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Technological innovation toward sustainability in manufacturing organizations: A circular economy perspective

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ABSTRACT

Technological innovation has been widely recognized both as a trigger and catalyzer towards sustainability. However, hardly ever manufacturing companies are ready and mature enough to employ technological innovations in their processes and business. Given the relevance of technological innovation in pursuing sustainability, it is hard to comprehend what are the prominent factors affecting the role of technological innovation to address sustainability and prioritize them. Therefore, the prime purpose of this study, applied to an emerging economy, is to analyze the contributions of technological innovation toward sustainability in manufacturing organizations with a circular economy (CE) perspective. To address this objective, a questionnaire has been developed and conducted, also using the Grey VIKOR method and a sensitivity analysis. The findings from the study illustrate that entrepreneurship direction towards innovation and market direction towards innovation are the two potential factors of technological innovation towards sustainability. The implications highlight that CE, sustainable education and stakeholder engagement solutions can be crucial to the competitiveness of a developing country's manufacturing businesses.

1. Introduction

Overconsumption of natural resources necessitates the search for alternative solutions to meet our needs. Overconsumption results in increased waste generation. The World Bank estimates that global waste generation could increase by 70% to reach up to 3.4 billion tonnes of waste per year by 2050 (Kaza et al., 2018). Circular Economy (CE) is a method of moving toward resource management that is more sustainable (Papaoikonomou et al., 2020; Zorpas et al., 2021). CE models are transforming different sectors of the manufacturing system in order to seize opportunities related to circular solutions, but also as a reply to climate change (Matlin et al., 2020; Papamichael et al., 2023b). The manufacturing organizations that do not decide to concentrate on sustainable and circular resources risk being non-competitive in the long run (Dwivedi et al., 2023b). Technology aims to identify innovative solutions which also follow CE models (Issaoui et al., 2022).

Technological innovation has been widely recognized both as a trigger and catalyzer towards sustainability (Kristoffersen et al., 2020). Manufacturing industry is continuously struggling to achieve sustainability under all the facets of the Triple Bottom Line of

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sustainability (economic, environmental and social) (WCED, 1987). To address this scope, technological innovation is a potential factor, pushed by Industry 4.0 (Patil et al., 2023), Industry 5.0 (Dwivedi et al., 2023a), blockchain (Patil et al., 2021) and produce service system (González Chávez et al., 2019). In this way, some researchers aim to identify a framework for digitalized sustainable manufacturing (Despeisse et al., 2022). However, hardly ever manufacturing companies are ready and mature enough to employ technological innovations in their processes and business (De Carolis et al., 2017; Sassanelli et al., 2020). Indeed, companies need to be supported by policy makers and governments (Hazen et al., 2020) through tailored regulations and directives (Garetti and Taisch, 2012), and by innovation ecosystems (European Commission, 2022), through an heterogeneity of services (Sassanelli and Terzi, 2022). Thanks to these actions, they could be able to effectively accomplish the full potential of technological innovations, to adequate their business model (Lamperti et al., 2023; Pirola et al., 2020; Sjödin et al., 2020), to attain new capabilities and skills (Baines et al., 2009; Bustinza et al., 2018; Paschou et al., 2018), and to widen their market horizons and network (Chiappetta Jabbour et al., 2020).

In this context, researchers detected different success factors capable to drive manufacturers towards sustainability through technological innovation. On one side, it should be considered the attitude of companies and its entrepreneurship towards innovation, the characteristics of the marked and its relationship with innovations. On the other side, also the government impact on the possibility and capability of innovate products through a change of technology should be taken in consideration. Also, it is difficult to comprehend which are the prominent factors affecting the contribution of technological innovation to address sustainability. Therefore, the prime intent of this study is to analyze the contribution of technological innovation towards sustainability in manufacturing organizations. The transition to sustainability in manufacturing enterprises is supposed to embody the budgetary path of circular business models (CBMs) (Dwivedi et al., 2023b). To address this objective, a questionnaire has been developed and conducted, also the Grey VIKOR methodology is adopted. This study is conducted on a developing country like India.

The study is categorized as shown. Section 2 reflects the research context about technology innovation, sustainability and CE, focusing on the factors of technological innovation towards sustainability. Section 3 shows the research method used. Section 4 provides the main results of the study and section 5 is aimed at discussing them, providing managerial implications and evidencing the main limitations. Finally, Sec. 6 highlights the contribution, also providing future research.

2. Literature review

This section is divided into three segments. In the first one, studies specific to technology innovation, sustainability and CE are highlighted. The second section reflects the identified factors of technological innovation towards sustainability considering the background of manufacturing industry. The categorization of the identified factors of technology innovation is provided in the third section.

