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An Expert Opinion-Based Soft Computing Framework for Comparing Nanotechnologies used in Agriculture

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ABSTRACT

Nanotechnology (NT) has revolutionized agriculture through precision farming, environmental protection, enhanced nutrient delivery and crop production, and effective pesticide control. The purpose of the present research is twofold. First, it aims to develop a novel soft computing model for multi-criteria decision analysis (MCDA) by proposing an Interval-valued p , q -Quasirung Orthopair Fuzzy Number (p , q -IVQROFN)-based hybrid MCDA framework. The CIMAS (Criteria Importance Assessment) method is employed to determine the weights of the criteria, while the WISP method ranks the alternatives. This paper introduces a modification to the WISP method by aggregating four distinct utility degrees using the Heron Mean. The second objective is to apply the proposed framework to compare leading NTs used in agriculture. An expert group decision-making approach is developed to evaluate eight NTs, guided by the theoretical frameworks of TOE (Technology–Organization–Environment) and TRI (Technology Readiness Index). Alternatives are ranked using experts' ratings within the proposed framework, followed by a risk assessment using the Fine–Kinney framework (FKF) to identify potential vulnerabilities. The NTs are compared based on both performance and risk profiles. The results indicate that nano-sensors (NT5), nano-fungicides (NT3), nano-fertilizers (NT2), nano-clays (NT6), and nano-herbicides (NT4) rank as the top nanotechnologies for agricultural applications. The reliability of the proposed model is confirmed through comparisons with other MCDA methods and sensitivity analysis. Overall, this paper presents a robust and practical methodology for sustainable agricultural planning.

1. Introduction

Nanotechnology (NT) encompasses the nuanced and synthesized manipulation of matter in the form of atomic and molecular structures, ranging from 1 to 100 nm, where unique optical, mechanical, and electrical properties are exhibited due to quantum effects and an increased surface area [1, 2]. Work on the evolutionary constituents of NT can be traced back to Feynman's 1959 lecture, "Plenty of Room at the Bottom," with pertinent milestones occurring around the 1980s,

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including the discovery of fullerenes and the emergence of DNA nanotechnology [3]. Hung *et al.*, [4] documented distinct evolutionary research in NT, beginning with fundamental sciences and extending it to its applied innovation. One notable historical scientific event was the establishment of the U.S. National Nanotechnology Initiative in 2000, which generated \$91 billion in domestic revenues through network-coordinated research efforts over ten years [5].

NT has multifaceted applications across multiple domains; in medicine, it facilitates targeted drug delivery and advanced diagnostics [6]; in agriculture, productivity can be boosted by nano-fertilizers and soil sensors [7]; and in energy, nanomaterials can boost solar cell efficiency and storage capacity [8]. Industrial applications include gecko-inspired adhesives [9] and cutting-edge manufacturing practices [10]. NT offers several crucial contributions to agricultural development [11]. NT has revolutionized agriculture. It enhances crop productivity and resilience. It also improves precision farming practices. Its integration promises sustainable solutions. These solutions address current agricultural challenges. They are smart, efficient, and eco-friendly. NT helps in sustainable farming through an innovative approach for plant growth, environmental protection, cleaning of water, efficient watering and harvesting, effective control of pests and diseases (by finding and delivering pesticides directly to the affected tissues), germination of seeds, limiting overuse of chemicals, innovative packaging (to enhance the shelf life of the perishable items) and several other ways [12-21].

However, we find that past studies have primarily focused on exploring the potential applications, benefits, and challenges of various NTs in agricultural use. Many scholars have contributed to the development of technology solutions. Some studies [12, 13] included a comparative analysis of multiple NTs in agriculture. Nevertheless, no prior work has contributed to the development of a multidimensional framework (based on feasibility, implementability, and risk) to compare the utilities of the NTs used in agriculture. Furthermore, none of the past studies have dedicated efforts to examining the potential risk scores of the NTs. In other words, there is a void in the existing literature. The aforementioned void in the literature has motivated us to undertake the present work, which aims to provide a managerial perspective for comparing NTs used in agriculture.

The utility of a specific NT depends on several aspects or criteria. Therefore, the current study employs a multi-criteria decision modelling (MCDM) approach. Since the use of NTs in agriculture has been limited to the introductory phase (heading towards the growth phase), not much objective information is available. To overcome this limitation, the current work focuses on an expert decision-making approach, based on subjective opinions. To address the imprecise information resulting from subjectivity, we develop an uncertain decision-making framework for MCDM using interval-valued p, q -Quasirung Orthopair fuzzy sets (p, q -IVQROFS).

The seminal concept of Fuzzy Sets and Logic was proposed by Zadeh [22] to address imprecise information in uncertain environments. However, the conventional Fuzzy Set only considers the variable degree of membership (M) whose value lies between 0 and 1. To effectively deal with the uncertainty, Atanassov [23] introduced a novel concept of Intuitionistic Fuzzy Set (IFS) that considers both variable degrees of membership and non-membership in such a way that $0 \leq M + N \leq 1$. Later, researchers recognized the need to upgrade IFS to provide greater flexibility for decision-makers in selecting membership and non-membership degrees. Consequently, scholars [24, 25] have developed a generalized version of IFS, namely, the q -run Orthopair Fuzzy Set (q -ROFS), which utilizes a natural number, q to encompass a wide range of values in defining the membership and non-membership functions, connected by the inequality $0 \leq M^q + N^q \leq 1; q \geq 1$. Later, a further generalization has been made by Seikh and Mandal [26] in the form of p, q Quasirung Orthopair Fuzzy Set that utilizes two natural numbers, $p, q (p, q \geq 1; p \leq, > q)$, such that the relationship $0 \leq M^p + N^q \leq 1; p, q \geq 1$ remains good.

The concept of using interval values in connection with uncertain models dates back to the 1990s when Atanassov [27] popularized the use of the Interval-valued IFS (IV-IFS). To address the deficiency in the cognitive capabilities of decision-makers in determining membership and non-membership values, IV-IFS was a pioneering concept [28]. The use of interval values allows the decision-maker to select a range of values (within the lower and upper bounds) for the membership and non-membership. Later, scholars have further generalized the concept of IV-IFS to extend the range of values for complex decision-making. The Interval-valued q -ROFS (IV- q ROFS) helps remove the constraint of selecting membership and non-membership values (as in the cases of IV-IFS, IV-Pythagorean Fuzzy Sets, etc.) and provides a better representation of uncertainty [29-34]. However, there is a further possibility of providing more flexibility to decision-makers. This motivates us to further generalize the concept of IV- q ROFS by using two natural numbers, p and q . Thus, the present research develops a flexible scientific basis to capture the uncertainty while utilizing MCDA methods. The primary research objectives of this paper are:

- i. RO 1. To carry out a multidimensional comparative analysis of NTs used in agriculture.
- ii. RO 2. To examine the potential risk levels of NTs for use in agriculture
- iii. RO 3. To develop a reliable soft computing decision analysis framework for technology selection

To perform the comparative analysis, the current work utilizes a hybrid CIMAS (criteria importance assessment) [35] and WISP (weighted sum product) [36] framework. The present research makes several contributions to the existing body of literature.

- 1) To the best of the authors' knowledge, the present paper is the first to provide an expert opinion-driven comparative analysis of the NTs used in agriculture in the Indian context.
- 2) This paper is a rare juxtaposition of acceptability (using MCDA) and risk analysis (utilizing FKF) of a new technology, such as NT in agriculture.
- 3) The present work exhibits a rare application of TOE and TRI together using the soft computing approach
- 4) The use of p, q – IVQROFN in MCDA models is a distinguished contribution.
- 5) The current study extends the applicability of FKF by utilizing a robust data-driven model based on p, q -IVQROFN.
- 6) The present paper provides a novel extension of the CIMAS and WISP method with p, q -IVQROFN.
- 7) This paper innovatively modifies the WISP method using the Heron mean to provide more flexibility and examine the sensitivity.

The remainder of this contribution is structured as follows. Section 2 discusses the theoretical foundations of TOE, TRI, and FKF. Alongside, it also exhibits the preliminary concepts to understand p, q -IVQROFN. Section 3 provides a brief overview of some related contributions. Section 4 describes the criteria and alternatives. Besides, it outlines the proposed research methodology. Section 5 reports the key findings of the data analysis. Additionally, it presents the results of a comparative analysis of several MCDA models and the findings of the sensitivity analysis. Section 6 highlights the notable inferences drawn from the findings. This section also outlines managerial, social, and policy implications of the present research. Some limitations and future scopes of the current work are reported. Section 7 concludes the paper.

2. Theoretical underpinning

2.1. TOE

The Technology-Organization-Environment (TOE) framework, introduced by Tornatzky and Fleischer [37], has been extensively applied across various research domains to analyse the adoption

of technological innovations. This framework categorizes the critical factors influencing technology adoption into three dimensions: technological, organizational, and environmental contexts.

The technological context comprises attributes such as relative advantage, compatibility, complexity, security, and observability, which significantly affect the adoption of innovations [38-41]. The organizational context encompasses internal factors, including top management support, firm size, technological orientation, decision-making capability, necessary infrastructure, knowledge base, and organizational readiness [38, 42, 43]. The environmental context encompasses external factors, including competitive pressure, government support, and regulatory frameworks [44]. In the context of adapting advanced technologies, scholars have extensively utilized the TOE framework. The examples include a strategic analysis of the adaptation of Industry 4.0 technologies in the sugarcane supply chains [45], the adaptation of organization-wide metaverse technologies [46], exploring the drivers behind blockchain implementation in banking [47], and the adoption of city digital twins for better governance and collaboration with citizens [42].

2.2. TRI

The Technology Readiness Index (TRI) is a theoretical framework developed to measure an individual's or an organization's propensity to embrace and utilize new technologies. Initially conceptualized by Parasuraman [48], the TRI is a multidimensional scale that evaluates readiness through four dimensions: optimism, innovativeness, discomfort, and insecurity. Optimism and innovativeness function as drivers of technology adoption, while discomfort and insecurity act as inhibitors [49]. TRI has been applied across various domains, including e-learning, e-services, social innovations, banking, and smart tourism. For instance, Cruz-Cárdenas *et al.*, [50] investigated how optimism and innovativeness influence consumers' tendencies to adopt technology-based services. In the context of e-learning, Kaushik and Agrawal [51] examined the role of TRI in student adoption. Wijanarko *et al.*, [52] investigated the customers' readiness to adopt advanced metaverse platforms in the digital banking system. Collectively, these studies affirm TRI's robustness and versatility in predicting technology adoption and utilization across diverse sectors, emphasizing both direct technological attitudes and their complex interactions with mediating factors, such as motivations and organizational characteristics.

2.3. Fine-Kinney framework

The Fine-Kinney Framework (FKF) is a time-honored approach for the objective assessment of risk or hazards, commonly used in occupational safety measures and industrial settings [53]. FKF assesses the risk scores of potential vulnerabilities based on three aspects: Probability or Likelihood ("how likely the risk would take place"), Consequence or Severity ("Likely impact of the event when it occurs"), and Exposure ("The frequency or repetition of occurrence"). Accordingly, the overall risk or hazard score is calculated as $ORS = L \times S \times E$. Several research contributions have utilized the FKF in hazard assessment problems across various domains (e.g., [54-56]). However, the experts [55] expressed concern about the sensitivity of the FKF-based assessment to variations in the ratings by opinion-makers and advocated for the development of uncertain modelling.

2.4. Preliminary concepts (p, q – IVQROFN)

This subsection presents some primary theoretical concepts, including various definitions, and operational rules that help understand the p, q – IVQROFN applications.

Definition 1. p, q -Quasiring Orthopair Fuzzy Set (p, q -QROFS)

Let, Ω is any ordinary non-empty set in the universe of discourse. Then, the p, q -QROFS, $\tilde{\rho}$ on Ω is defined as follows.

$$\tilde{\rho} = \{x, \langle M_{\tilde{\rho}}(x), N_{\tilde{\rho}}(x) \rangle : x \in \Omega\} \text{ such that } 0 \leq (M_{\tilde{\rho}}(x))^p + (N_{\tilde{\rho}}(x))^q \leq 1 \quad (1)$$

Definition 2. Interval-valued q -Rung Orthopair Fuzzy Set (IV- q ROFS)

The IV- q ROFS, \tilde{Q} on Ω is defined as follows.

$$\tilde{Q} = \left\{ x, \left\langle \left(M_{\tilde{Q}}(x), \overline{M_{\tilde{Q}}}(x) \right), \left(N_{\tilde{Q}}(x), \overline{N_{\tilde{Q}}}(x) \right) \right\rangle : x \in \Omega \right\} \quad (2)$$

In Eq. (2), $M_{\tilde{Q}}(x) = \left[M_{\tilde{Q}}(x), \overline{M_{\tilde{Q}}}(x) \right] : x \rightarrow [0,1]$ and $N_{\tilde{Q}}(x) = \left[N_{\tilde{Q}}(x), \overline{N_{\tilde{Q}}}(x) \right] : x \rightarrow [0,1]$ denote the membership and non-membership degrees of the element $x \in \Omega$ to \tilde{Q} such that

$$\left(\overline{M_{\tilde{Q}}}(x) \right)^q + \left(\overline{N_{\tilde{Q}}}(x) \right)^q \leq 1; q \geq 1 \quad (3)$$

The notation $\left[M_{\tilde{Q}}(x), \overline{M_{\tilde{Q}}}(x) \right]$ indicates the lower and upper bounds of the membership degree and $\left[N_{\tilde{Q}}(x), \overline{N_{\tilde{Q}}}(x) \right]$ denotes the lower and upper bounds of the non-membership degree, respectively. The degree of hesitancy or indeterminacy is derived as follows.

$$H_{\tilde{Q}}(x) = \left[H_{\tilde{Q}}(x), \overline{H_{\tilde{Q}}}(x) \right] \quad (4)$$

$$= \left[\sqrt[q]{1 - \left(\left(M_{\tilde{Q}}(x) \right)^q + \left(N_{\tilde{Q}}(x) \right)^q \right)}, \sqrt[q]{1 - \left(\overline{M_{\tilde{Q}}}(x) \right)^q + \left(\overline{N_{\tilde{Q}}}(x) \right)^q} \right]$$

Since p, q -QROFS is a generalization of the conventional q -ROFS, we can define the p, q -IVQROFS as a generalized version of the IV- q ROFS. Additionally, following the work of Wang *et al.*, (2019), we can define the operations, score, and accuracy functions of the p, q -IVQROFS. In the subsequent part, we present the definitions related to the p, q -IVQROFS.

