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Framework for evaluating sustainability index of a manufacturing system: a case illustration

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Abstract
A traditional manufacturing system leads to 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 frameworks. Therefore, relying on the concepts of stakeholder theory, resource-based theory, and institutional theory, this study has proposed a framework to evaluate the sustainability index. There are two aspects of the study: one is to explore the indicators of sustainability considering all dimensions of the triple-bottom-line and validation through a questionnaire survey, and another is prioritization and indexing of the sustainability performance using the Delphi method and Graph Theory Matrix Approach (GTMA). Finally, forty-five indicators have been considered for this study. The GTMA-based framework is proposed for evaluating the sustainability index. Its application is illustrated in the context of an Indian manufacturing organization. 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. This study will assist the concerned professionals in gauging their industrial sustainability performance.

Keywords Sustainable manufacturing systems · Triple bottom line · Structural equation modelling · GTMA · Sustainability index

1 Introduction

Manufacturing organizations have been perceived as a strong pillar in strengthening the nation's economy by generating employment and enhancing gross domestic product (GDP) for many years (Virmani et al. 2021). Globally, it acts as a driving force for economic building and social progress. But, it is accompanied by high consumption of materials and energy with rapid depletion of natural resources (Wang and Yang 2021). The manufacturing sector is facing a few sustainability challenges like greenhouse gas emissions, global warming, and a decline in biodiversity (Aktaş and Demirel 2021; Agrawal et al. 2023). 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 the 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). Therefore, 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).

With the same objective, Apple and Dell have adopted a refurbishing policy for their electronic products to minimize

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toxic seepage through buried solid wastes. In Wiesbaden, the first electric bus named 'eCitaro' was introduced by Mercedes as a 'Sustainable Bus' operated on solid-state batteries. Recently, Iceland has developed a concept of carbon capture and storage (CCS) which involves capturing and separating CO_2 from other gases, transporting it deep underground, and turning it into stone. The above-discussed examples give an insight into adopted SM practices as the key step of survival for these organizations and are considered a viable production approach (Ahmad and Wong 2018). The robustness of SM practices can empower organizations to stand out in a competitive market (Eslami et al. 2019). The harmful impact on human health and safety leading to quality of life can easily be eliminated including sustainable practices in product and process development,(Singh et al. 2019). SM operations also enhance the productivity, profitability of firms, and the upcoming opportunities for new product development and market expansion (Brones et al. 2014).

In developing nations, the diffusion of SM practices is relatively very 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, practically applicable sustainability indicators (Jamwal et al. 2021). Sustainability indicators (SI) assist 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 didn`t pay equal attention to environmental and social aspects with economic (Henao and Sarache 2022). Some researchers highlighted that stakeholder pressure can affect the behaviour 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, resulting in improved financial and operational performance. Baah et al. (2021) proposed that developing institutional pressure (coercive, mimetic, and normative) can motivate manufacturing organizations towards the implementation of sustainability practices. 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.

Previous research studies reveal an imbalance in the application of TBL within the manufacturing sector and give unequal emphasis on the economic and environmental aspects, while the social is comparatively neglected (Yip et al. 2023). Based on the availability of literature, indicators that are used in industries are purely generic, not viable concerning activities and size, and not so fully matured to monitor specific manufacturers (Wilson et al. 2007). Consequently, it becomes difficult to gauge the sustainability performance of an organization. The deficit of practical application and quantifiable indicators is responsible for discouragement among practitioners for not undertaking their sustainability assessment. The selection of the indicators should be able to evaluate all critical parameters (product, process & policy) considering three facets of sustainability (*viz.*, environmental, economic, and social). Based on the literature review, the following research gaps were observed:

- Limited research papers are available on a balanced assessment of SM practices with three-dimensional synchronization of the environmental, social, and economic controls (Jamwal et al. 2021; Yip et al. 2023).
- The notable imbalance between the management theories and practical approach to the SM concept has held back the adoption strategies of execution of SM systems in manufacturing organizations (Sabat et al. 2022).

To guide manufacturing organizations toward the adoption & connection of theoretical aspects with a practical paradigm of SM practices, this study addresses the following research questions (RQs):

RQ1: What are the indicators influencing the sustainability of manufacturing sector?
RQ2: How to compare the importance of sustainability indicators?
RQ3: How to prepare the sustainability index of an organization?

To answer the aforementioned questions, this research study explored the indicators of sustainability through a literature review and categorized them using factor analysis. The sustainability index is produced using GTMA to measure the sustainability of manufacturing organizations. All the indicators were rated on a five-point rating scale by the respondents and factor analysis has been used to make the cluster of indicators. All the clusters of sustainability indicators were indexed with the help of factor loadings of the indicators and GTMA. The indices for different clusters show their relative importance. The overall sustainability index of an organization has been calculated considering the indices of different clusters of the indicators. This study is based on the integrated concept of stakeholder theory (ST), resource-based theory (RBT), and Institutional Theory (IT). The theoretical concept of these theories has been pivotal in shaping the understanding of the organization for the combination of external and internal factors for achieving sustainable development. Many studies mentioned the adoption of the Resource-based view and institutional theory combination for better comprehension of organizational strategies (Peng et al. 2009; Sabat et al. 2022). The novel contribution of this study is given below:

(i) The combined theory of ST, RBT, and IT is utilized for the selection of SM indicators and for developing a framework for achieving sustainability in manufacturing organizations.
(ii) 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.
(iii) 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.

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 remaining part of this study is outlined as follows: Section 2 represents the literature review of SM indicators considering the triple-bottom-line perspective. Section 3 describes the research methodology framework. Section 4 represents the data analysis and its results. Section 5 represents the discussion and managerial/practitioners and academic implications. Section 6 provides the conclusions of the study with its limitations and the future scope.

2 Literature review

The Manufacturing sector is characterized by high energy consumption, waste generation, and greenhouse gas emissions, creating a void, that necessitates a shift toward energy-efficient SM practices (Cai et al. 2022). In view of organizations` quest for sustainable development, the prominent role of the manufacturing sector is widely acknowledged. In recent years, the manufacturing sector has seen a rising emphasis on sustainability. To effectively embrace sustainability, manufacturers encourage SM practices to maintain economic advantage with minimal impact on the environment and society (Huang and Badurdeen 2017). Sarkis et al. (2010) specified in their study that pressure from organizational stakeholders, including customers, employees, suppliers, and shareholders, plays a significant role in driving firms to adopt and implement proactive green production practices. This research work proposed a framework for evaluating the sustainability index of a manufacturing organization with the help of a case study.

Limited literature exists on the assessment and determination of the environmental and social impacts of production (Ahmad et al. 2019; Wu and Su 2020). However, the taxonomy of sustainability metrics and industrial units lacks uniformity. This necessitates the adoption of relevant measures and indicators for achieving the objectives of sustainable production processes and products (Chaim et al. 2018). Amidst a vast pool of indicators, it becomes tedious to define and implement comprehensive, standardized, and usable SM indicators (Singh et al. 2007). Therefore, the identification, categorization, and assessment of an exhaustive list of indicators are highly desirable for modelling manufacturing sustainability (Park and Kremer 2017; Bui et al. 2017; Sikdar 2019). A distinct set of indicators has been utilized and proposed by various researchers, because of diversity in the manufacturing sector (Gani et al. 2022). In this study, we initially identified fifty-two sustainability indicators through an extensive literature review, as shown in Table 1. After the questionnaire survey and the experts' opinions, seven indicators (volatile organic compounds, tool materials, particulate suspended matter, turnover, payback period, personal protective equipment, and workload) were removed. Insights from industry experts indicated, that these seven indicators are not significant for enhancing the sustainability of manufacturing organizations. ‘Volatile organic compounds’ and ‘particulate suspended matter’ are mostly significant in chemical industries. ‘Turnover’ and ‘payback period’ are related to management financial strategies and are not much influencive to economic sustainability. ‘Personal protective equipment’ and ‘workload’ have already been considered indirectly under the social sustainability indicators. The rest 45 indicators utilized in this study are presented in Table 2.

