Journal of Future Sustainability 5 (2025) 165–178

Contents lists available at GrowingScience

Journal of Future Sustainability

homepage: www.GrowingScience.com/jfs

Sustainable green manufacturing in the era of Industry 4.0 projects: A fuzzy TOPSIS based analysis

V.K. Chawla[a*] and Urfi Khan[a], Ananya Dixit[a], Kriti Mittal[a] and Khushi Pandey[a]

[a]*Department of Mechanical and Automation Engineering, Indira Gandhi Delhi Technical University for Women, India*

C H R O N I C L E

Article history:
Received: January 1, 2024
Received in revised format: June 2, 2024
Accepted: September 1, 2024
Available online: September 1, 2024

Keywords:
Fuzzy TOPSIS
Industry 4.0
Sustainable Green Manufacturing

A B S T R A C T

The advent of Industry 4.0 has revolutionized manufacturing, integrating advanced technologies to enhance efficiency and sustainability. However, the transition to sustainable green manufacturing presents numerous challenges. This paper analyzes these challenges using the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). By incorporating expert opinions and fuzzy logic, various obstacles are evaluated and prioritized in the implementation of green manufacturing practices in the context of Industry 4.0. The analysis reveals that market uncertainty in the economic landscape ranks as the top challenge, followed by high costs of implementation, maintenance, security, and integration. Uncertain benefits and trade-offs are also found as significant barriers. Key factors include the need for substantial investments, cybersecurity concerns, integration difficulties, and the complexities of predicting returns on investment. From the study, it is also evident that the impact of Industry 4.0 on supply chains and emissions from Electronics manufacturing is also a critical issue. The study provides actionable insights and strategic recommendations for policymakers and industry leaders to facilitate the adoption of sustainable green manufacturing practices in the era of Industry 4.0.

1. Introduction

Green manufacturing is defined as a financially driven, comprehensive, and coordinated approach to minimizing and eliminating all waste streams associated with the design, production, usage, and disposal of products and materials. Green Manufacturing has evolved significantly, becoming a focal point in both research and practice, prioritizing environmental impact reduction through waste minimization, resource optimization, and emission control. The concept has expanded to Sustainable Green Manufacturing (SGM), which integrates economic, social, and environmental dimensions, known as the triple bottom line (TBL) (Elkington, 1994; Chawla et al., 2021; Gupta et al., 2022; Aggarwal & Chawla, 2021).). SGM represents a paradigm shift in industrial production, aligning with global commitments for sustainability. In the era of Industry 4.0, integrating digital technologies and automation, the imperative for SGM is compelling for best decisions (Chawla et al., 2020; Kamble et al., 2018). However, this convergence presents challenges at the intersection of technology and sustainability. This research analyzes these challenges employing the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) as the method of analysis. The findings provide valuable insights for industry leaders, policymakers, and practitioners, facilitating the transition to sustainable manufacturing practices in the Industry 4.0 landscape.

In their study, Burke & Gaughran (2007) proposed a novel sustainability framework that recognizes green manufacturing, based on the experiences of small and medium-sized enterprise (SME) manufacturers who have obtained ISO 14001 certifications. Implementation of green manufacturing not only enhances corporate image but also results in improved competitiveness and marketing performance, ultimately leading to enhanced overall organizational performance. Angell & Klassen (1999) further emphasized that green manufacturing contributes to the growth of the economy, environmental conservation, and social well-being by reducing waste and costs.

* Corresponding author.
E-mail address: vivekchawla@igdtuw.ac.in (V. K. Chawla)

ISSN 2816-8151 (Online) - ISSN 2816-8143 (Print)

doi: 10.5267/j.jfs.2025.9.001

1.1 Green manufacturing in small and medium-sized enterprises (SMEs)

In 1995, Sarkis & Rashid elucidated the potential advantages inherent in Environmental Cost Management (ECM), accentuating improvements in facility safety, operational cleanliness, long-term cost reductions, mitigated environmental risks, and heightened product quality. Transitioning to 2003, Senthil et al. introduced an intricate life cycle environmental cost analysis amalgamating costing into life cycle accounting, furnishing a conceptual framework to assess and correlate environmental costs across all stages of a product's life cycle. Tseng et al. (2006) posited the significance of abating waste and emissions at the origin, contending that such measures could amplify both environmental and economic efficacy for organizations. In 2005, Ammenberg and Sundin scrutinized the factors influencing environmental management systems, with a specific emphasis on the formulation of environmentally and product-oriented management systems. In 2011, Santolaria et al. delved into Green Manufacturing drivers, elucidating these in terms of operational efficiencies, innovation, cost management, brand positioning, and communicative strategies. Yacob et al. (2012) underscored various impetuses for the integration of green practices by Malaysian SMEs, encompassing financial advantages, monetary incentives, stakeholder requisites, legislative compliance, resource allocation, motivational factors, and inspirational influences. The prominence of state regulations, customer expectations, internal motivation, and corporate performance are observed by Agan et al. (2013) as pivotal drivers in the realm of Green Manufacturing.

While the Brundtland Commission's delineation of sustainable development enjoys widespread recognition, its pragmatic applicability to manufacturing business and engineering leaders remains wanting. Despite the existence of various proposed definitions for sustainable manufacturing, a universally accepted standard is yet to emerge. The U.S. Department of Commerce (DOC) posits sustainable manufacturing as the creation of goods through processes that mitigate adverse environmental impacts, conserve energy and natural resources, ensure the safety of stakeholders, and demonstrate economic viability. It is pertinent to note a contradiction with prior author statements, as this definition neglects the pivotal concept of closing resource loops. Nevertheless, the DOC's effort to inject meaning into the term has contributed to the acknowledgment of sustainable manufacturing. As researchers, the imperative lies in addressing environmental concerns, augmenting societal advantages, and progressing the comprehension of sustainability within the expansive manufacturing community (Chawla et al., 2022).

The sustainability audit discerned challenges in evaluating sustainability, underscoring the imperative of collaborative endeavors and a more comprehensive cultural grasp. Methodologically, it underscored the inadequacy of individual methods in tackling inquiries within the realm of sustainability science. Guidelines have been introduced to empower managers in the identification and measurement of sustainability metrics, featuring optimal attributes. Drawing upon the precedent set by Wanigarathne et al. (1997), the study posited six factors influencing manufacturing sustainability, with three being readily quantifiable and three proving less amenable to measurement. General Motors emphasizes the paramountcy of sustainability metrics aligning with stakeholder needs, fostering innovation, and harmonizing with diverse business units. Regarding conceivable measurements for economically efficient assembly structures, the emphasis rests on realizable machining, encompassing financial, environmental, and social facets. The incorporation of sustainability into the sphere of product and process development necessitates the formulation of novel models, strategies, metrics, and approaches, underscoring the nexus between sustainability and organizational metamorphosis. In a nuanced content analysis, one article was found to deliberate on the integration of business elements, whereas eight articles delved into sustainability or the Triple Bottom Line (TBL) intertwined with business elements. These encompass various facets such as processes, decision-making, value creation, manufacturing practices, business procedures, production, technical and organizational measures, and operational and business activities.

