



## OPEN Technology adaptation in sugarcane supply chain based on a novel $p, q$ Quasirung Orthopair Fuzzy decision making framework

Sanjib Biswas<sup>1</sup>, Dragan Pamucar<sup>2</sup>✉ & Vladimir Simic<sup>3,4,5</sup>

The present paper contributes to the literature in two ways. First, it develops a novel  $p, q$  Quasirung Orthopair Fuzzy ( $p, q$  QOF) based group decision making framework to modify a recently developed multi-criteria decision making (MCDM) model such as Comparisons between Ranked Criteria (COBRAC). Second, the paper ruminates on the Strength-Weakness-Opportunity-Threat (SWOT) of the sugarcane supply chain (SSC) in India vis-à-vis adaptation of the advanced technologies featuring Industry 4.0. To set the sub-factors of various dimensions of SWOT, the theoretical ground of Technology-Organization-Environment (TOE) framework has been used. The sub-factors of SWOT have been derived through an informal in-depth discussion with the experts of the sugar industry. Then using a Likert five-point linguistic scale the experts rated the sub-factors based on their relative importance. To determine the weights the modified COBRAC method has been applied. In subsequent stages the reliability of the model has been tested and sensitivity analysis has been carried out to check the stability of the result. The analysis reveals that while experience, by-product utilization and high demand provides strength and create opportunities for SSC, the areas of concern are lack of variety, fragmented nature of supply chains, shortage of next-gen talent and inadequate infrastructure. However, there are enough promises for SSC. The paper shall provide impetus to strategic decision makers for the sugar industry and puts forth a new decision-making framework for the analysts.

**Keywords**  $p, q$  Quasirung Orthopair Fuzzy Numbers ( $p, q$  QOFN), Comparisons between Ranked Criteria (COBRAC), Sugar industry, Industry 4.0, Technology-Organization-Environment (TOE) framework, Strategic scanning

Sugar is an inevitable part of the items daily consumed by human beings. It is used as a source of sweeteners, energy and preservations<sup>1</sup>. Sugarcane is one of the main sources for production of sugar and other related by-products<sup>2</sup>. Sugar production is one of the oldest industries across the world in the agri-food sector, producing sugar and several by-products like biomass, bagasse, and molasses that are used for several purposes such as generation of electricity, renewable fuels, papers, chemicals and organic and bio-products<sup>3</sup>. A sugarcane supply chain (SSC) is a set of interconnected activities starting from field to mill and then distribution to customers' end including grow, harvest, transport, processing and recycling<sup>4</sup>. According to a recent study<sup>5</sup>, Indian sugar industry contributes around 10% of India's agricultural GDP and is a significant contributor to manufacturing output of the country.

While SSC is enjoying a higher market demand with multi-faceted use, there are a number of challenges such as lower yield rate (as compared with the countries like Brazil), inefficient allocation of resources, stagnancy in productivity, lack of varieties, increasing health consciousness among the consumers, growing competition and lack of resilience to economic, social, and environmental issues, mismatch of profit allocation among the members of SSC, fragmented in nature, and climate change<sup>6–8</sup>. In this regard, there is a need to embrace advanced technologies, building of digital capabilities, develop sustainable agro-techniques, overhauling of conversion processes<sup>7,9</sup>.

<sup>1</sup>Amity Business School, Amity University, Major Arterial Road, AA II, Newtown, Kolkata, West Bengal 700135, India.

<sup>2</sup>Széchenyi István University, Győr, Hungary. <sup>3</sup>Faculty of Transport and Traffic Engineering, University of Belgrade, Vojvode Stepe 305, Belgrade 11010, Serbia. <sup>4</sup>Department of Industrial Engineering and Management, Yuan Ze University, Taoyuan City, Taiwan. <sup>5</sup>Department of Computer Science and Engineering, College of Informatics, Korea University, Seoul 02841, Republic of Korea. ✉email: dpamucar@gmail.com

The present age is characterized by a massive technological development started with Industry 4.0. Industry 4.0 has revolutionized all facets of socio-economic and business environment through a cyber-physical ecosystem. The supply chains also need to embrace the power of Industry 4.0 to stay existent and competitive<sup>10</sup>. Industry 4.0 enables the supply chains to predict and critically analyze potential risks and showcase resilience<sup>11,12</sup>, enhancing transparency, scalability and flexibility, and productivity<sup>13</sup>, fostering real-time governance and collaboration, evidence-based decision-making<sup>14,15</sup>, improving communications and better understanding consumer needs<sup>16</sup> and contributes toward sustainability through lean and agile SCM<sup>17</sup>. Hence, Industry 4.0 is relevant for SSC. SSCs need to leverage Industry 4.0 to usher a transformed journey in quest of achieving sustainable development while meeting its potential growth. However, Indian sugar industry is at the crossroad. The one side of the story is sugar industry has a lot of potentials while the other part sheds light on a number of shortcomings. The adaptation of advanced technologies can bridge the gap between two contradictory aspects. Thus, it is required to carry out a strategic scanning of the environment for SSC. In this regard, the current work proposes a strength-weakness-opportunity-threat (SWOT) framework for SSC vis-à-vis embracing the advanced digital technologies. Whilst a good number of past studies found on sugarcane industry and SSC<sup>18,19</sup>, there is an apparent scantiness of work focusing on SWOT analysis of SSC vis-à-vis technology adaptation.

SWOT analysis intends to figure out the internal and external factors impacting the business performance<sup>20</sup>. The extant literature shows several examples of application of SWOT analysis in various context. Examples include digital ecosystem<sup>20</sup>, assessment of pharmaceutical environment for supply chains in India<sup>21</sup>, digital transformation of hospitals<sup>22</sup>, milk processing system<sup>23</sup>, barriers and future prospect of hydrogen driven economy<sup>24</sup> among others. In the context of sugarcane industry and its supply chain management, there has been a number of contributions in past. Ayu et al.<sup>25</sup> conducted a SWOT analysis on sugar industry in Indonesia to prioritize business strategies by using AHP method. Debnath and Roy<sup>26</sup> used AHP-TOPSIS methodology to unearth key drivers for inclusive growth in defence. Szum and Nazarko<sup>19</sup> developed an extended SWOT model to explore the determinants of successful implementation of Industry 4.0 in SSC. Kassem et al.<sup>27</sup> worked on formulating an appropriate strategy for contract farming in the Egyptian sugar industry. Asrol et al.<sup>18</sup> worked on identification of failure modes and their mitigation strategies to improve supply chain performance. The authors used Supply Chain Operation Reference (SCOR) framework and Fuzzy-Analytic Hierarchy Process (AHP) approach to draw the critical factors through SWOT analysis. Salehi et al.<sup>28</sup> concentrated on finding out the obstacles for adaptation of information technology in SSC Khuzestan province. The researchers used SWOT analysis and applied DEMATEL method to determine the weights of the factors. In the context of circular economy, the work of Jesus et al.<sup>29</sup> provided a SWOT analysis to figure out the barriers and implementation strategies for sugarcane ethanol sector in Brazil.

### Motivations behind the present study

The motivations of the present work stems from theoretical and methodological gaps in the existing literature. In what follows are the primary motivations behind the work.

- From the review of the past studies, it is apparent that SWOT analysis is a useful framework for strategic planning and environmental scanning. However, we do not find extensive use of theoretical frameworks in the context of SWOT analysis. This motivates us to develop a theoretical framework for carrying out SWOT analysis for adaptation of advanced technologies in SSC.
- Related to SSC, there has been several studies such as sustainability assessment of SSC<sup>30</sup>, identification of barriers to adopt information technology<sup>28</sup>, performance assessment and ranking of sugarcane farms<sup>31</sup>, material selection of SSC<sup>32</sup>, assessment of climate change effect<sup>33</sup> among others. These studies used MCDM models. However, there is a gap in the literature using MCDM model based comprehensive SWOT analysis of critical factors to adapt advanced technologies in SSC.
- There has been evidences of using MCDM models to determine the weights of the factors in SWOT analysis. We notice that past studies used subjective opinions and carried out uncertain model based analysis. However, we find a very limited or no efforts have been given to examine the robustness of the model through consistency checking while carrying out SWOT analysis. Of course, AHP has been used in some cases with calculation of reliability. But, AHP has the drawbacks like limitation of the number of criteria/factors and a higher number of pairwise comparison ( $n(n-1)/2$ ). Thus, there is a necessity to develop a subjective opinion-based robust SWOT framework with MCDM model.
- We observe a number of works conducted to find out critical issues related to adaptation of new technologies by using MCDM models<sup>34,35</sup>. However, there is a limited flexibility in selection of membership and non-membership grades.

### Research objectives

The current work fills the gap in the literature by fulfilling the following objectives.

**RO 1.** To carry out a SWOT analysis for SSC supported by the theoretical Technology-organisation-environment (TOE) framework.

TOE is a theoretical framework for assessment of technology adaptation<sup>36</sup>. TOE framework consists of three dimensions such as *technology* (relative advantage, perceived cost, compatibility, security, and complexity), *organization* (internal factors like technological readiness, resource availability, financial readiness, and top management support) and *environment* (external factors like government regulation, stakeholder relation, structure of the industry, vendors etc.)<sup>37</sup>. TOE framework has been found widely used in the literature<sup>38–41</sup>. In the context of adaptation of advanced technologies in Industry 4.0, there are a number of contributions made by the researchers<sup>42–44</sup>. Hence, the TOE framework is an appropriate technological framework for carrying out SWOT analysis for SSC.

RO 2. To develop a robust MCDM based framework for carrying out SWOT analysis.

Since SWOT analysis reveals multiple factors of varying importance, the current work applies a MCDM model such as COBRAC<sup>45</sup> to determine the factor weights based on opinions of a group of experts. To reduce the effect of subjectivity, the ongoing work uses a novel p, q-Quasirung Orthopair Fuzzy Number (p, q-QOFN) based COBRAC model.

The p, q-Quasirung Orthopair Fuzzy Set (p, q-QOFS) was developed<sup>46</sup> as a continuous advancement of the traditional fuzzy sets<sup>47,48</sup>, pentagonal fuzzy sets<sup>49</sup>, intuitionistic fuzzy set<sup>50</sup>, Pythagorean fuzzy set<sup>51,52</sup>, spherical fuzzy sets<sup>53</sup> and q-rung Orthopair fuzzy set<sup>54</sup>. p, q-QOFS offers more flexibility to the decision makers for selection of the degrees of membership ( $\mu$ ) and non-membership ( $\vartheta$ ) for a granular analysis. The underlying condition is  $0 \leq \mu^p + \vartheta^q \leq 1$  where,  $p, q (\geq 1)$  are the real numbers used as parameters. Here,  $p > q$  or  $p < q$  or  $p = q$ . By suitably increasing and fixing the values of  $p$  and  $q$  the DM can set the space of the acceptable Orthopairs. The literature shows a limited application of p, q-QOFS based applications<sup>55–58</sup>. Further, for aggregation of the responses of the experts, we use Aczel – Alsina (AA) t-norms and t-conorms based aggregation operator (AO). AA based AO provides the advantages like changeability of the parameters, equivalence and reliable results<sup>59,60</sup>.