2.1. Technology innovation, sustainability and circular economy

Literature presents several studies focusing on how to innovate through the adoption of circular business models. Goodarzian et al. (2023b) suggested a Mixed Integer Linear Programming Model (MILP) framework for designing a sustainable citrus Closed Loop Supply Chain (CLSC) network. The model is validated from a case study in Iran. A study to highlight the challenges to sustainable development in context of vehicle transport is presented (Goodarzian et al., 2023a). The study adopted a descriptive-analytical prospect for evaluating the challenges. Momenitabar et al. (2022b) performed a study to design an efficient Bioethanol Supply Chain Network (SBSCN). The study adopted ML and meta heuristic algorithms for obtaining the solutions. A sustainable CLSC network was designed considering back up suppliers (Momenitabar et al., 2022a). The findings from the study illustrate that lateral resupply and backup supplier could reduce total costs and shortages on the designed sustainable CLSC network. Bocken and Konietzko (2022) analyzed the important functions performed by the innovators towards consumer centric organizations as a contribution to Circular Business Model Innovation (CBMI). They accomplished a literature review analysis to evaluate the studies relevant to innovation activities based on various CBMI stages. Further, a study was performed to analyze the impact of CBMI and Digital Business Transformation (DBT) to measure the interaction among Industry 4.0 (I4.0) and sustainable performance (Belhadi et al., 2022). The results from this study reflect organizational ambidexterity as an alternate to CBMI in emerging sustainable business models. Instead, through a literature survey, Tanveer et al. (2022) highlighted the studies specific to technological innovation, CE and waste management. The study employed bibliometric analysis approach to assist policymakers and practitioners' transition to CE. Similarly, a study to analyze the literature related to CBMI and technology management strategies was performed by Mendoza et al. (2022). The results from the study is considered essential across low energy and renewable energy domain.

Also the significance of CE on sustainability oriented innovations was investigated (Rodríguez-Espíndola et al., 2022). A Structural Equation Modelling (SEM) analysis was employed on data extracted from Small and Medium Enterprises (SMEs) in Mexico. Also, Chauhan et al. (2022) performed a literature analysis to highlight studies at the crossroad of CE and digital technologies. The study identified Product Service System (PSS) as an essential business model innovation for attaining digitalization and CE practices. Further, another study was performed to review the commendable technological and non-technological eco-innovations, comprising of resource recovery for Solid Waste Management (SWM) (Rena et al., 2022), to assist policymakers and practitioners to enhance the SWM structure in emerging economies. Similarly, Rejeb et al. (2022) illustrated an approach to perform research and development innovation projects, further developing education training performed in a collective manner.

Considering the perspective of CE and sustainability, Corral-Marfil et al. (2021) investigated La Farga's business model and found that the barriers force to integrate both the linear and circular models with a purpose to remain competitive. Similarly, Cavalieri et al. (2021) demonstrated a study to comprehend in the manufacturing domain the interaction among Digital Transformation (DT) and Eco Innovation (EI), with the final aim of addressing environmental sustainability. They studied varied utilization of digital technologies with a prime purpose of CE adoption. Also, Ranta et al. (2021) developed a business model innovation for CE mobilized by digital technologies, highlighting the importance of radical business model innovation.

To explore the shift towards CE through CBMI, Konietzko et al. (2020) performed several experiments. In the same domain, Nuβholz et al. (2019) demonstrated a study to understand the importance of secondary material for decarbonization of building sector. On the other hand, Smol et al. (2017) developed a study to propose the potential of public policy and business model innovation. They highlighted five group of indicators for measuring CE and eco-innovation. Finally, Rama Mohan (2016) highlighted innovation policies necessary for new technologies, presenting strategies of innovation policy considering the example of biorefinery.

2.2. *Identification of factors of technological innovation towards sustainability*

The performed literature analysis and recommendations from the experts' reveals a total of thirteen potential factors of technological innovation in context of manufacturing industry. Table 1 reflects the list of factors of technological innovation towards sustainability.

2.3. *Classification of factors of technological innovation towards sustainability*

In this study, the factors of technological innovation towards sustainability are distributed into three main categories of prospects (namely social, technical, and environmental). Gathering and grouping among them (based on their commonalities) both the experts' recommendations and the literature survey results, the different prospects belonging to the three main categories were defined. In particular, the prospects considered for the study are illustrated below.

a) *Social Prospects:* those related to the empowerment of the managers in order to foster technological innovation. They are detailed in:
   - Management Capability (TI2),
   - Acquisition of external knowledge (TI6),
   - Managerial Competencies (TI7), and
   - Top management control (TI11).

b) *Environmental prospects:* those linked to the factors external to companies' organizations (e.g., surrounding environment, products, and governments). They can be split in:
   - Uncertain environment on technological innovation (TI3),
   - Product Innovation (TI4), and
   - Influence of government (TI5).

c) *Technical prospects:* those concerning the relation among innovation and other factors (e.g., market, stakeholders attitude, entrepreneurship) through technological means. They are detailed in:
   - Technology Change (TI1),
   - Market Knowledge (TI8),
   - Attitude towards innovation (TI9),
   - Technology Components (TI10),
   - Market direction towards innovation (TI12) and
   - Entrepreneurship direction towards innovation (TI13).

3. Research methodology

The research methodology section is separated into three segments. The first segment covers the data collection procedures, the second proposes the Grey VIKOR approach, and the third covers the sensitivity analysis. The analysis is conducted for a developing country like India.

Table 1
Factors of technological innovation towards sustainability.