2.1 Literature search

In this study, a detailed literature review has been conducted to evaluate the status of sustainability in the manufacturing sector. The process involves the review of past literature with appropriate search keywords, properly selected databases, and filtering the search database to access the most relevant research articles available (Rizvi et al. 2023). This research work follows processes for the data collection, thematic

Table 1 Sustainability indicators

	Acronym	Indicators	References
Environmental Sustainability	EN1	Recycling of used materials	Sala (2020), Beng and Omar (2014), Bonvoisin et al. (2014), Pinto et al. (2020)
	EN2	Consumption of recycled/refurbished materials/components	Sala (2020), Bonvoisin et al. (2014), Peralta Álvarez et al. (2017), Feil et al. (2019)
	EN3	Non-Hazardous materials consumption	Sala (2020), Eastwood and Haapala (2015), Feil et al. (2019), Hegab et al. (2023)
	EN4	Economic water consumption	Chaim et al. (2018), Razmjoo et al. (2020), Sharma (2021), Hegab et al. (2023)
	EN5	Green packaging materials	Bereketli and Erol Genevois (2013), Jin et al. (2017)
	EN6	Green transportation/ fuel economy and emission control	Badurdeen and Jawahir (2017), Feil et al. (2019), Sangwan et al. (2018)
	EN7	Reuse and recycling of wastewater	Sala (2020), Razmjoo et al. (2020), Pinto et al. (2020), Sharma (2021)
	EN8	Renewable energy Consumption	Cobut et al. (2015), Sharma (2021), Feil et al. (2019), Ahmad et al. (2019)
	EN9	Elimination of landfills & contamination	Sala (2020), Chaim et al. (2018), Pinto et al. (2020), Feil et al. (2019)
	EN10	Water Contamination	Sala (2020), Akbar and Irohara (2018), Razmjoo et al. (2020)
	EN11	Prevention of water pollution	Razmjoo et al. (2020), Pinto et al. (2020), Feil et al. (2019), Ahmad et al. (2019)
	EN12	Green Initiatives	Bracke et al. (2017), Moktadir et al. (2018)
	EN13	Emission control	Akbar and Irohara (2018), Eastwood and Haapala (2015), Pinto et al. (2020)
	EN14	Volatile organic compounds	Samuel et al. (2013), Ahmad et al. (2019)
	EN15	Labels and certificates (ISO 14001 & ISO 9001)	Beng and Omar (2014), Ghobadian et al. (2020), Urbaniak et al. (2022), Hegab et al. (2023)
	EN16	Quality control	Beng and Omar (2014), Moktadir et al. (2018)
	EN17	Materials of tools	Zhang and Haapala, (2015), Ahmad et al. (2019)
	EN18	Particulate suspended matters	Ahmad et al. (2019)
Economic Sustainability	EC1	Wages and operating cost	Ghobadian et al. (2020), Moktadir et al. (2018), Sharma (2021)
	EC2	Pollution control cost	Kim et al. (2013), Feil et al. (2019), Ahmad et al. (2019)
	EC3	Environmental treatment cost	Kim et al. (2013), Feil et al. (2019), Ahmad et al. (2019)
	EC4	Expenses on corporate social responsibility (CSR)	Badurdeen and Jawahir (2017), Moktadir et al. (2018), Sharma (2021)

Table 1 (continued)

	Acronym	Indicators	References
	EC5	Sales promotion	Borchardt et al. (2011), Feil et al. (2019), Ahmad et al. (2019)
	EC6	Facility expansion	Badurdeen and Jawahir (2017), Ocampo et al. (2016), Ahmad et al. (2019)
	EC7	Revenue generation	Feil et al. (2019), Ahmad et al. (2019), Sharma (2021)
	EC8	Investment in research and development	Butnariu and Avasilcai (2015), Feil et al. (2019), Ahmad et al. (2019)
	EC9	Profit earned	Butnariu and Avasilcai (2015), Ocampo et al. (2016), Feil et al. (2019)
	EC10	Annual Productivity	Feil et al. (2019)
	EC11	New Product Design and Development	Butnariu and Avasilcai (2015), Ahmad et al. (2019)
	EC12	Market share	Borchardt et al. (2011), Feil et al. (2019)
	EC13	Liability and Debt payment	(Singh et al. 2009), Sharma (2021)
	EC14	Depreciation	Feil et al. (2019), Ahmad et al. (2019)
	EC15	Maintenance	Kim et al. (2013), Ahmad et al. (2019)
	EC16	Prevention of scrap production	Kim et al. (2013), Ahmad et al. (2019)
	EC17	Turnover (selling inventory)	Butnariu and Avasilcai (2015), Ahmad et al. (2019)
	EC18	Payback period	Ahmad et al. (2019)
Social Sustainability	SC1	Job security and employee retention	Chaim et al. (2018), Ahmad et al. (2019), Sharma (2021)
	SC2	Health and Safety	Feil et al. (2019), Ahmad et al. (2019), Peruzzini et al. (2017)
	SC3	Human rights protection	Chaim et al. (2018), Holm (2018), Ahmad et al. (2019), Peruzzini et al. (2017), Sharma (2021)
	SC4	Employee performance	Bortolotti et al. (2015), Holm (2018), Sharma (2021)
	SC5	Employee satisfaction	Ocampo et al. (2016), Feil et al. (2019), Ahmad et al. (2019)
	SC6	Training and Development	Chaim et al. (2018), Holm (2018), Ahmad et al. (2019), Sharma (2021)
	SC7	Risk identification and employee feedback management	Badurdeen and Jawahir (2017), Chaim et al. (2018), Moreira et al. (2018)
	SC8	Customer satisfaction and relationship	Ghobadian et al. (2020), Feil et al. (2019), Ahmad et al. (2019), Sharma (2021)

Table 1 (continued)

Acronym	Indicators	References
SC9	Product quality	Chaim et al. (2018), Moktadir et al. (2018), Sharma (2021)
SC10	Trust development	Gebisa and Lemu (2017), Ahmad et al. (2019)
SC11	Customer feedback	Chaim et al. (2018), Ahmad et al. (2019), Sharma (2021)
SC12	Personal protective equipment	Ahmad et al. (2019)
SC13	Community feedback	Chaim et al. (2018), Peralta Álvarez et al. (2017), Sharma (2021)
SC14	The social and political aspects	Chaim et al. (2018), Holm (2018)
SC15	Technology development and support	Chaim et al. (2018), Ahmad et al. (2019), Peruzzini et al. (2017), Sharma (2021)
SC16	Work load	Zhang and Haapala (2015), Peruzzini et al. (2017), Ahmad et al. (2019)

evaluation focused on depicting concerned published papers, and segregation for identifying the most relevant sustainability indicators from the perspective of the manufacturing sector. The detailed literature review revealed that the sustainability aspects of manufacturing systems are mostly assessed by three main indicators, which are termed environmental, social, and economic (Akbar and Irohara 2018). The theoretical structure of the study and the three different clusters of sustainability indicators are reviewed subsequently.