1.2 Sustainable Green Manufacturing and Industry 4.0

The relationship between Sustainable Green Manufacturing (SGM) and Industry 4.0 is intricate and mutually beneficial, as revealed in the studies by Machado et al. (2020), Ghadge et al. (2022), and Stock & Seliger (2016), Chanda et al, 2018; Chawla et al., 2018. Machado et al. (2020) and Ghadge et al. (2022) define SGM as focusing on sustainability within the manufacturing domain, converging with Industry 4.0, which signifies Industry 4.0 as the integration of digital technologies into manufacturing processes. This convergence is notably evident in overlapping practices such as design, remanufacturing, and recycling, identified by Machado et al. (2020) and Ghadge et al. (2022). Delving into the sustainability benefits, the works of Stock & Seliger (2016), Machado et al. (2020), and Ghadge et al. (2022) collectively assert that Industry 4.0 brings substantial contributions to productivity, flexibility, and resource efficiency, aligning seamlessly with the core tenets of SGM. This alignment is not merely theoretical, as Stock & Seliger's study (2016) specifically demonstrates how Industry 4.0 practices, such as closed-loop cycles facilitated by smart data, empirically support sustainability objectives. Furthermore, the impact of Industry 4.0 solutions on sustainability dimensions is comprehensively explored by Bonvoisin et al. (2017), Machado et al. (2020), and other researchers. These studies collectively emphasize that Industry 4.0 not only directly influences environmental, economic, and social sustainability but also indirectly affects these dimensions. The interconnectedness between SGM and Industry 4.0, evident in shared practices and empirical evidence of mutual contributions to sustainability, underscores a mutualistic relationship that holds promise for fostering environmentally conscious and efficient manufacturing practices. Table 1: summarizes the key findings regarding the interdependencies between SGM and Industry 4.0. It highlights the definitions & concepts, shared practices, sustainability benefits of Industry 4.0, and Impact on

Sustainability Dimensions, providing a concise overview supported by relevant sources.

Table 1
Interdependencies of Sustainable green manufacturing and Industry 4.0

S.NO.	Field of research	Description	Researchers
1.	Definitions andConceptualization	SGM focuses on sustainability in manufacturing. Industry 4.0 integratesdigital tech	Stock & Seliger (2016) Machado et al. (2020), Ghadgeet al. (2022)
2.	Shared Practices	Emphasize shared practices: design,remanufacturing, recycling.	Machado et al. (2020), Ghadgeet al. (2022)
3	SustainabilityBenefits of Industry 4.0	Contributes to productivity, flexibility, andresource efficiency. Supports sustainabilitythrough smart data, closed-loop cycles, etc.	Stock & Seliger (2016), Machado et al. (2020), Ghadgeet al. (2022)
4.	Impact on SustainabilityDimensions	Industry 4.0 solutions impact sustainabilitydimensions directly and indirectly.	Bonvoisin et al. (2017), Machado et al. (2020), Ghadgeet al. (2022)

2. Analysis of sustainable green manufacturing challenges in Industry 4.0 using Fuzzy TOPSIS

In the era of Industry 4.0, characterized by the pervasive integration of digital technologies and automation into manufacturing processes, the pursuit of sustainable green manufacturing (SGM) takes on a paramount role. While Industry 4.0 promises increased efficiency, productivity, and innovation, it also brings forth a complex tapestry of challenges that intersect with the principles of environmental sustainability and social responsibility. Successful implementation of SGM practices within this high-tech landscape requires a nuanced understanding of the interdependencies and obstacles that arise. This introductory exploration delves into the analysis of the challenges encountered when harmonizing the realms of Industry 4.0 and sustainable green manufacturing, shedding light on the critical issues, potential solutions, and the imperative for a more eco-conscious and technologically advanced future of manufacturing.

Table 2
Analysis of Sustainable Green Manufacturing Challenges

Criteria	Challenges	Description
Environmental Impact	Increased Power Consumption (Sezen & Çankaya, 2013)	Industry 4.0 technologies can raise energy demands, potentially straining resources and in carbon emissions
	Electronic Waste (E-Waste) (Callahan et al., 1997)	The rapid turnover ofhigh-tech equipment leads to a growing the problem of electronic disposal and recycling.
	Resource Depletion (Sezen & Cankaya, 2013)	The production of advanced technologycomponents may contribute to the depletion of finite resources.
	Supply Chain Impacts (Beier et al., 2022)	Industry 4.0 systems can disrupt traditional supply chains, posing challenges in terms of resource allocation and management.
	Emissions from Electronic Manufacturing (Boks et al., 1998)	The production of electronic components can result in greenhouse gas emissions and envi pollution.
	Market uncertainty about the availability of green suppliers (Mittal et al., 2013)	Businesses may face uncertainty in finding reliable, environmentally-friendly suppliers ir ing Industry 4.0 landscape.
	Lack of awareness about green practices within the organization and among customers. (Kumar, 2021)	Many organizations and individuals may lack awareness of sustainable practices in the co Industry 4.0.
	Lack of technical support on Green-practices. (Kumar, 2021)	Access to technical guidance and support for implementing green practices in Industry 4.(limited, hindering sustainability efforts.
Societal Impact	Skill Gaps and Workforce Transition (Ngai et al., 2011)	The rapid technological advancements may lead to skill gaps among the workforce, hinde ability to utilize new technologies effectively.
	Ethical & Privacy Concerns (Rahanu et al., 2021)	Industry 4.0 technologies raise ethical dilemmas and privacy issues, particularly regardin lection and usage.
	Worker's well-being concern Kumar (2021)	Ensuring the physical and mental the well-being of workers in increasingly automated anc high-tech environments is a significant challenge.
	Lack of Communication and Engagement. (Mittal et al., 2013)	Effective communication and engagement with employees and stakeholders about the ber implications of Industry 4.0 can be challenging.
	Disruption of Social Infrastructure (Ngai et al., 2013)	The rapid adoption of new technologies can disrupt social and community structures, requiring thoughtful adaptation.
	Lack of guidance and rules on sustainability and lack of standardization (Kumar, 2021)	The absence of clear guidelines and regulations for sustainable practices.
Economic Impact	Sustainability Investments (Rusinko, 2007)	Allocating funds for sustainability initiatives within Industry 4.0 can be a financial challenge for many organizations.
	Market Uncertainty Mittal et al., 2013	Rapid technological advancements can create uncertainty in terms of market demands and the longevity of investments in Industry 4.0.
	High Maintenance Security and Integration Cost (Rajput & Datta 2020)	Ongoing expenses for maintaining, securing, and integrating Industry 4.0 technologies can strain budgets.
	Global Competition (Rajput & Datta 2020)	Stiff competition on a global scale necessitates substantial investments in technology and innovation to remain competitive.
	Uncertain benefits & trade-offs (Mittal et al., 2013)	Organizations may grapple with uncertainty regarding the benefits and potential trade-offs of Industry 4.0 adoption
	Neglected approach and lack of dedicated funds for sustainable projects (Rusinko 2007)	Sustainability initiatives may be overlooked, with insufficient funds allocated for SGM projects.

Sustainability encompasses the three fundamental aspects of the environment, economy, and society. With the integration of Information Technology (IT) in manufacturing as part of Industry 4.0 (I4.0), the adoption of sustainable practices has gained increased relevance. This emphasis on sustainable practices holds particular significance in developing economies.

