Multi-criteria analysis applied to the hydro-chemical classification of bottled waters marketed in Algeria

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Abstract:

Introduction/purpose: Mineral and spring waters play a crucial role in daily nutrition due to their taste and health benefits. In Algeria, the bottled water market is rapidly growing, yet there remains a lack of precise, objective systems to classify these waters based on organoleptic qualities and safety. This study aims to develop a reliable numerical model for the hydrochemical classification of bottled waters marketed in Algeria.

Methods: A hybrid multi-criteria decision-making approach was employed, integrating the DIBR II method to determine the weights of criteria based on expert judgments and the Bonferroni operator to aggregate these opinions. To effectively manage uncertainty and imprecision in the data, Triangular Neutrosophic Numbers (TNN) were utilized. Subsequently, the CODAS (COmbinative Distance-based ASsessment) method was applied to rank the bottled water brands. The evaluation focused on four key quality criteria: nitrate concentration, hardness, total mineralization, and hydrochemical nature. After constructing and aggregating the neutrosophic decision matrices and performing de-neutrosophication, CODAS computed a proximity coefficient for each brand, resulting in the final ranking.

Results: The study identified the top five brands of mineral waters (Daouia, Mansourah, Youkous, Alma, and N'Gaous) and spring waters (Taya, Ariaf, Arwa, Sidi Rached, and Hirouche). Sensitivity analysis confirmed the robustness of the ranking, validating the model's reliability and showed that nitrate content is the most influential criterion, highlighting its key role in assessing water quality. Comparative analysis also demonstrated that CODAS produces consistent and reliable rankings compared to other multi-criteria methods, with good discrimination among closely ranked alternatives.

Conclusion: This study developed an innovative and robust numerical model combining DIBR II and CODAS within a neutrosophic framework, providing a reliable hydrochemical classification of bottled mineral and spring waters in Algeria. The model incorporates expert weighting and accounts for data uncertainty to generate a clear and coherent brand ranking. Sensitivity analysis confirmed the stability of the rankings, particularly emphasizing the dominance of the nitrate criterion, demonstrating the model's value as a decision-support tool for various stakeholders in the sector.

Key words: multi-criteria classification, mineral water, spring water, DIBR II, CODAS, neutrosophic numbers.

Introduction

The bottled water sector in Algeria has experienced remarkable growth in recent years, marked by the multiplication of production units and a significant increase in per capita consumption (Hazzab, 2011). Faced with this expansion, it has become essential to evaluate and classify the quality of bottled waters available on the Algerian market (Lourenço et al., 2010).

Traditionally, hydrochemical analyses rely on graphical and statistical methods such as Piper and Schoeller-Berkaloff diagrams or Principal Component Analysis (PCA) (Ouhamdouch et al., 2018). Although these approaches are effective for visualizing the chemical composition of waters, they do not allow for an integrated and quantitative evaluation of water quality when several, sometimes conflicting, criteria are involved.

To overcome these limitations, multi-criteria decision-making (MCDM) methods have established themselves as powerful tools in complex decision-making processes involving multiple evaluation parameters. MCDM is a structured approach that enables decision-makers to rank or select alternatives based on multiple, often conflicting, criteria, each weighted according to its relative importance (Rahman et al., 2024). These methods are increasingly used in environmental management,

water resource assessment, and hydrogeochemical classification (Božanić et al., 2024).

Recent MCDM approaches can be grouped into two main categories. The first includes methods for determining criteria weights, which express the relative importance of each decision factor. Among these are AHP (Analytic Hierarchy Process) (Saaty, 1980), BWM (Best–Worst Method) (Rezaei, 2015), the entropy method (Zhou et al., 2023), and DIBR-II (Defining Interrelationships Between Ranked Criteria II) (Božanić et al., 2024). The second category concerns ranking or selection methods for the optimal alternative, which combine weighted criteria to produce a final ranking, such as CODAS (COmbinative Distance-based ASsessment) (Ghorabaee et al., 2016), VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) (Rahman et al., 2024), WASPAS (Weighted Aggregated Sum Product Assessment) (Lan et al., 2023), COPRAS (Complex Proportional Assessment) (Egbueri et al., 2023), as well as MOORA, EDAS, and their fuzzy or neutrosophic extensions (Wang et al., 2023).