Factor Code	Factors of technological innovation	References
TI1	Technology Change	Sumrit and Anuntavoranich (2013); Carroll and Conboy (2020)
TI2	Management Capability	Denicol and Davies (2022); Asamoah et al. (2021)
TI3	Uncertain environment on technological innovation	Kafetzopoulos et al. (2019); Haarhaus and Liening (2020)
TI4	Product Innovation	Lu et al. (2019); Xie et al. (2019)
TI5	Influence of government	Tian et al. (2019); Zhao et al. (2021)
TI6	Acquisition of external knowledge	Awan et al. (2021); Chen et al. (2021)
TI7	Managerial Competencies	Nevzorova and Karakaya (2020); Orobia et al. (2020)
TI8	Market Knowledge	Alshanty and Emeagwali (2019); Bagheri et al. (2019)
TI9	Attitude towards innovation	Talukder (2012); Chapman and Hewitt-Dundas (2018)
TI10	Technology Components	Momenitabar et al. (2023); George et al. (2020); Groba and Cao (2015)
TI11	Top Management Control	Lee et al. (2014); Bedford (2015)
TI12	Market direction towards innovation	Sprong et al. (2021); Kjellberg et al. (2015)
TI13	Entrepreneurship direction towards innovation	Ionescu et al. (2020); Karlsson et al. (2021)

3.1. Data gathering and questionnaire design

Quantitative approaches where there is no data availability require expert support, and the categories involved can be varied (Appolloni et al., 2021; Papamichael et al., 2023a). The strength of these methods is based on their expertise. After consulting with industry professionals, the factors influencing technological innovation toward sustainability in manufacturing organizations were classified into three dimensions in the current study: environment, society, and economic. A questionnaire was created to accumulate data on the experts' preference ratings for each factor based on the three selected dimensions. The information was gathered by experts in various roles such as professionals, scholars, and management in various industries. A total of ten experts were considered, four from academia and six from the manufacturing sector having expertise in the domain of CSC and sustainability. Because this study focuses on technological innovation, manufacturing organizations, and sustainability, the experts were chosen to assure knowledge in the relevant fields. The experts were informed of the study's goal via phone calls and in-person meetings. The research framework for conducting the procedure is shown in Fig. 1.

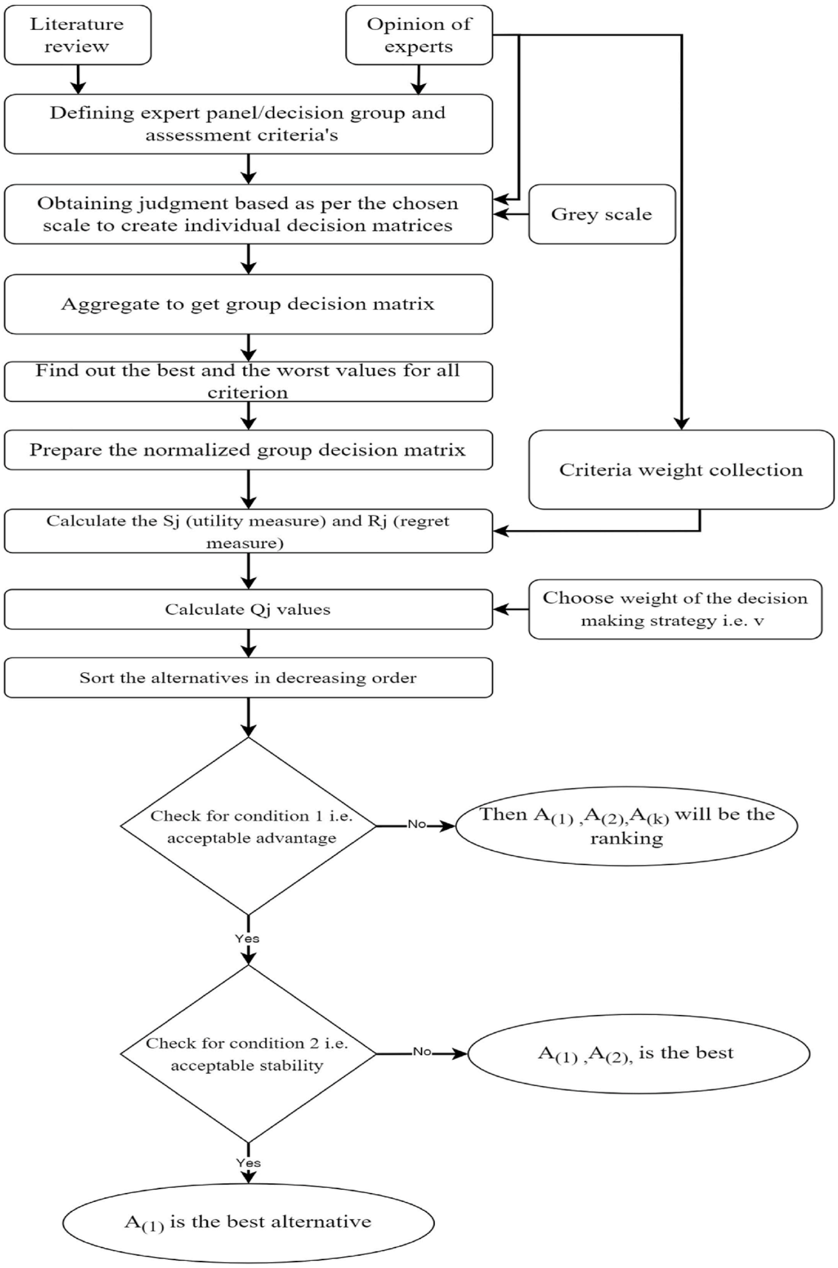

Fig. 1. Research framework.