Sangwan (2011) emphasized the necessity of sustainable industrial development in countries like India. After conducting a comprehensive review of the literature and consulting with experts, twenty challenges related to the implementation of sustainable manufacturing in Indian industries were identified. To gather insights from experts, a survey was carried out, involving academic professionals. The Fuzzy TOPSIS technique was employed to design an opinion form or questionnaire for collecting responses. The questionnaire was structured in a matrix format, employing a rating scale ranging from 0 to 4, where each rating corresponded to a level of influence (e.g., No influence, 0; Very low influence, 1; Low influence, 2; High influence, 3; Very High influence, 4). The challenges related to sustainable manufacturing are detailed in the Table 2 above.

3. Fuzzy TOPSIS methodology

The Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) methodology is selected due to its adept handling of uncertainty and imprecision inherent in sustainable green manufacturing in the context of Industry 4.0. It accommodates vague or fuzzy data crucial for real-world challenges and supports multi-criteria decision-making, vital for assessing sustainability in diverse manufacturing settings. Fuzzy TOPSIS is renowned for capturing decision-makers' preferences, and accommodating subjective judgments, and is widely recognized across various fields, making it a reliable choice for analyzing challenges in implementing sustainable green manufacturing in the Industry 4.0 era. The TOPSIS technique emerges as a pragmatic and efficient approach for decisions involving multiple criteria, utilizing benefit and cost categories to generate ideal solutions. Studies conducted by Mittal and Sangwan (2014), Wang and Lee (2009), Mahdavi et al. (2008), Awasthi et al. (2011), Sun (2010), Sadjadi & Sadi-Nezhad (2017), Naieni et al. 2019, Yadav & Chawla (2022) and Chawla et al., (2024). provide further insights into this strategy. To address uncertainty and bias, linguistic term guidelines provided by triangular fuzzy number (TFN) and observed to be essential in the application of Fuzzy TOPSIS by countering the challenge of translating human judgments accurately Yadav & Chawla (2022) and Chawla et al., (2024). This decision-making approach involves exploring alternatives and considering numerous criteria for a systematically prioritized ranking of challenges, as highlighted by Wang and Lee (2009). A set of three values, denoted by a triangular fuzzy number (TFN) as (a_1, a_2, a_3) serves as a representation. This approach finds extensive usage due to its straightforward computational nature. The membership function u•(x) associated with TFN's characteristics can be explored in the work by Mittal and Sangwan (Mittal and Sangwan, 2014). Let's assume there exist a total of m challenges, labeled as A_i (where *i = 1, 2, ..., m*), requiring assessment against *n* selection criteria denoted as c_j (where *j = 1, 2, ..., n*). The objective revolves around prioritizing the challenges based on their relative significance concerning the selection criteria. The process involves the following steps (Refer to Fig. 1).

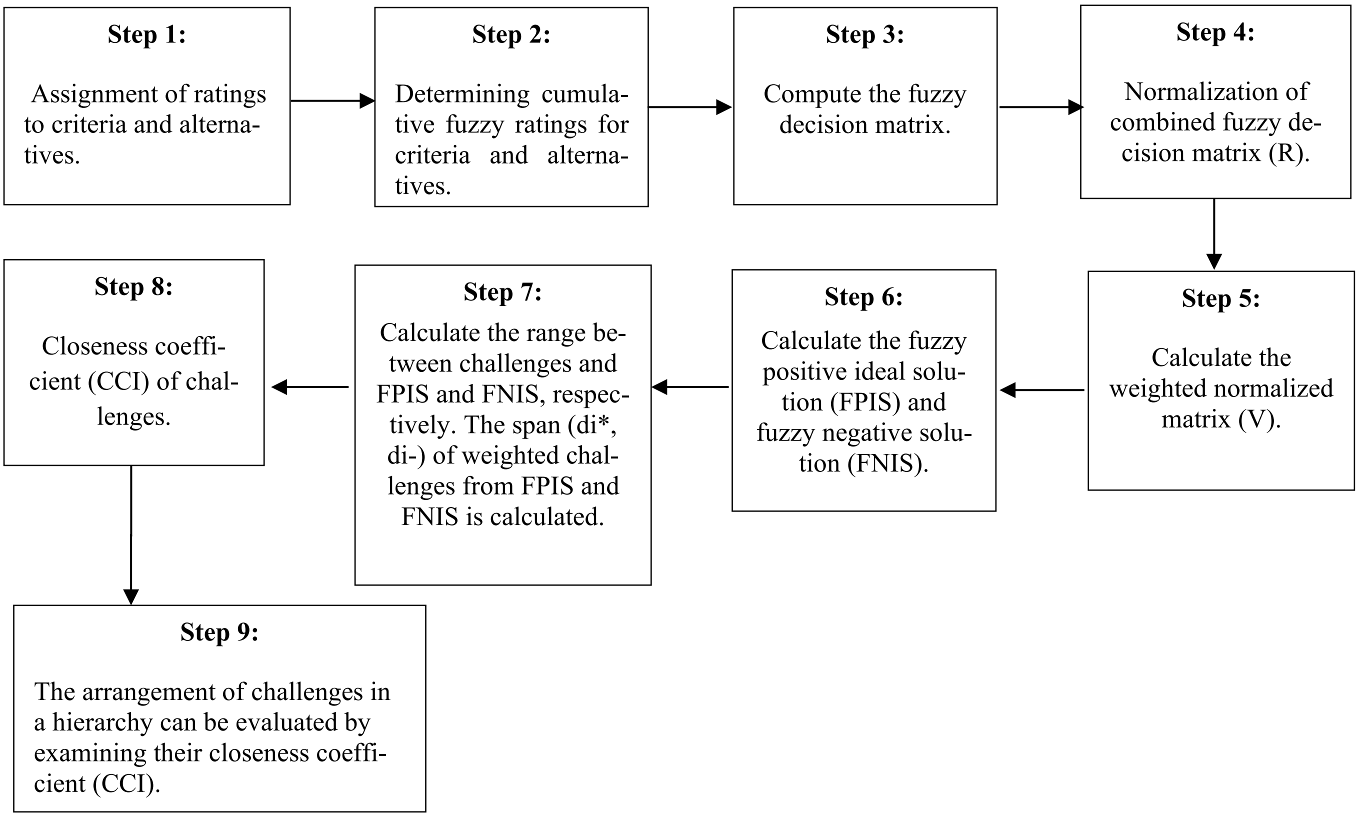

Fig. 1. A Fuzzy TOPSIS methodology flow chart

Step 1: Assignment of ratings to the criteria and alternatives.

Initially, the decision-maker D_k , assigns ratings to both the criteria and available alternatives. These relationship ratings pertain to each challenge concerning specific criteria. This is done independently for each D_k . Additionally, D_k also specifies the weight of each criterion.