In this paper the researchers apply a recently developed multi-criteria decision making (MCDM) model such as Comparisons Between Ranked Criteria (COBRAC) method<sup>45</sup> to derive the weights of the factors and rank them. COBRAC provides a number of advantages such as: a) better consistency in the decision making as it removes the need for distant pairwise comparisons; b) lesser number of pairwise comparisons (for attributes, COBRAC requires number of local comparisons) to better withstand variations in the decision-making and subjective bias; c) ability to provide a large scale range to the decision makers for local pairwise comparisons; d) ability to provide a reliable and consistent result even with the presence of a large number of attributes or criteria.

The research questions that the present work aims to address are:

- RQ 1 What are the key strengths and opportunities for SSC to adapt Industry 4.0 technologies?
- RQ 2 What are the critical threats and weaknesses of SSC that act as hindrances to adapt Industry 4.0 technologies?
- RQ 3 To what extent, on aggregate, do the strengths, weaknesses, opportunities and threats differ?
- RQ 4 How can a robust p, q-QOFN based MCDM model be developed for group decision-making?

## Contributions

The major contributions of the current work are twofold.

### a) Theoretical innovation

The present work uses a widely used and established theoretical basis like TOE to design the SWOT analysis. The use of such theoretical foundation helps to conduct a comprehensive multi-factors based SWOT analysis for identification of critical issues influencing the adaptation of advanced technologies of Industry 4.0 in the context of SSC.

### b) Methodological innovations

First, the current study provides a rare framework using SWOT, TOE and COBRAC for assessing the critical issues and key strengths and opportunities for adaptation of industry 4.0 by SSC in Indian context. Second, Recognizing the advantages of COBRAC method, the present work proposes a novel extension of the recently developed COBRAC model with p, q-QOFS and Aczel – Alsina (AA) t-norms and t-conorms based aggregation operator (AO) for group decision-making that provides changeability of the parameters, equivalence and reliable results.

### c) Practical relevance

Keeping in mind the sustainable development goals, the present work necessitates the importance of the adoption of technologies that support environmental stewardship. The framework used in this paper is tailored to withstand the complexities and uncertainties in SSC, unveiling critical issues and major prospects in the current landscape of SSC and necessary steps for modernization, facilitating better strategic decisions to enhance the competitiveness and efficiency.

The rest of the manuscript is constructed as follows. In section "Preliminary concepts" we describe the fundamental definitions and concepts of p, q-QOFS. Section "Research framework" discusses the research methodology at length including our proposed extension of COBRAC method. Section "Findings" summarizes the key findings while in section "Discussion" we draw critical inferences from the findings. Finally, section "Conclusion and future scope" concludes the paper while mentioning some of the future scope.

## Preliminary concepts

The ongoing section is constructed to describe some of the fundamental definitions and operational rules of p, q-QOFS.

**Definition 1.** Intuitionistic Fuzzy Set (IFS).

Let,  $\widetilde{A}_I$  is an IFS from the universe of discourse  $\cup$  and  $\widetilde{A}_I$  is defined<sup>50</sup> as

$$\widetilde{A}_I = \{x, \langle \mu_I(x), \vartheta_I(x) \rangle : x \in \cup\} \quad (1)$$

Here,  $\mu_I(x) \rightarrow [0, 1]$  and  $\vartheta_I(x) \rightarrow [0, 1]$  are denoting the membership degree (MD) and non-membership degree (NMD) respectively. The MD and NMD satisfy the condition  $0 \leq \mu_I(x) + \vartheta_I(x) \leq 1; \forall x \in \cup$ .

**Definition II.** Pythagorean Fuzzy Set (PyFS).

The PyFS was developed<sup>51,52</sup> as an extended version of IFS. Let,  $\widetilde{A}_P$  is an PyFS from the universe of discourse  $\cup$ . Then we have the definition as

$$\widetilde{A}_P = \{x, \langle \mu_P(x), \vartheta_P(x) \rangle : x \in \cup\} \quad (2)$$

The underlying condition is  $0 \leq \mu_P(x)^2 + \vartheta_P(x)^2 \leq 1; \forall x \in \cup$  and the hesitancy or indeterminacy degree (ID) is derived as

$$\pi_P = \sqrt{1 - (\mu_P(x))^2 - (\vartheta_P(x))^2}; \forall x \in \cup \quad (3)$$

**Definition III.** Fermatean Fuzzy Set (FFS).

Let,  $\widetilde{A}_F$  is an FFS from the universe of discourse  $\cup$ . Then  $\widetilde{A}_F$  is defined<sup>61,62</sup> subject to the underlying condition  $0 \leq \mu_F(x)^3 + \vartheta_F(x)^3 \leq 1; \forall x \in \cup$  as

$$\widetilde{A}_F = \{x, \langle \mu_F(x), \vartheta_F(x) \rangle : x \in \cup\} \quad (4)$$

The indeterminacy degree (ID) is obtained as

$$\pi_F = \sqrt[3]{1 - (\mu_F(x))^3 - (\vartheta_F(x))^3}; \forall x \in \cup \quad (5)$$

**Definition IV.**  $q$  Rung Orthopair Fuzzy Set ( $q$  ROFS).

Using the natural integer  $q$  as the power, the scholars<sup>54,63,64</sup> defined the  $q$  ROFS  $\widetilde{A}_Q$  is defined as

$$\widetilde{A}_Q = \{x, \langle \mu_Q(x), \vartheta_Q(x) \rangle : x \in \cup\} \quad (6)$$

The condition satisfied is  $0 \leq \mu_Q(x)^q + \vartheta_Q(x)^q \leq 1; \forall x \in \cup$  and ID is defined as

$$\pi_Q = \sqrt[q]{1 - (\mu_Q(x))^q - (\vartheta_Q(x))^q}; \forall x \in \cup \quad (7)$$

By changing the values of  $q$ , the other variants are obtained, for example,  $q = 1$  (IFS);  $q = 2$  (PyFS);  $q = 3$  (FFS).

**Definition V.**  $(p, q)$  Quasirung Orthopair Fuzzy Set ( $p, q$ -QOFS).

To proceed towards a further generalization, the  $p, q$ -QOFS  $A_{p,q}$  is defined as<sup>46</sup>

$$\widetilde{A}_{p,q} = \{x, \langle \mu_{p,q}(x), \vartheta_{p,q}(x) \rangle : x \in \cup\} \quad (8)$$

The values of the natural numbers  $p, q$  lead to the following condition.

$$0 \leq \mu_{p,q}(x)^p + \vartheta_{p,q}(x)^q \leq 1; \forall x \in \cup \quad (9)$$

Here,  $p, q \geq 1$  and  $p >, =, < q$ .

Subsequently, ID is computed as

$$\pi_{p,q} = \sqrt[\varepsilon]{1 - (\mu_{p,q}(x))^p - (\vartheta_{p,q}(x))^q}; \forall x \in \cup \quad (10)$$

Here,  $\varepsilon$  is a small number and  $\varepsilon = L.C.M(p, q)$ .

For further definitions and simple explanations, Seikh and Mandal<sup>46</sup> used Quasirung Orthopair Fuzzy Number ( $p, q$ -QOFN) to represent  $\widetilde{A}_{p,q}$ . Let,  $A = (\mu, \vartheta)$  is any  $p, q$ -QOFN following the definitions given by the Eqs. (8) to (10).

The  $p, q$ -QOFN  $A$  is changed to IFN or PyFN or FFN as follows<sup>65</sup>

- If  $p = q = 1$  then  $A$  is an IFN
- If  $p = q = 2$  then  $A$  is an PyFN
- If  $p = q = 3$  then  $A$  is an FFN
- If  $p = q$  then  $A$  is an  $q$  ROFN
- If  $p = 3; q = 4$  then  $A$  is a 3,4 Quasirung Fuzzy Number<sup>66</sup>

**Definition VI.** Basic operational rules for  $p, q$ -QOFN.

Let,  $A = (\mu, \vartheta), A_1 = (\mu_1, \vartheta_1)$  and  $A_2 = (\mu_2, \vartheta_2)$  are the three  $p, q$ -QOFNs. Then the following definitions are obtained<sup>46</sup>

$$\begin{aligned} \text{VIa)} \quad & A_1 \leq A_2 \text{ iff } \mu_1 \leq \mu_2 \text{ and } \vartheta_1 \geq \vartheta_2 \\ \text{VIb)} \quad & A_1 = A_2 \text{ iff } \mu_1 = \mu_2 \text{ and } \vartheta_1 = \vartheta_2 \end{aligned} \tag{11}$$

$$\text{VIc)} \quad A_1 \oplus A_2 = \left( \sqrt[p]{\mu_1^p + \mu_2^p - \mu_1^p \mu_2^p}, \vartheta_1 \vartheta_2 \right)$$

$$\text{VI d)} \quad A_1 \otimes A_2 = \left( \mu_1 \mu_2, \sqrt[q]{\vartheta_1^q + \vartheta_2^q - \vartheta_1^q \vartheta_2^q} \right) \tag{12}$$

$$\text{VIe)} \quad \lambda A = \left( \sqrt[p]{1 - (1 - \mu^p)^\lambda}, \vartheta^\lambda \right) \tag{13}$$

where  $\lambda (\geq 0) \in \mathbb{R}$  is a scalar quantity

$$\text{VI f)} \quad A^\lambda = \left( \mu^\lambda, \sqrt[q]{1 - (1 - \vartheta^q)^\lambda} \right) \tag{14}$$

where  $\lambda (\geq 0) \in \mathbb{R}$

$$\text{VIg)} \quad A^c = (\vartheta, \mu) \tag{15}$$

**Definition VII.** Score and Accuracy function.

The score function for a  $p, q$ -QOFN  $A$  is defined as<sup>46</sup>

$$\mathfrak{S}(A) = \frac{1 + \mu^p - \vartheta^q}{2}; \quad 0 \leq \mathfrak{S}(A) \leq 1 \tag{16}$$

In response to an increase in  $\mu$ , the score function also monotonically increases while it monotonically decreases as  $\vartheta$  increases.

