chain [ ]
   (g) Human Resource [ ]
   (h) Any other (Please specify) ……………………..
5. Education
   (a) Graduate [ ]
   (b) Post Graduate [ ]
   (c) Doctorate [ ]
6. Experience (in years)
   (a) <1 [ ]   (b) 1-5 [ ]   (c) 5-10 [ ]   (d) 10-15 [ ]   (e) 15-20 [ ]
   (f) ≥ 20 [ ]
7. Age (in years)
   (a) ≤30 [ ]   (b) 31-40 [ ]   (c) 41-50 [ ]   (d) 51-59 [ ]   (e) ≥ 60 [ ]

Part B: Organization information (Please Indicate)

1. Name of the Organization _______________________
2. Year of Establishment___________________________
3. Ownership (Organization)

   (a) Public Sector [ ]   (b) Indian [ ]   (c) Multinational [ ]

   (d) Others_________

4. Employees in the Organization (in number)

   (a) ≤ 1000 [ ]   (b) 1000-2500 [ ]   (c) 2500-5000 [ ]   (d) ≥ 5000 [ ]

5. Type of Manufacturing Organization

   (a) Automobile Manufacturing [ ]

   (b) Home Appliance Industries [ ]

   (c) Iron and Steel [ ]

   (d) Chemical and Industrial Fertilizer [ ]

   (e) Computer and Electronics [ ]

   (f) Textile Industries [ ]

   (g) Electronics Hardware and Component Manufacturing [ ]

   (h) Others (Pharmaceutical, Refrigeration and Air Conditioning, Cement, Plastic, and Rubber, etc.) [ ]

6. Annual turnover (in Crores)

   (a) Under 5 Cr. [ ]

   (b) 5-20 Cr. [ ]

   (c) 20-50 Cr. [ ]

   (d) 50- 100 Cr. [ ]

   (e) Over 100 Cr. [ ]

SECTION-II

Synergistic effect of Industry 4.0 Technologies and Circular Economy from the perception of Resource-based, Stakeholders`, and Dynamic Capability to achieve SDGs

Questionnaire for Survey

Please, use the mentioned rating scale and mark (√) for giving opinion:

❖ Sustainable Centric Innovative Practices

1. Industry 4.0 Technologies (I4.0 Ts)

Please mark the level of adoption of the following Industry 4.0 technologies in your company.

(1 – Very Low…………….to………………5 – Very High)

Industry 4.0 Technologies (I4.0 Ts)					
The adoption of artificial intelligence and machine learning (AIML) in the organization assists in demand forecasting and predicting purchase behavior **(I4.0 T1)**.	**1**	**2**	**3**	**4**	**5**
The adoption of the Internet of Things (IoT) in the organization assists in real-time data collection from production processes **(I4.0 T2).**	**1**	**2**	**3**	**4**	**5**
The adoption of Big data analytics (BDA) in the organization helps in new product development, supply chain traceability, and enhancing productivity **(I4.0 T3).**	**1**	**2**	**3**	**4**	**5**
The adoption of Blockchain technology in the organization assists in tracking product origins **(I4.0 T4).**	**1**	**2**	**3**	**4**	**5**
The adoption of Additive manufacturing (AM) in the organization helps in waste management and renewable & sustainable production **(I4.0 T5).**	**1**	**2**	**3**	**4**	**5**

The adoption of augmented reality and virtual reality (AR-VR) in the organization assists in enhancing industrial processes before their implementation **(I4.0 T6).**	**1**	**2**	**3**	**4**	**5**

2. Circular Economy Practices (CEP)

Please mark the level of adoption of the following circular economy practices in your company.

(1 – Very Low…………….to………………5 – Very High)

Circular Economy Practices (CEP)					
Remanufacturing of the product **(CEP1)**	**1**	**2**	**3**	**4**	**5**
Recyclability **(CEP2)**	**1**	**2**	**3**	**4**	**5**
New product design **(CEP3)**	**1**	**2**	**3**	**4**	**5**
Waste management **(CEP4)**	**1**	**2**	**3**	**4**	**5**
Reverse logistics **(CEP5)**	**1**	**2**	**3**	**4**	**5**
Cleaner production **(CEP6)**	**1**	**2**	**3**	**4**	**5**
Reduce resource exploitation **(CEP7)**	**1**	**2**	**3**	**4**	**5**
Reuse **(CEP8)**	**1**	**2**	**3**	**4**	**5**

3. Sustainable Performance of the Organization (SPO)

How do you rate the level of improvement of following sustainable performance in your organization?