Step 2: Determining Cumulative Fuzzy Ratings for Criteria and Alternatives

Collective fuzzy ratings, referred to as TFN, are calculated across all decision-makers. Each decision-maker's fuzzy rating is symbolized as R_k, represented as a_k, b_k, c_k where *k* denotes

different decision-makers (e.g., *1, 2, ... K*). The overall aggregate fuzzy rating is presented as $R_k = (a_k, b_k, c_k)$, where *k* ranges from *1* to *K*. The specific values are as follows:

a is the minimum value among a_k.

$$a = min\{a_k\} \tag{1}$$

b is calculated as the mean of all *bk* values across decision-makers ($\frac{1}{K} \times \sum b_k$ for $k = 1 \ to \ K$).

$$b = \frac{1}{K} \sum_{k=1}^{K} b_k \tag{2}$$

c represents the maximum value among c_k

$$c = max\{c_k\} \tag{3}$$

In instances where the fuzzy rating and significance weight for the *kth* decision-maker are denoted as

$x_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$ and $w_{ijk} = (w_{ijk}, w_{ijk}, w_{ijk})$, respectively, the combined fuzzy rating (x_{ijk})

for alternatives concerning each criterion is expressed as $x_{ij} = (a_{ij}, b_{ij}, c_{ij})$, where:

a_{ij} corresponds to the minimum of a_{ijk}.

$$a_{ij} = min\{a_{ijk}\} \tag{4}$$

b_{ij} is determined by averaging b_{ijk} values across decision makers $\frac{1}{K}\sum_{k=1}^{K} b_{ijk}$.

$$b_{ij} = \frac{1}{K} \sum_{k=1}^{K} b_{ijk} \tag{5}$$

c_{ij} represents the maximum among c_{ijk} .

$$c_{ij} = max\{c_{ijk}\} \tag{6}$$

The collective fuzzy weights (w_{ij}) or each criterion are computed as $w_{ij} = (w_{j1}\, w_{j2}\, w_{j3})$, with:
w_{j1} being the minimum value among w_{jk1} .

$$w_{j1} = min\{w_{jk1}\} \tag{7}$$

w_{j2} calculated as the mean of all w_{jk2} values across decision-makers $\frac{1}{K}\sum_{k=1}^{K} w_{jk2}$.

$$w_{j2} = \frac{1}{K} \sum_{k=1}^{K} w_{jk2} \tag{8}$$

w_{j3} represents the maximum value among w_{jk3} .

$$w_{j3} = max\{w_{jk3}\} \tag{9}$$

Step 3: Compute the fuzzy decision matrix.

The combined fuzzy decision matrix is given as:

$$D = \begin{matrix} & C_1 & C_2 \dots & C_n \\ A_1 \\ A_2 \\ A_3 \end{matrix} \begin{bmatrix} x_{11} & x_{12} \dots & x_{1n} \\ x_{21} & x_{22} \dots & x_{2n} \\ x_{m1} & x_{m2} \dots & x_{mn} \end{bmatrix} \quad (10)$$

Step 4: Normalization of combined fuzzy decision matrix (R) .
It is given by :

$$R = [r_{ij}]_{m \times n} \quad (11)$$

where,

$$r_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \text{ and } c_j^* = max_i\, c_{ij} \quad (12)$$

(benefit criteria)

$$r_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \text{ and } a_j^- = min_i\, a_{ij} \quad (13)$$

(cost criteria)

Step 5: Calculate the weighted normalized matrix V.

It is calculated by the product of (w_j) and r_{ij} where,

$$V = [v_{ij}]_{m\,X\,n} \qquad i = (1, 2, \dots m);\ j = (1, 2, \dots, n) \quad (14)$$

$$v_{ij} = r_{ij}(.)w_j \quad (15)$$

Step 6: Calculate the fuzzy positive ideal solution (FPIS) and fuzzy negative solution (FNIS). The FPIS and FNIS of the challenges are computed as follows:

$$A^* = (v_1^*, v_2^* .. v_n^*) \quad (16)$$

where $v_j^* = max\{ v_{ij3} \}$

$$A^- = (v_1, v_2 .. v_n) \quad (17)$$

where $v_j^- = min\{ v_{ij1} \}$

Step 7: Calculate the range between challenges and FPIS and FNIS, respectively.

The span (d_i^*, d_i^-) of weighted challenges from FPIS and FNIS is calculated as follows:

$$d_i^* = \sum_{j=1}^{n} d_v(v_{ij}, v_j^*) \quad (18)$$

$$d_i^- = \sum_{j=1}^{n} d_v(v_{ij}, v_j^-) \quad (19)$$

Step 8: Closeness coefficient (CCi) of challenges.

The closeness coefficient (CCi) denotes the range between FPIS (A*) and the FNIS (A-) and is computed as:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*} \quad (20)$$

Step 9: The arrangement of challenges in a hierarchy can be evaluated by examining their closeness coefficient CC_i. Challenges or obstacles with greater values of the proximity coefficient are deemed the most significant challenges; these are given the "first" rank. The remaining challenges are then ranked in decreasing order based on their proximity coefficients to handle uncertainty more effectively in upcoming research, there is potential to combine gray theory with TOPSIS. In this study, input is gathered from four decision-makers who provide their individual perspectives on obstacles and criteria weights using linguistic terms. These opinions are subsequently translated into fuzzy numbers. The criteria weights are then aggregated, and the linguistic terms, along with their corresponding fuzzy numbers, are detailed in Table 2. This tableoutlines the linguistic terms assigned to both criteria and challenges, accompanied by their respective membership functions represented as fuzzy numbers. Decision-makers express their responses to challenges related to criteria using linguistic terms, and these articulated weights, reflecting the decision-makers' viewpoints, are converted into fuzzy numbers. The challenges, as perceived by decision-makers, are presented as triangular fuzzy numbers in Table 3 and further refined into fuzzy numbers.

Table 3
Assessment of challenges and criteria

Assessment of challenges		Assessment of criteria	
Terminologies	Fuzzy Number	Terminologies	Fuzzy Number
Very low (VL)	(1,1,3)	Not important (NI)	(1,1,3)
Low (L)	(1,3,5)	Less important (LI)	(1,3,5)
Medium (M)	(3,5,7)	Fairly important (FI)	(3,5,7)
High (H)	(5,7,9)	Important (I)	(5,7,9)
Very high (VH)	(7,9,9)	Very important (VI)	(7,9,9)

Decision-makers express their responses to challenges related to criteria using linguistic terms, and these articulatedweights, reflecting the decision-makers' viewpoints, are converted into fuzzy numbers. The challenges, as perceivedby decision-makers, are presented as triangular fuzzy numbers in Table 4 (A) to Table 4 (D) and further refined intofuzzy numbers.

Table 4 (A)
Decision Maker 1 opinion in Fuzzy Number

DECISION MAKER 1									
Challenge No.	Environmental			Societal			Economic		
	7	9	9	3	5	7	1	3	5
1	7	9	9	3	5	7	3	5	7
2	7	9	9	1	3	5	1	1	3
3	3	5	7	3	5	7	3	5	7
4	5	7	9	1	3	5	5	7	9
5	7	9	9	3	5	7	1	3	5
6	3	5	7	3	5	7	5	7	9
7	3	5	7	5	7	9	1	3	5
8	3	5	7	3	5	7	1	3	5
9	1	1	3	5	7	9	3	5	7
10	1	1	3	5	7	9	3	5	7
11	1	1	3	5	7	9	3	5	7
12	1	3	5	3	5	7	5	7	9
13	1	3	5	7	9	9	3	5	7
14	5	7	9	5	7	9	1	3	5
15	3	5	7	3	5	7	7	9	9
16	1	3	5	1	3	5	7	9	9
17	1	3	5	3	5	7	7	9	9
18	1	3	5	5	7	9	3	5	7
19	7	9	9	3	5	7	7	9	9
20	3	5	7	1	3	5	5	7	9

Table 4(B)
Decision-maker 2 opinions in fuzzy no.