3.2. Grey VIKOR

The VIKOR technique was developed by (Opricovic, 1998), which is positioned on advanced decision making logic. Multi Criteria Decision Making (MCDM) approach is a method used to investigate sustainability in the manufacturing context (Ali et al., 2023). This method develops a compromise solution to problems with competing criteria, assisting decision-makers in making an informed decision (Shemshadi et al., 2011). This method classifies the best option in changing circumstances by judging the closest measure to the ideal alternative. After the alternatives have been evaluated using discrete criteria, compromised leveling can be performed (Opricovic, 2011). VIKOR compares a number of options to a set of potentially opposing and distinctive selection criteria, with an assumption that compromise is satisfactory for conflict resolution. VIKOR approach employs an aggregating function to determine whether a method is close to the ideal solution. The VIKOR method estimates the highest group utility and the lowest individual regret value when compared to other MCDM approaches (Opricovic, 2011). The Grey VIKOR method employs Grey theory to address numerous issues. The main advantage is that it can produce acceptable results with a limited amount of data or variables with a wide range of variability.

The VIKOR approach along with improvisations such as Grey VIKOR have been applied in different problem domains. Cheng et al. (2023) applied Grey VIKOR to choose the logistic service provider while keeping low-carbon emission as their strategy. Some authors researched and assessed the water supply and its security measures on urban areas using VIKOR-TOPSIS methodology (Yang et al., 2023). Other analysis combined Fuzzy VIKOR with Grey DEMATEL to assess the take-back pattern of vehicles focusing in China (Tian et al., 2019). However, literature provides also other applications. In fact, Rajesh (2018) used Clustering and VIKOR in conjunction with grey theory to assess the barriers that affect supply chain resiliency in the manufacturing sector. Parkouhi and Ghadikolaei (2017) used Grey VIKOR in conjunction with Fuzzy ANP to select the best supplier based on resiliency. Mardani et al. (2016) conducted a literature review on VIKOR and its variants methodology. They discovered that the Fuzzy and Grey variants were frequently used by the researchers. Chithambaranathan et al. (2015) used VIKOR in conjunction with Grey theory to assess the efficiency of service supply chains.

The Grey VIKOR method's steps are as follows.

***Step 1**: Determine the issue and the objectives of the decision-making procedure.*

***Step 2**: Identify and connect with the group of decision-makers to determine and clarify appropriate criteria.*

Step 3: *Select the linguistic expression that decision-makers will use to evaluate alternatives and criteria*. The experts rated the alternatives using a five-point scale to determine the importance of each criterion. Each linguistic phrase has a corresponding Grey number, as shown in Table 2.

Step 4: *Create a Grey decision matrix of alternatives based on decision-makers' (DMs') assessments*. Table 3 establishes the Grey decision matrix for the alternatives.

Step 5: *Create a Grey decision matrix based on the opinions of the experts*. For this study, A total of ten experts were considered from both industry and academia. The Grey decision matrix for aggregate weights is reflected in Table 4.

Table 2
Grey numbers and Linguistic terms.

Linguistic terms	Grey numbers
Very low influence (VL)	(0.1,0.3)
Low influence (L)	(0.2, 0.5)
Medium influence (M)	(0.4, 0.7)
High influence (H)	(0.6, 0.9)
Very high influence (VH)	(0.9, 1.0)

Table 3
Aggregate rating for the alternatives with respect to criteria.

Alternative/Criteria	C1	C2	C3
TI1	(0.44,0.74)	(0.36,0.66)	(0.6,0.9)
TI2	(0.28,0.54)	(0.78,0.96)	(0.48,0.7)
TI3	(0.6,0.9)	(0.2,0.5)	(0.6,0.9)
TI4	(0.4,0.7)	(0.32,0.62)	(0.44,0.74)
TI5	(0.36,0.66)	(0.44,0.74)	(0.6,0.9)
TI6	(0.6,0.82)	(0.22,0.46)	(0.62,0.8)
TI7	(0.2,0.5)	(0.6,0.9)	(0.4,0.7)
TI8	(0.4,0.7)	(0.4,0.7)	(0.6,0.9)
TI9	(0.6,0.9)	(0.2,0.5)	(0.56,0.86)
TI10	(0.28,0.58)	(0.62,0.8)	(0.28,0.58)
TI11	(0.36,0.66)	(0.46,0.72)	(0.52,0.82)
TI12	(0.52,0.82)	(0.47,0.71)	(0.59,0.79)
TI13	(0.76,0.9)	(0.7,0.88)	(0.55,0.79)

Table 4
Aggregate weights of each criterion (Acronym: E = Expert).

Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Aggregate Weight
C1	H	H	M	H	VH	H	H	M	VH	H	(0.53,0.78)
C2	L	L	H	L	M	L	VL	M	M	M	(0.27, 0.53)
C3	H	M	VH	M	M	H	H	VH	H	H	(0.54, 0.77)

Step 6: *Among the dedicated values, find the best f_j*= (p_i*, q_i*) and worst f_j^-= (p_i^-, q_i^-) values for criteria functions*. Table 5 shows aggregated grey values and subjective importance weights derived from equations (1) and (2) below.

$$< listaend > f_j^* = \max_j f_{ij} \text{ and } f_j^- = \min f_{ij}, \text{for maximize criteria} \tag{1}$$

$$f_j^* = \min_j f_{ij} \text{ and } f_j^- = \max f_{ij,} \text{for minimize criteria} \tag{2}$$

Step 7: *Determine the normalized grey difference values*. The aggregate values are normalized in this step. Table 6 summarizes the findings.