Definition 3. Interval-valued p, q -Quasirung Orthopair Fuzzy Set (p, q -IVQROFS)

The p, q -IVQROFS, $\tilde{\mathfrak{S}}$ on Ω is defined as follows.

$$\tilde{\mathfrak{S}} = \left\{ x, \left\langle \left(M_{\tilde{\mathfrak{S}}}(x), \overline{M_{\tilde{\mathfrak{S}}}}(x) \right), \left(N_{\tilde{\mathfrak{S}}}(x), \overline{N_{\tilde{\mathfrak{S}}}}(x) \right) \right\rangle : x \in \Omega \right\} \quad (5)$$

In Eq. (5), $M_{\tilde{\mathfrak{S}}}(x) = \left[M_{\tilde{\mathfrak{S}}}(x), \overline{M_{\tilde{\mathfrak{S}}}}(x) \right] : x \rightarrow [0,1]$ and $N_{\tilde{\mathfrak{S}}}(x) = \left[N_{\tilde{\mathfrak{S}}}(x), \overline{N_{\tilde{\mathfrak{S}}}}(x) \right] : x \rightarrow [0,1]$ denote the membership and non-membership degrees of the element $x \in \Omega$ to $\tilde{\mathfrak{S}}$ such that

$$\left(\overline{M_{\tilde{\mathfrak{S}}}}(x) \right)^p + \left(\overline{N_{\tilde{\mathfrak{S}}}}(x) \right)^q \leq 1; p, q \geq 1; p \leq, > q \quad (6)$$

The degree of hesitancy or indeterminacy is derived as follows.

$$H_{\tilde{\mathfrak{S}}}(x) = \left[H_{\tilde{\mathfrak{S}}}(x), \overline{H_{\tilde{\mathfrak{S}}}}(x) \right] \quad (7)$$

$$= \left[\sqrt[\varepsilon]{1 - \left(\left(M_{\tilde{\mathfrak{S}}}(x) \right)^p + \left(N_{\tilde{\mathfrak{S}}}(x) \right)^q \right)}, \sqrt[\varepsilon]{1 - \left(\overline{M_{\tilde{\mathfrak{S}}}}(x) \right)^p + \left(\overline{N_{\tilde{\mathfrak{S}}}}(x) \right)^q} \right]$$

In Eq. (7), ε is a small number, the least common multiple (l.c.m) of p and q .

For easy calculation purposes, let us treat the p, q -IVQROFN, $\mathfrak{S} = (M, N) = ([\underline{M}, \overline{M}], [\underline{N}, \overline{N}])$ as a representation of the p, q -IVQROFS.

Definition 4. Given the p, q -IVQROFN, $\mathfrak{S} = (M, N) = ([\underline{M}, \overline{M}], [\underline{N}, \overline{N}])$, the score function is defined as follows.

$$S(\mathfrak{S}) = \frac{1}{4} \left[(1 + \underline{M}^p - \underline{N}^q) + (1 + \overline{M}^p - \overline{N}^q) \right]; S(\mathfrak{S}) \in [0, 1] \quad (8)$$

Definition 5. The definition of the accuracy function is provided below.

$$A(\mathfrak{S}) = \frac{1}{2} \left[\underline{M}^p + \overline{M}^p + \underline{N}^q + \overline{N}^q \right]; A(\mathfrak{S}) \in [0, 1] \quad (9)$$

The rules of comparison of two p, q -IVQROFNs are as follows.

a) If $S(\mathfrak{S}_1) > S(\mathfrak{S}_2)$, then $\mathfrak{S}_1 > \mathfrak{S}_2$

b) If $\mathcal{S}(\mathfrak{S}_1) < \mathcal{S}(\mathfrak{S}_2)$, then $\mathfrak{S}_1 < \mathfrak{S}_2$

c) If $S(\mathfrak{S}_1) = S(\mathfrak{S}_2)$, then

$$A(\mathfrak{S}_1) > A(\mathfrak{S}_2) \Rightarrow \mathfrak{S}_1 > \mathfrak{S}_2;$$

$$A(\mathfrak{S}_1) < A(\mathfrak{S}_2) \Rightarrow \mathfrak{S}_1 < \mathfrak{S}_2;$$

$$A(\mathfrak{S}_1) = A(\mathfrak{S}_2) \Rightarrow \mathfrak{S}_1 = \mathfrak{S}_2;$$

Definition 6. Suppose we consider three p, q -IVQROFNs given as

$$\mathfrak{S} = ([\underline{M}, \overline{M}], [\underline{N}, \overline{N}]), \mathfrak{S}_1 = ([\underline{M}_1, \overline{M}_1], [\underline{N}_1, \overline{N}_1]) \text{ and } \mathfrak{S}_2 = ([\underline{M}_2, \overline{M}_2], [\underline{N}_2, \overline{N}_2]).$$

Then, the following operational rules can be defined.

$$6(a). \mathfrak{S}_1 \oplus \mathfrak{S}_2 = \left(\left[\sqrt[p]{\underline{M}_1^p + \underline{M}_2^p - \underline{M}_1^p \underline{M}_2^p}, \sqrt[p]{\overline{M}_1^p + \overline{M}_2^p - \overline{M}_1^p \overline{M}_2^p} \right], \left[\underline{N}_1 \underline{N}_2, \overline{N}_1 \overline{N}_2 \right] \right);$$

$$6(b). \mathfrak{S}_1 \otimes \mathfrak{S}_2 = \left(\left[\underline{M}_1 \underline{M}_2, \overline{M}_1 \overline{M}_2 \right], \left[\sqrt[q]{\underline{N}_1^q + \underline{N}_2^q - \underline{N}_1^q \underline{N}_2^q}, \sqrt[q]{\overline{N}_1^q + \overline{N}_2^q - \overline{N}_1^q \overline{N}_2^q} \right] \right);$$

$$6(c). \beta \mathfrak{S} = \left(\left[\sqrt[p]{1 - (1 - \underline{M}^p)^\beta}, \sqrt[p]{1 - (1 - \overline{M}^p)^\beta} \right], \left[(\underline{N})^\beta, (\overline{N})^\beta \right] \right), \beta > 0;$$

$$6(d). (\mathfrak{S})^\beta = \left(\left[(\underline{M})^\beta, (\overline{M})^\beta \right], \left[\sqrt[q]{1 - (1 - \underline{N}^q)^\beta}, \sqrt[q]{1 - (1 - \overline{N}^q)^\beta} \right] \right), \beta > 0;$$

$$6(e). \mathfrak{S}^c = ([\underline{N}, \overline{N}], [\underline{M}, \overline{M}]) \text{ (Complement)}$$

Definition 7. Aggregation operations

Suppose $\mathfrak{S}_j = (M_j, N_j) = ([\underline{M}_j, \overline{M}_j], [\underline{N}_j, \overline{N}_j])$ ($j = 1, 2, \dots, h$) be a series of p, q -IVQROFNs with

corresponding weights $\omega_j > 0$, $\sum_{j=1}^h \omega_j = 1$, then the aggregation operations are conducted as follows.

7(a). p, q -IVQROFN weighted average (p, q -IVQROFNWA)

$$p, q - IVQROFNWA(\mathfrak{S}_1, \mathfrak{S}_2, \dots, \mathfrak{S}_h) = \sum_{j=1}^h \omega_j \mathfrak{S}_j$$

$$= \left(\left[\sqrt[p]{1 - \prod_{j=1}^h \left(1 - \left(M_j\right)^p\right)^{\omega_j}}, \left[\prod_{j=1}^h \left(N_j\right)^{\omega_j}, \prod_{j=1}^h \left(\bar{N}_j\right)^{\omega_j} \right] \right], \left[\sqrt[p]{1 - \prod_{j=1}^h \left(1 - \left(\bar{M}_j\right)^p\right)^{\omega_j}}, \left[\prod_{j=1}^h \left(N_j\right)^{\omega_j}, \prod_{j=1}^h \left(\bar{N}_j\right)^{\omega_j} \right] \right] \right) \quad (10)$$

7(b). p, q-IVQROFN weighted geometric average (p, q-IVQROFNWGA)

$$p, q - IVQROFNWGA(\mathfrak{S}_1, \mathfrak{S}_2, \dots, \mathfrak{S}_h) = \prod_{j=1}^h \mathfrak{S}_j^{\omega_j}$$

$$= \left(\left[\prod_{j=1}^h \left(M_j\right)^{\omega_j}, \prod_{j=1}^h \left(\bar{M}_j\right)^{\omega_j} \right], \left[\sqrt[q]{1 - \prod_{j=1}^h \left(1 - \left(N_j\right)^q\right)^{\omega_j}}, \sqrt[q]{1 - \prod_{j=1}^h \left(1 - \left(\bar{N}_j\right)^q\right)^{\omega_j}} \right] \right) \quad (11)$$

3. Related studies

3.1. Applications of nanotechnology in agriculture

The contributions toward the application of NT in the agricultural field are on a growth trajectory. The following table (Table 1) provides a summary of some of the prominent recent applications relevant to the current research.

Table 1
 Summary of some applications of NT in agriculture

Author(s)	Contribution(s)	Methodology	Data type
Iavicoli <i>et al.</i> , [11]	Reviews potential applications of NTs with special emphasis on occupational and other risks and critical issues.	Review	Content
Garg <i>et al.</i> , [12]	Discusses the development of the precision algorithm and highlights the applicability and challenges of various NTs in precision farming for controlling variability.	Review	Content
Thakur and Yadav [13]	Review of various NTs for sustainable agriculture through precision farming.	Review	Content
Neme <i>et al.</i> , [14]	Summarizes various applications of NTs in agriculture while focusing on discussing the risks associated with food security.	Review and conceptual model	Content
Miguel-Rojas <i>et al.</i> , [15]	Discusses potential applications of nanobiosensors and nanoformulations in enhancing crop production and mitigating environmental risks. It also highlights implementation issues.	Review	Content
Mgadi <i>et al.</i> , [16]	Reviews the plant-associated microorganisms concerning the applications of nanoparticles and discusses various control measures.	Review	Content
Chaturvedi <i>et al.</i> , [17]	Discusses various applications of nanobiosensors and their associated challenges.	Review	Content
Santos <i>et al.</i> , [18]	Highlights various applications of NTs to boost crop production and discusses various challenges, especially the regulatory issues	Review	Content
Ali <i>et al.</i> , [20]	Discusses potential applications and risks associated with pesticides and herbicides.	Review	Content
Kekeli <i>et al.</i> , [21]	Discusses the effects of using nanofertilizers on crop yield, plant growth, and quality.	Review	Content

3.2. Applications of IV-qROFS and p, q -IVQROFS

The concept of IV-qROFS has been applied in several research problems. Table 2 provides a summary of some of the recent contributions related to IV-qROFS.

Table 2

Summary of development and applications related to IV-qROFS

Author(s)	Application area	Key contribution(s)
Joshi <i>et al.</i> , [29]	-----	Theoretical development of IV-qROFS and its properties
Wang <i>et al.</i> , [30]	Green supplier selection	Proposed IV-qROFS Hamy aggregation operators and their properties.
Gao <i>et al.</i> , [31]	Supplier selection for medical products	Extension of the VIKOR method using IV-qROFS for MCDA applications
Feng <i>et al.</i> , [57]	Numerical examples	Defined the dual hesitant linguistic IV-qROFS and its operations, including the Maclaurin symmetric mean (MSM) for MCDA applications.
Garg <i>et al.</i> , [58]	Numerical examples	Possibility degree-based comparison approach.
Garg <i>et al.</i> , [59]	Numerical examples	Development of q -connection numbers and q -exponential operational laws for MCDA applications.
Garg <i>et al.</i> , [60]	Numerical examples	<ul style="list-style-type: none"> a) Defined the complex IV-qROFS and related properties for MCDA applications b) Extension of the TOPSIS and AHP methods using complex IV-qROFS
Ali <i>et al.</i> , [61]	Facility location selection for setting up a wind power plant	Defined the concept and application of IV-qROFS-based soft sets for MCDA problems
Khan <i>et al.</i> , [62]	Selection of optimum strategic decisions for green supply chain management	<ul style="list-style-type: none"> a) Proposed generalized p-distance, Hamming distance, and Euclidean distance measures b) Extension of the CODAS method using IV-qROFS.
Wan <i>et al.</i> , [63]	Numerical examples	<ul style="list-style-type: none"> a) IV-qROFS-based Dombi aggregation b) Extension of the Qualiflex method using IV-qROFS.
Zhang <i>et al.</i> , [64]	Evaluation of the health risk	<ul style="list-style-type: none"> a) Neutrality aggregation for IV-qROFS b) Development of extended PSI-COPRAS framework using IV-qROFS
Ahemad <i>et al.</i> , [65]	Numerical examples	Development of the GRA-IV-qROFS framework for MCDA application with varying information about the criteria weights.
Korucuk <i>et al.</i> , [32]	Adopting technology to improve logistics service quality in 3PL operations	Extension of the ARAS method using IV-qROFS for MCDA applications
Rong <i>et al.</i> , [33]	Risk assessment in the shipbuilding process	<ul style="list-style-type: none"> a) Development of IV-qROFS-based Aczel–Alsina aggregation operators and their properties. b) Definition of a new score function c) Extension of the WASPAS and LOPCOW methods using IV-qROFS for MCDA applications d) Development of a new FMEA model with IV-qROFS.
Zheng <i>et al.</i> , [34]	Medical diagnosis	Development of IV-qROFS-based Entropy and CoCoSo for MCDA applications

The application of the p, q -IVQROFS in MCDA is in its early stages. The existing literature shows scant applications of the p, q -IVQROFS. For instance, Ali and Khan [66] demonstrated the application of the p, q -IVQROFS with exponential aggregation and the TODIM approach for the supplier selection

problem. In another recent work, Chen *et al.*, [67] defined the Maclaurin symmetric mean and Archimedean operational laws for p, q -IVQROFS.