The accuracy function is defined as<sup>46</sup>

$$\lambda(A) = \mu^p + \vartheta^q; \quad 0 \leq \lambda(A) \leq 1 \tag{17}$$

Rules for comparing two  $p, q$ -QOFNs.

- i) If  $\mathfrak{S}(A_1) < \mathfrak{S}(A_2)$  then  $A_1 \prec A_2$
- ii) If  $\mathfrak{S}(A_1) > \mathfrak{S}(A_2)$  then  $A_1 \succ A_2$

$$\lambda(A_1) < \lambda(A_2) \Rightarrow A_1 \prec A_2$$

- iii) If  $\mathfrak{S}(A_1) = \mathfrak{S}(A_2)$  then  $\lambda(A_1) > \lambda(A_2) \Rightarrow A_1 \succ A_2$

$$\lambda(A_1) = \lambda(A_2) \Rightarrow A_1 = A_2$$

**Definition VIII.** Aggregation operators (AO).

Let,  $A_j = (\mu_j, \vartheta_j); j = 1, 2, \dots, n$  is a family of  $p, q$ -QOFNs. Then, the  $p, q$ -QOF weighted averaging ( $p, q$ -QOFWA) and  $p, q$ -QOF weighted geometric ( $p, q$ -QOFWG) AOs are defined as<sup>46</sup>

$$p, q - QOFWA(A_1, A_2, \dots, A_n) = \bigoplus_{j=1}^n \omega_j A_j = \left( \sqrt[p]{1 - \prod_{j=1}^n (1 - \mu_j^p)^{\omega_j}}, \prod_{j=1}^n \vartheta_j^{\omega_j} \right) \tag{18}$$

$$p, q - QOFWG(A_1, A_2, \dots, A_n) = \bigotimes_{j=1}^n A_j^{\omega_j} = \left( \prod_{j=1}^n \mu_j^{\omega_j}, \sqrt[q]{1 - \prod_{j=1}^n (1 - \vartheta_j^q)^{\omega_j}} \right) \tag{19}$$

$\omega_j$  denotes the weight of  $A_j$  such that  $\omega_j > 0; \sum_{j=1}^n \omega_j = 1$ .

**Definition IX.** Aczel–Alsina (AA) t-norm.

The AA t-norm and AA t-conorm are given as<sup>65</sup>

$$T_{AA}^\alpha(x_1, x_2) = \begin{cases} T_D(x_1, x_2); & \text{if } \alpha = 0 \\ \text{Min}(x_1, x_2); & \text{if } \alpha = \infty \\ e^{-((-\ln x_1)^\alpha + (-\ln x_2)^\alpha)^{\frac{1}{\alpha}}}; & \text{otherwise} \end{cases} \tag{20}$$

For special cases  $T_{AA}^\infty = \min, T_{AA}^0 = T_D, T_{AA}^1 = T_P$

$$S_{AA}^\alpha(x_1, x_2) = \begin{cases} S_D(x_1, x_2); & \text{if } \alpha = 0 \\ \text{Max}(x_1, x_2); & \text{if } \alpha = \infty \\ 1 - e^{-((-\ln(1-x_1))^\alpha + (-\ln(1-x_2))^\alpha)^{\frac{1}{\alpha}}}; & \text{otherwise} \end{cases} \tag{21}$$

For special cases  $S_{AA}^\infty = \max, S_{AA}^0 = S_D, S_{AA}^1 = S_P$ .

Let,  $\alpha \in [0, \infty]$  is the parameter of AA norms, and  $x_1$  and  $x_2$  are the elements of  $\cup$ . Then we have

$$T_D(x_1, x_2) = \begin{cases} x_1; & \text{if } x_2 = 1 \\ x_2; & \text{if } x_1 = 1 \text{ (drastic t - norm)} \\ 0 \end{cases} \tag{22}$$

$$T_P(x_1, x_2) = x_1 x_2 \text{ (product t - norm)} \tag{23}$$

$$S_D(x_1, x_2) = \begin{cases} x_1; & \text{if } x_2 = 0 \\ x_2; & \text{if } x_1 = 0 \text{ (drastic t - conorm)} \\ 0 \end{cases} \tag{24}$$

$$S_P(x_1, x_2) = (x_1 + x_2 - x_1 x_2) \text{ (probabilistic sum)} \tag{25}$$

It may be noted that AA t-norm and t-conorm are dual to each other.

**Definition X.** AA aggregation operators.

For a family of p, q-QOFNs  $A_j = (\mu_j, \vartheta_j); j = 1, 2, \dots, n$ , the p, q-QOF AA weighted averaging (p, q-QOFAAWA) is defined as under<sup>65</sup>.

$$p, q - QOFAAWA(A_1, A_2, \dots, A_n) = \left( \begin{array}{l} \sqrt[p]{\frac{1 - e^{-\left(\sum_{j=1}^n \omega_j (-\ln(1-\mu_j^p))^\alpha\right)^{1/\alpha}}}{\alpha}} \\ \sqrt[q]{\frac{e^{-\left(\sum_{j=1}^n \omega_j (-\ln \vartheta_j^q)^\alpha\right)^{1/\alpha}}}{\alpha}} \end{array} \right) \tag{26}$$

### Research framework

In this section we provide a step-by-step description of the research methodology.

#### Identification of the factors under SWOT

First, we identify the factors under each category such as S, W, O, and T. In this regard, the factors are identified based on the related past studies and informal discussions made with the experts. The theoretical framework of TOE is used. A group of ten experts took part in the study. The sample size satisfies the minimum requirement for group decision-making<sup>67,68</sup>. The experts are selected mostly from the sugar industry (six numbers). These experts are having substantial experience of working (more than 15 years) at various functional areas in industry, such as operations and supply chain management (five), HRM (one), marketing (two), finance (one). One of the experts has been selected from academia (faculty member of operations and supply chain management). Table 1 provides the list of factors based on SWOT analysis.

The experts have been engaged in the SWOT analysis and then rating of the factors (identified through SWOT analysis) using the linguistic scales given in Table 2.

#### p, q QOFN based COBRAC method using p, q-QOFAAWA

Let,  $F_j (j = 1, 2, \dots, m)$  are the factors under a given category of SWOT framework with corresponding weights

as  $\omega_j (\omega_j \geq 0; \sum_{j=1}^m \omega_j = 1)$ .

$E_i (i = 1, 2, \dots, n)$  are the experts who took part in the study.

$A_{ij} = (\mu_{ij}, \vartheta_{ij})$  is the rating (using p, q QOFN scale) of the  $j^{th}$  factor given by expert  $E_i$ .

$\phi_j = (\mu_j, \vartheta_j)$  is the aggregated p, q QOFN for the  $j^{th}$  factor.

The steps of p, q QOFN based COBRAC method using p, q-QOFAAWA are described below.

*Step 1.* Aggregation of the responses of the experts for each factor.

S/L	Factors	Category	Dimension
S1	Experience of the industry (more than 120 years old)	Strength (S)	Tech
S2	Lower attrition rate resulting into knowledge retention		Org
S3	Supply chain capacity utilization		Org
S4	Simple supply chain structure		Tech
S5	Availability of sustainable materials		Tech
S6	Lower conversion cost		Tech
S7	Optimum utilization of by products and waste		Org
W1	Compatibility issue to adapt cutting-edge technologies	Weakness (W)	Tech
W2	Old generation industry, learning from other industries is very less		Org
W3	Mostly rural based remote operations		Env
W4	Emigration of next-gen fresh talent		Org
W5	A higher average age of the workmen ((55 years and above—60%)		Org
W6	Inadequate support from top management		Org
W7	Inadequate infrastructure to embrace digital technologies		Org
W8	Internet connectivity and availability of electricity		Env
W9	High cost of installation		Tech
W10	Lack of advanced decision support system and R&D facilities		Tech
W11	Resistance to accept changes		Org
W12	Lack of standards and systems		Org
OP 1	Opportunity for development of famer economy and inclusive growth	Opportunity (O)	Env
OP 2	Multi-faceted use of products in various industries resulting into collaborations		Env
OP 3	Demand is always high and stable		Tech
OP 4	Increase in ethanol use		Env
OP 5	Government focus on sugarcane-based products		Env
OP 6	Branding and promotion		Tech
T1	Fragmented supply chain with a lot of unorganized players and interventions	Threat (T)	Env
T2	Misalignment of incentives among the players of the supply chains		Env
T3	Lack of awareness of modern technologies across the supply chain		Org
T4	Intra-industry rivalry: Unhealthy competition		Env
T5	Fluctuation of raw material price while sugar price is regulated		Env
T6	Limited quota (e.g., Molasses) and regulation		Env
T7	Lack of variety and volume of production		Tech
T8	Availability of substitute products		Env
T9	Environmental uncertainties resulting into less yield and supply		Env

**Table 1.** List of factors identified through SWOT analysis.

Linguistic rating scale	Code	$\mu$	$\vartheta$
Very High	5	0.85	0.25
High	4	0.70	0.40
Medium	3	0.55	0.55
Low	2	0.40	0.70
Very Low	1	0.25	0.85

**Table 2.** Linguistic rating scale and corresponding p, q QOFNs.

Using the definition of  $p, q$ -QOFAAWA operator the individual responses (for each factor) are aggregated as under.

$$\begin{aligned}
 \phi_j &= (\mu_j, \vartheta_j) = p, q - QOFAAWA(A_1, A_2, \dots, A_n) \\
 &= \left( \begin{array}{l} \sqrt[p]{1 - e^{-\left(\sum_{i=1}^n w_i (-\ln(1 - \mu_{ij}^p))^\alpha\right)^{1/\alpha}}} \\ \sqrt[q]{e^{-\left(\sum_{i=1}^n w_i (-\ln \vartheta_{ij}^q)\right)^\alpha}}^{1/\alpha} \end{array} \right) \tag{27}
 \end{aligned}$$

In this case,  $w_i$  denotes the weight assigned to the expert  $E_i$ .

*Step 2.* Calculation of the score values for the aggregated p, q QOFNs. Using Eq. 16, the score value for each factor  $F_j$  is computed as

$$\mathfrak{S}(\phi_j) = \frac{1 + \mu_j^p - \vartheta_j^q}{2}; 0 \leq \mathfrak{S}(\phi_j) \leq 1 \tag{28}$$

Next, the steps of the conventional COBRAC method<sup>45</sup> are followed.

*Step 3.* Ranking of the factors.

Assuming that  $F_k (k \in [1, m])$ , any factor from the set, is the dominant (most influential for the decision-making, i.e., most important) one, the ranking (as per relative importance) order is obtained as  $F_{k(1)} > F_{k(2)} > \dots > F_{k(t)}$  where  $t \in [1, m]$  is the rank of the factors.