$$d_{ij=} \left(f_j^* - f_{ij)/} \mathrm{f}_i^* - f i_j i_j^-\right), \text{for the maximize criteria} \tag{3}$$

$$d_{ij=} \left(f_i j - f_i *_{)/} \mathrm{f}_i^* - f i_j i_j^-\right), \text{for the minimize criteria} \tag{4}$$

Step 8: *Calculate S_i= (S_i^p, S_i^q) and R_i= (R_i^p, R_i^q)*. The *Si* and *Ri* values for all factors using equations (5) and (6) are highlighted in Table 7.

$$S_i = \sum_{j=1}^{m} \left(w_{j*} d_{ij}\right) \tag{5}$$

$$R_i = \max_j \ \left(w_{j*} d_{ij}\right) \tag{6}$$

in which wj = weight of jth criteria and v = weight of maximum group utility and mostly kept 0.5.
Step 9: *Determine the value of Q_i= (Q_i^p, Q_i^q)*. Table 7 highlights the values of Q for all alternatives using equation (7).

$$Q_i = v \ \left(S_i - S_i^*\right) / \left(S_i^- S_i^*\right) + (1 - v) \ \left(R_i - R_i^*\right) / \left(R_i^- R_i^*\right) \tag{7}$$

in which S_i^* = $\min_i S_i$, S_i^- = $\max_i S_i$, R_i^* = $\min R_i$, R_i^- = $\max R_i$, v = maximum group utility and 1 – v = weight of particular regret.

Table 5
The grey best and worst values.

	C1	C2	C3
Fj*	(0.76,0.9)	(0.78,0.96)	(0.62,0.9)
Fj-	(0.2,0.5)	(0.2,0.46)	(0.28,0.58)

Table 6
The normalized grey decision matrix.

Alternative/Criteria	C1	C2	C3
TI1	(0.029,0.657)	(0.158,0.789)	(-0.452,0.484)
TI2	(0.314,0.886)	(-0.237,0.237)	(-0.129,0.677)
TI3	(-0.2,0.429)	(0.368,1)	(-0.452,0.484)
TI4	(0.086,0.714)	(0.211,0.842)	(-0.194,0.742)
TI5	(0.143,0.771)	(0.053,0.684)	(-0.452,0.484)
TI6	(-0.086,0.429)	(0.421,0.974)	(-0.29,0.452)
TI7	(0.371,1)	(-0.158,0.474)	(-0.129,0.806)
TI8	(0.086,0.714)	(0.105,0.737)	(-0.452,0.484)
TI9	(-0.2,0.429)	(0.368,1)	(-0.387,0.548)
TI10	(0.257,0.886)	(-0.026,0.447)	(0.065,1)
TI11	(0.143,0.771)	(0.079,0.658)	(-0.323,0.613)
TI12	(-0.086,0.543)	(0.092,0.645)	(-0.274,0.5)
TI13	(-0.2,0.2)	(-0.132,0.342)	(-0.274,0.565)

Table 7
Si, Ri and Qi values.

Alternatives	S	R	Q
TI1	(-0.186,1.304)	(0.043,0.513)	(0.053,0.191)
TI2	(0.033,1.338)	(0.167,0.691)	(0.188,0.314)
TI3	(-0.25,1.237)	(0.099,0.53)	(0.074,0.185)
TI4	(-0.002,1.575)	(0.057,0.571)	(0.109,0.297)
TI5	(-0.154,1.337)	(0.076,0.602)	(0.083,0.256)
TI6	(-0.089,1.198)	(0.114,0.516)	(0.123,0.167)
TI7	(0.085,1.652)	(0.197,0.78)	(0.22,0.45)
TI8	(-0.17,1.32)	(0.045,0.557)	(0.059,0.224)
TI9	(-0.216,1.287)	(0.099,0.53)	(0.082,0.198)
TI10	(0.164,1.698)	(0.136,0.77)	(0.201,0.455)
TI11	(-0.077,1.422)	(0.076,0.602)	(0.102,0.278)
TI12	(-0.169,1.15)	(0.025,0.423)	(0.046,0.095)
TI13	(-0.29,0.772)	(0,0.435)	(0,0.007)

Step 10: *Converting into Crisp value of S_i, R_i, Q_i.* The centroid method is used to compute crisp values for S_i, R_i and Q_i. Table 8 re-examines the preliminary ranking of the alternatives on the basis of S, R, and Q. The prefinal ranking is obtained based on the Q_i table values as follows:$TI_{13} > TI_{12} > TI_1 > TI_3 > TI_9 > TI_8 > TI_6 > TI_5 > TI_{11} > TI_4 > TI_2 > TI_{10} > TI_7$.

There are two conditions that are required to be fulfilled before finalizing alternatives with the minimum score of Q_i (Agrawal et al., 2022). The analysis reveals Entrepreneurship direction towards innovation (TI13) as the best factor of technological innovation (see Table 8).

Step 11: *Select the most important alternative by selecting $Q(^{TI(M)})$ as the best compromise solution with the lowest Q_i value.* "Entrepreneurship direct towards innovation" (TI_{13}) is the most important factor with a Qi value of 0.0048.

3.3. Sensitivity analysis

A sensitivity analysis is performed to evaluate the stability and reliability of the suggested strategy. The sensitivity analysis is conducted with a 0.1 increment between 0 and 1. A total of eleven tests were performed, as shown in Tables 9 and 10, and their corresponding information are shown in Figs. 2 and 3, respectively.