2.2 Theoretical foundation

Predominantly, the performance measuring framework for an SM system is multifaceted. Organizations aiming to transform their system should combine external and internal factors to attain sustainable development and enhance the firm's performance. In an organization, resources cannot be combined independently, they need some form of temporary commitment by a governing entity (Stout 2012). McGahan (2021) stated that "stakeholders bind resources". Stakeholder theory views resource development in the organization from two aspects, one is the development of human capital, and the second is the interaction between customers, communities, investors, and government, leading to sustainability. The resource-based theory leads to the utilization of the resources developed using the stakeholder theory. The institutional theory puts pressure on the management to fulfill the various parameters of environmental, social, and economic sustainability. To fulfill these needs, resources are required and effectively utilized. Consequently, these three theories are collectively utilized to enhance the capacity of the organization to fulfill the sustainability criteria. In the past, various research studies have employed an integrated theoretical framework to promote sustainable development and address issues related to environmental degradation and climate change. Horbach et al. (2023) utilized the concepts of three theoretical theories namely ST, IT, and resource-based view to identify the antecedents of firms` greenness. Ozdemir et al. (2023) applied ST, RBT, and the knowledge-based view theory to promote innovation collaboration in a Spanish technological panel industry, emphasizing the effectiveness of resource utilization through collaborations with multiple stakeholders. Ijaz Baig and Yadegaridehkordi (2023) employ RBT, ST, and TBL theory as a foundation for assessing the sustainable performance of a Malaysian manufacturing enterprise. They underscored the positive impact of organizational capabilities, stakeholder pressure, and green orientation and marketing on organizational sustainability. The adopted theoretical lenses for this study have been sequentially elucidated.

The stakeholder theory 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 of '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 lack 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.

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 the 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 production system is a well-thought example of an internal resource with inference for economic, and environmental performance. The logical thought is that the waste generation, emissions, and other environmental impacts are simply indications of an inefficient production system. The firm can reduce the cost by diminishing those environmental footprints.

Institutional theory (IT), 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 elaborating 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 (León-Bravo et al. 2019; Khurshid et al. 2021).

The integrated theoretical framework based on the application of ST, RBT, and IT is depicted in Fig. 1.

2.3 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).

2.4 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.

2.5 Social sustainability indicators

The National Institute of Standards and Technology (NIST) has identified that manufacturing activities and products can pose challenges to the social dimension of sustainability, which encompasses the well-being of employees, customers, and communities (Kibira et al. 2018). Social indicators, such as the health & safety of both employees and customers, have been employed to assess the societal impacts of various manufacturing processes and products (Chaim et al. 2018). SM expects a workplace that is sustainable and promote an empowered, informed, and willing workforce, despite of factors like age, gender, abilities, and individual growth in light of a diminishing recruiting pool (Gebisa and Lemu 2017). Fundamental principles like equality, empowerment, inclusion, engagement, sharing, cultural identity, and institutional cohesion form the foundation of social sustainability (Henao et al. 2017). Diversity, Equity, and Inclusion (DEI) related perspectives are considered under the dimension of Human rights protection. 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 individuals (Holm 2018). These proactive visions are vital for the potential growth of the industries, not only to ensure demographic continuity and meet employee requirements but also to promote work-life balance, and the welfare of all stakeholders. Moreover, they rely on enhancing customer satisfaction and community relations through effective feedback mechanisms (Zhou et al. 2016).

Manufacturing industries can boost productivity and sustainability, gaining a competitive edge by incorporating human resource management aspects, such as training, employee engagement, skill development, rewards, incentives, and commitment (Muduli et al. 2020). A healthy workplace, proper training, risk identification, feedback mechanism, financial support, suitable working hours, and medico-legal benefits promote employee satisfaction and their ability to perform effectively (Reiman and Pietikäinen 2010). Employee satisfaction plays a key role in improving the productivity of manufacturing organizations considering aspects like organizational culture, work environment, equality policies, and the provision 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) serve as a guiding source for a company`s growth (Moreira et al. 2018). In a broader context, stakeholders such as customers, employees, the public, suppliers, and shareholders can exert various forms of institutional pressure - mimetic, coercive, and normative pressure to influence firms to adopt sustainable practices.

The major works done on all three dimensions of sustainability in manufacturing systems are summarized in Table 1.

3 Research methodology

The identification, categorization, and evaluation of SM indicators were executed in three phases. At first, the most adequate, and leading indicators of SM were explored and incorporated through an exhaustive literature review. The depicted indicators were then assessed through the administration of a questionnaire, whose content was validated by academic and industrial experts. We have approached 15 experts from both industry and academia for the pilot study. Out of this group, only two industry experts and three academics have expressed their interest in taking part in our questionnaire survey and interview. Both the industrial experts are having an average experience of 10 years, one serves as a General Manager in production, while the other holds the position of Deputy General Manager in the Research & Development Department. As for the academic experts, two are esteemed professors with a research focus on the renewable energy sector, while the third member is an Associate Professor with expertise in non-conventional manufacturing processes. These experts meticulously evaluated and confirmed the validity and acceptability of our proposed scale. The response data collected was initially subjected to scrutiny based on mean values, leading us to select only those factors whose mean values exceeded the threshold of 3.

In the second phase, the scrutinized 45 sustainability indicators were categorized, i.e., 15-environmental, 16-economic, and 14-social into 10-subgroups using exploratory factor analysis (EFA), with subsequent validation via confirmatory factor analysis (CFA). The nomenclature assigned to these 10 subgroups was influenced by the defining characteristics of the factors lying in that corresponding group. The third and final phase involves a detailed discussion with the experts' panel, utilizing the Delphi technique. This phase facilitated pairwise comparisons of the indicators across all 10 subgroups, leading to a sustainability index tailored for manufacturing organizations using GTMA.

To ensure minimum ambiguity among expert opinions, the following selection criteria were considered:

- Experts should have substantial experience within 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. The process flow chart of the research methodology is shown in Fig. 2.

3.1 Questionnaire administration and data collection

A questionnaire was prepared in consultation with academic experts and professionals/practitioners from the manufacturing sector for data collection. The questionnaire comprised 52 distinct indicators. These indicators were systematically assessed using a 5-Point-Likert scale, wherein a score of 5 indicates strongly agree and a score of 1 indicates strongly disagree. The questionnaire was communicated among manufacturing firms operating in the northern region of India. To ensure accuracy and effectiveness, data has been collected across different age groups, distinct experienced professionals, and varying academic qualifications. In total, we received 444 completed responses, while 12 responses were found to be incomplete and were consequently excluded from our analysis. The demographic characteristics of the respondents are shown in Table A1 (Appendix).

3.2 Data reliability/validation

The data collected through the questionnaire survey was initially analyzed based on mean values, because of a large number of indicators. The indicators whose mean values come out to be less than 3, as per the descriptive analysis of the respondent data, were ignored from further consideration, shown in Table A2 (Appendix). The less mean value (<3) indicators (volatile organic compounds, tool materials, particulate suspended matter, turnover, payback period, personal protective equipment, and workload) were also discussed with the experts, and they suggested to overlook them for further analysis. The remaining set of 45 indicators was then validated using Bartlett's test of sphericity, also known as the correlation test, and Kaiser-Meyer-Olkin (KMO) analysis to check the adequacy of the sample. The KMO value greater than 0.6 and the significance level value less than 0.05 signified that factor analysis could be applied to the given data set (Kumar et al. 2021a). Furthermore, the reliability of the dataset was assessed through the Cronbach alpha test, which measures the internal consistency of the data. A Cronbach Alpha value equal to or greater than 0.7 is considered indicative of high reliability (Agrawal et al. 2017).