(1 – Very Low…………….to………………5 – Very High)

Sustainable Performance of the Organization (SPO)					
Reduction in greenhouse gas emissions & hazardous wastes **(SPO1)**	**1**	**2**	**3**	**4**	**5**
Reduction in consumption of harmful materials **(SPO2)**	**1**	**2**	**3**	**4**	**5**
Renewable energy consumption **(SPO3)**	**1**	**2**	**3**	**4**	**5**

Eco-friendly product design **(SPO4)**	**1**	**2**	**3**	**4**	**5**
Increase in sales and productivity **(SPO5)**	**1**	**2**	**3**	**4**	**5**
Improved market competitiveness **(SPO6)**	**1**	**2**	**3**	**4**	**5**
Health and safety **(SPO7)**	**1**	**2**	**3**	**4**	**5**
Government subsidies for utilizing renewable energy **(SPO8)**	**1**	**2**	**3**	**4**	**5**
Increased in product Quality **(SPO9)**	**1**	**2**	**3**	**4**	**5**
Reduction in plant rejections **(SPO10)**	**1**	**2**	**3**	**4**	**5**
Compliance with government Labels and certificates **(SPO11)**	**1**	**2**	**3**	**4**	**5**

4. Sustainable Development Goals (SDGs)

How do you rate the level of agreement of following sustainable development goals in your organization?

(1 – Totally disagree…………….to………………5 – Totally agree)

Sustainable Development Goals (SDGs)					
SDG 1 (End Poverty) _Target-1.1, 1.2, 1.5 and 1. b	**1**	**2**	**3**	**4**	**5**
SDG 2 (End Hunger) _Targets-2.1, 2.2, and 2.3	**1**	**2**	**3**	**4**	**5**
SDG 6 (Sustainable Management of Water and Sanitation) _Targets-6.1, 6.2, 6.3, and 6.4	**1**	**2**	**3**	**4**	**5**
SDG 7 (Sustainable and Affordable energy) _Targets-7.1, 7.2, and 7.3	**1**	**2**	**3**	**4**	**5**
SDG 8 (Sustainable Economic Growth and Productive Employment) _Targets-8.2 & 8.4	**1**	**2**	**3**	**4**	**5**
SDG 9 (Sustainable Industrialization, Innovation and Resilient Infrastructure) _Targets-9.1, 9.2, 9.5, and 9.C	**1**	**2**	**3**	**4**	**5**
SDG 11 (Resilient and Sustainable Cities, and Communities) _Target-11.6 and 11. B	**1**	**2**	**3**	**4**	**5**
SDG 12 (Sustainable Consumption and Production) _Targets-12.2, 12.4, and 12.5	**1**	**2**	**3**	**4**	**5**
SDG 14 (Life below water) _Targets-14.2 and 14.3	**1**	**2**	**3**	**4**	**5**
SDG 15 (Life on Land) _Targets-15.1, 15.2, and 15.3	**1**	**2**	**3**	**4**	**5**

SECTION III

Factors affecting the social performance of an organization

Questionnaire for Survey

Please, mark (√) the importance of the following social sustainability factors for your organization on five-points rating scale.

1	2	3	4	5
Least Important	Less Important	Important	Very Important	Most Important

S. No.	Statements	Least Important	Less Important	Important	Very Important	Most Important
1	Job availability					
2	Job security					
3	Employee turnover rate					
4	Employee performance					
5	Absentee's rate of employee					
6	Equality policy					
7	Training and development					
8	Occupational risk prevention and management					
9	Career advancement					
10	Psychological risk prevention and management					
11	Legal benefit					
12	Product information					
13	Customer satisfaction					
14	Product quality					
15	Public trust					
16	Demographic aspect					
17	Technology development					
18	Human rights protection					
19	Infrastructure Development					
20	Employee feedback					
21	Customer feedback					
22	Community feedback					
23.	Quality of life					
24	Security assurance					
25.	Social well-being					

SECTION-IV

Importance of Sustainable Manufacturing Indicators

Questionnaire for Survey

Please, mark (√) the importance of the following sustainable manufacturing indicators for your organization on five-point rating scale.