DECISION MAKER 2									
Challenge No.	Environmental			Societal			Economic		
	7	9	9	7	9	9	3	5	7
1	7	9	9	7	9	9	7	9	9
2	7	9	9	7	9	9	5	7	9
3	3	5	7	7	9	9	7	9	9
4	3	5	7	7	9	9	7	9	9
5	7	9	9	7	9	9	7	9	9
6	5	7	9	1	3	5	1	3	5
7	7	9	9	1	3	5	5	7	9
8	5	7	9	1	3	5	1	3	5
9	1	3	5	5	7	9	5	7	9
10	1	3	5	7	9	9	7	9	9
11	1	3	5	5	7	9	5	7	9
12	1	3	5	5	7	9	5	7	9
13	5	7	9	7	9	9	7	9	9
14	7	9	9	5	7	9	7	9	9
15	7	9	9	7	9	9	5	7	9
16	1	3	5	5	7	9	5	7	9
17	7	9	9	7	9	9	7	9	9
18	7	9	9	7	9	9	7	9	9
19	1	3	5	3	5	7	3	5	7
20	5	7	9	5	7	9	3	5	7

Table 4(C)
Decision-maker 3 opinion in fuzzy no.

DECISION MAKER 3									
Challenge No.	**Environmental**			**Societal**			**Economic**		
	7	9	9	3	5	7	3	5	7
1	7	9	9	3	5	7	7	9	9
2	7	9	9	1	3	5	7	9	9
3	3	5	7	3	5	7	3	5	7
4	1	3	5	5	7	9	5	7	9
5	1	1	3	1	3	5	1	3	5
6	3	5	7	3	5	7	1	3	5
7	1	3	5	5	7	9	3	5	7
8	7	9	9	1	3	5	5	7	9
9	3	5	7	5	7	9	1	3	5
10	1	1	3	3	5	7	5	7	9
11	7	9	9	1	1	3	3	5	7
12	5	7	9	3	5	7	1	3	5
13	3	5	7	1	3	5	3	5	7
14	1	3	5	3	5	7	5	7	9
15	3	5	7	3	5	7	3	5	7
16	5	7	9	1	3	5	5	7	9
17	1	3	5	3	5	7	7	9	9
18	3	5	7	5	7	9	1	1	3
19	5	7	9	1	3	5	7	9	9
20	1	3	5	5	7	9	1	1	3

Table 4(D)
Decision-maker 4 opinion in fuzzy no

DECISION MAKER 4									
Challenge No.	Environmental			Societal			Economic		
	7	9	9	5	7	9	3	5	7
1	7	9	9	3	5	7	7	9	9
2	7	9	9	3	5	7	1	3	5
3	3	5	7	5	7	9	5	7	9
4	3	5	7	1	3	5	3	5	7
5	7	9	9	1	3	5	1	3	5
6	3	5	7	5	7	9	5	7	9
7	3	5	7	5	7	9	1	3	5
8	3	5	7	1	3	5	1	3	5
9	1	3	5	5	7	9	1	3	5
10	1	3	5	5	7	9	1	3	5
11	1	3	5	5	7	9	1	3	5
12	1	3	5	3	5	7	3	5	7
13	1	3	5	7	9	9	3	5	7
14	5	7	9	5	7	9	5	7	9
15	3	5	7	1	3	5	7	9	9
16	1	3	5	1	3	5	7	9	9
17	1	3	5	3	5	7	7	9	9
18	1	3	5	3	5	7	3	5	7
19	1	3	5	3	5	7	5	7	9
20	1	3	5	1	3	5	5	7	9

The combined decision matrix of challenges, considering SGM and I4.0 integration, is outlined in Table 5, aligning with steps 2 and 3 of the fuzzy TOPSIS methodology. Table 6 illustrates the normalized fuzzy decision matrix, computed using the equation outlined in step 4.

Table 5
Combined decision matrix

Challenge No.	**Environmental**			**Societal**			**Economic**		
1	7	9	9	3	6	9	3	8	9
2	7	9	9	1	5	9	1	5	9
3	3	5	7	3	6.5	9	3	6.5	9
4	1	5	9	1	5.5	9	3	7	9
5	1	7	9	1	5	9	1	4.5	9
6	3	5.5	9	1	5	9	1	5	9
7	1	5.5	9	1	6	9	1	4.5	9
8	3	6.5	9	1	3.5	7	1	4	9
9	1	3	7	5	7	9	1	4.5	9
10	1	2	5	3	7	9	1	6	9

Table 5
Combined decision matrix (Continued)

Challenge No.	Environmental			Societal			Economic		
11	1	4	9	1	5.5	9	1	5	9
12	1	4	9	3	5.5	9	1	5.5	9
13	1	4.5	9	1	7.5	9	3	6	9
14	1	6.5	9	3	6.5	9	1	6.5	9
15	3	6	9	1	5.67	9	3	7.5	9
16	1	4	9	1	4	9	5	8	9
17	1	4.5	9	3	6	9	7	9	9
18	1	5	9	3	7	9	1	5	9
19	1	5.5	9	1	4.5	7	3	7.5	9
20	1	4.5	9	1	5	9	1	5	9

The normalized fuzzy decision matrix, crafted through the application of the formula specified in step 4, represents a comprehensive evaluation of the data which is shown in Table 6. This process involves scaling the values within the matrix to ensure a standardized and comparable framework. By employing this equation, the matrix becomes a refined tool for assessing and comparing the various factors, contributing to a clearer understanding of their relative importance and impact within the given context.

Table 6
Normalized fuzzy decision matrix

Challenge No.	Environmental			Societal			Economic		
1	0.78	1	1	0.33	0.67	1	0.11	0.13	0.33
2	0.78	1	1	0.11	0.56	1	0.11	0.2	1
3	0.33	0.56	0.78	0.33	0.72	1	0.11	0.15	0.33
4	0.11	0.56	1	0.11	0.61	1	0.11	0.14	0.33
5	0.11	0.78	1	0.11	0.56	1	0.11	0.22	1
6	0.33	0.61	1	0.11	0.56	1	0.11	0.2	1
7	0.11	0.61	1	0.11	0.67	1	0.11	0.22	1
8	0.33	0.72	1	0.11	0.39	0.78	0.11	0.25	1
9	0.11	0.33	0.78	0.56	0.78	1	0.11	0.22	1
10	0.11	0.22	0.56	0.33	0.78	1	0.11	0.17	1
11	0.11	0.44	1	0.11	0.61	1	0.11	0.2	1
12	0.11	0.44	1	0.33	0.61	1	0.11	0.18	1
13	0.11	0.5	1	0.11	0.83	1	0.11	0.17	0.33
14	0.11	0.72	1	0.33	0.72	1	0.11	0.15	1
15	0.33	0.67	1	0.11	0.63	1	0.11	0.13	0.33
16	0.11	0.44	1	0.11	0.44	1	0.11	0.13	0.2
17	0.11	0.5	1	0.33	0.67	1	0.11	0.11	0.14
18	0.11	0.56	1	0.33	0.78	1	0.11	0.2	1
19	0.11	0.61	1	0.11	0.5	0.78	0.11	0.13	0.33
20	0.11	0.5	1	0.11	0.56	1	0.11	0.2	1

Table 7 presents the weighted normalized fuzzy decision matrix, a result of step 5, where criteria weights are multiplied by the corresponding weights given to each criterion. This matrix offers a comprehensive view of the combined impact of criteria and challenges, providing valuable insights into their relative significance in the decision-making process.