Using EFA, the SM indicators were categorized into the respective groups/criteria based on common patterns, nature, and similarities (Mittal and Sangwan 2014). The factor analysis technique has been widely used for data minimization, development of scale measurement, and sorting. EFA encompasses three segments; factor extraction, rotation, and interpretation (Thompson 2004). Factor interpretation is executed to calculate underlying factors that completely explain the observed correlation among the indicators (Williams et al. 2010).

3.2.1 Confirmatory factor analysis

CFA is performed for the detailed quantification of principal latent variable structure, and to validate the results obtained during EFA. The principal aim of CFA is to check the unidimensionality aspects of the data (Mittal and Sangwan 2014). CFA is employed to verify the structure of the factors and to compute the covariance weights between latent factors (identified from EFA) and their variables. The formulated model is validated in terms of statistical measures for checking its goodness of fit, shown in Table A3 (Appendix).

3.2.2 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 pairwise 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 (Kek and Gurumurthy 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:

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

Matrices are formulated on a rating scale of 0-10 (shown in Table A4, Appendix) to define the relative importance of indicators using experts' opinions.

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 3 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 Fig. 3. 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. Correspondingly, the IPM of the remaining dimensions can be formulated. The overall interaction among SM indicators, i.e., environmental (I1), economic (I2), and social (I3). The IPM of the SM system represents the resultant value of sustainability for an organization, computed as:

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

4 Data analysis and results

The results of the study are analyzed and discussed in the succeeding two sub-sections. The first sub-section covers the exploratory and CFA of SM indicators, and the second sub-section discusses the outcomes of GTMA.

4.1 Exploratory factor analysis and confirmatory factor analysis

In this study, the responses of considered forty-five (45) SM indicators whose mean values are greater than 3, were analyzed through EFA for estimating their dimensionality, and to frame the factorial structure of GTMA. The construct`s reliability test was conducted using Cronbach's alpha. The calculated value of Cronbach alpha was 0.917 which is considered a good indicator of reliability, i.e. greater than the threshold of 0.7 (Vinodh and Joy 2012). Further Kaiser-Meyer-Olkin's (KMO) assessment of sampling adequacy is 0.857 which is more than the recommended level of 0.80 (Kaiser 1970). Bartlett's test of sphericity ($p < 0.01$) calculates the overall correlation among the indicators (Lučić 2020). The KMO and Bartlett`s test results are shown in Table A5 (Appendix) with acceptable values.

In this study, we successfully grouped the 45 indicators into 10 latent factors, consisting of 4 latent factors for environmental sustainability (EN), 3 for economic sustainability (EC), and 3 for social sustainability (SC) by factor analysis as presented in Table 2. These ten latent factors were formulated based on eigenvalues exceeding one and collectively explained 69.44% of the total variance. Notably, the first group contributed 22.87 % to the total variance, while the subsequent latent factors contributed as follows: the second (8.80%), the third (7.67%), the fourth (6.74%), the fifth (5.27%), the sixth (5.02%), the seventh (4.27%), the eighth (4.00%), the ninth (2.54%), and the tenth (2.26%). All 45 indicators were meticulously categorized with their corresponding labeled rotated factor loadings and Cronbach`s alpha value exceeding 0.7. Table 2 shows that the internal consistency among the indicators under each dimension (environmental, economic, and social) was strong, with reliability ratings of more than 0.67 for all factors (Thorndike 1995).

CFA is used to confirm the loadings of the identified indicators and assess the relationships between individual criteria. EFA alone can`t be adequate for getting all the requisite constructs (Pathak et al. 2020). In this study, CFA was run on the assessment model comprising ten factors, composed of sustainability indicators for an SM system. This analysis was employed in gauging the validity of the developed structure, testing construct validity, assessing discriminant validity, and evaluating the goodness of fit of the model. The outcomes pertaining to the goodness of fit measures are shown in Table A6 (Appendix), indicating their alignment with acceptable values.

The Chi-square ($\chi 2$) test provides evidence that a CMIN/DF value closer to zero signifies a good fit (Thompson 2004). In our developed structure, the CMIN/DF value stands at 2.715, falling within the acceptable threshold of 3. The value of RMSEA is 0.062, which is within the acceptable limit of 0.1. The standardized RMR (root mean square residual) is .0460, which is calculated by the square root of the variation between the model and sample covariance matrices (Coughlan et al. 2008). RMSR value less than 0.14 is considered allowable. The developed model has a Goodness of fit Index (GFI) = 0.817, comparative fit index (CFI) = 0.871, parsimony comparative fit index (PCFI) = 0.792, and PGFI (Parsimony Goodness of Fit Index) = 0.710. Importantly, all these calculated values fall within the approved threshold limits (Bentler 1990; Hair 2014).

We also calculated the average variance extracted (AVE) for each latent factor, all of which exceeded 0.50, surpassing the recommended threshold (shown in Table 2) and showing adequate convergence (Fornell and Larcker 1981). To further validate the constructs, we determined the composite reliability (CR) for each factor, with values consistently exceeding 0.7, indicating statistical significance. The CFA diagram, generated using AMOS 23.0, illustrates ten factors/criteria with a total of forty-five indicators, as depicted in Fig. 4. We also checked and determined discriminant validity for the constructs, presented in Table A7 (Appendix). Discriminant validity reveals that indicators should be more strongly related to their latent factor than to others (Fornell and Larcker 1981). As a consequence of the above discussions and the results from Table 2, A6, A7, and Fig. 4, we have successfully classified and confirmed in total ten factors; four from environmental sustainability, named as material and energy consumption, water consumption, environmental factor, and global certification and control; three from economic sustainability, namely, initial investment & operating cost, value creation, indirectly-associated expenses; and lastly three from social sustainability, named employees, customers, and the community.

4.2 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 headquarters 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