1	2	3	4	5
Least Important	Less Important	Important	Very Important	Most Important

❖ Environmental Sustainability Indicators

Materials and Energy consumption (MEC)					
Recycling of used materials (MEC 1)	**1**	**2**	**3**	**4**	**5**
Consumption of recycled/refurbished materials/components (MEC 2)	**1**	**2**	**3**	**4**	**5**
Non-Hazardous materials consumption (MEC 3)	**1**	**2**	**3**	**4**	**5**
Green packaging materials (MEC 4)	**1**	**2**	**3**	**4**	**5**
Green transportation/ fuel economy and emission control (MEC 5)	**1**	**2**	**3**	**4**	**5**
Renewable energy Consumption (MEC 6)	**1**	**2**	**3**	**4**	**5**
Water consumption (WC)					
Economic water consumption (WC 1)	**1**	**2**	**3**	**4**	**5**
Water Contamination (WC 2)	**1**	**2**	**3**	**4**	**5**
Reuse and recycling of waste water (WC 3)	**1**	**2**	**3**	**4**	**5**
Environmental Factors (EF)					
Prevention of water pollution (EF 1)	**1**	**2**	**3**	**4**	**5**
Elimination of Land fill & contamination (EF 2)	**1**	**2**	**3**	**4**	**5**

Emission control (EF 3)	**1**	**2**	**3**	**4**	**5**
Global certification and control (GCC)					
Labels and certificates (ISO 14001 & ISO 9001) (GCC 1)	**1**	**2**	**3**	**4**	**5**
Green Initiatives (GCC 2)	**1**	**2**	**3**	**4**	**5**
Quality control (GCC 3)	**1**	**2**	**3**	**4**	**5**

- **Economic Sustainability Indicators**

Initial Investment & Operating Cost (IIOC)					
Wages and operating cost (IIOC 1)	**1**	**2**	**3**	**4**	**5**
Liability and Debt payment (IIOC 2)	**1**	**2**	**3**	**4**	**5**
Environmental treatment cost (IIOC 3)	**1**	**2**	**3**	**4**	**5**
Expenses on corporate social responsibility (CSR) (IIOC 4)	**1**	**2**	**3**	**4**	**5**
Sales promotion (IIOC 5)	**1**	**2**	**3**	**4**	**5**
Value Creation (VC)					
Revenue generation (VC 1)	**1**	**2**	**3**	**4**	**5**
Profit earned (VC 2)	**1**	**2**	**3**	**4**	**5**
Annual Productivity (VC 3)	**1**	**2**	**3**	**4**	**5**
New Product Design and Development (VC 4)	**1**	**2**	**3**	**4**	**5**
Market share (VC 5)	**1**	**2**	**3**	**4**	**5**
Facility expansion (VC 6)	**1**	**2**	**3**	**4**	**5**
Indirectly-Associated Expenses (IAE)					
Depreciation (IAE 1)	**1**	**2**	**3**	**4**	**5**
Maintenance (IAE 2)	**1**	**2**	**3**	**4**	**5**
Pollution control cost (IAE 3)	**1**	**2**	**3**	**4**	**5**

Investment in research and development (IAE 4)	**1**	**2**	**3**	**4**	**5**
Prevention of scrap production (IAE 5)	**1**	**2**	**3**	**4**	**5**

❖ **Social Sustainability Indicators**

Employee (EM)					
Job security and Employee retention (EM 1)	**1**	**2**	**3**	**4**	**5**
Health and Safety (EM 2)	**1**	**2**	**3**	**4**	**5**
Employee performance (EM 3)	**1**	**2**	**3**	**4**	**5**
Training and Development (EM 4)	**1**	**2**	**3**	**4**	**5**
Risk identification and employee feedback management (EM 5)	**1**	**2**	**3**	**4**	**5**
Employee satisfaction (EM 6)	**1**	**2**	**3**	**4**	**5**
Customer (CU)					
Customer satisfaction and relationship (CU 1)	**1**	**2**	**3**	**4**	**5**
Product quality (CU 2)	**1**	**2**	**3**	**4**	**5**
Customer feedback (CU 3)	**1**	**2**	**3**	**4**	**5**
Trust development (CU 4)	**1**	**2**	**3**	**4**	**5**
Community (CO)					
Social and political aspect (CO 1)	**1**	**2**	**3**	**4**	**5**
Technology development and support (CO 2)	**1**	**2**	**3**	**4**	**5**
Human rights protection (CO 3)	**1**	**2**	**3**	**4**	**5**
Community feedback (CO 4)	**1**	**2**	**3**	**4**	**5**