3.3. Applications of CIMAS and WISP

This section discusses the contributions made to the development and applications of the CIMAS and WISP methods. These methods have been introduced recently and show a promising growth in the applications. Table 3 summarizes some of the prominent studies that used the CIMAS method in various applications.

Table 3
 Summary of development and applications related to the CIMAS method

Author(s)	Application	Methodology	Data type
Aytekin & Korucuk [68]	Explores the key determinants of the innovation capability	CIMAS	Crisp
Švadlenka <i>et al.</i> , [69]	Assessment of potential vulnerabilities in the crowd-shipping operation	CIMAS	Crisp
Kara <i>et al.</i> , [70]	Selection of a blockchain platform	CIMAS-WISP	Interval-valued spherical fuzzy number
Kara <i>et al.</i> , [71]	Evaluation of the financial performance of technology firms	CIMAS-CRITIC-RBNAR	Single-valued neutrosophic fuzzy number
Cui [72]	Comparison of offline and online teaching modes	CIMAS-COBRA	Triangular Linguistic Neutrosophic Cubic Fuzzy Number
Liu & Lai [73]	Comparison of operation strategies	CRITIC-CIMAS-WASPAS	T-Spherical fuzzy number
Joshi <i>et al.</i> , [74]	Selection of solar panels	CIMAS-CRITIC-Entropy method	Crisp
Biswas <i>et al.</i> , [75]	Comparison of e-commerce platforms	CIMAS-BORDA-MPSI-RAM	Crisp
This paper	Comparison of nanotechnology in agriculture	CIMAS and Modified WISP	Interval-valued p, q -Quasirung Orthopair Fuzzy Number

The WISP method has been explored more by scholars than the CIMAS method. Table 4 provides some recent contributions related to the WISP method.

Table 4
 Summary of development and applications related to the WISP method

Author(s)	Application	Methodology	Data type
Ulutaş <i>et al.</i> , [76]	Pallet truck selection problem	MEREC – Simple WISP method	Crisp data
Ulutaş <i>et al.</i> , [77]	Sustainable supplier selection for a textile firm	BWM-WISP method	Grey numbers
Karabašević <i>et al.</i> , [78]	Numerical illustration	Simple WISP method	Triangular Fuzzy numbers
Diniz <i>et al.</i> , [79]	Aircraft carrier selection	AHP-WISP method	Crisp data
Rani <i>et al.</i> , [80]	Location selection for setting up an offshore wind plant	RANCOM-WISP method	Interval-valued Intuitionistic Fuzzy Numbers
Görçün <i>et al.</i> , [81]	Selection of the telescopic forklift	PIPRECIA- WISP	Interval-valued Fermatean Fuzzy Numbers
Cao <i>et al.</i> , [82]	Selection of an ERP solution	BWM-WISP	Rough set
Bulut [83]	Assessment of healthcare capacity	CRITIC-WISP	Crisp data
This paper	Comparison of nanotechnology in agriculture	CIMAS and Modified WISP	Interval-valued p, q -Quasirung Orthopair Fuzzy Number

3.4. Research gaps

According to the literature review, the following gaps are identified.

- 1) There are no apparent studies that have compared NTs in agriculture. The field of NT in agriculture is in a development phase. The literature has primarily contributed to the development of NTs, experimental evaluations, and possible applications in agriculture, as well as their benefits and risk factors. The data-driven comparison of NTs and the analysis of potential vulnerabilities in use, as well as the analysis of practical implications, are yet to be explored extensively.
- 2) From the theoretical point of view, the integration of the TOE and TRI frameworks in addressing the technology adoption issues in agriculture is quite rarely found in the existing literature.
- 3) The limitations in using p, q -IVQROFN in MCDA for real-life problems. Only a few contributions have been found in the existing literature. The p, q -IVQROFN provides a generalized and flexible approach for analysts to handle complex decision-making scenarios. We also notice that IV-qROFN has not been widely explored in the fields of sustainability, technology management, and agriculture. These suggest that there is a possibility of developing a robust uncertain decision model using a flexible and generalized fuzzy measure.
- 4) The literature review also reveals that there has been no contribution that has used a flexible and generalized uncertainty measure, such as p, q -IVQROFN, for WISP applications. The WISP method is a reliable and straightforward approach. However, the use of p, q -IVQROFN enhances its flexibility and provides a better approach to deal with imprecise information.

4. Materials and methods

4.1. Description of the alternatives

The present paper compares popular NTs that have been mentioned in various technical reports and scholarly contributions. Table 5 provides a brief description of the NTs being compared in this study.

Table 5
 Description of the NTs used in agriculture

S/L	Description	Purpose (s)	References
NT 1	Nanoparticles	Protect against microbial growth and diseases; enhance crop yield, resilience, and longevity by increasing salicylic acid concentrations and reducing reactive oxygen species in seeds.	[12-14], [16], [18, 19], [84, 85]
NT 2	Nano fertilizers	Boost plant growth and use antioxidant properties. They improve solubility, stability, and controlled release. This makes pest control more accurate and crucial in today's environmentally conscious food production.	[12-14], [18-19], [21], [86, 87]
NT 3	Nano fungicides	Nano fungicides and Nano herbicides are superior to regular chemical products due to their direct targeting, reduced chemical usage, and long-lasting effectiveness. Nano-fungicides protect from pathogenic fungi. Nano herbicides are helpful in the eradication of weeds.	[89, 88] [12-14] [18-19][20]
NT 4	Nano herbicides		
NT 5	Nano sensors	Detection of pesticides, monitoring plant nutrition, and environmental monitoring. Nano-biosensors are crucial in precision agriculture. They facilitate real-time assessment of soil and plant health. They help identify environmental changes. They ensure timely pesticide administration. Nano biosensors enhance data-driven decision-making.	[90] [12-15] [17-19]

Table 5

Continued

S/L	Description	Purpose (s)	References
NT 6	Nanoclays	Nanoclays help control the release of agrochemicals and help in water retention. Additionally, it enhances nutrient delivery, improves soil quality, protects pesticides from environmental degradation, and prevents microbial attacks.	[12-14] [18-19]
NT 7	Nano materials	Protect from contamination and maintain soil health. They maintain soil pH, moisture content, nutrient levels, and prevent the presence of pathogens.	[12-14] [18-19]
NT 8	Carbon Nanotubes	Help in nutrient delivery and seed germination. They help maintain the balance of reactive oxygen species. They also increase enzyme activity, particularly in areas affected by saline conditions in agriculture. These nanomaterials improve photosynthetic efficiency and plant growth. They boost resistance to environmental stress.	[85, 89], [12-14], [18-19]

4.2. Description of the criteria

As stated earlier, the current study is grounded in the theoretical framework of TOE and TRI to determine the criteria for comparing nanotechs. There has been no prior study that has comprehensively compared the NTs in agriculture in terms of accessibility, implement ability, usability, benefits, and risks. Therefore, this paper relies on related studies that discuss the challenges to adopt NT. Table 6 provides a brief description of the criteria used to evaluate nanotechnology in agriculture.

Table 6

Summary of the criteria to compare the NTs in agriculture

S/L	Criteria	Description	Category	Dimension (TOE)	Dimension (TRI)	Reference
CR 1	Complexity	Difficulty in using the technology	Lower is better	Technology (T)	Discomfort (D)	[11]
CR 2	Yield	Support for boosting agricultural yield	Higher is better	Technology (T)	Optimism (O)	[18, 91]
CR 3	Scalability	Ability to be implemented across diverse farmland quickly	Higher is better	Technology (T)	Innovativeness (IN)	[92]
CR 4	Availability	The market potential of the technology (to grow and become available), as well as knowledge about using it.	Higher is better	Environment (E)	Optimism (O)	[11, 18]
CR 5	Adoption barriers	Regulatory and legal barriers to adoption. Apprehension of the farmers	Lower is better	Environment (E)	Insecurity (I)	[18]
CR 6	Resource efficiency	Optimizing the utilization of resources like water, nutrients, pesticides etc.	Higher is better	Organization (O)	Optimism (O)	[91]

Table 6
Continued

S/L	Criteria	Description	Category	Dimension (TOE)	Dimension (TRI)	Reference
CR 7	Operating risk	Health and safety concerns (such as toxicity and bioaccumulation) for the use of the technology	Lower is better	Environment (E)	Insecurity (I)	[11, 12, 93]
CR 8	Environmental sustainability	Protects the environment by reducing the ecological footprint	Higher is better	Environment (E)	Optimism (O)	[11, 18]
CR 9	Affordability	Budget-friendly cost-effective solution	Higher is better	Organization (O)	Innovativeness (IN)	[12, 92, 93]
CR 10	Compatibility	Compatibility with existing systems for integration and collaboration of the stakeholders	Higher is better	Technology (T)	Innovativeness (IN)	[92]

4.3. Proposed method

This sub-section outlines the steps of the proposed methodology.

Suppose

There are $i = 1, 2, \dots, g$ alternatives (NTs) and $j = 1, 2, \dots, h$ criteria, denoted by NT_i and CR_j respectively. There are $k = 1, 2, \dots, t$ experts who evaluated the alternatives.

The utility (expressed in terms of p, q-IVQROFN) of NT_i subject to the effect of CR_j according to the decision-maker E_k is $U_{ij}^k = (M_{ij}^k, N_{ij}^k) = \left(\left[\underline{M}_{ij}^k, \overline{M}_{ij}^k \right], \left[\underline{N}_{ij}^k, \overline{N}_{ij}^k \right] \right)$.

The importance (expressed in terms of p, q-IVQROFN) of CR_j according to the expert E_k is denoted as $I_{kj} = (\hbar_{kj}, \tilde{\lambda}_{kj}) = \left(\left[\underline{\hbar}_{kj}, \overline{\hbar}_{kj} \right], \left[\underline{\tilde{\lambda}}_{kj}, \overline{\tilde{\lambda}}_{kj} \right] \right)$.

According to the decision-maker E_k , the risk score (expressed in terms of p, q-IVQROFN) of NT_i subject to the effect of r^{th} risk dimension is $R_{ir}^k = (\varphi_{ir}^k, \gamma_{ir}^k) = \left(\left[\underline{\varphi}_{ir}^k, \overline{\varphi}_{ir}^k \right], \left[\underline{\gamma}_{ir}^k, \overline{\gamma}_{ir}^k \right] \right)$

4.3.1. Procedural steps to evaluate the utility scores of NTs

Step 1. Determination of the criteria weights (CIMAS method)

Step 1.1. Obtain the expert evaluation of the criteria in the linguistic scale and then convert the linguistic ratings into corresponding p, q-IVQROFNs. Table 7 displays the seven-point linguistic scales and their corresponding p, q-IVQROFNs. The evaluation criteria matrix is provided below.

$$J = \begin{pmatrix} (\hbar_{11}, \tilde{\lambda}_{11}) & \cdots & (\hbar_{1h}, \tilde{\lambda}_{1h}) \\ \vdots & \ddots & \vdots \\ (\hbar_{k1}, \tilde{\lambda}_{k1}) & \cdots & (\hbar_{kj}, \tilde{\lambda}_{kj}) \end{pmatrix}_{k \times h} \quad (12)$$

Table 7
 Linguistic rating scales and corresponding p, q-IVQROFNs

Linguistic description	Code	Membership		Non-membership	
		Lower	Upper	Lower	Upper
Extremely Low (or Bad)	1	0.05	0.10	0.90	0.95
Very Low (or Bad)	2	0.20	0.25	0.80	0.85
Low (or Bad)	3	0.35	0.40	0.65	0.70
Medium	4	0.50	0.55	0.50	0.55
High (or Good)	5	0.65	0.70	0.35	0.40
Very High (or Good)	6	0.80	0.85	0.20	0.25
Extremely High (or Good)	7	0.90	0.95	0.05	0.10

Step 1.2. Calculate the weights of the experts

The expert weights are determined based on their experience and qualifications [94]. For this purpose, we use a three-point linguistic scale (Table 8). The experts' profiles are given in Table 9.

Table 8
 Linguistic rating scales and corresponding p, q-IVQROFNs for expert weight

Linguistic description	Code	Membership		Non-membership	
		Lower	Upper	Lower	Upper
Low	1	0.10	0.15	0.90	0.95
Medium	2	0.50	0.55	0.50	0.55
High	3	0.90	0.95	0.10	0.15

Table 9
 Expert Profile

Expert	Qualification	Years of experience	Functional Expertise	Sector
E1	Ph.D.	15 to 20	Electronics Engineering	Academics
E2	Ph.D.	Above 20	Environmental Science	Industry
E3	Graduate	10 to 15	Agriculture	Industry
E4	Post-graduate	10 to 15	Management	Industry
E5	Ph.D.	15 to 20	Chemistry	Academics
E6	Post-graduate	10 to 15	Agriculture	Industry
E7	Post-graduate	10 to 15	Management	Academics
E8	Ph.D.	15 to 20	Agriculture	Industry
E9	Ph.D.	Above 20	Mechanical Engineering	Academics
E10	Post-graduate	15 to 20	Bio-Science	Industry

The experts' weights are determined using Eq. (13) as follows.