Table 2 EFA and CFA results of SM indicators

			Factor Loadings												
			Environmental sustainability				**Economic sustainability**			**Social sustainability**			Cronbach Alpha	AVE	CR
Sub Category	**Indicators**	**Notation**	**$I1_1$ (MEC)**	**$I1_2$ (WC)**	**$I1_3$ (EF)**	**$I1_4$ (GCC)**	**$I2_1$ (IIOC)**	**$I2_2$ (VC)**	**$I2_3$ (IAE)**	**$I3_1$ (EM)**	**$I3_2$ (CU)**	**$I3_3$ (CO)**			
Materials and Energy consumption (MEC)	EN1	$I1_1^1$	0.714										0.858	0.502	0.858
	EN2	$I1_1^2$	0.683												
	EN3	$I1_1^3$	0.693												
	EN5	$I1_1^4$	0.735												
	EN6	$I1_1^5$	0.706												
	EN8	$I1_1^6$	0.779												
Water consumption (WC)	EN4	$I1_2^1$		0.735									0.913	0.782	0.915
	EN10	$I1_2^2$		0.724											
	EN7	$I1_2^3$		0.749											
Environmental Factors (EF)	EN11	$I1_3^1$			0.862								0.854	0.663	0.855
	EN9	$I1_3^2$			0.854										
	EN13	$I1_3^3$			0.855										
Global Certification and Control (GCC)	EN15	$I1_4^1$				0.670							0.793	0.562	0.794
	EN12	$I1_4^2$				0.741									
	EN16	$I1_4^3$				0.701									
Initial Investment & Operating Cost (IIOC)	EC1	$I2_1^1$					0.830								
	EC13	$I2_1^2$					0.722						0.831	0.502	0.834
	EC3	$I2_1^3$					0.723								
	EC4	$I2_1^4$					0.738								
	EC5	$I2_1^5$					0.693								
Value Creation (VC)	EC7	$I2_2^1$						0.821					0.916	0.643	0.914
	EC9	$I2_2^2$						0.832							
	EC10	$I2_2^3$						0.791							
	EC11	$I2_2^4$						0.720							
	EC12	$I2_2^5$						0.778							
	EC6	$I2_2^6$						0.765							
Indirectly-Associated Expenses (IAE)	EC14	$I2_3^1$							0.774				0.860	0.561	0.863
	EC15	$I2_3^2$							0.746						
	EC2	$I2_3^3$							0.775						
	EC8	$I2_3^4$							0.772						
	EC16	$I2_3^5$							0.756						

Table 2 (continued)

			Factor Loadings												
			Environmental sustainability				Economic sustainability			Social sustainability			Cronbach Alpha	AVE	CR
Sub Category	**Indicators**	**Notation**	**$I1_1$ (MEC)**	**$I1_2$ (WC)**	**$I1_3$ (EF)**	**$I1_4$ (GCC)**	**$I2_1$ (IIOC)**	**$I2_2$ (VC)**	**$I2_3$ (IAE)**	**$I3_1$ (EM)**	**$I3_2$ (CU)**	**$I3_3$ (CO)**			
Employees (EM)	SC1	$I3_1^1$								0.829			0.890	0.576	0.890
	SC2	$I3_1^2$								0.771					
	SC4	$I3_1^3$								0.737					
	SC6	$I3_1^4$								0.829					
	SC7	$I3_1^5$								0.835					
	SC5	$I3_1^6$								0.702					
Customers (CU)	SC8	$I3_2^1$									0.795		0.837	0.563	0.837
	SC9	$I3_2^2$									0.776				
	SC11	$I3_2^3$									0.778				
	SC10	$I3_2^4$									0.746				
Community (CO)	SC14	$I3_3^1$										0.859	0.879	0.651	0.882
	SC15	$I3_3^2$										0.812			
	SC3	$I3_3^3$										0.833			
	SC13	$I3_3^4$										0.784			

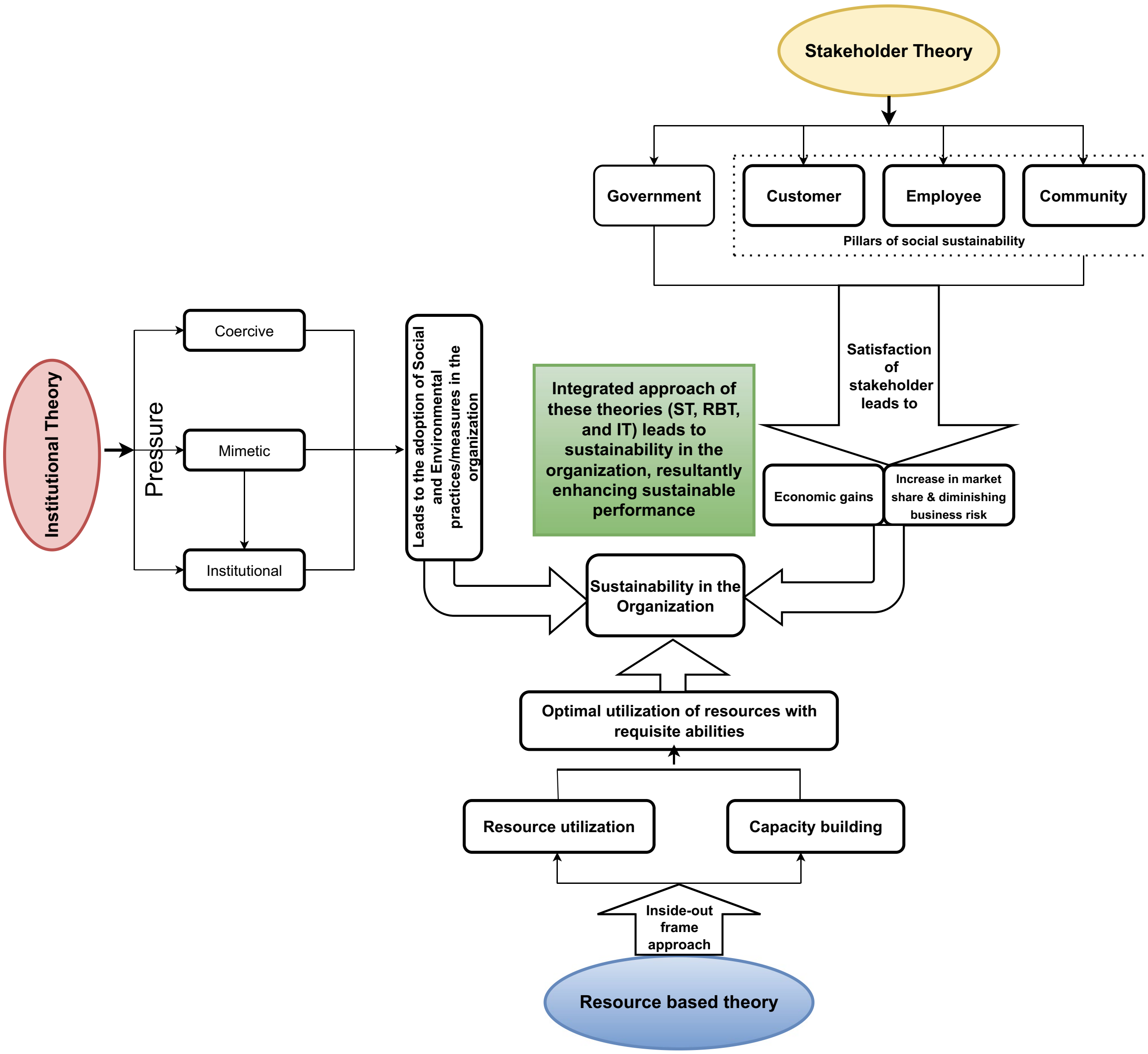

Fig. 1 The integrated theoretical framework based on the application of ST, RBT, and IT

this manufacturing organization. The panel of experts (details discussed in the methodology section) was consulted for data collection.

4.2.1 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 3.1.1. Quantification of the matrix is achieved by an expert's score based on a rating scale (shown in Table A4, Appendix). Notations used for the main categories are I1 (environmental sustainability), I2 (economic sustainability), and I3 (social sustainability). The step-by-step result of IPM calculation for each SM dimension is shown below by applying equations (2) to (3).