*Step 4.* Pairwise comparison of the factors.

After pairwise comparison of the factor, each pair is assigned with a preferred value  $\xi$ . For instance,  $\xi_{1,2}$  is the assigned value to the first and second ranked factors and  $\xi_{m-1,m}$  is the assigned value to the second-to-last and last ranked factors. Then the values  $\xi_{1,2}, \xi_{2,3}, \dots, \xi_{m-1,m}$  meet the condition  $\xi \in [0, 1]$ . For example, for the two factors  $F_{j(m-1)}$  and  $F_{j(m)}$  where  $F_{j(m-1)} > F_{j(m)}$ , the value  $\xi_{m-1,m} = 0.64$  indicates that  $F_{j(m-1)}$  holds 64% of the interval [0,1] while the contribution of  $F_{j(m)}$  is 36%.

*Step 5.* Calculation of the weights of the factors.

The COBRAC method performs  $(m - 1)$  number of pairwise comparisons for  $m$  factors. Hence, there are  $(m - 1)$  number of relationships formulated as given below

$$\begin{aligned} \omega_1 : \omega_2 &= \xi_{1,2} : (1 - \xi_{1,2}); \\ \dots & \\ \omega_{m-1} : \omega_m &= \xi_{m-1,m} : (1 - \xi_{m-1,m}); \end{aligned} \tag{29}$$

According to the condition of transitivity, we can write

$$\frac{\omega_{m-1}}{\omega_m} - \frac{\xi_{m-1,m}}{(1 - \xi_{m-1,m})} = 0 \tag{30}$$

However, in reality there could be some deviations from the consistency. Hence, the objective is set to minimize the deviations, i.e.,  $\left| \frac{\omega_{m-1}}{\omega_m} - \frac{\xi_{m-1,m}}{(1 - \xi_{m-1,m})} \right| \leq 0; j = 1, 2 \dots m$ . Accordingly, the model for calculating the weights of the factors is formulated as

$$\begin{aligned} \min \max_j & \left\{ \left| \frac{\omega_{m-1}}{\omega_m} - \frac{\xi_{m-1,m}}{(1 - \xi_{m-1,m})} \right| \right\} \\ \text{s.t.} & \\ \sum_{j=1}^m \omega_j &= 1; \omega_j \geq 0 \forall j \end{aligned} \tag{31}$$

The above model can be then expressed as a non-linear model (i.e., final model) for calculating the weights as

$$\begin{aligned} \text{Min } \chi & \\ \text{s.t.} & \\ \left| \frac{\omega_{m-1}}{\omega_m} - \frac{\xi_{m-1,m}}{(1 - \xi_{m-1,m})} \right| &\leq \chi, \forall j \\ \sum_{j=1}^m \omega_j &= 1; \omega_j \geq 0 \forall j \end{aligned} \tag{32}$$

The methodological steps are depicted in Fig. 1.

### Findings

Under this section we highlight the findings of the data analysis. The responses of the experts (i.e., ratings of the factors derived through SWOT analysis) are recorded in Table A.1 to A.4 (see Online Appendix A). Now, by using p, q-QOFNs (as given in Table 2) we obtain the ratings of the factors for further analysis. In what follows is the demonstration of the calculation of weights of the factors. Let us start with the category Strength (S). Table 3 exhibits the rating of the factors expressed in p, q-QOFNs.

To begin with the analysis the first step deals with the aggregation of individual ratings for each factor using p, q-QOFAAWA (see Eq. (27)). In this case, the number of factors under Strength category is  $m = 7$  and the number of experts (rated the factors) is  $n = 10$ . We have assumed an equal importance for all experts. Thus, weight for each expert is  $w_j = \frac{1}{j} = \frac{1}{n} = \frac{1}{10} = 0.1$ . Table 4 shows the aggregated ratings (in p, q QOFNs) for all factors.

Next, we calculate the score values for  $S_1, S_2, S_3, \dots, S_7$  using the Eq. (28). After that the steps of the COBRAC method are followed by applying Eqs. (29) to (32) to formulate the final model and calculation of the weights of the factors. Table 5 exhibits the calculation of the weights.

Final model (to calculate the weights of the strength factors)

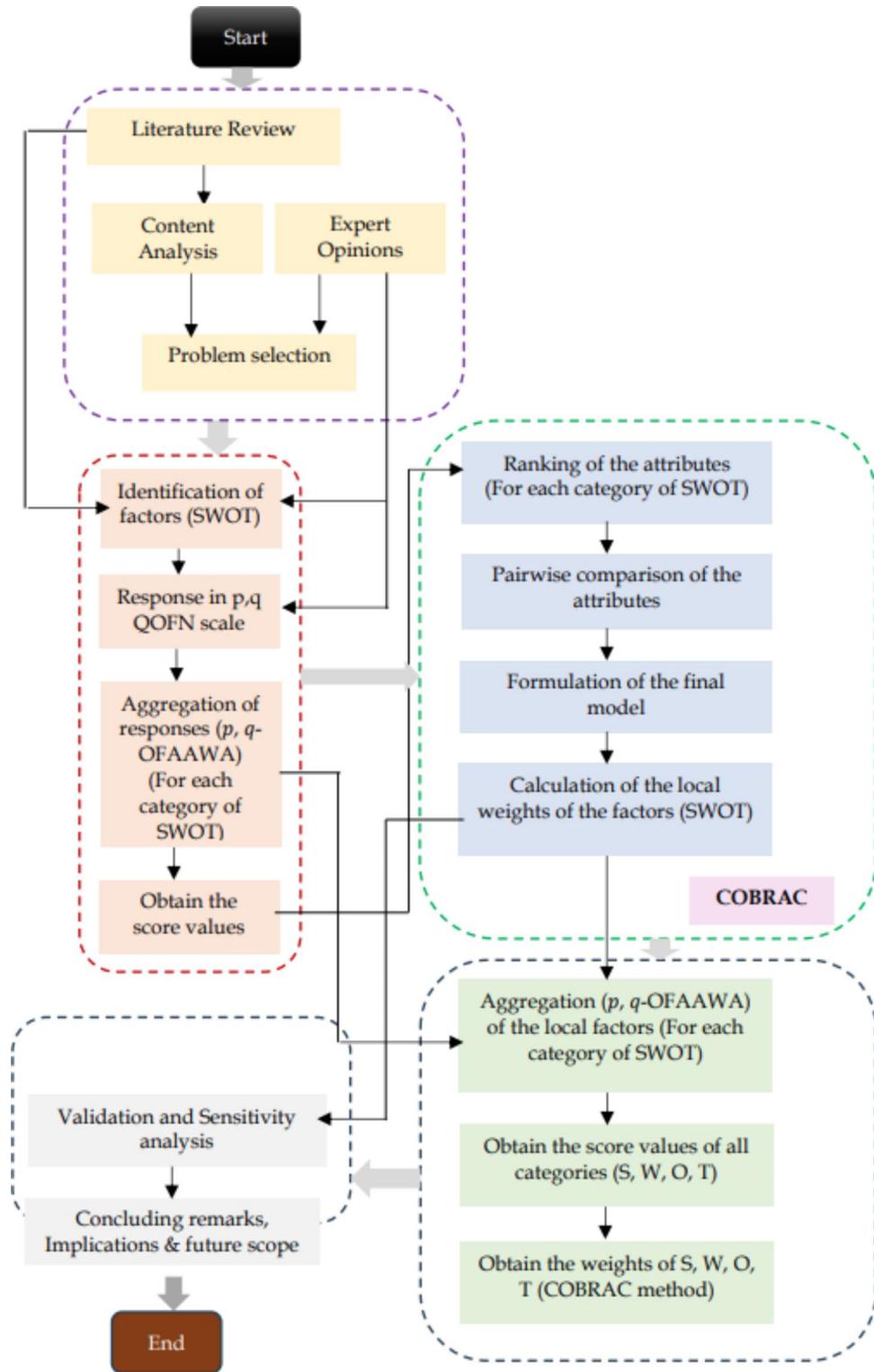


Fig. 1. Flowchart of research methodology.

Factors/ Expert	S1		S2		S3		S4		S5		S6		S7	
E1	0.85	0.25	0.55	0.55	0.70	0.40	0.55	0.55	0.25	0.85	0.55	0.55	0.70	0.40
E2	0.70	0.40	0.70	0.40	0.55	0.55	0.70	0.40	0.40	0.70	0.40	0.40	0.70	0.40
E3	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
E4	0.70	0.40	0.70	0.40	0.40	0.70	0.55	0.55	0.40	0.70	0.40	0.40	0.70	0.40
E5	0.85	0.25	0.55	0.55	0.55	0.55	0.55	0.55	0.40	0.70	0.55	0.55	0.85	0.25
E6	0.85	0.25	0.85	0.25	0.55	0.55	0.70	0.40	0.25	0.85	0.25	0.25	0.85	0.25
E7	0.55	0.55	0.55	0.55	0.40	0.70	0.40	0.40	0.40	0.70	0.40	0.40	0.55	0.55
E8	0.70	0.40	0.70	0.40	0.70	0.40	0.55	0.55	0.25	0.85	0.70	0.40	0.70	0.40
E9	0.85	0.25	0.70	0.40	0.40	0.70	0.55	0.55	0.40	0.70	0.40	0.40	0.70	0.40
E10	0.85	0.25	0.70	0.40	0.55	0.55	0.70	0.40	0.25	0.85	0.25	0.25	0.70	0.40

**Table 3.** Rating of the factors (Strengths) by experts (expressed in p, q QOFNs).

Factor	S1		S2		S3		S4	
Aggregated Rating	0.7445	0.4040	0.6465	0.4983	0.5312	0.6120	0.5672	0.5725
Factor	S5		S6		S7			
Aggregated Rating	0.3605	0.7768	0.4639	0.6895	0.6904	0.4544		

**Table 4.** Aggregated rating of the factors (Strengths) (expressed in p, q QOFNs).

Factor	Score	$\xi$	1- $\xi$	$\xi/(1-\xi)$	$\omega$	Rank
S1	0.6247	0.5267	0.4733	1.1130	0.2051	1
S7	0.5613	0.5235	0.4765	1.0985	0.1843	2
S2	0.5110	0.5446	0.4554	1.1956	0.1678	3
S4	0.4274	0.5244	0.4756	1.1025	0.1403	4
S3	0.3876	0.5539	0.4461	1.2416	0.1273	5
S6	0.3122	0.5847	0.4153	1.4081	0.1025	6
S5	0.2217				0.0728	7
				Sum	1.0000	