SECTION-V

Framework for evaluating sustainability index of a manufacturing system

Questionnaire for Delphi Study

Evaluation of the intensity of Sustainable Manufacturing Indicators based on mutual correlations

In this phase a detailed discussion with the experts' panel was done on the identified 45 indicators of sustainable manufacturing. The following questions were asked from the experts for the depicted sustainable manufacturing indicators, given below:

S.No.	Acronym	Indicators
1	EN1	Recycling of used materials
2	EN2	Consumption of recycled/refurbished materials/components
3	EN3	Non-Hazardous materials consumption
4	EN4	Economic water consumption
5	EN5	Green packaging materials
6	EN6	Green transportation/ fuel economy and emission control
7	EN7	Reuse and recycling of wastewater
8	EN8	Renewable energy Consumption
9	EN9	Elimination of landfills & contamination
10	EN10	Water Contamination
11	EN11	Prevention of water pollution
12	EN12	Green Initiatives
13	EN13	Emission control
14	EN14	Labels and certificates (ISO 14001 & ISO 9001)
15	EN15	Quality control
16	EC1	Wages and operating cost
17	EC2	Pollution control cost
18	EC3	Environmental treatment cost
19	EC4	Expenses on corporate social responsibility (CSR)
20	EC5	Sales promotion
21	EC6	Facility expansion
22	EC7	Revenue generation
23	EC8	Investment in research and development
24	EC9	Profit earned
25	EC10	Annual Productivity
26	EC11	New Product Design and Development

27	EC12	Market share
28	EC13	Liability and Debt payment
29	EC14	Depreciation
30	EC15	Maintenance
31	EC16	Prevention of scrap production
32	SC1	Job security and employee retention
33	SC2	Health and Safety
34	SC3	Human rights protection
35	SC4	Employee performance
36	SC5	Employee satisfaction
37	SC6	Training and Development
38	SC7	Risk identification and employee feedback management
39	SC8	Customer satisfaction and relationship
40	SC9	Product quality
41	SC10	Trust development
42	SC11	Customer feedback
43	SC12	Community feedback
44	SC13	The social and political aspects
45	SC14	Technology development and support

Q. 1. Kindly assess the indicators of sustainable manufacturing identified from the literature review. Does this selection of indicators can be able to implement sustainability in the Indian manufacturing organization? If not, what additional realistic indicators could be incorporated?

Q.2. Please, classify all the indicators of sustainable manufacturing into the selected 10 distinct category named as: Materials and Energy consumption, Water consumption, Environmental factors, Global certification and control, Initial Investment & Operating Cost, Value creation, Indirectly-associated expenses, Employee, Customer, and Community.

Q.3. Please assign a numerical value to the indicators for the estimation of the intensity of sustainable manufacturing indicators based on mutual correlations. The rating scale for the interdependency estimation of indicators to measure sustainability index is given below:

- Rating scale for Interdependency estimation of Indicators

Qualitative description	Relative Dependence	
	Sij	Sji = (10- Sij)
Exceptionally low influencing	0	10
Extremely low influencing	1	9
Very low influencing	2	8
Below average influencing	3	7
Average influencing	4	6
Above-average influencing	5	5
Moderate influencing	6	4
High influencing	7	3
Very high influencing	8	2
Extremely high influencing	9	1
Exceptionally high influencing	10	0

- Sample table of sustainable manufacturing indicators for interdependency estimation

			MEC1	**MEC2**	**MEC3**	**MEC4**	**MEC5**	**MEC6**
Materials and Energy consumption (MEC)	Recycling of used materials	**MEC1**						
	Consumption of recycled/ refurbished materials/components	**MEC2**						
	Non-Hazardous materials consumption	**MEC3**						
	Green packaging materials	**MEC4**						
	Green transportation/ fuel economy and emission control	**MEC5**						
	Renewable energy Consumption	**MEC6**						

LIST OF PUBLICATIONS

INTERNATIONAL JOURNAL PUBLICATIONS:

1. **Deepak Sharma**, Pravin Kumar, Rajesh Kr. Singh **(2023). "*Framework for evaluating sustainability index of a manufacturing system: A case illustration*"**, **Operations Management Research**, https://link.springer.com/article/10.1007/s12063-023-00438-0 **(SSCI Indexed, Q-1, Impact Factor: 9.0).**
2. **Deepak Sharma**, Pravin Kumar, Rajesh Kr. Singh **(2023). "*Empirical Study of Integrating Social Sustainability Factors: An Organizational Perspective*"**, Process Integration and Optimization for Sustainability, https://doi.org/10.1007/s41660-023-00330-1 **(Scopus and ESCI Indexed, Impact Factor: 2.4)**.
3. **Deepak Sharma (2021), *"Strategies for assessment and implementation of sustainable manufacturing"*** Journal of Engineering Research (JER), ICARI special issue, pp. 184-193. DOI: https://doi.org/10.36909/jer.ICARI.15267, **(SCIE Indexed, Impact Factor: 1.0)**.