4. Results, discussion and implications

This study attempts to recognize, categorize, and rank various factors of technological innovation specific to manufacturing organizations. A total of thirteen potential technological innovation factors were identified for the efficient employment of sustainable practices in manufacturing organizations. In consultation with experts and deliberation from the literature survey, the identified potential factors were classified into three categories: social, technical, and environmental. The recognized factors were then prioritized using the Grey VIKOR approach. According to the study's findings, the following technological innovation factors are considered very important: Entrepreneurship direction towards innovation (TI13), Market direction towards innovation (TI12), Technology Change (TI1), Uncertain environment on technological innovation (TI3), and Attitude towards innovation (TI9).

The results summarized in Table 8 reflects the factors of technological innovation summarized as $TI_{13} > TI_{12} > TI_1 > TI_3 > TI_9 > TI_8 > TI_6 > TI_5 > TI_{11} > TI_4 > TI_2 > TI_{10} > TI_7$. Based on the results of the analysis, the manufacturing industries can consider the importance of these factors in achieving sustainability. A sensitivity analysis is performed to reflect the importance of technological innovation factors by alternating the value of 'v' with a 0.1 increment from 0 to 1. A total of eleven experiments were performed for the sensitivity analysis. The results of the sensitivity analysis represent the best three factors, Entrepreneurship di-

Table 8
The final ranking of alternatives.

	S	R	Q	S Ranking	R Ranking	Q Ranking
TI1	0.744984	0.370135	0.162822	6	3	3
TI2	0.913962	0.571619	0.334488	10	11	11
TI3	0.657646	0.419649	0.172591	3	7	4
TI4	1.048336	0.418755	0.270302	11	5	10
TI5	0.788654	0.451619	0.226041	8	9	8
TI6	0.739708	0.419825	0.193347	5	8	7
TI7	1.157712	0.651238	0.446845	12	13	13
TI8	0.766819	0.401714	0.188558	7	4	6
TI9	0.71399	0.419649	0.186765	4	6	5
TI10	1.241321	0.60419	0.437719	13	12	12
TI11	0.89678	0.451619	0.253242	9	10	9
TI12	0.654343	0.298865	0.094334	2	2	2
TI13	0.321602	0.289785	0.004807	1	1	1

Table 9
Q_i values obtained.

Alternative/sensitivity	v = 0	v = 0.1	v = 0.2	v = 0.3	v = 0.4	v = 0.5	v = 0.6	v = 0.7	v = 0.8	v = 0.9	v = 1
TI1	0.112628	0.122667	0.132706	0.142745	0.152783	0.162822	0.172861	0.1829	0.192939	0.202978	0.213017
TI2	0.37094	0.36365	0.356359	0.349069	0.341778	0.334488	0.327197	0.319907	0.312616	0.305326	0.298035
TI3	0.176107	0.175404	0.1747	0.173997	0.173294	0.172591	0.171887	0.171184	0.170481	0.169778	0.169074
TI4	0.174961	0.194029	0.213097	0.232165	0.251233	0.270302	0.28937	0.308438	0.327506	0.346574	0.365643
TI5	0.217094	0.218883	0.220673	0.222462	0.224252	0.226041	0.227831	0.22962	0.23141	0.233199	0.234988
TI6	0.176332	0.179735	0.183138	0.186541	0.189944	0.193347	0.19675	0.200153	0.203556	0.206959	0.210362
TI7	0.473016	0.467782	0.462547	0.457313	0.452079	0.446845	0.44161	0.436376	0.431142	0.425908	0.420673
TI8	0.153114	0.160202	0.167291	0.17438	0.181469	0.188558	0.195647	0.202736	0.209825	0.216914	0.224003
TI9	0.176107	0.178239	0.18037	0.182502	0.184633	0.186765	0.188897	0.191028	0.19316	0.195291	0.197423
TI10	0.412698	0.417703	0.422707	0.427711	0.432715	0.437719	0.442723	0.447727	0.452731	0.457735	0.46274
TI11	0.217094	0.224324	0.231553	0.238783	0.246013	0.253242	0.260472	0.267701	0.274931	0.282161	0.28939
TI12	0.021255	0.035871	0.050487	0.065102	0.079718	0.094334	0.10895	0.123565	0.138181	0.152797	0.167413
TI13	0.009614	0.008653	0.007692	0.00673	0.005769	0.004807	0.003846	0.002884	0.001923	0.000961	0

Table 10
Ranking of the alternatives.

Alternative/Sensitivity	v = 0	v = 0.1	v = 0.2	v = 0.3	v = 0.4	v = 0.5	v = 0.6	v = 0.7	v = 0.8	v = 0.9	v = 1
TI1	3	3	3	3	3	3	4	4	4	5	6
TI2	11	11	11	11	11	11	11	11	10	10	10
TI3	7	5	5	4	4	4	3	3	3	3	3
TI4	5	8	8	9	10	10	10	10	11	11	11
TI5	9	9	9	8	8	8	8	8	8	8	8
TI6	8	7	7	7	7	7	7	6	6	6	5
TI7	13	13	13	13	13	13	12	12	12	12	12
TI8	4	4	4	5	5	6	6	7	7	7	7
TI9	6	6	6	6	6	5	5	5	5	4	4
TI10	12	12	12	12	12	12	13	13	13	13	13
TI11	10	10	10	10	9	9	9	9	9	9	9
TI12	2	2	2	2	2	2	2	2	2	2	2
TI13	1	1	1	1	1	1	1	1	1	1	1