Step 1.2(a). Let, the importance of the k^{th} expert be $\tilde{\omega}_k^{ed} = (\varsigma_k^{ed}, \eta_k^{ed}) = \left([\varsigma_k^{ed}, \eta_k^{ed}], [\overline{\varsigma}_k^{ed}, \overline{\eta}_k^{ed}] \right)$ and $\tilde{\omega}_k^{ex} = (\varsigma_k^{ex}, \eta_k^{ex}) = \left([\varsigma_k^{ex}, \eta_k^{ex}], [\overline{\varsigma}_k^{ex}, \overline{\eta}_k^{ex}] \right)$ based on education qualifications and experience, respectively. Then, the weights of the experts (based on education and experience) are calculated as follows.

$$\omega_k^{ed} = \frac{\frac{1}{4} \left[\left(1 + (\varsigma_k^{ed})^p - (\eta_k^{ed})^q \right) + \left(1 + (\overline{\varsigma}_k^{ed})^p - (\overline{\eta}_k^{ed})^q \right) \right]}{\sum_{k=1}^t \left(\frac{1}{4} \left[\left(1 + (\varsigma_k^{ed})^p - (\eta_k^{ed})^q \right) + \left(1 + (\overline{\varsigma}_k^{ed})^p - (\overline{\eta}_k^{ed})^q \right) \right] \right)} \quad (13)$$

$$\omega_k^{ex} = \frac{\frac{1}{4}[(1+(\zeta_k^{ex})^p - (\eta_k^{ex})^q) + (1+(\overline{\zeta}_k^{ex})^p - (\overline{\eta}_k^{ex})^q)]}{\sum_{k=1}^t \left(\frac{1}{4}[(1+(\zeta_k^{ex})^p - (\eta_k^{ex})^q) + (1+(\overline{\zeta}_k^{ex})^p - (\overline{\eta}_k^{ex})^q)] \right)} \quad (14)$$

Step 1.2(b). Obtain the final weights of the experts

The final weights of the experts are calculated as follows.

$$\omega_k = \frac{\omega_k^{ed} + \omega_k^{ex}}{2} \quad (15)$$

Step 1.3. Obtain the score values of the elements of the expert-rated criteria evaluation matrix

The score values are obtained using Eq. (16) as follows.

$$S(J_{kj}) = \frac{1}{4} \left[\left(1 + \underline{h}_{kj}^p - \underline{\lambda}_{kj}^q \right) + \left(1 + \overline{h}_{kj}^p - \overline{\lambda}_{kj}^q \right) \right]; S(J_{kj}) \in [0,1] \quad (16)$$

Step 1.4. Normalize the criteria evaluation matrix

The elements of the normalized criteria evaluation matrix are obtained as follows.

$$S^N(J_{kj}) = \frac{S(J_{kj})}{\sum_{k=1}^t S(J_{kj})} \quad (17)$$

Step 1.5. Multiply the experts' weights with the corresponding elements of the score-based criteria evaluation matrix. The multiplication operation results in the formation of an expert-weighted criteria evaluation matrix whose elements are obtained as follows.

$$\ell_{kj} = \omega_k \times S^N(J_{kj}) \quad (18)$$

Step 1.6. Obtain the maximum and minimum weighted values for each criterion

The maximum and minimum values for the j^{th} criterion are obtained as

$$\ell_j^+ = \text{Max}_{k=1,2,\dots,t} (\ell_{kj}) \quad (19)$$

$$\ell_j^- = \text{Min}_{k=1,2,\dots,t} (\ell_{kj})$$

Step 1.7. Obtain the difference values of the maximum and minimum or the range of the weighted values for each criterion

The difference is obtained by using Eq. (20) as follows.

$$\Lambda_j = \ell_j^+ - \ell_j^- \quad (20)$$

Step 1.8. Compute the criteria weights

The criteria weights are calculated as follows.

$$w_j = \frac{\Lambda_j}{\sum_{j=1}^h \Lambda_j}; \Lambda_j > 0; \sum \Lambda_j = 1 \quad (21)$$

Step 2. Evaluation and ranking of the alternatives (WISP-M method)

Step 2.1. Formulation of the alternative evaluation matrix for each alternative

The p, q-IVQROFN-based alternative evaluation matrix is constructed based on the opinion of the k^{th} expert in the following form.

$$\Theta^k = \begin{pmatrix} (M_{11}^k, N_{11}^k) & \dots & (M_{1h}^k, N_{1h}^k) \\ \vdots & \ddots & \vdots \\ (M_{g1}^k, N_{g1}^k) & \dots & (M_{gh}^k, N_{gh}^k) \end{pmatrix}_{g \times h} \quad (22)$$

$$\text{Here, } (M_{ij}^k, N_{ij}^k) = \left([M_{ij}^k, N_{ij}^k], [\overline{M}_{ij}^k, \overline{N}_{ij}^k] \right)$$

Step 2.2. Aggregate the individual opinions and formulate the aggregated p, q-IVQROFN-based alternative evaluation matrix

The elements of the aggregated p, q-IVQROFN-based alternative evaluation matrix are obtained by applying the p, q-IVQROFNWGA operation (considered in this work) as follows.

$$\begin{aligned} \theta_{ij} &= (M_{ij}, N_{ij}) = \left(\left[\underline{M}_{ij}, \overline{M}_{ij} \right], \left[\underline{N}_{ij}, \overline{N}_{ij} \right] \right) = p, q - IVQROFNWGA(\theta^1, \theta^2, \dots, \theta^t) = \prod_{k=1}^t (\theta^k)^{\omega_k} \\ &= \left(\left[\prod_{k=1}^t \left(M_{ij}^k \right)^{\omega_k}, \prod_{k=1}^t \left(\overline{M}_{ij}^k \right)^{\omega_k} \right], \left[\sqrt[q]{1 - \prod_{k=1}^t \left(1 - \left(N_{ij}^k \right)^q \right)^{\omega_k}}, \sqrt[q]{1 - \prod_{k=1}^t \left(1 - \left(\overline{N}_{ij}^k \right)^q \right)^{\omega_k}} \right] \right) \end{aligned} \quad (23)$$

Step 2.3. Obtain the score value-based alternative evaluation matrix (SAEM)

The elements of SAEM are obtained as

$$y_{ij} = S(\theta_{ij}) = \frac{1}{4} \left[\left(1 + M_{ij}^p - N_{ij}^q \right) + \left(1 + \overline{M}_{ij}^p - \overline{N}_{ij}^q \right) \right]; S(\theta_{ij}) \in [0,1] \quad (24)$$

Step 2.4. Normalization of the SAEM

The linear max-type normalization-II [95] is used to normalize the SAEM as follows.

$$y_{ij}^* = \begin{cases} \frac{y_{ij}}{\max_{i=1,2,\dots,g} (y_{ij})}; & j \in B \\ \frac{\min_{i=1,2,\dots,g} (y_{ij})}{y_{ij}}; & j \in NB \end{cases} \quad (25)$$

Step 2.5. Obtain the weighted normalized SAEM

The elements of WSAEM are derived by multiplying each element of SAEM by the corresponding criteria weights. Accordingly, we derive the elements of WSAEM as follows.

$$(26)$$

Step 2.6. Calculation of four distinct utility score values

a) Utility score value-I (USV-I)

The USV-I is obtained as the difference between the cumulative effects of the beneficial and non-beneficial criteria on the alternatives using Eq. (27) given below.

$$U_{i(1)} = \sum_{\substack{j \in B \\ j=1,2,\dots,h}} \vartheta_{ij} - \sum_{\substack{j \in NB \\ j=1,2,\dots,h}} \vartheta_{ij}; i = 1, 2, \dots, g \quad (27)$$

b) Utility score value-II (USV-II)

The USV-II is the difference of the multiplicative aggregate effects of the beneficial and non-beneficial criteria on the alternatives and is obtained as follows.

$$U_{i(2)} = \prod_{\substack{j \in B \\ j=1,2,\dots,h}} \vartheta_{ij} - \prod_{\substack{j \in NB \\ j=1,2,\dots,h}} \vartheta_{ij}; i = 1, 2, \dots, g \quad (28)$$

c) Utility score value-III (USV-III)

The USV-III is the ratio of the cumulative effects of the beneficial and non-beneficial criteria on the alternatives, derived as follows.

$$U_{i(3)} = \frac{\sum_{\substack{j \in B \\ j=1,2,\dots,h}} \vartheta_{ij}}{\sum_{\substack{j \in NB \\ j=1,2,\dots,h}} \vartheta_{ij}}; i = 1, 2, \dots, g \quad (29)$$

d) Utility score value-IV (USV-IV)

The USV-IV is the ratio of the multiplicative aggregate effects of the beneficial and non-beneficial criteria on the alternatives and is obtained as follows.

$$U_{i(4)} = \frac{\prod_{j \in B} \vartheta_{ij}}{\prod_{j \in NB} \vartheta_{ij}}; i = 1, 2, \dots, g \quad (30)$$

Step 2.7. Standardization of the USVs

The standardized USVs (S-USVs) are obtained as follows.

$$U_{i(1)}^* = \frac{1 + U_{i(1)}}{1 + \text{Max}_{i=1,2,\dots,g} (U_{i(1)})} \quad (31)$$

$$U_{i(2)}^* = \frac{1 + U_{i(2)}}{1 + \text{Max}_{i=1,2,\dots,g} (U_{i(2)})} \quad (32)$$

$$U_{i(3)}^* = \frac{1 + U_{i(3)}}{1 + \text{Max}_{i=1,2,\dots,g} (U_{i(3)})} \quad (33)$$

$$U_{i(4)}^* = \frac{1 + U_{i(4)}}{1 + \text{Max}_{i=1,2,\dots,g} (U_{i(4)})} \quad (34)$$

Step 2.8. Aggregation of the S-USVs to obtain the overall utility score value (O-USV)

The classical WISP method [36] and one of its latest extensions [70] used an arithmetic averaging approach. However, this paper modifies the classical approach and introduces the use of the Heron mean (HeM). HeM is an innovative approach that utilizes both arithmetic (sum-based) and geometric (product-based) averaging techniques, providing a smoothing effect [71]. Additionally, the use of the aggregation coefficient, ζ , provides the decision-maker with flexibility to vary the S-USVs and examine the sensitivity of the outcome. The value of ζ lies between 0 and 1. For the initial case, $\zeta = 0.5$ is set for the analysis [71]. Accordingly, the O-SUV of the i^{th} alternative is derived as

$$\xi_i = \left\{ (1 - \zeta) (U_{i(1)}^* U_{i(2)}^* U_{i(3)}^* U_{i(4)}^*)^{\frac{1}{4}} \right\} + \left\{ \zeta \frac{U_{i(1)}^* + U_{i(2)}^* + U_{i(3)}^* + U_{i(4)}^*}{4} \right\} \quad (35)$$

Step 2.9. Ranking of the alternatives

The alternative with the highest ξ_i value is ranked first, and subsequently, the other alternatives are ranked in descending order. Figure 1 displays the flowchart of the proposed research methodology.

4.3.2. Procedural steps to evaluate the risk scores of NTs

The steps for calculating the overall risk scores (ORS) of the alternatives using the FKF are described below.

Step 1. Identify the risk scores of the NTs based on the dimensions of FKF

We use the linguistic scale described in Table 7. The experts rate each alternative with respect to their likelihood of potential failures (or creating hazards), consequence or severity and exposure of such failures.

Suppose the risk score (expressed in terms of p, q-IVQROFN) of NT_i subject to the effect of r^{th} risk dimension is $R_{ir}^k = (\varphi_{ir}^k, \gamma_{ir}^k) = \left(\left[\underline{\varphi}_{ir}^k, \overline{\varphi}_{ir}^k \right], \left[\underline{\gamma}_{ir}^k, \overline{\gamma}_{ir}^k \right] \right)$ according to the decision-maker E_k .

In this case, $r = 1$ (Likelihood); 2 (Severity); 3 (Exposure).

Step 2. Aggregation of the expert opinions by applying p, q-IVQROFNWGA.

The aggregated risk score (expressed in terms of p, q-IVQROFN) of NT_i subject to the effect of r^{th} risk dimension is obtained as follows.

$$R_{ir} = (\varphi_{ir}, \gamma_{ir}) = \left(\left[\varphi_{ir}, \overline{\varphi_{ir}} \right], \left[\gamma_{ir}, \overline{\gamma_{ir}} \right] \right) = p, q - IVQROFNWGA(R_{ir}^1, R_{ir}^2, \dots, R_{ir}^t) = \prod_{k=1}^t (R_{ir}^k)^{\omega_k} = \left(\left[\prod_{k=1}^t (\varphi_{ir}^k)^{\omega_k}, \prod_{k=1}^t (\overline{\varphi_{ir}^k})^{\omega_k} \right], \left[\sqrt[q]{1 - \prod_{k=1}^t (1 - (\gamma_{ir}^k)^q)^{\omega_k}}, \sqrt[q]{1 - \prod_{k=1}^t (1 - (\overline{\gamma_{ir}^k})^q)^{\omega_k}} \right] \right) \quad (36)$$

Step 3. Obtain the crisp score values of the aggregated risk scores (expressed in terms of p, q-IVQROFN)

The crisp values are obtained using Eq. (37) as follows.

$$rs_{ir} = S(R_{ir}) = \frac{1}{4} \left[(1 + \varphi_{ir}^p - \gamma_{ir}^q) + (1 + \overline{\varphi_{ir}^p} - \overline{\gamma_{ir}^q}) \right]; S(R_{ir}) \in [0,1] \quad (37)$$

Step 4. Calculate the ORSs of the NTs

The ORS of a specific NT is calculated as follows.

$$\Psi_i = \prod_{r=1}^3 rs_{ir} = rs_{i(\text{Likelihood})} \times rs_{i(\text{Severity})} \times rs_{i(\text{Exposure})} \quad (38)$$

The alternative that yields a high ORS is considered riskier.