Environmental sustainability index evaluation:

$$Per\left[i1_1(MEC)\right] = ()$$

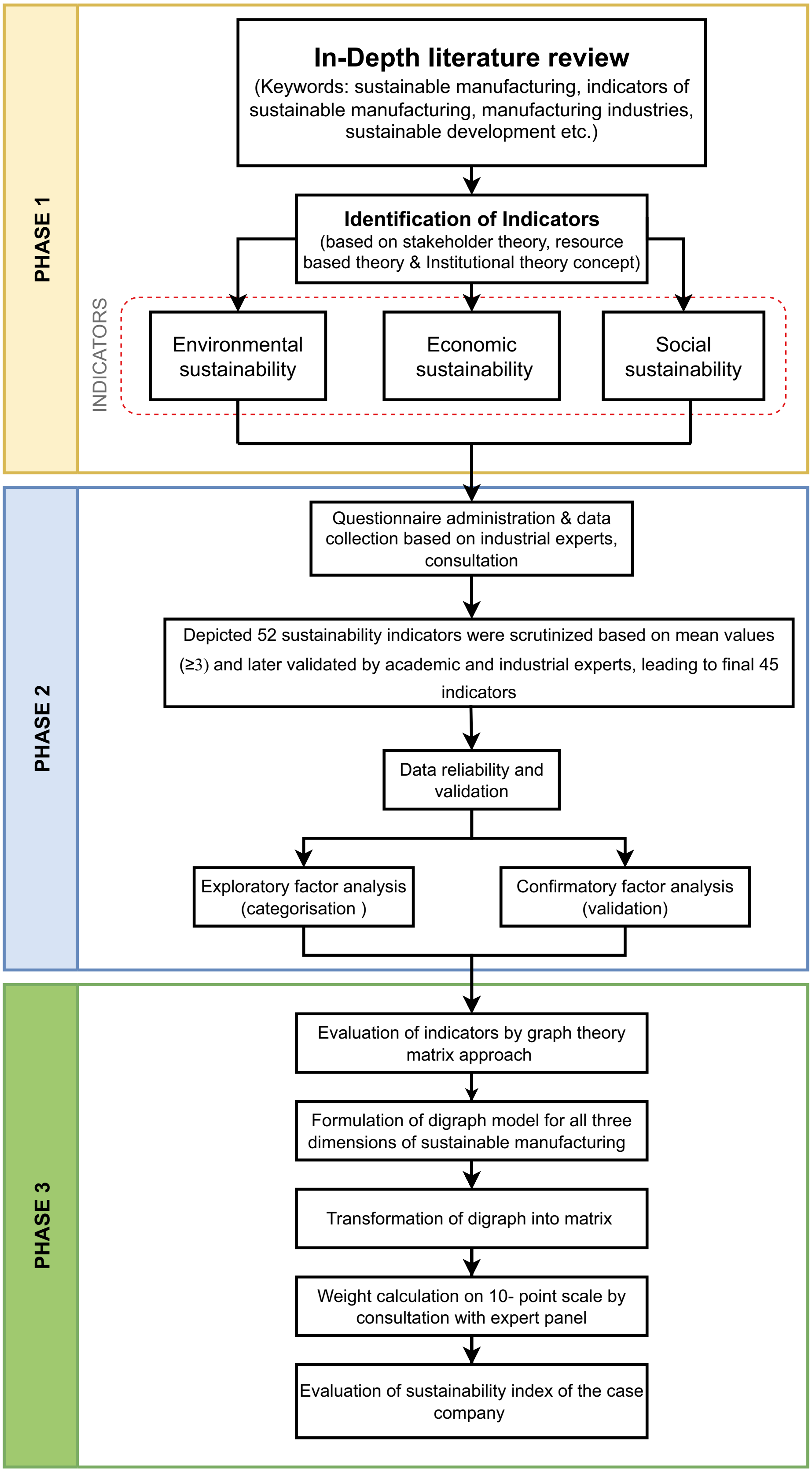

Fig. 2 A framework used for the research methodology

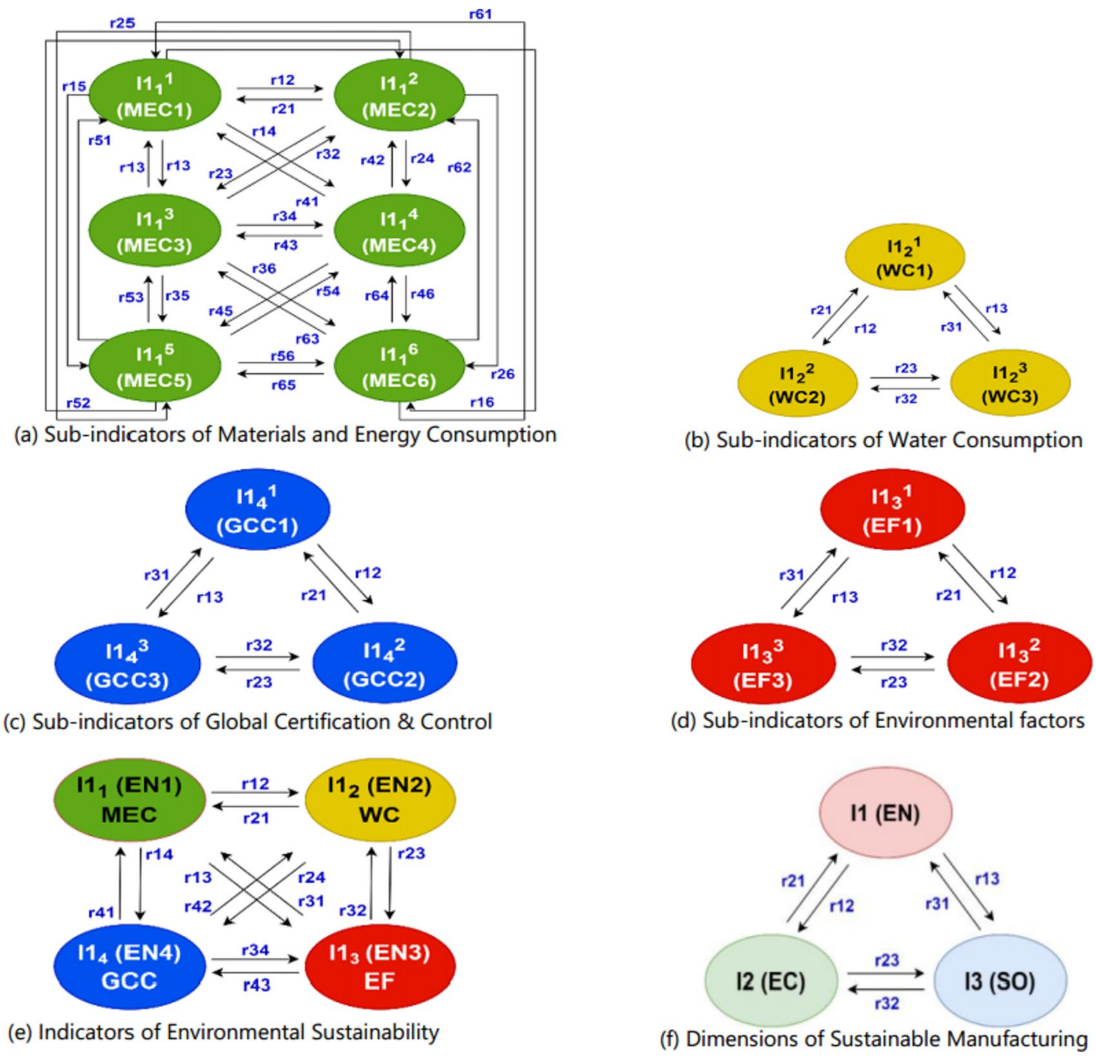

Fig. 3 Digraph related to environmental sustainability and its subgroup indicators

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

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

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

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

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).