**Table 5.** Calculation of weights of strength factors (COBRAC method).

Factor	Score	$\xi$	1- $\xi$	$\xi/(1-\xi)$	$\omega$	Rank
W4	0.6153	0.5177	0.4823	1.0735	0.1009	1
W7	0.5732	0.5108	0.4892	1.0442	0.0990	2
W10	0.5490	0.5179	0.4821	1.0743	0.0938	3
W1	0.5110	0.5070	0.4930	1.0283	0.0885	4
W8	0.4969	0.5064	0.4936	1.0260	0.0874	5
W6	0.4843	0.5276	0.4724	1.1169	0.0874	6
W2	0.4336	0.5280	0.4720	1.1186	0.0854	7
W3	0.3876	0.5259	0.4741	1.1093	0.0816	8
W5	0.3495	0.5301	0.4699	1.1281	0.0809	9
W9	0.3098	0.5540	0.4460	1.2421	0.0739	10
W11	0.2494	0.5065	0.4935	1.0262	0.0641	11
W12	0.2430				0.0571	12
				Sum	1.0000	

**Table 6.** Calculation of weights of weakness factors (COBRAC method). ( $\chi = 0.00000$ )

$$\begin{aligned}
 &Min \chi \\
 &s.t \\
 &\left| \frac{\omega_1}{\omega_7} - 1.1130 \right| \leq \chi, \left| \frac{\omega_7}{\omega_2} - 1.0985 \right| \leq \chi, \left| \frac{\omega_2}{\omega_4} - 1.1956 \right| \leq \chi, \left| \frac{\omega_4}{\omega_3} - 1.1025 \right| \leq \chi, \\
 &\left| \frac{\omega_3}{\omega_6} - 1.2416 \right| \leq \chi, \left| \frac{\omega_6}{\omega_5} - 1.4081 \right| \leq \chi \\
 &\omega_1 + \omega_2 + \omega_3 + \omega_4 + \omega_5 + \omega_6 + \omega_7 = 1; \\
 &\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6, \omega_7 > 0
 \end{aligned}
 \tag{33}$$

It is found that  $\chi = 0.000001$  which indicates that there is a negligible deviation and thus, the model shows significant consistency. In the similar way, we calculate the weights of various factors under weakness, opportunity and threat categories (See Tables 6, 7, 8).

We then move to find out the composite score of each category of SWOT by aggregating the p, q-QOFNs of constituting factors using p, q-QOFAAWA. In this case we use the calculated weights of the factors. After that we apply the procedural steps of COBRAC method (as demonstrated above) to determine the weights of SWOT categories (see Table 9).

### Comparative analysis

It is important to ascertain the reliability of the result of any MCDM model as it may be susceptible to the variations in the external conditions and underlying assumptions<sup>69</sup>. As a common practice followed in the past studies<sup>70-74</sup>, the present paper compares the calculated weights of the factors with the other methods like LBWA,

Factor	Score	$\xi$	$1-\xi$	$\xi/(1-\xi)$	w	Rank
OP 3	0.6530	0.5149	0.4851	1.0612	0.2094	1
OP 2	0.6153	0.5089	0.4911	1.0363	0.1973	2
OP 4	0.5938	0.5147	0.4853	1.0604	0.1904	3
OP 1	0.5599	0.5472	0.4528	1.2085	0.1795	4
OP 5	0.4633	0.6651	0.3349	1.9858	0.1486	5
OP 6	0.2333				0.0748	6
				Sum	1.0000	

**Table 7.** Calculation of weights of opportunity factors (COBRAC method). ( $\chi = 0.00000$ )

Factor	Score	$\xi$	$1-\xi$	$\xi/(1-\xi)$	w	Rank
T1	0.6347	0.5040	0.4960	1.0160	0.1530	1
T7	0.6247	0.5273	0.4727	1.1157	0.1506	2
T9	0.5599	0.5109	0.4891	1.0444	0.1350	3
T3	0.5362	0.5416	0.4584	1.1814	0.1293	4
T6	0.4538	0.5213	0.4787	1.0892	0.1094	5
T4	0.4167	0.5258	0.4742	1.1087	0.1005	6
T5	0.3758	0.5681	0.4319	1.3153	0.0906	7
T2	0.2858	0.5233	0.4767	1.0978	0.0689	8
T8	0.2603				0.0627	9
				Sum	1.0000	

**Table 8.** Calculation of weights of threat factors (COBRAC method). ( $\chi = 0.000002$ )

Category	Score	$\xi$	$1-\xi$	$\xi/(1-\xi)$	w	Rank
OP	0.5710	0.5260	0.4740	1.1096	0.2795	1
T	0.5146	0.5115	0.4885	1.0469	0.2518	2
S	0.4916	0.5133	0.4867	1.0545	0.2406	3
W	0.4662				0.2281	4
				Sum	1.0000	

**Table 9.** Calculation of weights of SWOT (COBRAC method). ( $\chi = 0.00000$ )

Method	Coefficient	COBRAC
FUCOM	Spearman's rho	0.964*
LBWA	Spearman's rho	0.964*
SWARA	Spearman's rho	0.929*
PIPRECIA	Spearman's rho	0.929*
BWM	Spearman's rho	0.857*

**Table 10.** Comparison of COBRAC with other MCDM methods. \*Significant at 0.05 level (two-tailed).

FUCOM and PIPRECIA. Table 10 shows that the result of Spearman rank correlation test (SRCT) for the factors under strength category. It is evident that COBRAC maintains a consistency with other MCDM models.

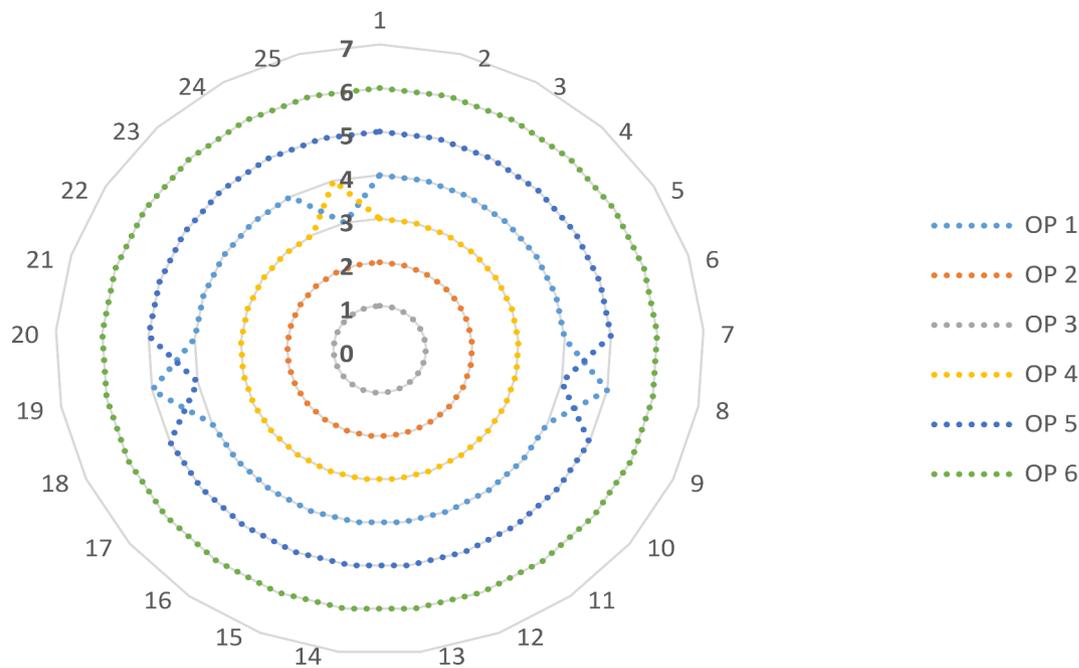
In the similar way we compare the results of COBRAC method with other MCDM models for all other categories of SWOT framework and find the consistency.

### Sensitivity analysis

One of the important requirements for MCDM models is its stability of the result which often gets violated because of changes in the defined conditions, for instance, changes in the criteria and alternative set, variations in the parameter value for aggregation and so on<sup>75</sup>. In this work there are three vital parameters used in aggregation, such as  $p$ ,  $q$  and  $\alpha$ . To figure out whether changes in the values of these parameters affect the calculated weights of the factors and their subsequent rankings, the sensitivity analysis is performed. Guided by the previous studies<sup>76–78</sup>, we vary the parameter values (see Table 11) and calculate the weights of the factors.

Cases	Parameter values			Cases	Parameter values		
	p	q	$\alpha$		p	q	$\alpha$
Initial	3	2	1	Case 13	3	5	1
Case 1	4	2	1	Case 14	3	7	1
Case 2	5	2	1	Case 15	3	9	1
Case 3	7	2	1	Case 16	3	10	1
Case 4	9	2	1	Case 17	3	20	1
Case 5	10	2	1	Case 18	3	50	1
Case 6	20	2	1	Case 19	3	2	2
Case 7	50	2	1	Case 20	3	2	3
Case 8	1	2	1	Case 21	3	2	4
Case 9	2	2	1	Case 22	3	2	5
Case 10	3	1	1	Case 23	3	2	7
Case 11	3	3	1	Case 24	3	2	9
Case 12	3	4	1				

**Table 11.** Experimental cases for sensitivity analysis.



**Fig. 2.** Outcome of the sensitivity analysis (for opportunity factors).

Figure 2 showcases an example of the ranking distribution of the factors under the opportunity category subject to variations in the parameter values during sensitivity analysis. It is noticed that the ranking does not show any significant variation. Hence, it may be contended that our model provides a stable solution.

### Discussion

The study reveals several noteworthy observations. Experts believe that factors like experience in the industry (S1), optimum utilization of by-products and waste (S7), and lesser attrition rate (S2) are the top strengths of SSC. The researchers<sup>79,80</sup> argued that maturity in terms of the number of years of existence in business helps the firms to build capabilities, withstand vulnerabilities and embrace changes in the environment. The maturity of the supply chains provides an opportunity to assimilate knowledge and improve technological strength<sup>81</sup>. The sugar industry is more than 120 years old, which is an indication of the maturity of SSC. The utilization of by-products and waste has emerged as a second necessary strength. Experts from the sugar industry indicated that molasses is used for ethanol production and is sold to the government. The residue part (bagasse) is used for boiler fuel to generate captive power. These are also sold to the State grid, paper industry, and manufacturing of MDF furniture. Therefore, SSC is enabled to contribute towards sustainability, which is an essential driver for adopting new technology and helps firms satisfy their stakeholders<sup>82</sup>. For adaptation to a new technology, it is

essential to have stable human resources. The lower attrition rate helps retain knowledge within the organization. As a result of knowledge retention, the firms can reap the advantage of a learning curve, integrate the learnings over time, build dynamic capabilities, and embrace technological changes<sup>83,84</sup>. Thus, the identified top three strengths encourage SSC to adopt digital technologies.