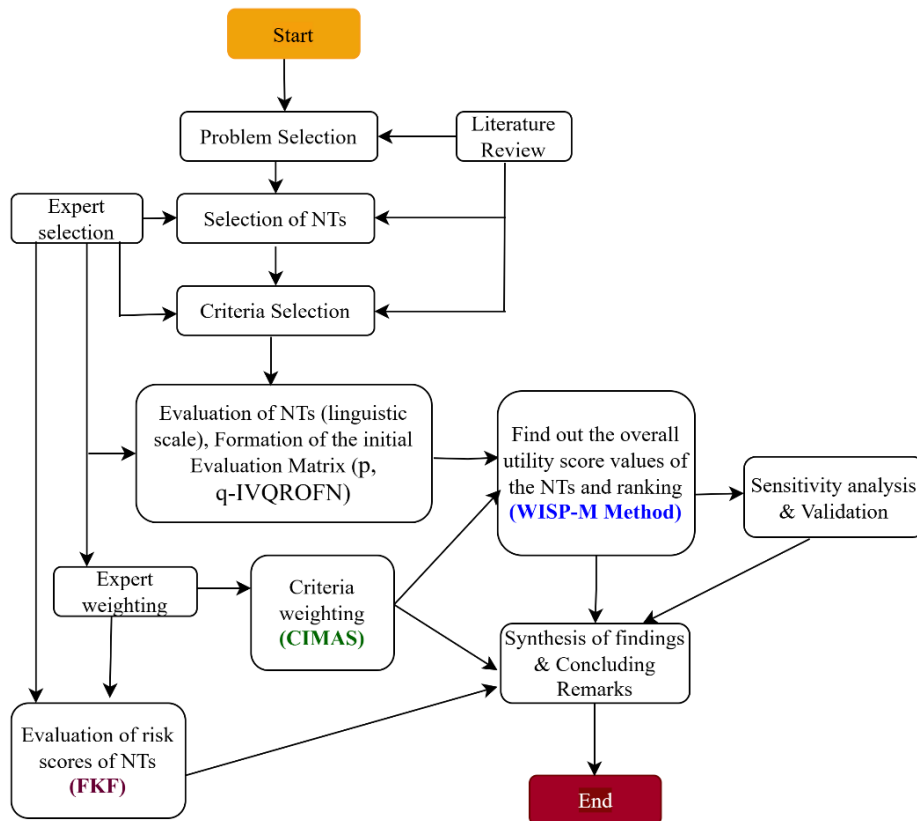


Fig. 1. Flowchart of the methodological framework.

5. Findings

This section reports the key findings of the data analysis using our proposed approach. As stated earlier, in this paper, we have eight alternatives and ten criteria (i.e., $g = 8; b = 10$). The alternatives were rated by the experts using a seven-point linguistic scale (given in Table 7). Tables A1 to A11 (Appendix A) report the responses of the experts about the evaluation of the criteria' importance

and the utility of the alternatives, respectively. It is noteworthy to mention that this project has been enriched by the opinions of ten experts (Table 9).

To begin with, we first determine the priority weights of the experts. The experts were rated in terms of their experience and education using the linguistic scale given in Table 8. Then we determine the weights of the experts using Eqs. (13, 14, 15). Table 10 reports the calculated expert weights. The initial values for the parameters, p and q , are set to 3 and 2, respectively [45].

Table 10
 Linguistic ratings and calculated weights of the experts

Expert	Rating (Qualification)	Weight (Qualification)	Rating (Experience)	Weight (Experience)	Final Weight
E1	3	0.1421	2	0.1142	0.1281
E2	3	0.1421	3	0.2333	0.1877
E3	1	0.0117	1	0.0192	0.0154
E4	2	0.0695	1	0.0192	0.0443
E5	3	0.1421	2	0.1142	0.1281
E6	2	0.0695	1	0.0192	0.0443
E7	2	0.0695	1	0.0192	0.0443
E8	3	0.1421	2	0.1142	0.1281
E9	3	0.1421	3	0.2333	0.1877
E10	2	0.0695	2	0.1142	0.0918

Step 1.

Next, we proceed to calculate criteria weights using the procedural steps of the CIMAS method. First, we convert the linguistic ratings into corresponding p, q -IVQROFNs, and then obtain score values of the elements of the expert-rated criteria evaluation matrix using Eq. (16) for each expert (Table 11). Next, Eq. (17) is applied to normalize the expert-rated criteria evaluation matrix. Then we multiply each element of the normalized expert-rated criteria evaluation matrix by the weight of the corresponding experts (Table 12). Eq. (18) helps to obtain the expert-weighted and normalized criteria evaluation matrix.

We proceed further to obtain the maximum and minimum weighted values for all criteria (Eq. 19) and their differences (Eq. 20). Eq. (21) is then applied to obtain criteria weights (Table 13).

Table 11
 Score values of the expert-rated p, q – IVQROFN criteria evaluation matrix

Expert Weight	Criteria/ Experts	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
0.1281	E1	0.8935	0.2986	0.5838	0.7559	0.2986	0.2986	0.4347	0.2986	0.2986	0.4347
0.1877	E2	0.8935	0.1653	0.7559	0.7559	0.1653	0.2986	0.2986	0.2986	0.7559	0.5838
0.0154	E3	0.7559	0.1653	0.5838	0.7559	0.4347	0.4347	0.2986	0.2986	0.8935	0.4347
0.0443	E4	0.7559	0.0722	0.7559	0.7559	0.1653	0.4347	0.2986	0.1653	0.5838	0.5838
0.1281	E5	0.8935	0.1653	0.7559	0.8935	0.2986	0.2986	0.4347	0.4347	0.7559	0.5838
0.0443	E6	0.7559	0.0722	0.5838	0.5838	0.1653	0.4347	0.5838	0.1653	0.5838	0.7559
0.0443	E7	0.8935	0.1653	0.8935	0.7559	0.2986	0.5838	0.2986	0.2986	0.5838	0.7559
0.1281	E8	0.7559	0.0722	0.7559	0.5838	0.1653	0.1653	0.4347	0.1653	0.7559	0.7559
0.1877	E9	0.8935	0.0722	0.5838	0.7559	0.2986	0.4347	0.4347	0.2986	0.5838	0.5838
0.0918	E10	0.7559	0.1653	0.8935	0.5838	0.2986	0.4347	0.4347	0.2986	0.5838	0.5838

Table 12
 Normalized expert-weighted criteria evaluation matrix

Criteria/ Experts	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
E1	0.0139	0.0271	0.0105	0.0135	0.0148	0.0100	0.0141	0.0141	0.0060	0.0092
E2	0.0203	0.0219	0.0199	0.0198	0.0120	0.0147	0.0142	0.0206	0.0222	0.0181
E3	0.0014	0.0018	0.0013	0.0016	0.0026	0.0018	0.0012	0.0017	0.0022	0.0011
E4	0.0041	0.0023	0.0047	0.0047	0.0028	0.0050	0.0034	0.0027	0.0041	0.0043
E5	0.0139	0.0150	0.0136	0.0159	0.0148	0.0100	0.0141	0.0205	0.0152	0.0123
E6	0.0041	0.0023	0.0036	0.0036	0.0028	0.0050	0.0065	0.0027	0.0041	0.0055
E7	0.0048	0.0052	0.0055	0.0047	0.0051	0.0068	0.0034	0.0049	0.0041	0.0055
E8	0.0117	0.0065	0.0136	0.0104	0.0082	0.0055	0.0141	0.0078	0.0152	0.0160
E9	0.0203	0.0096	0.0153	0.0198	0.0216	0.0214	0.0206	0.0206	0.0172	0.0181
E10	0.0084	0.0107	0.0115	0.0075	0.0106	0.0105	0.0101	0.0101	0.0084	0.0089

Table 13
 Calculation of criteria weights (Final steps)

Criteria/ Value	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10	Sum
Max	0.0203	0.0271	0.0199	0.0198	0.0216	0.0214	0.0206	0.0206	0.0222	0.0181	
Min	0.0014	0.0018	0.0013	0.0016	0.0026	0.0018	0.0012	0.0017	0.0022	0.0011	
Max-min	0.0189	0.0253	0.0186	0.0181	0.0191	0.0196	0.0195	0.0189	0.0201	0.0170	0.1950
Weight	0.0970	0.1295	0.0953	0.0930	0.0977	0.1006	0.0999	0.0969	0.1030	0.0871	1.0000
Rank	6	1	8	9	5	3	4	7	2	10	

Now, we step into the evaluation and ranking of the alternatives (using the WISP-M method).
Step 2.

First, we convert the linguistic evaluations of the alternatives (Tables A2 to A11) by various experts into corresponding p, q -IVQROFNs (use Table 7). Then we aggregate the individual opinions and formulate the aggregated p, q -IVQROFN-based alternative evaluation matrix. We apply the p, q -IVQROFNWGA operation (Eq. 23). A simple illustration of such aggregation is given in Appendix B. Next, we obtain the score value-based alternative evaluation matrix (SAEM) using Eq. (24). The SAEM is exhibited in Table 14. Then, we proceed to normalize the SAEM using Eq. (25). After that, we multiply the elements of the normalized SAEM by the corresponding criteria weights (Eq. 26). Criteria weights are recorded in Table 13. The weighted normalized SAEM is displayed in Table 15.

Table 14
 Score value-based crisp alternative evaluation matrix

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	0.6999	0.7559	0.5553	0.7559	0.7559	0.5838	0.7559	0.5838	0.8673	0.7612
NT 2	0.3340	0.3191	0.2732	0.1802	0.2986	0.1952	0.3232	0.2986	0.2986	0.1488
NT 3	0.7371	0.5755	0.5838	0.7432	0.5960	0.4399	0.7559	0.4347	0.5838	0.5726
NT 4	0.5838	0.4347	0.4347	0.4347	0.2986	0.2986	0.4347	0.2986	0.5838	0.2986
NT 5	0.8444	0.6739	0.7888	0.8910	0.7612	0.7904	0.8645	0.8935	0.8910	0.8578
NT 6	0.5398	0.4033	0.5838	0.5290	0.4455	0.4347	0.5838	0.4347	0.5838	0.5553
NT 7	0.8380	0.6310	0.7559	0.7559	0.7371	0.5838	0.8308	0.7559	0.8935	0.8601
NT 8	0.2551	0.1653	0.1321	0.1401	0.2020	0.0722	0.1653	0.1653	0.1653	0.0722

It is noteworthy to mention that CR 1, CR 5, and CR 7 are the non-beneficial criteria (i.e., lower is better).

Table 15
 Weighted and normalized alternative evaluation matrix

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	0.0354	0.1295	0.0671	0.0789	0.0261	0.0743	0.0218	0.0633	0.1000	0.0771
NT 2	0.0741	0.0547	0.0330	0.0188	0.0661	0.0248	0.0511	0.0324	0.0344	0.0151
NT 3	0.0336	0.0986	0.0706	0.0776	0.0331	0.0560	0.0218	0.0471	0.0673	0.0580
NT 4	0.0424	0.0745	0.0525	0.0454	0.0661	0.0380	0.0380	0.0324	0.0673	0.0302
NT 5	0.0293	0.1155	0.0953	0.0930	0.0259	0.1006	0.0191	0.0969	0.1027	0.0869
NT 6	0.0459	0.0691	0.0706	0.0552	0.0443	0.0553	0.0283	0.0471	0.0673	0.0562
NT 7	0.0295	0.1081	0.0914	0.0789	0.0268	0.0743	0.0199	0.0820	0.1030	0.0871
NT 8	0.0970	0.0283	0.0160	0.0146	0.0977	0.0092	0.0999	0.0179	0.0190	0.0073

Then we proceed to calculate four distinct USVs (Eqs. 27-30). Next, we apply Eqs. (31)-(34) to standardize USVs. Finally, we aggregate the standardized USVs using Eq. (35) (Heron mean) to obtain O-USVs of the alternatives for ranking them. As stated earlier, the initial value of the aggregation coefficient (ζ) is set to 0.5. Table 16 presents the calculated USVs, S-USVs, and O-USVs of the alternatives along with their corresponding ranks.

Table 16
 Calculation of O-USVs and ranking of the alternatives

Technologies	USV-1	USV-2	USV-3	USV-4	S-USV-1	S-USV-2	S-USV-3	S-USV-4	O-USV	Rank
NT 1	0.2757	-0.000168	2.3864	0.0000	0.9465	0.9998	0.8419	1.0000	0.9459	6
NT 2	0.2034	-0.000026	3.0223	0.0000	0.8928	1.0000	1.0000	1.0000	0.9726	3
NT 3	0.2694	-0.000085	2.8315	0.0000	0.9418	0.9999	0.9526	1.0000	0.9734	2
NT 4	0.2158	-0.000077	2.5924	0.0000	0.9020	0.9999	0.8931	1.0000	0.9481	5
NT 5	0.3478	-0.000170	2.6671	0.0000	1.0000	0.9998	0.9117	1.0000	0.9775	1
NT 6	0.2357	-0.000107	2.5526	0.0000	0.9168	0.9999	0.8832	1.0000	0.9493	4
NT 7	0.2810	-0.000178	2.3384	0.0000	0.9504	0.9998	0.8300	1.0000	0.9437	7
NT 8	0.1545	-0.000014	2.2238	0.0000	0.8566	1.0000	0.8015	1.0000	0.9124	8
Max	0.3478	0.0000	3.0223	0.0000						

5.1. Validation

The validation is done through two steps: a) a comparison of several MCDA models with our framework (recommended in several past studies, for example, [96-100]); b) a sensitivity analysis. This study presents a comparative analysis of the results obtained using several other MCDA models, such as PIV, SRP, COPRAS, CoCoSo, and RAM, alongside our WISP-M method. The criteria weights obtained using the CIMAS method are applied to all MCDA methods for ranking. Then we perform Spearman’s rank correlation test to examine the comparability of the ranking orders of alternatives across various MCDA methods (Table 17). It is observed that the WISP-M method holds statistically significant and very high correlation coefficient values compared with other MCDA models. Figure 2 displays the comparison of the ranking of NTs using various MCDA methods.