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

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 to structure their SM system.

Economic sustainability evaluation:

$$\text{Per } [I2_1 \text{ (IIOC)}] = 214097 \quad (7)$$

$$\text{Per } [I2_2 \text{ (VC)}] = 6708522 \quad (8)$$

$$\text{Per } [I2_3 \text{ (IAE)}] = 205420 \quad (9)$$

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

Social sustainability evaluation:

$$\text{Per } [I3_1 \text{ (EM)}] = 7139994 \quad (11)$$

$$\text{Per } [I3_2 \text{ (CU)}] = 9431 \quad (12)$$

$$\text{Per } [I3_3 \text{ (CO)}] = 9716 \quad (13)$$

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

Overall sustainability index score (SIS) for selected manufacturing system

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

4.2.2 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.

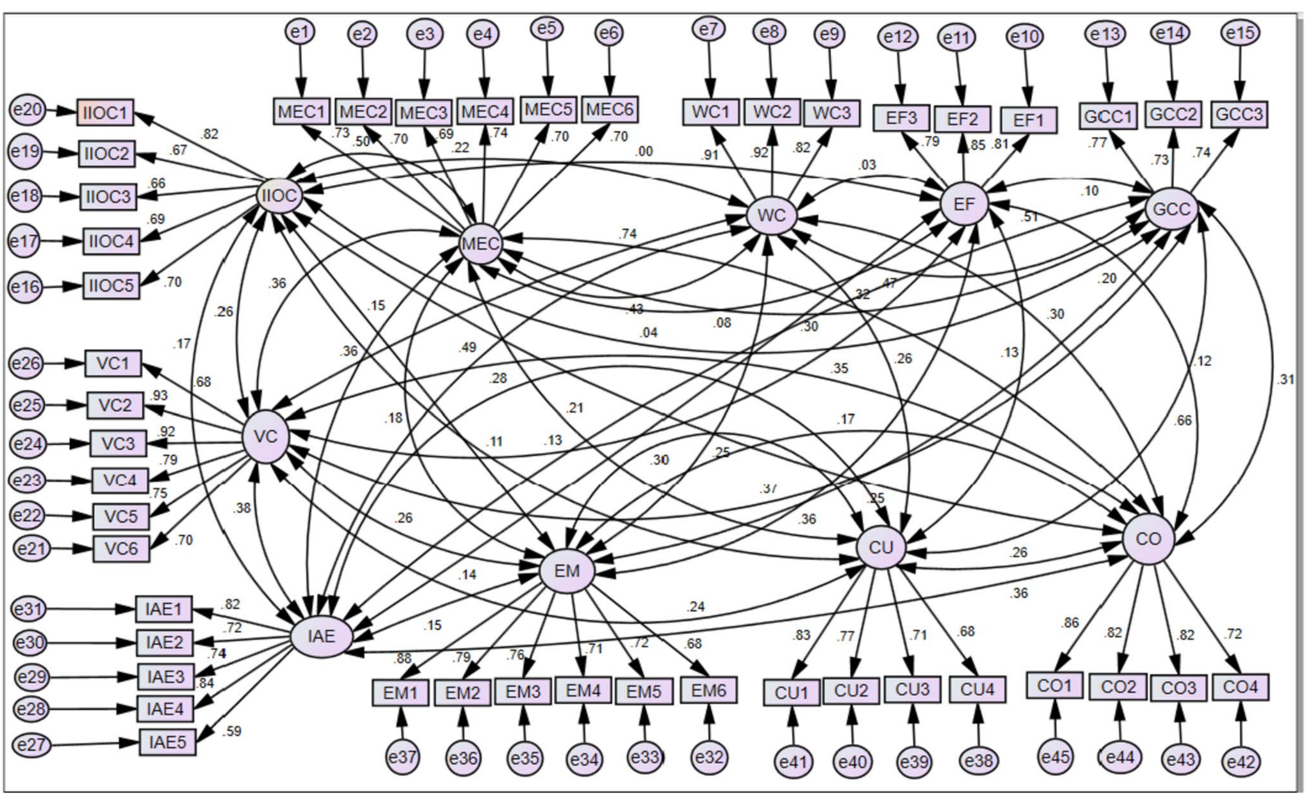

Fig. 4 Measurement model of SM indicators

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 A8 (Appendix). 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:

$$\text{Per [I1(Environmental sustainability)]} = 38.27 \times 10^{14}$$

$$\text{Per [I2(Economic sustainability)]} = 93.15 \times 10^{16}$$

$$\text{Per [I3(Social sustainability)]} = 22.42 \times 10^{14}$$

$$\text{Per (SM system) or SIS} = 97.94 \times 10^{47}$$

Worst case scenario permanent values of the SM indicators:

$$\text{Per [I1(Environmental sustainability)]} = 13.54 \times 10^{13}$$

$$\text{Per [I2(Economic sustainability)]} = 76.43 \times 10^{15}$$

$$\text{Per [I3(Social sustainability)]} = 20.13 \times 10^{13}$$

$$\text{Per (SM system) or SIS} = 20.84 \times 10^{44}$$

The existing permanent matrix values (Table A8 Appendix) 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.

5 Discussion and implications

As per the results summarized in Table A8 (Appendix), the following five sub-groups 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 to enhance 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 to achieve excellence in business, goals, and sustainable competitive gains (Ghosh 2013). Under the social dimensions of sustainability, customer feedback (SC11), community feedback (SC13), and the social and political aspects (SC14) play an important role in enhancing the sustainability of an organization. Also, it is observed that the factor loading of the social and political aspects is highest (0.859) in the community-related subsection of the social dimensions. However, most organizations have not indicated much interest in these areas which are to be one of the important aspects of social sustainability. Resource-based theory advocates the proper utilization of the human resource and other resources and the enhancement of the capability. 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 towards 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 costs, 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 to transform the existing system. In the current business environment of economic slowdown, manufacturers are noticing waste reduction and value creation; and customers assre seeking products of high quality at low cost (Kumar et al. 2021b). In the last five years, we have 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 and Murty (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. Stakeholder theory leads to the fulfillment of the vested interests of all the stakeholders of the organization. Thus, it is concerned with all three dimensions of sustainability.

5.1 Managerial implications

This study has identified a realistic set of sustainability indicators that will help managers in the decision-making process, and allow them to fully commit to their use for achieving sustainability in manufacturing processes. The distinctive contribution of the study is its mathematical model. The sustainability indicators will be positively perceived by the managers at a business level. 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. 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.

5.2 Academic implications

This study basis is not underpinned by the concept of a single theory, but utilizes the integrated contributions of three theories Resource-based theory, Stakeholder theory, and Institutional theory. The combination effect suggests that to gain competitive advantage, an organization must be focused primarily on internal strengths and weaknesses, bonded by stakeholders, and motivated by legitimacy. This study may motivate researchers and practitioners to explore some more management theories to address sustainability indicators. Also, they can use this framework 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.

6 Conclusion, limitation, and future scope

In this study the sustainability indicators are grouped into ten clusters using factor analysis and indexing of these clusters 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.* This underscores the significance of environmental sustainability as a key pillar of the triple bottom line. This research utilized the theoretical foundation of stakeholder theory, resource-based theory, and institutional theory applied for the analysis of sustainability indicators, explored through the in-depth literature review. The sustainability index has been developed with the help of experts from the automobile sector, iron & steel sector, and chemical & pharmaceutical sector as a case study, however, the sustainability indicators are selected based on the opinions of the respondents from different manufacturing industries. Therefore, the findings are more suitable for the automobile sector, iron & steel sector, and chemical & pharmaceutical sector, and also applicable for the other manufacturing sectors.