Table 7
Weighted normalized fuzzy decision matrix

Weights	7	9	9	3	6.5	9	1	4.5	7
Challenge e No.									
1	5.44	9	9	1	4.33	9	0.11	0.56	2.33
2	5.44	9	9	0.33	3.61	9	0.11	0.9	7
3	2.33	5	7	1	4.69	9	0.11	0.69	2.33
4	0.78	5	9	0.33	3.97	9	0.11	0.64	2.33
5	0.78	7	9	0.33	3.61	9	0.11	1	7
6	2.33	5.5	9	0.33	3.61	9	0.11	0.9	7
7	0.78	5.5	9	0.33	4.33	9	0.11	1	7
8	2.33	6.5	9	0.33	2.53	7	0.11	1.13	7
9	0.78	3	7	1.67	5.06	9	0.11	1	7
10	0.78	2	5	1	5.06	9	0.11	0.75	7
11	0.78	4	9	0.33	3.97	9	0.11	0.9	7
12	0.78	4	9	1	3.97	9	0.11	0.82	7
13	0.78	4.5	9	0.33	5.42	9	0.11	0.75	2.33
14	0.78	6.5	9	1	4.69	9	0.11	0.69	7
15	2.33	6	9	0.33	4.09	9	0.11	0.6	2.33
16	0.78	4	9	0.33	2.89	9	0.11	0.56	1.4
17	0.78	4.5	9	1	4.33	9	0.11	0.5	1
18	0.78	5	9	1	5.06	9	0.11	0.9	7

Table 7
Weighted normalized fuzzy decision matrix (Continued)

Weights	7	9	9	3	6.5	9	1	4.5	7
Challenge e No.									
19	0.78	5.5	9	0.33	3.25	7	0.11	0.6	2.33
20	0.78	4.5	9	0.33	3.61	9	0.11	0.9	7
A*	**5.44**	**9**	**9**	**1.67**	**5.42**	**9**	**0.11**	**1.13**	**7**
A-	**0.78**	**2**	**5**	**0.33**	**2.53**	**7**	**0.11**	**0.5**	**1**

In Table 8, the depiction of the Fuzzy Negative Ideal Solution (FNIS) and Fuzzy Positive Ideal Solution (FPIS) is integral to assessing the relative performance and desirability of challenges in the given context. The FNIS represents the ideal scenario where challenges exhibit minimal characteristics or deviations from the negative ideal, while the FPIS represents the ideal scenario where challenges align closely with positive attributes. The corresponding ranks assigned to these solutions offer a systematic way to quantify and compare the challenges. Higher ranks indicate challenges that are more aligned with the positive ideal, showcasing favorable characteristics, whereas lower ranks signify challenges that deviate further from the negative ideal. This ranking system provides astructured approach to identify challenges that excel or fall short in relation to the established benchmarks. In essence, Table 8 serves as a valuable tool for decision-makers to prioritize challenges based on their alignment with the ideal solutions, offering a nuanced understanding of their relative performance and aiding in strategic decision-making processes.

Table 8
Distance from FPIS, FNIS and final rank

Challenge No.	Distance from FPIS			di*	Challenge No.	Distance from FNIS			di-	cci	Rank
1	0	0.73	2.71	3.45	1	5.38	1.6	0.77	7.75	4.45	19
2	0	1.3	0.13	1.43	2	5.38	1.31	3.47	10.16	2.43	20
3	3.15	0.57	2.71	6.42	3	2.27	1.75	0.78	4.79	7.42	6
4	3.55	1.13	2.71	7.39	4	2.89	1.42	0.77	5.09	8.39	4
5	2.93	1.3	0.07	4.3	5	3.7	1.31	3.48	8.49	5.3	15
6	2.7	1.3	0.13	4.13	6	3.2	1.31	3.47	7.98	5.13	16
7	3.37	0.99	0.07	4.43	7	3.07	1.56	3.48	8.1	5.43	14
8	2.3	2.17	0.07	4.47	8	3.59	1.31	3.48	7.07	5.47	13
9	4.54	0.21	0.07	4.82	9	1.29	2.01	3.48	6.78	5.82	12
10	5.38	0.44	0.22	6.03	10	2.27	1.9	3.47	5.37	7.03	8
11	3.95	1.13	0.13	5.21	11	2.58	1.42	3.47	7.48	6.21	9
12	3.95	0.92	0.18	5.04	12	2.58	1.48	3.47	7.53	6.04	11
13	3.74	0.77	2.7	7.22	13	2.72	2.03	0.78	5.54	8.22	5
14	3.06	0.57	0.25	3.87	14	3.48	1.75	3.47	8.69	4.87	18
15	2.5	1.08	2.71	6.29	15	3.39	1.47	0.77	5.63	7.29	7
16	3.95	1.65	3.25	8.85	16	2.58	1.17	0.23	3.99	9.85	1
17	3.74	0.73	3.48	7.96	17	2.72	1.6	0.77	4.33	8.96	2
18	3.55	0.44	0.13	4.12	18	2.89	1.9	3.47	8.26	5.12	17
19	3.37	1.87	2.71	7.95	19	3.07	0.42	0.77	4.26	8.95	3
20	3.74	1.3	0.13	5.17	20	2.72	1.31	3.47	7.51	6.17	10

4. Result and Discussion

The analysis illustrates that among the twenty challenges, market uncertainty in the economic landscape holds the highest proximity coefficient, securing the top position.

Following closely, the challenges of high implementation, maintenance, security, integration, as well as uncertain benefits and trade-offs are ranked second and third, identifying them as the foremost obstacles in the implementation of sustainable green manufacturing during the industry 4.0 era. Refer to Figure 2 for a radar chart visualizing these challenges.

Securing a position among the top five challenges is contingent on grappling with market uncertainty, a multifaceted issue shaped by dynamic technological advancements in IoT, AI, and robotics. The evolving landscape demands swift adaptation from businesses, compounded by globalization exposing them to economic trends, geopolitical shifts, and regulatory fluctuations. Data security concerns amplify uncertainties, with extensive data exchange posing risks of breaches, cyber-attacks, and evolving data protection laws. Transitioning to Industry 4.0 brings about adoption challenges involving substantial investments, with uncertainties surrounding adoption pace, return on investment (ROI), and system compatibility. Market dynamics and heightened customer expectations introduce further uncertainty, alongside evolving regulations in data governance, intellectual property, and industry standards. Another significant factor influencing a top-five standing is the high implementation, maintenance, security, and integration costs associated with Industry 4.0. Substantial upfront investments act as a formidable barrier, and ongoing maintenance expenses encompass updates, patches, and ensuring optimal performance. Cybersecurity measures incur significant spending to counter potential breaches and data threats. Integration challenges add to the financial burden, including costs related to integrating new technologies with existing systems, ensuring compatibility, and maintaining seamless operations. Skill development costs, operational downtime during implementation and integration, and scalability challenges contribute to the financial complexities faced by businesses. Uncertainty regarding benefits and trade-offs associated with Industry 4.0 is a key determinant for a top-five position. Predicting returns on investments proves challenging, and decision-making involves intricate trade-offs between costs, benefits, and risks. Long-term viability concerns arise, questioning the lasting impact and potential obsolescence of chosen technologies. The intricate interdependencies among integrated technologies complicate impact prediction. Balancing innovation with operational stability becomes a struggle, and allocating resources amid uncertainties in technology, training, and process reengineering poses a significant challenge. Navigating evolving regulations and ethical considerations further adds to the complexity of decision-making. Industry 4.0's impact on supply chains, with its inherent complexity, secures a place among the top challenges.