Sensitivity analysis (SSA) plays a crucial role in ascertaining the reliability and stability of the outcomes of MCDA models [101, 102]. The SSA is performed to examine the degree and nature of the sensitivity of the decision variables, i.e., alternatives, to changes in external conditions, such as variations in criteria weights, aggregation coefficients, normalization approaches, criteria, and

alternative sets [103-105]. This paper conducts the SSA to examine the reliability and stability of the criteria ranking (in terms of their calculated weights) and the evaluation ranking of alternatives (in terms of their O-USVs). The effects of variations in the values of the parameters p and q on the criteria and alternative ranking are examined, while the impact of variations in the values of the aggregation coefficient (ζ) on the alternatives is also addressed. Tables 18 and 19 exhibit various experimental cases for the SSA, and Figures 3-5 depict the results.

Table 17
 Spearman’s rank correlation test to compare the ranking of the alternatives

Methods	PIV	SRP	COPRAS	CoCoSo	RAM
WISP-M	0.929	0.976	0.905	0.905	0.976

Note: All correlation coefficients are significant at the 0.05 level (two-tailed)

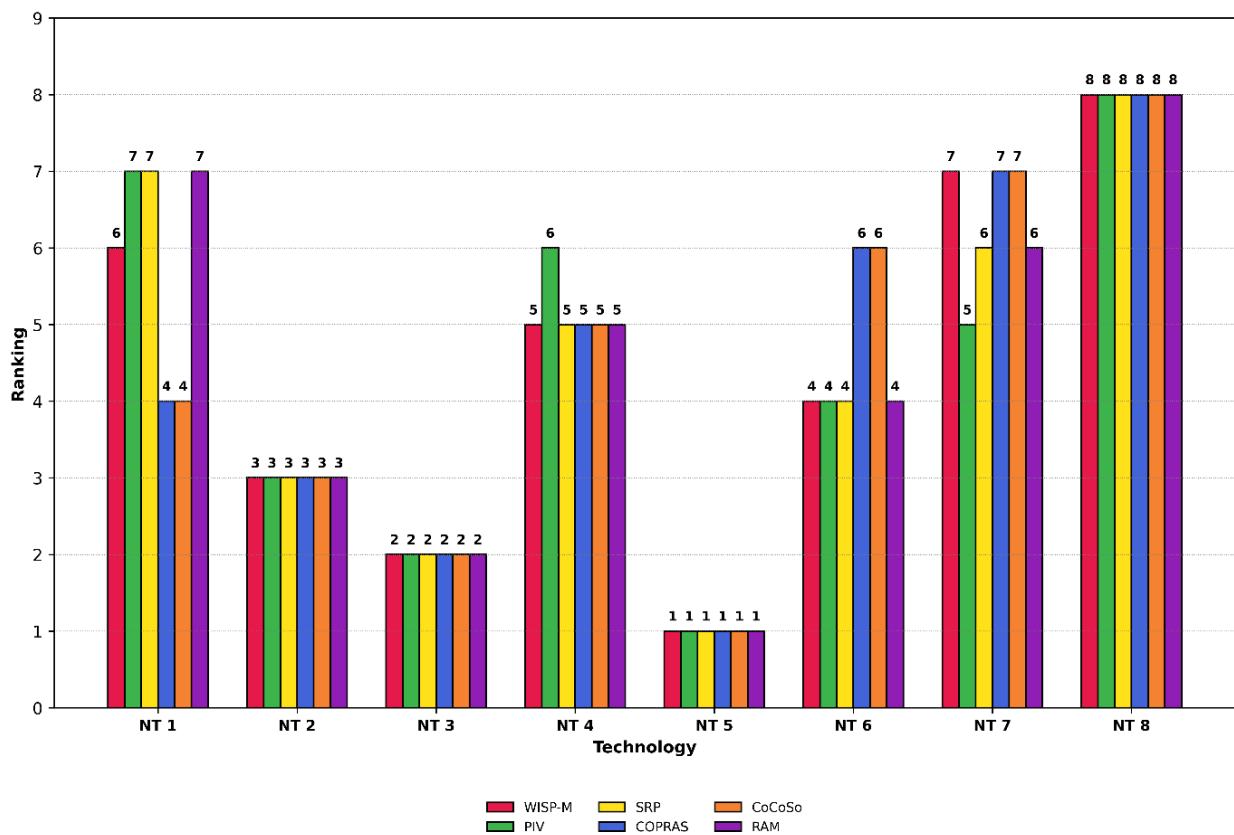


Fig. 2. Result of the comparison of the ranking of NTs by various MCDA methods

Table 18
 Scenarios for sensitivity analysis (Varying p and q values)

Parameter / Scenario	p	q	Parameter / Scenario	p	q	Parameter / Scenario	p	q	Parameter / Scenario	p	q
Initial	3	2	Case 7	9	2	Case 13	3	3	Case 19	3	9
Case 1	2	2	Case 8	10	2	Case 14	3	4	Case 20	3	10
Case 2	4	2	Case 9	20	2	Case 15	3	5	Case 21	3	20
Case 3	5	2	Case 10	30	2	Case 16	3	6	Case 22	3	30
Case 4	6	2	Case 11	50	2	Case 17	3	7	Case 23	3	50
Case 5	7	2	Case 12	100	2	Case 18	3	8	Case 24	3	100
Case 6	8	2									

Table 19
 Scenarios for sensitivity analysis (Varying ζ values)

Parameter / ζ	Scenario	Parameter / ζ	Scenario	Parameter / ζ	Scenario
Initial	0.5	Case 3	0.3	Case 6	0.7
Case 1	0.1	Case 4	0.4	Case 7	0.8
Case 2	0.2	Case 5	0.6	Case 8	0.9

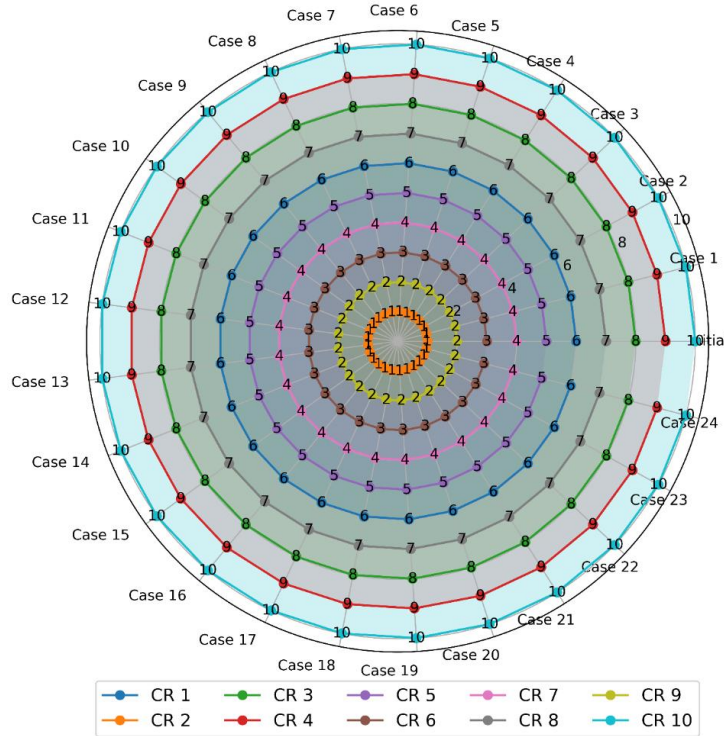


Fig. 3. Result of the sensitivity analysis- criteria ranking (Varying p and q values)

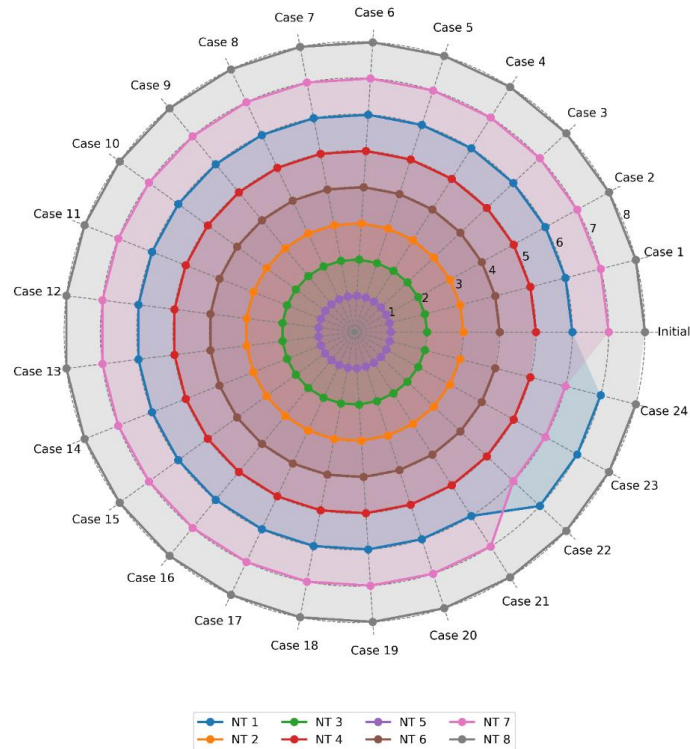


Fig. 4. Result of the sensitivity analysis- alternative evaluation (Varying p and q values)

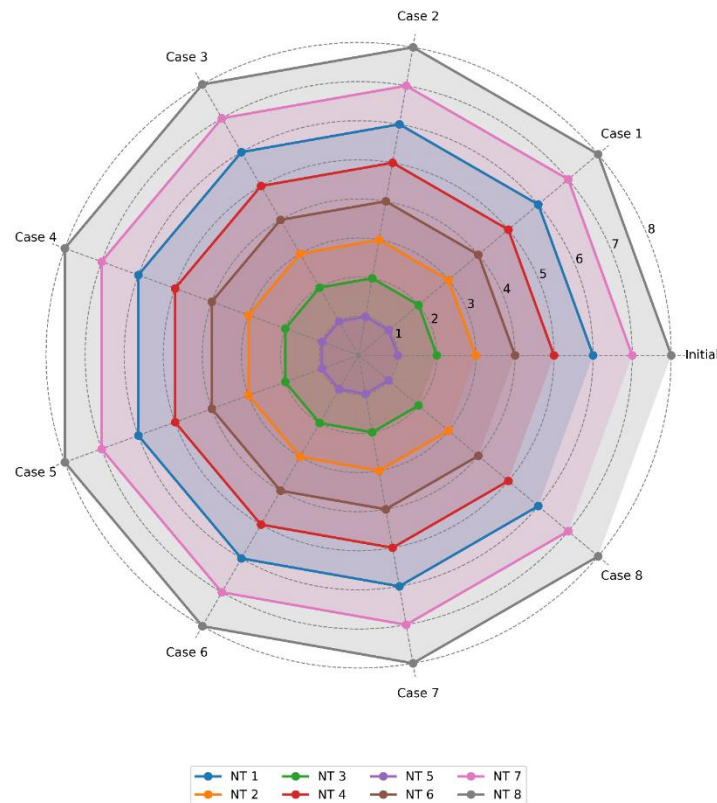


Fig. 5. Result of the sensitivity analysis- alternative evaluation (Varying ζ values)

5.2. Assessment of risk scores

We follow the steps outlined in section 4.3.2 to assess the ORS of NTs. The assessment of NTs (in linguistic terms mentioned in Table 7) based on the dimensions of the FKF, such as L, S, and E, is provided in Tables C.1 to C.10 (Appendix C). Subsequently, we aggregate individual assessments (by the experts) using Eq. (36) and obtain aggregated risk scores (expressed in terms of p, q-IVQROFNs). Then, we obtain the crisp score values of the aggregated risk scores using Eq. (37). We apply Eq. (38) to derive the ORS for each alternative, thereby ranking them. Table 20 reports the aggregated crisp scores and calculated ORS values for the alternatives. The heatmap (Figure 6) showcases the comparative analysis of the risk levels of the alternatives. We also examine the SSA of the findings, following the procedure outlined in Section 5.1, and obtain satisfactory results. The result of the SSA is depicted in Figure 7. We also categorize the alternatives based on their relative riskiness, depending on calculated ORS values.