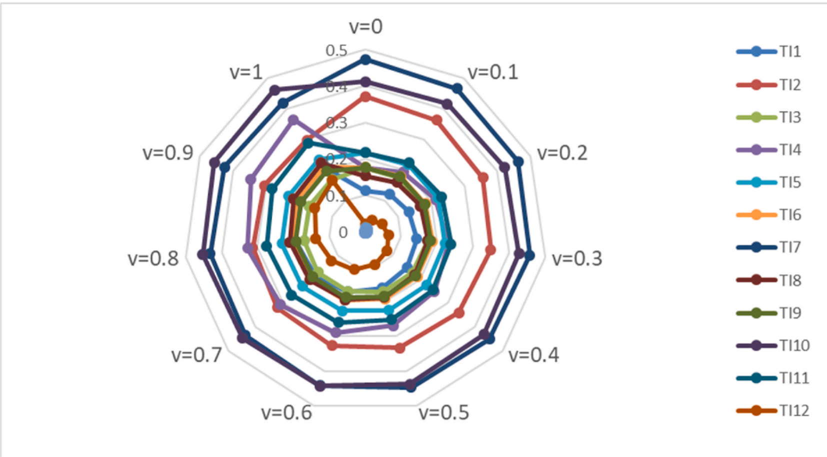

Fig. 2. Sensitivity analysis of "Q" values.

rection towards innovation (TI13), Market direction towards innovation (TI12) and Technology change (TI1), are consistent with the current approach. In nearly every experiment, there is a minor discrepancy in the prioritized list of remaining factors. The existing study's findings confirm that the recommended model is robust and less sensitive to criteria weights.

According to the study's findings, 'entrepreneurship direction toward innovation' is an important factor for technological innovation toward sustainability in the Indian context. This factor has the lowest Q_i value and ranks first in the analysis. Both innovation and entrepreneurship are viewed as potential factors in meeting global challenges such as climate change and sustainable energy (Ionescu et al., 2020). In addition, a conceptual framework identifies stakeholder engagement for innovation management and entrepreneurship development (Leonidou et al., 2020), but also as the enabling factor for sustainability in the context of manufacturing (D'Adamo, 2022).

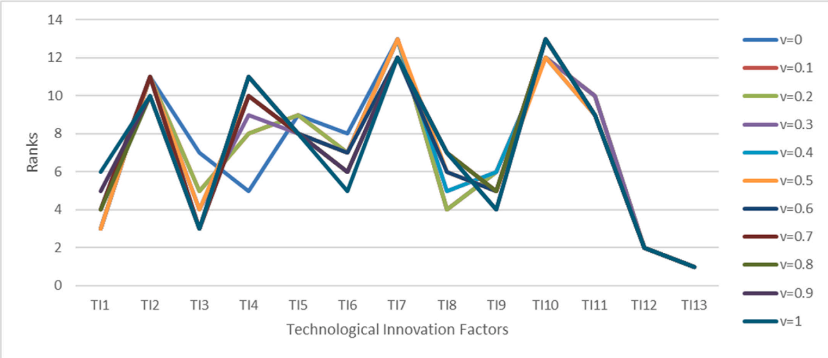

Fig. 3. Sensitivity analysis of rankings.

Among the 13 identified potential factors to technological innovation toward sustainability, the factor 'market direction toward innovation' has risen to second place. Market innovation is defined as changing the way businesses operate (Kjellberg et al., 2015). Furthermore, market innovation entails incorporating technical, social, and cultural aspects into changing market scenarios through the collaboration of manufacturers and consumers (Sprong et al., 2021). Some findings emphasize the interactions among innovation and sustainability, acknowledging that digital transformation tools commit to the value creation process over time (Di Vaio et al., 2021). Industry 4.0 technology appears to be environmentally sustainable, as it produces goods more efficiently and consumes fewer resources (Javaid et al., 2022).

The factor 'technology change' emerged in third place in the analysis. Information systems can play a significant role as a mechanism for improving sustainable indicators, making them an important promoter of technological change (Bengtsson and Ågerfalk, 2011). According to some findings, economic growth and material flows are the primary drivers of CO_2 emissions (Schandl et al., 2016). Technological progress has the potential to help reduce these emissions (Leitão et al., 2022). In the manufacturing context, the economic dimension is important, but the significance of sustainable technology on the supply side and responsible consumption on the demand side cannot be ignored (Dwivedi et al., 2023b).

'Uncertain environment on technological innovation' is listed as the fourth important factor for technological innovation toward sustainability in manufacturing organizations. Some authors investigated the impact of an uncertain environment on green technological innovation in industries (Cheng et al., 2023). To improve production efficiency and market competitiveness, businesses must change their production methods through green technological innovation. This can be achieved by integrating sustainability concepts within university pathways in order to integrate the technological process with the use of materials with low environmental impact (Ocampo-López et al., 2019), encouraging recycling practices (Ferella et al., 2010) and combining the different goals of sustainability (Soni et al., 2022).