WORKING PAPERS:

1. **Deepak Sharma**, Pravin Kumar, Rajesh Kr. Singh**, "*Unlocking the potential of Industry 4.0 and Circular Economy in the pursuit of SDGs*"** (Communicated).
2. **Deepak Sharma**, Pravin Kumar, Rajesh Kr. Singh, "***Coupling of Green Innovation, Organizational Learning, and Institutional Pressure for achieving Sustainable Development: Case study on Petroleum Refinery Sector***" (Communicated).

INTERNATIONAL CONFERENCES PUBLICATIONS:

1. **Deepak Sharma**, Pravin Kumar, Rajesh Kr. Singh **(2022), *"Quantifiable contribution of Sustainable Manufacturing Enablers in Indian SMEs"*,** Lecture Notes in Mechanical Engineering, book series (LNME), Springer, Singapore, pp 123-135.
2. **Deepak Sharma**, Pravin Kumar, Rajesh Kr. Singh **(2021), *"Modelling interrelationships of Sustainable manufacturing barriers by using interpretive structural modelling"*,** Lecture Notes in Mechanical Engineering, book series (LNME), Springer, Singapore, pp 211-218.

BRIEF PROFILE OF THE CANDIDATE

Deepak Sharma

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Date of Birth: 24th August 1988
Present Address: House No -505, Sector -55, Faridabad (121004), Haryana.

Education

1. **Pursuing Ph.D. from Delhi Technological University (Formerly Delhi College of Engineering) since July 2016.**
   Course Work: I did my course work with the SGPA of **9.38**
   Ph.D. Topic: Study of select issues in context to Sustainable Manufacturing Systems.

2. **Master of Technology (M. Tech), 2010 - 12**
   Maharshi Dayanand University, Rohtak, India
   Manufacturing Technology & Automation – **75%**
   M.Tech project on *"The Effects of Heat Treatment Processes on Mechanical properties & Microstructures of alloy steel EN24".*

3. **Bachelor of Technology (B. Tech), 2005 - 09**
   Doon Valley Institute of Engineering & Technology, Karnal (Kurukshetra University) Haryana, India.
   Mechanical Engineering - **68 %**

Experience

1. **Teaching/Research**
   - **Feb 2017 to Till Now:** Working as an "Assistant Professor" in the Department of Mechanical Engineering at GLA University Mathura, Uttar Pradesh, India.
   - **July 2012 to Jan 2017:** Worked as an "Assistant Professor" in Rawal Institute of Engineering & Technology, **Faridabad**, in Department of Mechanical Engineering, Haryana, India.

2. **Industry**
   - **Production Engineer (10thAugust09 – 7thAug10), PSL LIMITED, GANDHIDHAM (GUJARAT), ISO 14001- 2004**.

Patents (02)

- **April 2020:** Title: **"Medi-Ambulance", Application No: 202011015677**, Date of Filing: April 10, 2020.
- **December 2019**: Title: **"Smart Bird"** (Smart Bike), **Application No: 201911052365**, Date of Filing: **December 17, 2019.** This Patent has been **granted on 29th Jan 2021** for the term **of 20 years** with **Patent No: 357023.**

Funded Project (02)

- **January 2022:** Received funds of **Rs 1.95 Lacs**, for making **"Portable Plastic Recyclable Machine"** under the scheme of NewGen IEDC, form NSTEDB - DST Govt. of India, implemented by EDII, Ahmedabad.
- **December 2020:** Received fund of **Rs 1.0 Lacs**, for making the project of **"Medi-Ambulance"** under the scheme of NewGen IEDC, form NSTEDB - DST Govt. of India, implemented by EDII, Ahmedabad.
- **January 2019:** Received fund of **Rs 1.6 Lacs**, for making the project of **"Smart Bird" (Hybrid Bike)** under the scheme of NewGen IEDC, form NSTEDB - DST Govt. of India, implemented by EDII, Ahmedabad.

Research Publications

More than 15 papers published in various National and International Journals and Conference proceedings