Table 20
 Assessment of risk levels of the alternatives

Dimension/ Technologies	Likelihood	Severity	Exposure	Overall Risk Score	Rank	Level
NT 1	0.8791	0.8543	0.7612	0.5716	1	Low
NT 2	0.3621	0.2920	0.2917	0.0308	7	Low to Medium
NT 3	0.6993	0.7559	0.5755	0.3042	3	Medium
NT 4	0.8935	0.7559	0.7290	0.4924	2	High
NT 5	0.1914	0.1074	0.1447	0.0030	8	Low
NT 6	0.5755	0.5191	0.5775	0.1725	5	High
NT 7	0.5525	0.5167	0.4347	0.1241	6	Medium to High
NT 8	0.5603	0.6665	0.5838	0.2180	4	Medium

(Risk score > 0.5 (High); > 0.3 up to 0.5 (Medium to High); > 0.2 to 0.3 (Medium); > 0.1 up to 0.2 (Low to Medium); <=0.1 (Low))

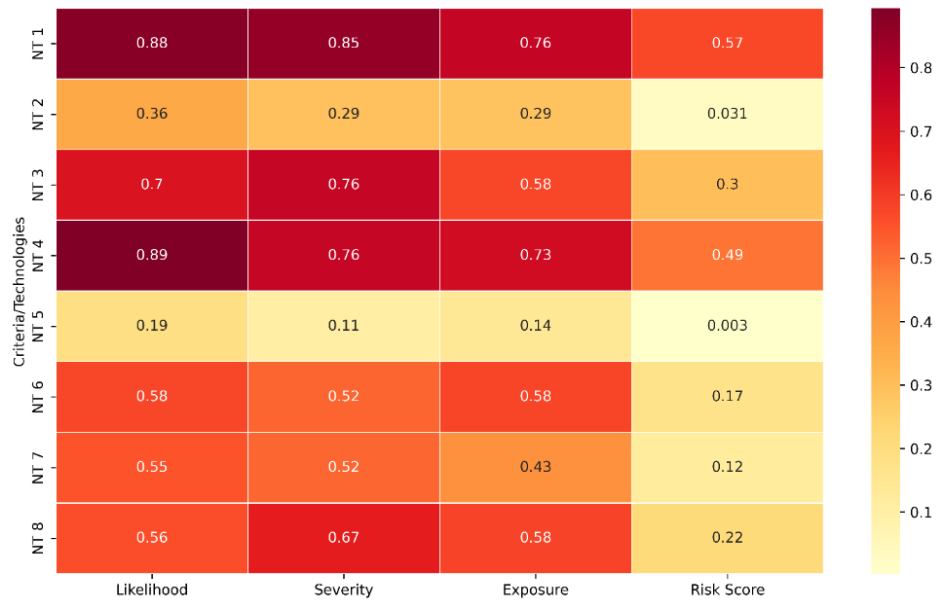


Fig. 6. Heat map representing the risk profiles of the NTs

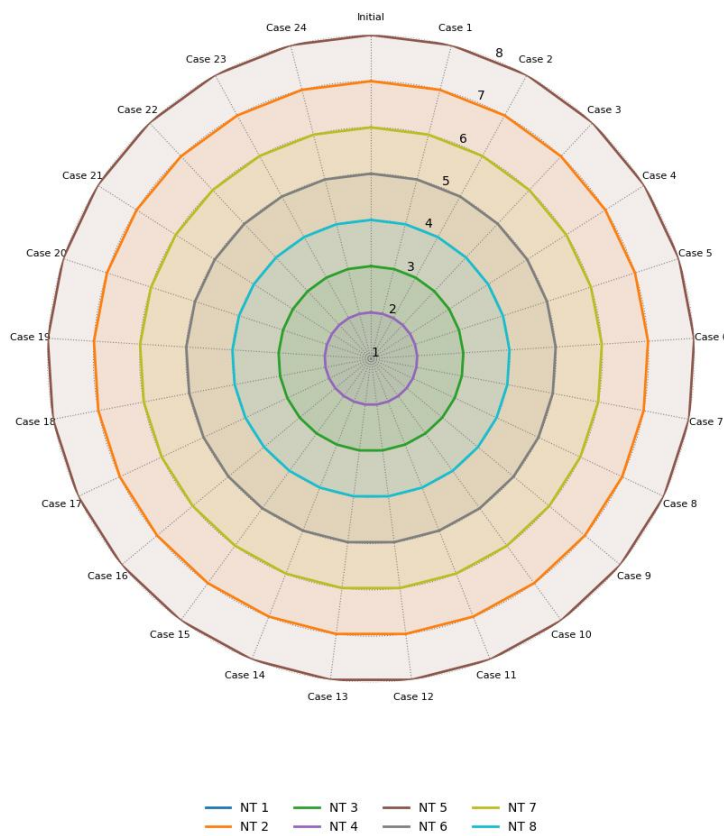


Fig. 7. Result of the sensitivity analysis- risk evaluation (Varying p and q values)

5.3. Synthesis of findings

The synthesis of O-USVs and ORS values of the alternatives is done through plotting (Figure 8).

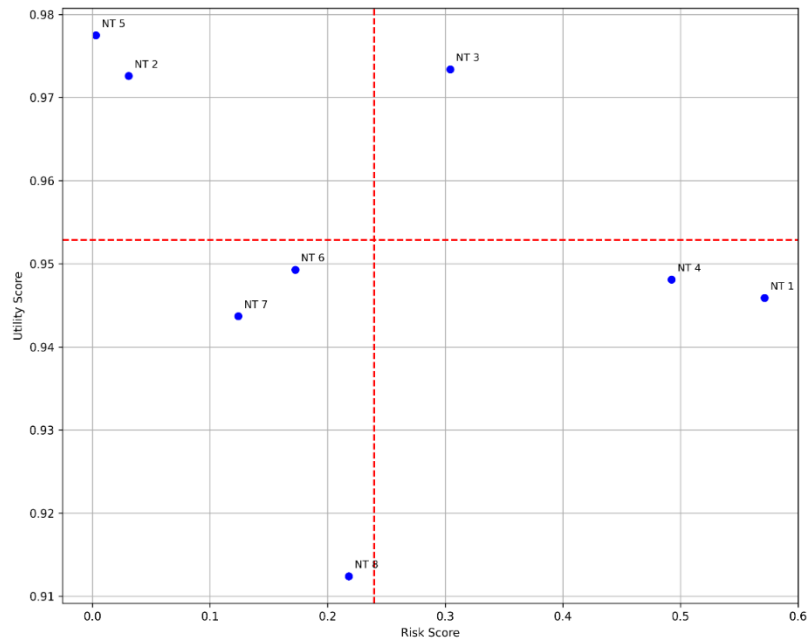


Fig. 8. Pictorial representation of the utility scores and risk profiles of NTs

6. Discussion

The findings reveal that crop yield is the top-ranked criterion, helping to maintain food security and the economy. Affordability is the second crucial criterion for the adoption of nanotechnologies, especially in developing regions where costs are particularly sensitive. Resource efficiency and operating risk are also high, reflecting concerns about the environmental impact of agricultural inputs and the need to reduce risks associated with technology use. Adoption barriers are high, but these hurdles are not impossible when the benefits in yield, cost, and efficiency are significant. Availability and scalability are less important, suggesting that early-stage nanotechnologies are being tested on a small scale. Compatibility is low, suggesting that new technologies can be integrated with existing farming methods, as they are modular or adaptable. Complexity is in the middle, indicating a trade-off between user-friendliness and the benefits of the technology. User-friendliness is crucial in farming, especially for those unfamiliar with technology. However, it may be acceptable if the benefits of nanotechnology are clear and measurable. The results highlight the complexity of utilizing technology in farming, particularly nanotechnologies that promise to alter input usage and enhance yields.

The utility value for nano sensors (NT 5) is the highest at 0.9775. This demonstrates the importance of these devices in monitoring soil health, crop status, and environmental variables in real-time. Next are nano-fungicides (NT 3) and nano-fertilizers (NT 2), which have utility values of 0.9734 and 0.9726, respectively. These show promise for enhancing crop protection and nutrient delivery with little effect on the environment. Nanoclays (NT 6) and nano herbicides (NT 4) are in the middle, with scores of 0.9493 and 0.9481, respectively. This means that people are taking longer to adopt them because they are concerned about obtaining clearance from regulators, the product's durability in the environment, and whether it will function effectively in the intended application. Nanoparticles (NT 1) and nanomaterials (NT 7) are interesting, but they do not seem very appealing at first because they can be used in a variety of ways. NT 8 has the lowest utility score (0.9124). This could be because they are more expensive, there are questions about how they would affect living organisms, and there is not much evidence that they will benefit farming on a large scale. Even if they can perform mechanical and electrical work, they may not be instrumental in agriculture at

present. The utility scores for several nanotechnologies in agriculture demonstrate the complexity of their applications and potential advantages.

When examining the sensitivity of the criteria for selecting nanotechnology in agriculture, we find a consistent and stable approach (under varying p and q values). Based on 24 scenarios, the rankings of the criteria reveal a pattern in which specific needs are commonly prioritized. CR 2 (Yield) and CR 9 (Affordability) stay at the top of the list, even though the order of decision-making priorities has changed. CR 10 (Compatibility) has the lowest ratings, indicating that it has a minimal impact on the decision-making process. The rankings for CR 5 (Adoption Barriers), CR 6 (Resource Efficiency), and CR 7 (Operating Risk) remain relatively stable. There are slight differences between CR 4 (Availability) and CR 3 (Scalability), which suggests that their value may rely on the infrastructure in the area, supply chain issues, or the size of the agricultural enterprises. The fact that the criteria rankings remain the same indicates that the decision support approach is robust.

The sensitivity analysis of the alternative ranking (under varying p and q values) reveals that NTs demonstrate a visible stability in the overall pattern. The study shows that NT 5 (Nano sensors) remains at the top of the list, highlighting their importance for precision agriculture. NT 3 (Nano fungicides), NT 2 (Nano fertilizers), NT 4 (Nano herbicides), and NT 6 (Nanoclays) remain the same, indicating that they effectively protect crops and boost yields. NT 8 (Carbon Nanotubes) is still in the outermost layer, which means it has less value because it is expensive, bad for the environment, or not widely used in mainstream agriculture. NT 7 (Nanomaterials) and NT 1 (Nanoparticles) shift slightly since they are sensitive to changes in input parameters. Depending on who makes the choice or the situation, these technologies may be viewed in different ways. The decision support system, on the other hand, is robust and reliable, and the positions of the alternatives remain relatively stable throughout the 24 scenarios. The sensitivity analysis enhances the credibility of the selection framework by demonstrating that the best options (NT 5, NT 3, and NT 2) remain stable. It also highlights possibilities based on the situation and points out less desirable technologies, such as NT 8, that can be examined more closely or used in specific situations.

From the sensitivity analysis of the alternatives (under varying ζ values) (Figure 5), we find that NT 5 (Nano sensors) is the strongest and most popular choice in all ζ scenarios, due to its accuracy, responsiveness, and potential to enhance data-driven precision farming. NT 3 (Nano fungicides) and NT 2 (Nano fertilizers) perform well, maintaining inner rings and remaining stable across preference models, making them crucial for sustainable agriculture. NT 8 (Carbon Nanotubes) is the least favored, possibly due to issues with cost, environmental risk, and technological maturity. NT 1 (Nanoparticles) and NT 6 (Nanoclays) have some variation in relative positions across different ζ values. NT 4 (Nano herbicides) and NT 7 (Nano materials) exhibit a similar trend of low sensitivity, which may be helpful in certain situations. The decision framework is stable and reliable, with no extreme volatility or sudden changes in ranking, suggesting the model's stability and trustworthiness. The fundamental rankings and suggestions remain mostly unchanged.

The heatmap (Figure 6) indicates that different nanotechnologies exhibit varying levels of risk, with no discernible pattern of high or low risk. Key elements that affect overall risk include likelihood, severity, exposure, and risk score. The study identifies that NT 1 has high likelihood, severity, and exposure values, indicating its potential for use but also high risk. NT 2 has a lower overall risk, suggesting it may be a safer choice with fewer exposure chances. NT 3 and NT 4 exhibit moderate to high-risk patterns, characterized by high likelihood and severity values, indicating a substantial likelihood of adverse outcomes even with controlled exposure. NT 4 has a slightly higher overall risk due to its higher likelihood and risk score. NT 5 is considered the least risky nanotechnology, with very low values in all areas. It is considered helpful in farming where safety is paramount. NT 6, NT 7, and NT 8 have moderate risk profiles, with some differences. NT 6 has moderate values for likelihood,

severity, and exposure, giving it a moderate Risk Score (0.17). NT 7 has lower exposure and risk scores, while NT 8 has a modest likelihood and exposure but higher Severity (0.67), giving it a Risk Score of 0.22.

The visual depiction (Figure 8) suggests prioritizing low-risk, high-use nanotechnologies, such as NT 5 and NT 2, for agricultural applications due to their balance of low risk and high usefulness. A comprehensive risk-benefit analysis is necessary for high-utility nanotechnologies, such as NT 3, which are both valuable and pose risks. The bottom-right quadrant of nanotechnologies (NT 1 and NT 4) is least preferred, and it is suggested to consider investing more money or time in these areas, or focusing on making them more useful, lowering their risk profiles, or exploring other nanotechnology options.

The CIMAS method is straightforward to execute, yet it can effectively handle a large number of criteria. Additionally, it considers experts' experience and education (i.e., demographic background) to set their priorities. In effect, it produces a realistic objective measurement of criteria weights. This paper further extends its application horizon through uncertainty analysis. The apparent drawback of this method lies with the inseparability of experts. On the other hand, WISP is computationally simple. It offers a unique advantage by combining the effects of both additive and multiplicative utilities. It offers a high discrimination power. Additionally, the use of the Heron mean provides more flexibility. This paper presents an innovative extension of the WISP-M method incorporating uncertain modelling.

6.1. Research implications

This paper offers several significant research implications.

- a) **Managerial Implications:** The study demonstrates the importance of the MCDA framework for managers and strategic decision-makers in agriculture. It shows that nanotechnologies, such as nano-sensors, nano-fungicides, and nano-fertilizers, are more effective since they are more useful, stable, and have lower risk profiles. This enables managers to make informed investment decisions based on data and weighted factors, such as cost, return, and risk. Prioritizing criteria based on expert opinion ensures that management decisions align with the actual trends in both developed and developing agricultural markets. Risk-benefit visualizations aid in planning phased adoption methods, prioritizing helpful and low-risk technologies, and mitigating the risks associated with higher-risk innovations.
- b) **Social Implications:** The study highlights the significance of nanotechnology in ensuring food availability, particularly in resource-limited areas. It emphasizes the need for affordability and user-friendliness for smallholder and marginal farmers. Nano-sensors and other precision technologies contribute to sustainable farming and responsible consumption by improving efficiency and reducing environmental impact. However, barriers to adoption, such as unclear rules and difficulty in understanding the technology, need to be addressed to prevent further disparities. Encouraging training, awareness initiatives, and cooperative models can help close this gap and ensure fair distribution of benefits among all socioeconomic groups in agriculture.
- c) **Policy Implications:** The research argues that the agriculture sector needs to find a balance between new ideas and rules. It should focus on low-risk, high-benefit nanotechnologies, such as nano-sensors and nano-fertilizers. Policies that encourage people to adopt new technologies should include subsidies or other incentives. At the same time, clear, science-based rules should deal with health and environmental issues. National agricultural policies should encourage cooperation between the public and private sectors, promote investment in research and development, and integrate farmer training programs into the system as a

regular component. We need to build up infrastructure and local supply chains so that potential nanotechnologies may be used in a scalable way in each region.