The fifth essential factor for technological innovation in the manufacturing industry has been identified as "attitude toward innovation". In the background of innovation, the behavior of managers and other stakeholders in the manufacturing industry have received more attention (Chapman and Hewitt-Dundas, 2018). Top management support for innovation is critical for developing an industry-wide innovation-centric environment (Kraiczy et al., 2015). Employees are further motivated to participate in innovation practices when they have a positive attitude toward innovation. Innovation produces changes on the social perspective (regulations, attitudes) and on the technical perspective (infrastructure, production processes) - (Blum et al., 2017). The literature pays attention to the social attitude and behavior that requires knowledge exchange, education and regulatory relief measures toward a low-carbon transition (Papamichael et al., 2022).

In this analysis, 'market knowledge' is identified as the sixth essential factor for technological innovation. Some authors investigated the interactions between technological innovation capabilities and market knowledge (Yu et al., 2017). In addition, the relevance of market knowledge on an industry's long-term competitive advantage is investigated. Market knowledge is identified as a factor accountable for the acceptable performance of green product innovation with the goal of promoting stakeholder engagement (Redante et al., 2019). Based on the increased Q_i value, other factors are analyzed in this study but have less relevance. However, in order to arrive at an overall performance that is effective and efficient, it is essential to consider the entire set of factors. The prioritized list of factors can assist the industry managers to consider the factors that are most important and put less concentration on the factors that are at the bottom of the list.

Finally, it emerges from this study that the paradigm shift from linear to circular requires several aspects to be considered. One aspect that cuts across the factors analyzed is that of sustainable education (Biancardi et al., 2023) and building a framework in which innovation is based on citizen engagement and training (Eliades et al., 2022).

The CE model mainly concerns the materiality of physical resources, however, a theme to be explored is that of human resources. In fact flexibility, principles from the school of human relations, but especially concepts from the sustainable development goals with stakeholder involvement will play a key role (Ali et al., 2023).

4.1. Managerial implications

Technological innovation is considered essential to contribute towards sustainability and circular practices in various organizations. The existing literature is inadequate to identify the factors of technological innovation in the context of manufacturing organizations for emerging economy like India. This research has attempted to narrow this gap. The present study could assist managers and practitioners comprehend the factors of technological innovation. The managerial implications can be outlined as follows.

- The factor 'uncertain environment on technological innovation' reflects that the manager's perception of real choices in their organization will have positive consequences for technological innovation (Verdu et al., 2012). This would lead to efficient working of the organizations under uncertain environment conditions.
- Technology change assists organizations develop acceptability, consumer interaction and understanding among various stakeholders towards progress. Also, the technology change requires change in management and perception in the attainment of managerial and organizational prospects (Matarazzo et al., 2021).
- The managers of business organizations are suggested to study the significance of technological innovation on organization performance with the contributions towards sustainability (Zhang et al., 2019).

4.2. Limitations

Even if this study identified a set of factors for technological innovation to foster the development of sustainable practices, showing the effectiveness of quantitative approaches to identify the most suitable strategies of manufacturing firms in developing countries, one of its main limitations is the lack of analysis of how the factors detected could be monitored to evaluate their relevance in developed countries, and at the same time to consider synergies at the global level.

A further limitation of this research emerges from the fact that this study is based on the knowledge of experienced people, as changing the panel of experts could change the results. However, no alternative scenario can be evaluated unless preliminary analyses are provided.

Concerning quantitative tools, in this analysis Grey VIKOR approach has been used to evaluate the impact of technological innovation towards sustainability in manufacturing industry. This could be a methodological limit other MCDM tools, (e.g., TISM, TOPSIS, ANP and DEMATEL) could be employed.

Finally, in the present study, the experts were selected from a specific region, and this can represent a limitation when the aim is to extend the results found at the national level, leading to the need to extend the survey on a wider scale.

5. Conclusions and future research directions

This study identifies and proposes a set of thirteen potential factors for technological innovation to foster the development of sustainable practices in manufacturing sectors. These include technical ones in the top positions as opposed to social and environmental ones. The first two most relevant factors are entrepreneurship direction towards innovation and market direction towards innovation, followed by technology change, uncertain environment on technological innovation and attitude towards innovation. The results of this study show how quantitative approaches are essential for identifying the strategies of manufacturing firms in developing countries.

Sustainability is a challenge that cannot be won at the local level. CE models allow for rethinking the structure of business, and the literature highlights how redefining material flows generates economic opportunities while at the same time pursuing social equity and countering climate change. This is a challenge that cannot be met unless changes in production patterns are joined by changes in consumption patterns. The main implications of this study identify how sustainable education and stakeholder engagement can cut across different factors by directing technological innovation to move toward circular choices. CE models are capable of adding value to manufacturing sector activities.

This study proposes analyses under baseline and alternative scenarios, using an established methodology Grey VIKOR. Clearly, expert support provides a characteristic of subjectivity to the reported values, but nevertheless it appears to be valid since it is based on the knowledge of experienced people.

Grey VIKOR approach is adopted in this study to cater the evaluation problem of technological innovation towards sustainability in manufacturing industry, various other MCDM tools, such as TISM, TOPSIS, ANP and DEMATEL, can be practiced in future to address such problems. In the present study, the experts were selected from a particular region. To speculate the result and to make it relevant at the national level, it is recommended that the survey to be performed on a larger scale.

Technological innovation combined with CBMs is thus a long-term strategy. In fact, this mix is an opportunity to develop low-carbon economies by combining human and ecosystem needs.

CRediT authorship contribution statement

Ashish Dwivedi: Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Claudio Sassanelli:** Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Dindayal Agrawal:** Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Ernesto Santibañez Gonzalez:** Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Idiano D'Adamo:** Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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