Future research can be focused on diverse industrial sectors for other developing economies like China and Malaysia for comparative analysis and validation. In the future, sample size can be extended and statistical and causal analysis can be applied to enhance result reliability. Exploring sustainability within the context of a net-zero economy, and incorporating additional relevant indicators into the framework, could be a valuable aspect of forthcoming investigations. Additionally, broadening the application of MCDM methods through multiple case studies would contribute to improving the generalizability of the outcomes.

Appendix

Table A1 Respondent's profile

Category	Item	Frequency	Percentage
Gender	Male	396	89.18
	Female	48	10.81
Age	≤29	95	21.39
	30-39	149	33.56
	40-49	121	27.25
	50-59	58	13.06
	≥60	21	4.73
Experience	<1 year	28	6.31
	1–5 years	84	18.92
	5–10 years	93	20.95
	10–15 years	101	22.75
	15–20 years	87	19.59
	≥ 20 years	51	11.48
Organization type	Automobile	147	33.13
	Sheet Metal processing	56	12.61
	Iron and Steel	68	15.32
	Chemical and industrial fertilizer	39	8.78
	Pharmaceutical	52	11.71
	Textile Industries	34	7.66
	Electrical and Electronics	29	6.53
	Others	19	4.28
Position held	Lower management	191	43.02
	Middle management	167	37.61
	Higher management	86	19.37
Education	Graduate	232	52.25
	Post Graduate	165	37.16
	Doctorate	47	10.58

Table A2 Descriptive analysis of the depicted indicators

SM Dimensions	Acronym	Indicators	Mean	Standard Deviation
Environmental Sustainability	EN1	Recycling of used materials	3.73	0.974
	EN2	Consumption of recycled/refurbished materials/components	3.65	0.988
	EN3	Non-Hazardous materials consumption	3.77	0.966
	EN4	Economic water consumption	3.38	1.225
	EN5	Green packaging materials	3.76	0.995
	EN6	Green transportation/ fuel economy and emission control	3.76	0.952
	EN7	Reuse and recycling of wastewater	3.25	1.191
	EN8	Renewable energy Consumption	3.74	0.948
	EN9	Elimination of landfills & contamination	3.15	1.094
	EN10	Water Contamination	3.28	1.314
	EN11	Prevention of water pollution	3.13	1.211
	EN12	Green Initiatives	3.42	1.178
	EN13	Emission control	3.18	1.129
	EN14	Volatile organic compounds	2.11	0.891
	EN15	Labels and certificates (ISO 14001 & ISO 9001)	3.41	1.235
	EN16	Quality control	3.53	1.151
	EN17	Materials of tools	1.75	0.777
	EN18	Particulate suspended matters	1.98	0.796
Economic Sustainability	EC1	Wages and operating cost	3.20	1.259
	EC2	Pollution control cost	3.30	1.092
	EC3	Environmental treatment cost	3.28	1.152
	EC4	Expenses on corporate social responsibility (CSR)	3.28	1.220
	EC5	Sales promotion	3.20	1.239
	EC6	Facility expansion	3.18	1.275
	EC7	Revenue generation	3.32	1.232
	EC8	Investment in research and development	3.28	0.969
	EC9	Profit earned	3.19	1.240
	EC10	Annual Productivity	3.18	1.273
	EC11	New Product Design and Development	3.18	1.188
	EC12	Market share	3.16	1.231
	EC13	Liability and Debt payment	3.18	1.218
	EC14	Depreciation	3.33	1.056
	EC15	Maintenance	3.34	1.074
	EC16	Prevention of scrap production	3.30	1.139
	EC17	Turnover (selling inventory)	2.47	1.092
	EC18	Payback period	2.50	1.103
Social Sustainability	SC1	Job security and employee retention	3.51	1.199
	SC2	Health and Safety	3.25	1.061
	SC3	Human rights protection	3.26	1.079
	SC4	Employee performance	3.21	1.152
	SC5	Employee satisfaction	3.41	1.104
	SC6	Training and Development	3.30	1.191
	SC7	Risk identification and employee feedback management	3.32	1.195
	SC8	Customer satisfaction and relationship	3.24	1.282
	SC9	Product quality	3.26	1.245
	SC10	Trust development	3.23	1.239
	SC11	Customer feedback	3.29	1.185
	SC12	Personal protective equipment	2.17	0.928
	SC13	Community feedback	3.20	1.231
	SC14	The social and political aspects	3.18	1.269
	SC15	Technology development and support	3.22	1.242
	SC16	Work load	1.69	0.779

Table A3 Structural model fit Indices

Model fit measures	Acceptance level
Absolute measures	
CMIN/DF	<2 (good) 5 (acceptable)
GFI (Goodness of Fit Index)	>0.9 (good) 0.95 (very good)
RMSEA	<0.05 (very good) 0.08 (good) 0.1 (poor)
RMR (Root mean square residual)	< 0.10
Relative measures	
CFI (Comparative fit index)	>0.9 (good) 0.95 (very good)
Parsimony measures	
PCFI (Parsimony Comparative Fit Index)	>0.6 (reasonable) 0.8 (good)
PGFI (Parsimony Goodness of Fit Index)	>0.6 (reasonable) 0.8 (good)

Table A4 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

Table A5 KMO and Bartlett's Test results

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		.857
	Approx. Chi-Square	12495.710
Bartlett's Test of Sphericity	df	990
	Sig.	0.000

Table A6 Goodness of fit measures of SM indicators

Fit Indices	Calculated values	Accepted values
CMIN/DF	2.715	<2 (good) 5 (acceptable)
GFI (Goodness of Fit Index)	0.817	>0.8 (average), >0.9 (good), 0.95 (very good)
RMSEA	0.062	<0.05 (very good) 0.08 (good) 0.1 (poor)
RMR (Root mean square residual)	0.062	< 0.10
CFI (Comparative fit index)	0.871	>0.85 (good) 0.95 (very good)
PCFI (Parsimony Comparative Fit Index)	0.792	>0.6 (reasonable) 0.8 (good)
PGFI (Parsimony Goodness of Fit Index)	0.710	>0.6 (reasonable) 0.8 (good)

Table A7 Correlation and discriminant validity of SM indicators

Constructs	EM	MEC	VC	CU	IIOC	CO	IAE	EF	GCC	WC
EM	0.759									
MEC	0.183	0.708								
VC	0.262	0.360	0.802							
CU	0.300	0.211	0.243	0.751						
IIOC	0.153	0.496	0.260	0.114	0.709					
CO	0.166	0.323	0.349	0.260	0.246	0.807				
NAE	0.153	0.362	0.376	0.283	0.168	0.358	0.749			
EI	0.361	0.082	0.133	0.133	-0.002	0.117	0.138	0.814		
GCC	0.199	0.303	0.371	0.661	0.041	0.309	0.515	0.103	0.750	
WC	0.253	0.432	0.736	0.262	0.216	0.304	0.485	0.033	0.470	0.884

Table A8 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)		7.99×10^{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

Data availability statements The datasets generated during and/or analysed during the current study are not publicly available, but are available from the corresponding author on reasonable request.

Declarations

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