- d) **Technical Implications:** The research argues that the agriculture sector needs to find a balance between new ideas and rules. It should focus on low-risk, high-benefit nanotechnologies, such as nano-sensors and nano-fertilizers. Policies that encourage people to adopt new technologies should include subsidies or other incentives. At the same time, clear, science-based rules should deal with health and environmental issues. National agricultural policies should encourage cooperation between the public and private sectors, promote investment in research and development, and integrate farmer training programs into the system as a regular component. We need to build up infrastructure and local supply chains so that potential nanotechnologies may be used in a scalable way in each region.

7. Conclusion and future scope

The ongoing research brings forth an innovative decision-making framework for uncertainty analysis. The present work demonstrates the application of a novel p, q -IVQROFN based CIMAS and WISP-M methodology to evaluate the utilities and risk levels of eight recognized NTs used in agriculture. The study emphasizes the importance of conducting a comprehensive, Nanotechnology-Specific risk assessment to establish robust selection criteria for the ethical and sustainable use of nanotechnology in agriculture. Based on the opinions of ten experts, the study has observed that nano-sensors, nano-fungicides, and nano-fertilizers are the most effective, safest, and cost-effective choices. Carbon nanotubes have been the least popular because they were expensive and considered environmentally harmful. The Fine-Kinney risk assessment examines the safety factor, making the study more relevant for making informed judgments about farming in the real world. The study links innovative methods to their implementation in the real world, which helps policymakers, agricultural managers, and technology developers make choices that promote food security, sustainability, and technological inclusivity. It also emphasizes the importance of investing in safe, scalable, and affordable nanotechnologies, as well as regulations that foster innovation while preserving the environment and society.

7.1. Future scope

While the current work offers several innovations and practical usefulness, there is scope for further extensions.

- 1) The first possible extension arises from the need to consider experimental data for the comparison of NTs. The current work is based on the subjective opinions of experts. However, a comprehensive assessment could be conducted by considering both subjective and objective information. In this context, criteria such as remaining useful life, life-cycle costing, and greenhouse gas emissions are paramount.
- 2) It is possible to include several other emerging nanotechnologies (NTs), such as nano-emulsions and nano-encapsulated agrochemicals, among others, for comparison.
- 3) The present work is limited by the size of the expert group, which could be enhanced to conduct a large-scale decision analysis.
- 4) The causal analysis of the effects of various criteria on agricultural production, including the effects of climate change, could also be explored.
- 5) Future work could also consider integrating the real-time data generated through sensors and IoT systems to compare the implementation of NTs.
- 6) It would be interesting to compare NTs in regional and crop contexts. A cross-regional and multi-crop study to compare NTs would reveal some interesting implications.

- 7) The ongoing work demonstrates a novel application of p, q-IVQROFN in agriculture, which could be explored to be applied in various other complex problems.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

Table A1

Linguistic evaluation (coded) of the criteria by the experts

Criteria/ Experts	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
E1	7	3	5	6	3	3	4	3	3	4
E2	7	2	6	6	2	3	3	3	6	5
E3	6	2	5	6	4	4	3	3	7	4
E4	6	1	6	6	2	4	3	2	5	5
E5	7	2	6	7	3	3	4	4	6	5
E6	6	1	5	5	2	4	5	2	5	6
E7	7	2	7	6	3	5	3	3	5	6
E8	6	1	6	5	2	2	4	2	6	6
E9	7	1	5	6	3	4	4	3	5	5
E10	6	2	7	5	3	4	4	3	5	5

Table A2

Linguistic evaluation (coded) of the alternatives by expert 1

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	6	6	5	6	6	5	6	5	7	6
NT 2	4	3	3	2	3	2	4	3	3	2
NT 3	6	5	5	6	5	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	7	5	7	7	6	6	7	7	7	7
NT 6	5	4	5	5	4	4	5	4	5	5
NT 7	7	5	6	6	6	5	7	6	7	7
NT 8	3	2	2	2	3	1	2	2	2	1

Table A3

Linguistic evaluation (coded) of the alternatives by expert 2

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	6	6	5	6	6	5	6	5	7	6
NT 2	3	4	3	2	3	4	2	3	3	2
NT 3	6	5	5	6	5	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	7	7	5	7	6	6	6	7	7	6
NT 6	4	3	5	4	4	4	5	4	5	4
NT 7	7	6	6	6	6	5	6	6	7	7
NT 8	3	2	2	1	2	1	2	2	2	1

Table A4

Linguistic evaluation (coded) of the alternatives by expert 3

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	6	6	5	6	6	5	6	5	7	6
NT 2	3	3	2	4	3	2	4	3	3	3
NT 3	6	5	5	5	5	4	6	4	5	4
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	7	6	6	6	6	6	7	7	6	7
NT 6	4	4	5	4	4	4	5	4	5	5
NT 7	7	5	6	6	6	5	7	6	7	7
NT 8	3	2	2	2	3	1	2	2	2	1

Table A5

Linguistic evaluation (coded) of the alternatives by expert 4

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	5	6	6	6	6	5	6	5	5	7
NT 2	4	3	3	2	3	2	4	3	3	2
NT 3	5	5	5	6	6	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	7	6	7	7	7	6	7	7	7	7
NT 6	5	4	5	5	4	4	5	4	5	5
NT 7	6	6	6	6	5	5	6	6	7	7
NT 8	3	2	2	2	3	1	2	2	2	1

Table A6

Linguistic evaluation (coded) of the alternatives by expert 5

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	6	6	5	6	6	5	6	5	7	6
NT 2	3	3	3	3	3	2	3	3	3	1
NT 3	6	5	5	6	5	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	7	5	7	7	6	6	7	7	7	7
NT 6	5	4	5	5	4	4	5	4	5	5
NT 7	7	5	6	6	6	5	7	6	7	7
NT 8	2	2	1	2	2	1	2	2	2	1

Table A7

Linguistic evaluation (coded) of the alternatives by expert 6

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	6	6	5	6	6	5	6	5	7	6
NT 2	4	3	3	2	3	2	4	3	3	2
NT 3	5	4	5	5	6	5	6	4	5	4
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	7	5	7	7	6	6	7	7	7	7
NT 6	4	4	5	3	7	4	5	4	5	6
NT 7	7	5	6	6	6	5	7	6	7	7
NT 8	3	2	2	2	3	1	2	2	2	1

Table A8

Linguistic evaluation (coded) of the alternatives by expert 7

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	5	6	5	6	6	5	6	5	6	6
NT 2	4	3	3	2	3	2	4	3	3	2
NT 3	6	5	5	6	5	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	6	6	7	7	6	6	7	7	7	6
NT 6	5	4	5	5	4	4	5	4	5	5
NT 7	6	5	6	6	5	5	7	6	7	5
NT 8	3	2	2	2	3	1	2	2	2	1

Table A9

Linguistic evaluation (coded) of the alternatives by expert 8

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	6	6	5	6	6	5	6	5	7	6
NT 2	2	3	2	2	3	2	3	3	3	2
NT 3	6	5	5	6	5	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	7	5	7	7	6	6	7	7	7	7
NT 6	5	4	5	5	4	4	5	4	5	5
NT 7	7	5	6	6	6	5	7	6	7	7
NT 8	2	2	1	2	1	1	2	2	2	1

Table A10

Linguistic evaluation (coded) of the alternatives by expert 9

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	5	6	4	6	6	5	6	5	7	6
NT 2	4	3	3	2	3	2	4	3	3	2
NT 3	6	5	5	6	5	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	6	6	6	7	6	7	7	7	7	7
NT 6	5	4	5	5	4	4	5	4	5	5
NT 7	6	5	6	6	6	5	6	6	7	7
NT 8	3	2	2	2	3	1	2	2	2	1

Table A11

Linguistic evaluation (coded) of the alternatives by expert 10

Criteria/ Technologies	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10
NT 1	6	6	5	6	6	5	6	5	7	6
NT 2	4	3	3	2	3	2	4	3	3	2
NT 3	6	5	5	6	5	4	6	4	5	5
NT 4	5	4	4	4	3	3	4	3	5	3
NT 5	6	5	7	7	6	7	7	7	7	7
NT 6	5	4	5	5	4	4	5	4	5	5
NT 7	6	6	6	6	6	5	7	6	7	6
NT 8	3	2	2	2	3	1	2	2	2	1

Appendix B

Sample calculation (the p, q -IVQROFNWGA operation)

Suppose there are three p, q -IVQROFNs, such as

$$\theta_1 = (M_1, N_1) = \left([M_1^-, \overline{M}_1], [N_1^-, \overline{N}_1] \right) = ([0.80, 0.85], [0.20, 0.25])$$

$$\theta_2 = ([0.65, 0.70], [0.35, 0.40])$$

$$\theta_3 = ([0.65, 0.70], [0.35, 0.40])$$

Suppose their weights are 0.1281, 0.0443 and 0.0443, respectively.

Assuming, $q = 2$, the aggregation can be done as follows.

$$\theta = (M, N) = \left([M^-, \overline{M}], [N^-, \overline{N}] \right)$$

$$= p, q - IVQROFNWGA(\theta_1, \theta_2, \theta_3) = \prod_{k=1}^3 (\theta^k)^{\omega_k}$$

$$= \left(\left[\prod_{k=1}^3 (M_{ij}^k)^{\omega_k}, \prod_{k=1}^3 (\overline{M}_{ij}^k)^{\omega_k} \right], \left[\sqrt[2]{1 - \prod_{k=1}^3 \left(1 - (N_{ij}^k)^2 \right)^{\omega_k}}, \sqrt[2]{1 - \prod_{k=1}^3 \left(1 - (\overline{N}_{ij}^k)^2 \right)^{\omega_k}} \right] \right)$$

$$= \left(\left[((0.80)^{0.1281} \times (0.65)^{0.0443} \times (0.65)^{0.0443}, ((0.85)^{0.1281} \times (0.70)^{0.0443} \times (0.70)^{0.0443}) \right], \left[\left(1 - ((1 - (0.20)^2)^{0.1281} \times (1 - (0.35)^2)^{0.0443} \times (1 - (0.35)^2)^{0.0443}) \right)^{0.5}, \left(1 - ((1 - (0.25)^2)^{0.1281} \times (1 - (0.40)^2)^{0.0443} \times (1 - (0.40)^2)^{0.0443}) \right)^{0.5} \right] \right)$$

$$= ([0.9354, 0.9489], [0.1291, 0.1531])$$

Appendix C

Table C1

Linguistic Evaluation (coded) of the risk levels of the alternatives by expert 1

Criteria/Technologies	L	S	E
NT 1	7	7	6
NT 2	4	3	4
NT 3	6	6	5
NT 4	7	6	6
NT 5	3	2	2
NT 6	5	5	5
NT 7	5	5	4
NT 8	5	6	5

Table C2

Linguistic Evaluation (coded) of the risk levels of the alternatives by expert 2

Criteria/Technologies	L	S	E
NT 1	7	7	6
NT 2	3	3	2
NT 3	6	6	5
NT 4	7	6	6
NT 5	2	1	1
NT 6	5	4	5
NT 7	5	4	4
NT 8	5	6	5

Table C3
 Linguistic Evaluation (coded) of
 the risk levels of the alternatives by
 expert 3

Criteria/Technologies	L	S	E
NT 1	7	7	6
NT 2	3	4	4
NT 3	6	6	5
NT 4	7	6	6
NT 5	3	2	2
NT 6	5	5	6
NT 7	5	4	4
NT 8	5	5	5

Table C4
 Linguistic Evaluation (coded) of
 the risk levels of the alternatives by
 expert 4

Criteria/Technologies	L	S	E
NT 1	7	7	6
NT 2	4	3	4
NT 3	6	6	5
NT 4	7	6	6
NT 5	3	2	2
NT 6	5	5	5
NT 7	5	5	4
NT 8	5	6	5

Table C5
 Linguistic Evaluation (coded) of
 the risk levels of the alternatives by
 expert 5

Criteria/Technologies	L	S	E
NT 1	7	6	6
NT 2	3	3	4
NT 3	6	6	5
NT 4	7	6	6
NT 5	3	2	3
NT 6	5	5	5
NT 7	5	5	4
NT 8	5	6	5

Table C6
 Linguistic Evaluation (coded) of
 the risk levels of the alternatives by
 expert 6

Criteria/Technologies	L	S	E
NT 1	7	7	7
NT 2	4	3	4
NT 3	6	6	5
NT 4	7	6	6
NT 5	3	2	2
NT 6	5	5	4
NT 7	4	5	4
NT 8	5	6	5

Table C7
 Linguistic Evaluation (coded) of
 the risk levels of the alternatives by
 expert 7

Criteria/Technologies	L	S	E
NT 1	7	7	6
NT 2	3	2	4
NT 3	6	6	4
NT 4	7	6	6
NT 5	3	2	1
NT 6	4	5	5
NT 7	5	5	4
NT 8	5	6	5

Table C8
 Linguistic Evaluation (coded) of
 the risk levels of the alternatives by
 expert 8

Criteria/Technologies	L	S	E
NT 1	7	6	6
NT 2	4	3	2
NT 3	6	6	5
NT 4	7	6	5
NT 5	2	1	2
NT 6	5	5	5
NT 7	4	5	4
NT 8	4	6	5

Table C9

Linguistic Evaluation (coded) of the risk levels of the alternatives by expert 9

Criteria/Technologies	L	S	E
NT 1	7	7	6
NT 2	4	3	3
NT 3	5	6	5
NT 4	7	6	6
NT 5	2	1	2
NT 6	5	4	5
NT 7	5	4	4
NT 8	5	4	5

Table C10

Linguistic Evaluation (coded) of the risk levels of the alternatives by expert 10

Criteria/Technologies	L	S	E
NT 1	6	7	6
NT 2	3	3	4
NT 3	5	6	5
NT 4	7	6	6
NT 5	1	2	2
NT 6	5	5	5
NT 7	5	5	4
NT 8	5	6	5

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