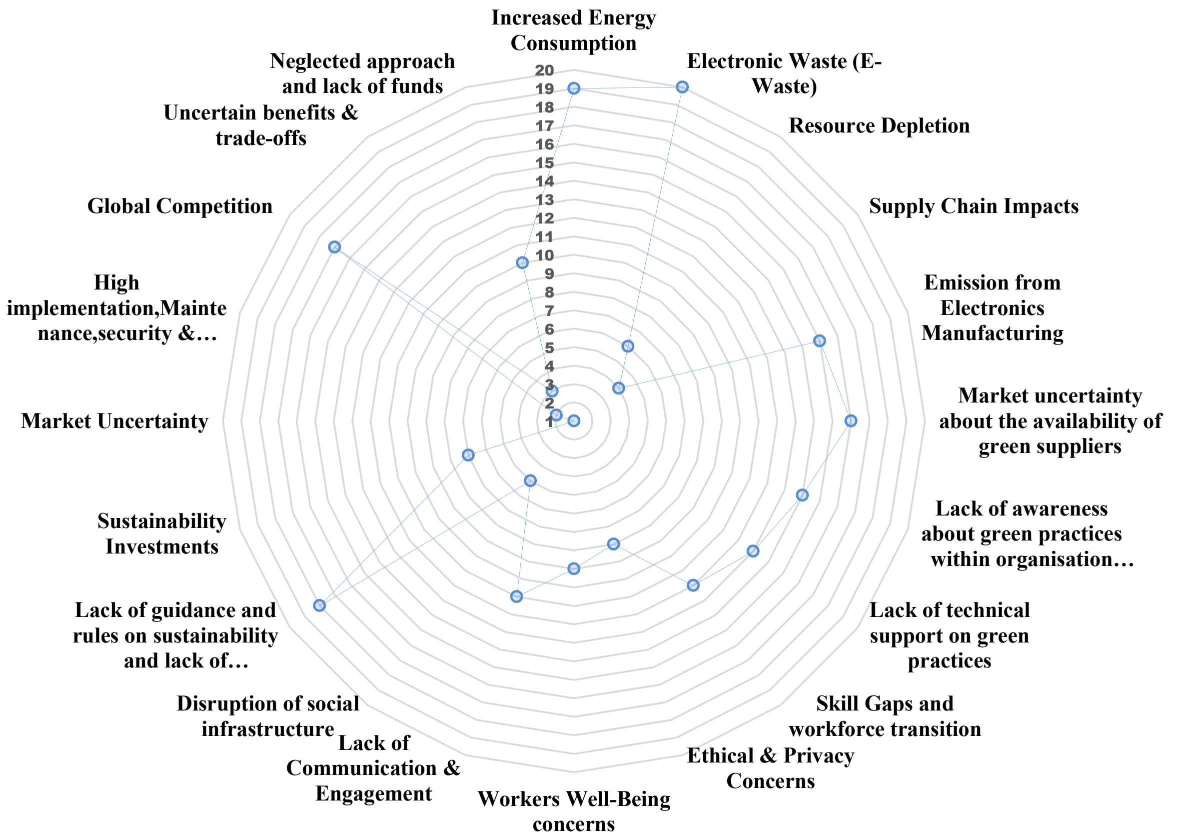

Fig. 2. Radar chart depicting challenges

Concerns about resource consumption andwaste generation arise due to the intricate nature of supply chains. The production and disposal of Industry 4.0 technologies raise environmental concerns, emphasizing the need for sustainable practices. Automation, robotics, and data centers may lead to increased energy consumption, posing environmental challenges if not managed sustainably. Technological advancements contribute to electronic waste (e-waste), necessitating proper disposal and recycling practices. Supply chain transparency, while a benefit of Industry 4.0, reveals environmental issues, pressuring businesses to address their impacts. Optimizing supply chain operations may affect transportation and logistics, potentially leading to increased emissions if not managed sustainably. Adapting to evolving environmental regulations adds complexity to supply chain management in the Industry 4.0 context. Emission from electronics manufacturing emerges as a top challenge due to various factors. The resource-intensive processes involved in Industry 4.0 electronics manufacturing emit pollutants during material extraction and processing. Significant energy demand in semiconductor fabrication and electronics assembly contributes to greenhouse gas emissions. Inadequate management of manufacturing chemicals can lead to emissions of volatile organic compounds (VOCs) and other pollutants. The entire lifecycle of electronics, including disposal, contributes to emissions, with potential increases in disposal-related emissions due to rapid technological advancements.

Global electronics supply chains further contribute to emissions from shipping and logistics, highlighting the need for sustainable practices throughout the industry. Theenvironmental impact of manufacturing processes, generating significant waste, underscores the importance of proper waste management to mitigate pollution and emissions.

5. Conclusion and Future Scope

In summary, the research extensively examines challenges in implementing sustainable green manufacturing in the Industry 4.0 era, focusing on 20 challenges using a prioritization model based on Fuzzy TOPSIS Following can be concluded.

i) Uncertainty regarding benefits and trade-offs associated with Industry 4.0 is a key determinant for a top-five position.

ii) Market uncertainty, implementation costs, security, and uncertain benefits emerge as critical concerns.

iii) Market uncertainty in the economic landscape is the biggest challenge. This can be controlled by swift adaptation from businesses, compounded by globalization and stabilizing it according to economic trends, geopolitical shifts, and regulatory fluctuations.

The future scope includes exploring emerging technologies, benchmarking best practices, investigating supply chain sustainability, integrating Life Cycle Assessment, addressing regulatory compliance, fostering collaborative initiatives, enhancing skill development, measuring impact, innovating business models, and promoting cross-sector collaboration. This paper aims to provide valuable insights and practical recommendations for navigating challenges and seizing opportunities in sustainable green manufacturing within the Industry 4.0 framework.

Acknowledgment

The authors would like to express their sincere thanks to the anonymous reviewers for their valuable observations and comments for an earlier version of this research paper.

References

Agan, Y., Acar, M. F., & Borodin, A. (2013). Drivers of environmental processes and their impact on performance: a study of Turkish SMEs. *Journal of cleaner production*, *51*, 23-33.

Aggarwal, A., & Chawla, V. K. (2021). A sustainable process for conversion of petrol engine vehicle to battery electric vehicle: A case study. *Materials Today: Proceedings*, *38*, 432-437.

Ammenberg, J., & Sundin, E. (2005). Products in environmental management systems: drivers, barriers and experiences. *Journal of Cleaner Production*, *13*(4), 405-415.

Angell, L. C., & Klassen, R. D. (1999). Integrating environmental issues into the mainstream: an agenda for research in operations management. *Journal of operations management*, *17*(5), 575-598.

Awasthi, A., Chauhan, S. S., & Omrani, H. (2011). Application of fuzzy TOPSIS in evaluating sustainable transportation systems. *Expert systems with Applications*, *38*(10), 12270-12280.

Beier, G., Matthess, M., Guan, T., Grudzien, D. I. D. O. P., Xue, B., de Lima, E. P., & Chen, L. (2022). Impact of Industry 4.0 on corporate environmental sustainability: Comparing practitioners' perceptions from China, Brazil and Germany. *Sustainable production and consumption*, *31*, 287-300.

Boks, C., Nilsson, J., Masui, K., Suzuki, K., Rose, C., & Lee, B. H. (1998, May). An international comparison of product end-of-life scenarios and legislation for consumer electronics. In *Proceedings from the IEEE Symposium on Electronics and the Environment* (Vol. 19, p. 24).