Going to the weakness factors, we observe that emigration of next-gen fresh talent (W4), inadequate infrastructure to embrace digital technologies (W7), and lack of advanced decision support system and R&D facilities (W10) are the top three factors. It is understood that next-gen talents are reluctant to join a conventional business-like sugarcane processing. As a result, SSC needs more new ideas and innovative work systems, which are essential cornerstones for technology adaptation. Furthermore, being an age-old industry, SSC needs more modern setups and R&D to support the implementation of advanced technologies. Also, the experts noted that SSC works in a traditional way, where there is a need for more advanced analytical models powered by AI/ML. The outdated working style, lack of learning, digital capabilities, and shortage of next-gen innovative talents pose significant challenges for SSC to adapt to new technologies<sup>85,86</sup>.

However, SSC enjoys the advantage of having a high demand (OP 3), providing stability to the firms. The researchers<sup>87</sup> argued that a stable and high market demand drives firms to stretch their efforts to fulfil customers' requirements and, therefore, urge them to adopt new technologies. The multi-faceted use of products in various industries (OP 2) has bolstered the market demand. The experts mentioned the extension of demand from B2B to B2C. As a result, the firms take advantage of the increasing possibility of building collaborations with other industries and economic sustainability through innovative financing<sup>88</sup>. The surge in the use of ethanol (OP 4) has also provided a notable opportunity for SSC. Experts mentioned that 20–25% of ethanol-based fuels are used for the automobile sectors in India, helping the country reduce import dependency. Thus, SSC has many opportunities for future growth and sustainable development.

Considering the threats, it is noted that fragmentation of SSC (T1), lack of variety and volume of production (T7), and environmental uncertainties (T9) pose considerable threats to SSC. SSC is comprised of several players, including a large number of unorganized intermediaries. As a result, there needs to be more clarity about balancing the incentives across the chain and matching the digital capabilities and goals across SSC. Collaboration among the partners across SSC is a critical success factor<sup>89</sup>. It poses a significant threat to the successful adaptation of advanced technologies. Because of a high number of failure modes, the volume of production and yield is inferior, as remarked by the experts. Further, SSC suffers from a lack of product varieties vis-à-vis competition and market demands. However, these threats necessitate the adaptation of advanced technologies in SSC to achieve sustainability and competitive advantage.

Theoretically, COBRAC model provides an inherent robustness check through solving the MILP model. It provides an advantage of a lesser number of pairwise comparisons of  $(n - 1)$  numbers within a local domain. The counterparts like BWM requires  $(2n - 3)$  number of comparisons. FUCOM also requires  $(n-1)$  number of comparisons but not in a local interval. SWARA and PIPRECIA requires an additional sorting of criteria at the initial and depend significantly on the selection of rating values. These show the theoretical benefits of COBRAC. For numerical validation, Table 10 shows the reliability and Fig. 2 demonstrates the stability of the outcome of COBRAC based analysis.

## Research impact and implications

The current research offers several impactful insights and implications for both practitioners and researchers.

### a) Managerial and Policy Implications

The ongoing work provides many insights for managerial decision making and policy formulation. First, by integrating the theoretical framework of TOE with SWOT analysis the present work brings in a comprehensive strategic planning approach. This proposed approach helps the decision-makers not only to identify the critical factors for adaptation of advanced technologies in SSC but also showcases their dynamics. In effect, the organizations can successfully utilize the TOE-SWOT framework to formulate futuristic action plans to overcome the challenges (weaknesses and threats) while leveraging the strengths and opportunities. Second, the ongoing work sheds light on the requirement to align sustainable development goals with technology adaptation, especially through the utilization of by-products like molasses for ethanol production. The findings of this study necessitate adoption of contemporary practices contributing to environmental conservation and resource efficiency. Third, the current study reveals two crucial challenges such as talent retention and upgradation of infrastructure within SSC for sustainable growth riding on advanced technologies. These findings reinstate the need to invest in human capital development and modern infrastructure for embracing technological changes and creating an ecosystem for innovation. Fourth, the results of the present work indicate an increasing demand for ethanol paving the way towards B2C models. A thorough analysis and understanding of the market trends and shift in business enables to decide strategic initiatives and technology investments which helps the firms to stay ahead of the competition. Fifth, the present study offers some significant actionable insights such as need for collaboration, financial incentive planning and creating a conducive ecosystem to foster innovation and develop organizational capabilities to embrace future technologies.

### b) Technical Implications

The current work provides a novel, robust group decision-making framework that may be utilized for complex problem-solving. The use of p, q QORFS extends a greater flexibility to the decision maker for dealing with imprecise information under uncertainty. This framework allows stakeholders to evaluate multiple criteria effectively, leading to more informed and strategic decisions regarding technology adoption. Compared to

earlier studies, the current work provides COBRAC model-based SWOT analysis which not helps to obtain a reliable outcome but also supports the consistency in decision-making. Hence, the proposed methodology of the current work can be effectively used for other industries in various contexts of strategic analysis.

### Advantages and limitations

The proposed work on technology adaptation in the sugarcane supply chain (SSC) presents several advantages and limitations. The advantages of the current work include: a) the SWOT analysis framework grounded on TOE provides a comprehensive and theoretically sound approach to unearth the factors influencing technology adaptation. This framework can be utilized in several other contexts (other industries and technologies) in Industry 4.0 transitioning to society 5.0; b) the proposed framework enhances the flexibility and accuracy of evaluations. This tool allows decision-makers to consider varying degrees of membership and non-membership. The proposed methodology can be utilized for several other complex problem solving; c) the findings accentuate the need to utilize by-products and waste focusing towards sustainability; d) the application of robust decision-making framework for imprecise information and lesser subjective bias.

However, there are some limitations. First, the present work is limited to only environmental scanning. It does not show any explicit direction for establishing any causal relationship. Hence, the analysis does not adequately capture the dynamicity. Second, participation of a limited number of experts limits the generalizability. Third, lack of empirical substantiation is another area of concern. The present work is confined to limited opinions and a specific industry only. Fourth, from methodological point of view, this study uses a particular aggregation such as Aczel-Alsina aggregator. Despite its advantages, this operator is a bit complex than Dombi and does not consider the neutrality effect explicitly like neutrality aggregator. Fifth, the current work intends to unearth the relative importance of the factors pertaining to SWOT for bring in a strategic perspective from environmental scanning. For that reason, we consider strategic decision-makers/ experts' subjective rating. However, the same can be supplemented to an operational level analysis using objective information and defined indicating variables. Sixth, there is a possibility to examine how do the factors can be optimized using the approach followed by Sadhu et al.<sup>90</sup> to generate desired competitive advantage.

### Conclusion and future scope

The researchers have designed the present work to discern the critical factors for adaptation of advanced technologies to SSC in Industry 4.0. Through a SWOT analysis based on experts' opinions, the factors have been identified under the theoretical framework of TOE. The identified factors have been rated by ten experts and a MCDM model using  $p$ ,  $q$ -QOFN based COBRAC method has been applied to prioritize the factors pertaining to each category of SWOT framework. For aggregation of experts' rating,  $p$ ,  $q$ -QOFAAWA approach has been followed. The results reflect that there is enough scope for availing a number of opportunities while capitalizing the strengths and improving the weaknesses. It is noted that the organizations must focus on attracting, developing and retaining next-gen talents and develop necessary infrastructure. Also, it is required to extend the product line and infuse varieties. The MCDM model used in this paper provides a reliable and stable solution.

### Future scope

The present work provides several opportunities for further extensions in future. In what follows are some of the future scopes:

- a) The present work does not provide a detailed empirical validation, especially, related to possible causal relationship among technology adaptation, organizational performance, and sustainability outcomes in the SSC. In a future work, one can try to establish and validate a causal model in this regard by using a large-scale empirical survey.
- b) For implementation of any new technology, soft factors like open-ended organizational culture and motivational climate, leadership support, employee engagement among others play critical roles. Understanding the status of the firms regarding these factors and their influence on technology adaptation can be a subject matter of future research.
- c) Besides adaptation of an advanced technology, it is also important to study the technology journey and success/failure case studies. It provides a deep introspection of organizational capability building and their impact on firm performance. Thus, a future work may address a longitudinal assessment of the dynamics of adaptation and the evolving nature of the supply chain.
- d) Likewise, SSC, there are other traditional yet large-scale agro-industries in operation. The present work can be extended to include a comparative study of several such industries with SSC in regard to adaptation of advanced technologies. In this context, it may be an interesting idea to compare technology adaptation by SSC of several other countries towards developing a comprehensive framework.
- e) A future work may explore the readiness and challenges to adapt specific technologies like digital twin, blockchain, IoT, smart drone, 3D printing, AI/ML and others in SSC. Subsequently, a comparative analysis may be carried out and investigations can be made to see how these technologies can enhance efficiency, transparency, and sustainability in the supply chain.
- f) For adaptation of advanced technologies, it is important to get policy support. The sugar cane industry is a regulated one. Hence, future research could focus on developing comprehensive policy frameworks that support technology adaptation in the SSC. This could involve analyzing the effectiveness of existing policies and proposing new initiatives.
- g) Climate change is one of the greatest concerns for SSC. From the present work, an initiative can be taken to delve deep into several sustainability issues pertaining to SSC. Future studies could concentrate on how

- climate-related factors influence technology adaptation in the SSC to overcome environmental challenges and develop resilient supply chains.
- h) SSC is a fragmented in many respects with a lot of organized and unorganized players involved. Hence, a future work may concentrate on multi-stakeholder engagement and its impact on technology implementation.
  - i) In this paper we have developed a  $p, q$ -QOFN based COBRAC with  $p, q$ -QOFAAWA. In a further work one may use different other aggregations to examine the robustness of methodological framework.
  - j) As a gradual extension, several other fuzzy numbers like  $p, q, r$  spherical fuzzy number or rough numbers can also be utilized for developing comprehensive MCDM models.

Nevertheless, the current work underscores the importance for a deep introspection of SSC at the crossroad under phenomenal growth of advanced technologies and provides a robust decision analysis framework for the policy makers and analysts.

### Availability of data and materials

All data generated or analysed during this study are included in this published article.