Bonvoisin, J., Stark, R., & Seliger, G. (2017). *Field of research in sustainable manufacturing* (pp. 3-20). Springer International Publishing.

Burke, S., & Gaughran, W. F. (2007). Developing a framework for sustainability management in engineering SMEs. *Robotics and Computer-Integrated Manufacturing*, *23*(6), 696-703.

Callahan, J. S., Dunne, R. A., & Stanaback, S. (1997). New Jersey county dismantles recycling and emissions problems. *World Wastes*, *40*(3), 7-8.

Chanda, A. K., Chawla, V. K., & Angra, S. K. (2018). A modified memetic particle swarm optimization algorithm for sustainable multi-objective scheduling of automatic guided vehicles in a flexible manufacturing system. *International Journal of Computer Aided Manufacturing*, *4*(1), 33-47.

Chawla, V., Chanda, A., & Angra, S. (2018). Sustainable multi-objective scheduling for automatic guided vehicle and flexible manufacturing system by a grey wolf optimization algorithm. *International Journal of Data and Network Science*, *2*(1), 27-40.

Chawla, V., Angra, S., Suri, S., & Kalra, R. (2020). A synergic framework for cyber-physical production systems in the context of industry 4.0 and beyond. *International Journal of Data and Network Science*, *4*(2), 237-244.

Chawla, V. K., Chhabra, D., Gupta, P., & Naaz, S. (2021). Evaluation of green operations management by fuzzy analytical hierarchy process. *Materials Today: Proceedings*, *38*, 274-279.

Chawla, V. K., Chanda, A. K., Angra, S., & Bonyadi, A. (2022). Coexistent scheduling in the tandem flow path configuration of a flexible manufacturing system by using an advanced grey wolf optimizer. *Scientia Iranica*, *29*(6), 3404-3417.

Chawla, V., Itika, I., Singh, P., & Singh, S. (2024). A fuzzy Pythagorean TODIM method for sustainable ABC analysis in inventory management. *Journal of Future Sustainability*, *4*(2), 85-100.

Elkington, J. (1994). Towards the sustainable corporation: Win-win-win business strategies for sustainable development. *California management review*, *36*(2), 90-100.

Ghadge, A., Mogale, D. G., Bourlakis, M., Maiyar, L. M., & Moradlou, H. (2022). Link between Industry 4.0 and green supply chain management: Evidence from the automotive industry. *Computers & Industrial Engineering*, *169*, 108303.

Gupta, P., Chawla, V., Jain, V., & Angra, S. (2022). Green operations management for sustainable development: An explicit analysis by using fuzzy best-worst method. *Decision Science Letters*, *11*(3), 357-366.

Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2018). Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process safety and environmental protection*, *117*, 408-425.

Kumar, R. (2021). Sustainable manufacturing in the era of Industry 4.0: a DEMATEL analysis of challenges. In *Research Anthology on Cross-Industry Challenges of Industry 4.0* (pp. 1807-1815). IGI Global.

Machado, C. G., Winroth, M. P., & Ribeiro da Silva, E. H. D. (2020). Sustainable manufacturing in Industry 4.0: an emerging research agenda. *International Journal of Production Research*, *58*(5), 1462-1484.

Mahdavi, I., Mahdavi-Amiri, N., Heidarzade, A., & Nourifar, R. (2008). Designing a model of fuzzy TOPSIS in multiple criteria decision making. *Applied mathematics and Computation*, *206*(2), 607-617.

Mittal, V. K., & Sangwan, K. S. (2014). Fuzzy TOPSIS method for ranking barriers to environmentally conscious manufacturing implementation: government, industry and expert perspectives. *International Journal of Environmental Technology and Management*, *17*(1), 57-82.

Mittal, V. K., Egede, P., Herrmann, C., & Sangwan, K. S. (2013). Comparison of drivers and barriers to green manufacturing: a case of India and Germany. In *Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013* (pp. 723-728). Springer Singapore.

Naeini, A. B., Mojaradi, B., Zamani, M., & Chawla, V. K. (2019). Prevention of cardiovascular diseases by combining GIS with fuzzy best-worst decision-making algorithm in areas of Tehran. *International Journal of Industrial Engineering and Production Research*, *30*(3), 255-271.

Ngai, E. W., Chau, D. C., & Chan, T. L. A. (2011). Information technology, operational, and management competencies for supply chain agility: Findings from case studies. *The Journal of Strategic Information Systems*, *20*(3), 232-249.

Rahanu, H., Georgiadou, E., Siakas, K., Ross, M., & Berki, E. (2021). Ethical issues invoked by Industry 4.0. In *Systems, Software and Services Process Improvement: 28th European Conference, EuroSPI 2021, Krems, Austria, September 1–3, 2021, Proceedings 28* (pp. 589-606). Springer International Publishing.

Rajput, S. P., & Datta, S. (2020). Sustainable and green manufacturing–A narrative literature review. *Materials today: proceedings*, *26*, 2515-2520.

Rusinko, C. (2007). Green manufacturing: an evaluation of environmentally sustainable manufacturing practices and their impact on competitive outcomes. *IEEE transactions on engineering management*, *54*(3), 445-454.

Sadjadi, S., & Sadi-Nezhad, S. (2017). Ranking Canadian oil and gas projects using TOPSIS. *Journal of Project Management*, *2*(3), 87-92.

Sangwan, K. S. (2011). Quantitative and qualitative benefits of green manufacturing: an empirical study of Indian small and medium enterprises. In *Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd-4th, 2011* (pp. 371-376). Springer Berlin Heidelberg.

Santolaria, M., Oliver-Solà, J., Gasol, C. M., Morales-Pinzón, T., & Rieradevall, J. (2011). Eco-design in innovation driven companies: perception, predictions and the main drivers of integration. The Spanish example. *Journal of Cleaner Production*, *19*(12), 1315-1323.

Sarkis, J., & Rasheed, A. (1995). Greening the manufacturing function. *Business Horizons*, *38*(5), 17-27.

Senthil, K. D., Ong, S. K., Nee, A. Y. C., & Tan, R. B. (2003). A proposed tool to integrate environmental and economical assessments of products. *Environmental Impact Assessment Review*, *23*(1), 51-72.

Sezen, B., & Cankaya, S. Y. (2013). Effects of green manufacturing and eco-innovation on sustainability performance. *Procedia-Social and Behavioral Sciences*, *99*, 154-163.

Stock, T., & Seliger, G. (2016). Opportunities of sustainable manufacturing in industry 4.0. *Procedia CIRP*, *40*, 536-541.

Sun, C. C. (2010). A performance evaluation model by integrating fuzzy AHP and fuzzy TOPSIS methods. *Expert systems with applications*, *37*(12), 7745-7754.

Tseng, M. L., Chiu, A. S., Lin, Y. H., & Chinag, J. H. (2006). The relationship of continuous improvement and cleaner production on operational performance: An empirical study in electronic manufacturing firms, Taiwan China. *International Journal of Management Science and Engineering Management*, *1*(1), 71-80.

Wang, T. C., & Lee, H. D. (2009). Developing a fuzzy TOPSIS approach based on subjective weights and objective weights. *Expert systems with applications*, *36*(5), 8980-8985.

Yadav, E., & Chawla, V. K. (2022). Fault detection in rotating elements by using fuzzy integrated improved local binary pattern method. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *44*(12), 596.