Received: 22 June 2024; Accepted: 7 October 2024

Published online: 03 November 2024

### References

- DiNicolantonio, J. J. & Berger, A. Added sugars drive nutrient and energy deficit in obesity: A new paradigm. *Open Heart* 3(2), e000469 (2016).
- Rajaeifar, M. A., Hemayati, S. S., Tabatabaei, M., Aghbashlo, M. & Mahmoudi, S. B. A review on beet sugar industry with a focus on implementation of waste-to-energy strategy for power supply. *Renew. Sustain. Energy Rev.* 103, 423–442 (2019).
- Eggleston, G. & Lima, I. Sustainability issues and opportunities in the sugar and sugar-bioproduct industries. *Sustainability* 7(9), 12209–12235 (2015).
- Kadwa, M. & Bezuidenhout, C. N. Modelling sugarcane supply consistency at a sugar mill. *Comput. Electron. Agric.* 111, 107–111 (2015).
- Sheetal, Singh, R., Shashi, & Kumar, R. A case-based analysis of the competitiveness of the North Indian sugar industry. *Global Bus. Organ. Excell.* 40(1), 6–18 (2020).
- Asrol, M. & Yani, M. A multi-criteria model of supply chain sustainability assessment and improvement for sugarcane agroindustry. *Heliyon* 10(7), e28259 (2024).
- Arun, J. V. & Premkumar, A. Sugarcane growth in India: Problems and prospects. *SAARC J. Agric.* 20(2), 133–144 (2022).
- Chouhan, V. K., Khan, S. H. & Hajiaghahi-Keshteli, M. Sustainable planning and decision-making model for sugarcane mills considering environmental issues. *J. Environ. Manag.* 303, 114252 (2022).
- Teixeira, E. D. S., Rangel, S., Florentino, H. D. O. & de Araujo, S. A. A review of mathematical optimization models applied to the sugarcane supply chain. *Int. Trans. Oper. Res.* 30(4), 1755–1788 (2023).
- Ghadge, A., Er, K. M., Moradlou, H. & Goswami, M. The impact of industry 4.0 implementation on supply chains. *J. Manuf. Technol. Manag.* 31(4), 669–686 (2020).
- Ivanov, D. & Dolgui, A. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Prod. Plan. Control* 32(9), 775–788 (2021).
- Marinagi, C., Reklitis, P., Trivellas, P. & Sakas, D. The impact of industry 4.0 technologies on key performance indicators for a resilient supply chain 4.0. *Sustainability* 15(6), 5185 (2023).
- Hahn, G. J. Industry 4.0: A supply chain innovation perspective. *Int. J. Prod. Res.* 58(5), 1425–1441 (2020).
- Hopkins, J. L. An investigation into emerging industry 4.0 technologies as drivers of supply chain innovation in Australia. *Comput. Ind.* 125, 103323. <https://doi.org/10.1016/j.heliyon.2024.e28259> (2021).
- Veile, J. W., Schmidt, M. C., Müller, J. M. & Voigt, K. I. The transformation of supply chain collaboration and design through Industry 4.0. *Int. J. Logist. Res. Appl.* 27(6), 986–1014 (2024).
- De Vass, T., Shee, H. & Miah, S. IoT in supply chain management: Opportunities and challenges for businesses in early industry 4.0 context. *Oper. Supply Chain Manag. Int. J.* 14(2), 148–161 (2021).
- de Oliveira-Dias, D., Maqueira-Marin, J. M., Moyano-Fuentes, J. & Carvalho, H. Implications of using Industry 4.0 base technologies for lean and agile supply chains and performance. *Int. J. Prod. Econ.* 262, 108916 (2023).
- Asrol, M., Yani, M. & Taira, E. Risk management for improving supply chain performance of sugarcane agroindustry. *Ind. Eng. Manag. Syst.* 20(1), 9–26 (2021).
- Szum, K. & Nazarko, J. Exploring the determinants of Industry 4.0 development using an extended SWOT analysis: A regional study. *Energies* 13(22), 5972 (2020).
- Namugenyi, C., Nimmagadda, S. L. & Reiners, T. Design of a SWOT analysis model and its evaluation in diverse digital business ecosystem contexts. *Procedia Comput. Sci.* 159, 1145–1154 (2019).
- Wahab, S. N., Ahmed, N. & Ab Talib, M. S. An overview of the SWOT analysis in India's pharmaceutical supply chain. *Arab Gulf J. Sci. Res.* <https://doi.org/10.1108/AGJSR-03-2023-0102> (2023).
- Quan, N. H. K., Singh, H., Khanh, T. H. T. & Rajagopal, P. A SWOT analysis with a digital transformation: A case study for hospitals in the pharmaceutical supply chain. *J. Inform. Web Eng.* 2(1), 38–48 (2023).
- Mandi, K. et al. SWOT analysis of dairy processing supply chain of JMF using analytical hierarchy process. *Asian J. Dairy Food Res.* 42(2), 255–261 (2023).
- Khan, M. I. & Al-Ghamdi, S. G. Hydrogen economy for sustainable development in GCC countries: A SWOT analysis considering current situation, challenges, and prospects. *Int. J. Hydrogen Energy* 48(28), 10315–10344 (2023).
- Ayu, K., Daryanto, A. & Sasongko, H. Competitive position and business strategy of sugar cane plantation company (case study PTPN X Surabaya). *Jurnal Manajemen & Agribisnis* 15(3), 289–289 (2018).
- Debnath, A., & Roy, J. (2018). Integrated fuzzy AHP-TOPSIS model for optimization of national defense management based on inclusive growth drivers using SWOT analysis. In *Handbook of Research on Military Expenditure on Economic and Political Resources* (pp. 81–105). IGI Global. <https://doi.org/10.4018/978-1-5225-4778-5.ch005>
- Kassem, H. S., Alotaibi, B. A. & Bagadeem, S. Strategic planning approach to the development of contract farming in the Egyptian sugar industry. *J. Agric. Ext.* 24(4), 171–183 (2020).
- Salehi, R., Asaadi, M. A., Rahimi, M. H. & Mehrabi, A. The information technology barriers in supply chain of sugarcane in Khuzestan province, Iran: A combined ANP-DEMATEL approach. *Inf. Process. Agric.* 8(3), 458–468. <https://doi.org/10.1016/j.inpa.2020.09.005> (2021).
- Jesus, G. M. K., Jugend, D., Paes, L. A. B., Siqueira, R. M. & Leandrin, M. A. Barriers to the adoption of the circular economy in the Brazilian sugarcane ethanol sector. *Clean Technol. Environ. Policy* 25(2), 381–395 (2023).

30. Asrol, M., Yani, M. & Taira, E. Supply chain fair profit allocation based on risk and value added for sugarcane agro-industry. *Oper. Supply Chain Manag. An Int. J.* **13**(2), 150–165 (2020).
31. Deepa, N., Senthil Kumar, N., Srinivasan, K., Chang, C. Y. & Bashir, A. K. An efficient ensemble VTOPES multi-criteria decision-making model for sustainable sugarcane farms. *Sustainability* **11**(16), 4288. <https://doi.org/10.3390/su11164288> (2019).
32. Hussain, S. A. I., Chandra, H., & Mandal, U. K. (2022). Comparison of cross-entropy based MCDM Approach for selection of material in sugar industry. In *Advances in Decision Making* (pp. 45–65). IntechOpen.
33. Ali, I. & Khan, N. Evaluating the impact of climate change on the agriculture sector of Pakistan using Multi Criteria Decision Making (MCDM). *Natural Appl. Sci. Int. J. (NASIJ)* **3**(2), 72–84 (2022).
34. Nila, B. & Roy, J. Analysing the key success factors of logistics center 4.0 implementation using improved Pythagorean fuzzy DEMATEL method. *Arab. J. Sci. Eng.* <https://doi.org/10.1007/s13369-023-08398-0> (2023).
35. Nila, B. & Roy, J. Analysis of Critical success factors of logistics 4.0 using D-number based pythagorean Fuzzy DEMATEL method. *Decis. Making Adv.* **2**(1), 92–104 (2024).
36. Tornatzky, L. & Fleischer, M. *The process of technology innovation* (Lexington, 1990).
37. Baker, J. The technology–organization–environment framework. *Inf. Syst. Theory Explain. Predict. Digit. Soc.* **1**, 231–245 (2012).
38. Chatterjee, S., Rana, N. P., Dwivedi, Y. K. & Baabdullah, A. M. Understanding AI adoption in manufacturing and production firms using an integrated TAM-TOE model. *Technol. Forecast. Social Change* **170**, 120880 (2021).
39. Das, S. D. & Bala, P. K. What drives MLOps adoption? An analysis using the TOE framework. *J. Decis. Syst.* <https://doi.org/10.1080/012460125.2023.2214306> (2023).
40. Chittipaka, V., Kumar, S., Sivarajah, U., Bowden, J. L. H. & Baral, M. M. Blockchain technology for supply chains operating in emerging markets: an empirical examination of technology-organization-environment (TOE) framework. *Ann. Oper. Res.* **327**(1), 465–492 (2023).
41. Hamadneh, S., Alshurideh, M., Akour, I., Kurdi, B. & Joghe, S. Factors affecting e-supply chain management systems adoption in Jordan: An empirical study. *Uncertain Supply Chain Manag.* **11**(2), 411–422 (2023).
42. Raj, A. & Jeyaraj, A. Antecedents and consequents of industry 4.0 adoption using technology, organization and environment (TOE) framework: A meta-analysis. *Ann. Oper. Res.* **322**(1), 101–124 (2023).
43. Zhong, Y. & Moon, H. C. Investigating the impact of industry 4.0 technology through a TOE-based innovation model. *Systems* **11**(6), 277 (2023).
44. Santos, B., Dieste, M., Orzes, G. & Charrua-Santos, F. Resources and capabilities for Industry 4.0 implementation: Evidence from proactive Portuguese SMEs. *J. Manuf. Technol. Manag.* **34**(1), 25–43 (2023).
45. Pamucar, D., Simic, V., Görçün, Ö. F. & Küçükönder, H. Selection of the best Big Data platform using COBRAC-ARTASI methodology with adaptive standardized intervals. *Expert Syst. Appl.* **239**, 122312. <https://doi.org/10.1016/j.eswa.2023.122312> (2024).
46. Seikh, M. R. & Mandal, U. Multiple attribute group decision making based on Quasirung Orthopair Fuzzy sets: Application to electric vehicle charging station site selection problem. *Eng. Appl. Artif. Intell.* **115**, 105299 (2022).
47. Zadeh, L. A. Fuzzy sets. *Inf. Control* **8**(3), 338–353 (1965).
48. Alamin, A., Rahaman, M. & Mondal, S. P. Geometric approach for solving first order non-homogenous fuzzy difference equation. *Spectr. Oper. Res.* **2**(1), 61–71. <https://doi.org/10.31181/sor2120257> (2024).
49. Gazi, K. H., Raisa, N., Biswas, A., Azizadeh, F. & Mondal, S. P. Finding the most important criteria in women's empowerment for sports sector by pentagonal fuzzy DEMATEL methodology. *Spectr. Decis. Making Appl.* **2**(1), 28–52. <https://doi.org/10.31181/sdmap21202510> (2024).
50. Atanassov, K. T. Intuitionistic fuzzy sets. *Fuzzy Sets Syst.* **20**(1), 87–96 (1986).
51. Yager, R. R. (2013, June). Pythagorean fuzzy subsets. In 2013 joint IFSA world congress and NAFIPS annual meeting (IFSA/NAFIPS) (pp. 57–61). IEEE.
52. Yager, R. R. (2016). Properties and applications of Pythagorean fuzzy sets. Imprecision and Uncertainty in information representation and processing: new tools based on intuitionistic fuzzy sets and generalized nets, 119–136.
53. Hussain, A. & Ullah, K. An intelligent decision support system for spherical fuzzy Sugeno-weber aggregation operators and real-life applications. *Spectr. Mech. Eng. Oper. Res.* **1**(1), 177–188. <https://doi.org/10.31181/smeor11202415> (2024).
54. Yager, R. R. Generalized orthopair fuzzy sets. *IEEE Trans. Fuzzy Syst.* **25**(5), 1222–1230 (2016).
55. Rahim, M., Akhtar, Y., Yang, M. S., Ali, H. E. & Elhag, A. A. Improved COPRAS method with unknown weights under p, q-Quasirung Orthopair Fuzzy environment: Application to green supplier selection. *IEEE Access.* **12**, 69783–69795. <https://doi.org/10.1109/ACCESS.2024.3400016> (2024).
56. Rahim, M., Garg, H., Khan, S., Alqahtani, H. & Khalifa, H. A. E. W. Group decision-making algorithm with sine trigonometric p, q-quasirung orthopair aggregation operators and their applications. *Alex. Eng. J.* **78**, 530–542 (2023).
57. Rahim, M. et al. Confidence levels-based p, q-Quasirung Orthopair Fuzzy operators and its applications to criteria group decision making problems. *IEEE Access* **11**, 109983–109996 (2023).
58. Chu, Y. M. et al. Some p, q-cubic quasi-rung orthopair fuzzy operators for multi-attribute decision-making. *Complex Intell. Syst.* **10**(1), 87–110 (2024).
59. Aczél, J. & Alsina, C. Characterizations of some classes of quasilinear functions with applications to triangular norms and to synthesizing judgements. *Aequationes Mathematicae* **25**(1), 313–315 (1982).
60. Imran, R., Ullah, K., Ali, Z. & Akram, M. A Multi-criteria group decision-making approach for robot selection using interval-valued intuitionistic fuzzy information and Aczel-Alsina Bonferroni Means. *Spectr. Decis. Making Appl.* **1**(1), 1–32. <https://doi.org/10.31181/sdmap1120241> (2024).
61. Senapati, T. & Yager, R. R. Fermatean fuzzy weighted averaging/geometric operators and its application in multi-criteria decision-making methods. *Eng. Appl. Artif. Intell.* **85**, 112–121 (2019).
62. Senapati, T. & Yager, R. R. Some new operations over Fermatean fuzzy numbers and application of Fermatean fuzzy WPM in multiple criteria decision making. *Informatika* **30**(2), 391–412 (2019).
63. Yager, R. R. & Alajlan, N. Approximate reasoning with generalized orthopair fuzzy sets. *Inf. Fusion* **38**, 65–73 (2017).
64. Yager, R. R., Alajlan, N. & Bazi, Y. Aspects of generalized orthopair fuzzy sets. *Int. J. Intell. Syst.* **33**(11), 2154–2174 (2018).
65. Ali, J. & Naeem, M. Analysis and application of p, q-Quasirung Orthopair Fuzzy Aczel-Alsina aggregation operators in multiple criteria decision-making. *IEEE Access* **11**, 49081–49101. <https://doi.org/10.1109/ACCESS.2023.3274494> (2023).
66. Seikh, M. R. & Mandal, U. Multiple attribute decision-making based on 3, 4-quasirung fuzzy sets. *Granular Comput.* **7**, 965–978. <https://doi.org/10.1007/s41066-021-00308-9> (2022).
67. Biswas, S. Exploring the implications of digital marketing for higher education using intuitionistic fuzzy group decision making approach. *BIMTECH Bus. Perspect.* **2**(1), 33–51 (2020).
68. Kendall, M. G. *Rank correlation methods* (Hafner Publishing House, 1948).
69. Asif, M., Ishtiaq, U. & Argyros, I. K. Hamacher aggregation operators for pythagorean fuzzy set and its application in multi-attribute decision-making problem. *Spectr. Oper. Res.* **2**(1), 27–40. <https://doi.org/10.31181/sor2120258> (2024).
70. Božanić, D. et al. Application of the DIBR II-rough MABAC decision-making model for ranking methods and techniques of lean organization systems management in the process of technical maintenance. *Facta Universitatis, Series: Mech. Eng.* **22**(1), 101–123 (2024).
71. Radovanović, M. et al. Application of hybrid DIBR-FUCOM-LMAW-Bonferroni-grey-EDAS model in multicriteria decision-making. *Facta Universitatis, Series: Mech. Eng.* **21**(3), 387–403 (2023).

72. Biswas, S. & Pamučar, D. S. Combinative distance based assessment (CODAS) framework using logarithmic normalization for multi-criteria decision making. *Serb. J. Manag.* **16**(2), 321–340 (2021).
73. Pamucar, D. & Biswas, S. A novel hybrid decision making framework for comparing market performance of metaverse crypto assets. *Decis. Making Adv.* **1**(1), 49–62 (2023).
74. Kara, K., Özyürek, H., Yalçın, G. C. & Burgaz, N. Enhancing financial performance evaluation: The MEREC-RBNAR hybrid method for sustainability-indexed companies. *J. Soft Comput. Decis. Anal.* **2**(1), 236–257. <https://doi.org/10.31181/jscda21202444> (2024).
75. Biswas, S. & Joshi, N. A performance based ranking of initial public offerings (IPOs) in India. *J. Decis. Anal. Intell. Comput.* **3**(1), 15–32 (2023).
76. Sahoo, S. K., Choudhury, B. B. & Dhal, P. R. A bibliometric analysis of material selection using MCDM methods: Trends and insights. *Spectr. Mech. Eng. Oper. Res.* **1**(1), 189–205. <https://doi.org/10.31181/smeor11202417> (2024).
77. Wang, H., Zhao, W. & Zheng, J. Improved q-Rung Orthopair Fuzzy WASPAS method based on softmax function and frank operations for investment decision of community group-buying platform. *J. Soft Comput. Decis. Anal.* **2**(1), 188–212. <https://doi.org/10.31181/jscda21202442> (2024).
78. Biswas, S., Božanić, D., Pamučar, D. & Marinković, D. A spherical fuzzy based decision making framework with Einstein aggregation for comparing preparedness of SMEs in Quality 4.0. *Facta Universitatis, Series: Mech. Eng.* **21**(3), 453–478 (2023).
79. Muthuswamy, V. V. & Al-ameryeen, M. F. I. Effects of supply chain management practices on SME's performance: Examining moderating role of firm age. *Int. J. Constr. Supply Chain Manag.* **12**(2), 93–107 (2022).
80. Benrqya, Y., Chetioui, Y. & Jerboui, C. Investigating the relationship between supply chain maturity and performance: An emerging market study. *Int. J. Product. Perform. Manag.* **73**(6), 1772–1796 (2024).
81. Gopalakrishnan, S. & Bierly, P. E. The impact of firm size and age on knowledge strategies during product development: A study of the drug delivery industry. *IEEE Trans. Eng. Manag.* **53**(1), 3–16 (2006).
82. Saberi, S., Kouhizadeh, M., Sarkis, J. & Shen, L. Blockchain technology and its relationships to sustainable supply chain management. *Int. J. Prod. Res.* **57**(7), 2117–2135 (2019).
83. Marsh, S. J. & Stock, G. N. Creating dynamic capability: The role of intertemporal integration, knowledge retention, and interpretation. *J. Product Innov. Manag.* **23**(5), 422–436 (2006).
84. Shamout, M. et al. A conceptual model for the adoption of autonomous robots in supply chain and logistics industry. *Uncertain Supply Chain Manag.* **10**(2), 577–592 (2022).
85. Stentoft, J., Adbøll Wickstrøm, K., Philipsen, K. & Haug, A. Drivers and barriers for Industry 4.0 readiness and practice: Empirical evidence from small and medium-sized manufacturers. *Prod. Plan. Control* **32**(10), 811–828 (2021).
86. Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A. B. L. & Rajak, S. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *Int. J. Prod. Econ.* **224**, 107546 (2020).
87. Yang, M., Fu, M. & Zhang, Z. The adoption of digital technologies in supply chains: Drivers, process and impact. *Technol. Forecast. Soc. Change* **169**, 120795 (2021).
88. Pu, G., Qamruzzaman, M. D., Mehta, A. M., Naqvi, F. N. & Karim, S. Innovative finance, technological adaptation and SMEs sustainability: the mediating role of government support during COVID-19 pandemic. *Sustainability* **13**(16), 9218 (2021).
89. Nicolaas Bezuidenhout, C., Bodhanya, S. & Brenchley, L. An analysis of collaboration in a sugarcane production and processing supply chain. *Br. Food J.* **114**(6), 880–895 (2012).
90. Sadhu, T. et al. A comparative study of metaheuristics algorithms based on their performance of complex benchmark problems. *Decis. Making Appl. Manag. Eng.* **6**(1), 341–364 (2023).

## Author contributions

SB, DP and VS performed the conceptualization and made the formal analysis, developed the methodology. They also carried out supervision and validation and wrote the original draft. SB and DP carried out the data curation and investigation, as well as the conceptualization. Their contribution also reflects in writing the original draft and the review editing. SB conducted the formal analysis and developed the methodology and the software as well; he was also responsible for the visualization and writing the original draft. SB, DP and VS contributed in the formal analysis, supervision, the writing of the original draft, and the review and editing, too. All the authors have read and approved the final manuscript.

## Funding

No funding was received for conducting this study.

## Declarations

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1038/s41598-024-75528-5>.

**Correspondence** and requests for materials should be addressed to D.P.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2024