In this study, the CODAS method, recognized for its clarity, robustness, and efficiency in multi-criteria ranking, was used in combination with the DIBR-II method for criteria weighting. Integrated within a neutrosophic framework, this approach offers an objective and reproducible model for hydrochemical classification.

The proposed model was applied to a representative sample of mineral and spring waters marketed in Algeria, considering four main criteria: hardness, nitrate content, mineralization, and hydrochemical nature, with the aim of establishing a scientific and transparent classification.

A sensitivity analysis confirmed the robustness of the ranking obtained by CODAS against variations in criteria weighting, while a comparison with other multi-criteria methods validated the relevance and reliability of the approach.

Thus, the study contributes to improving the quality and transparency of the bottled water sector in Algeria by providing consumers and professionals with a reliable tool for evaluating and comparing the different brands available on the market.

Materials and methods

Methodology for classifying bottled water marketed in Algeria

This study proposes a numerical model based on the CODAS method for the hydrochemical classification of bottled waters marketed in Algeria. The process, illustrated in Figure 1, begins with the collection and recording of physico-chemical data obtained from the labels of various brands. The classification criteria are then defined and weighted according to expert opinions using the DIBR II method, with the weights merged through the Bonferroni operator. A neutrosophic decision matrix is developed for each expert, aggregated, and de-neutrosophicated to produce a single matrix. The CODAS method is subsequently applied to compute an assessment score based on the Euclidean and Taxicab distances from the negative-ideal solution, thereby enabling the ranking of the water samples. Finally, a sensitivity and comparative analysis was conducted to evaluate the robustness of the rankings against variations in criteria weighting and to assess the consistency of CODAS relative to other multi-criteria decision-making methods.

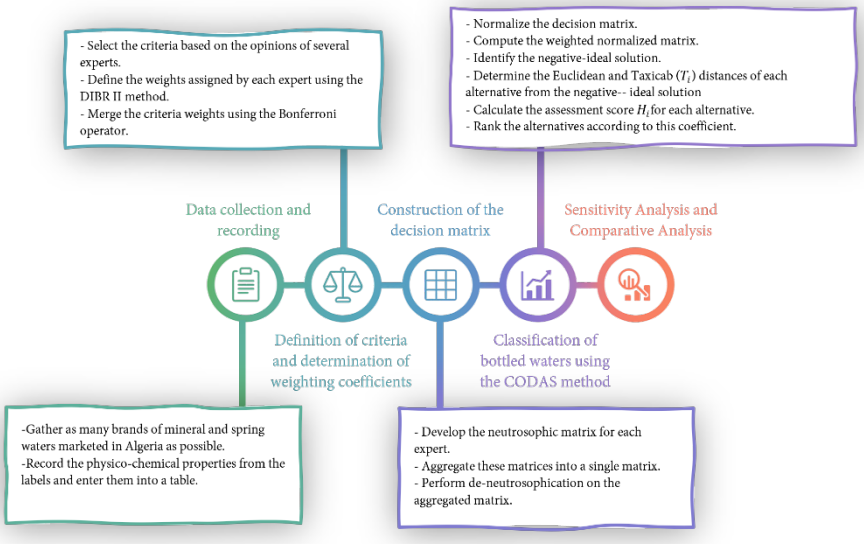


Figure 1 – Procedure for the classification of bottled water marketed in Algeria

Mathematical concepts

This section presents the fundamental mathematical tools used in this article, beginning with the DIBR II method employed to determine the relative importance of decision criteria. It then addresses fuzzy and neutrosophic sets along with their properties and definitions. Finally, the steps of the CODAS method, a multi-criteria technique, are presented.

The DIBR and DIBR II methods (defining interrelationships between ranked criteria)

The DIBR method is a mathematical technique that determines the relative importance of decision criteria in multi-criteria problems, providing essential weighting coefficients that reflect each criterion's influence on the overall objective. Used as a complementary tool, it generates reliable weights integrated into other methods such as AHP or CODAS, establishing a solid basis for ranking options or selecting the best alternative.

The DIBR II version, published by Božanić et al. in 2024, enhances this initial method with a process summarized as follows:

- Identification and ranking of criteria: The user or a group of experts identifies relevant criteria $(C_i)_{i=1,\dots,n}$for the decision problem and ranks them in descending order of importance ($C_1 > C_2 > \cdots > C_n$).

- Definition of relationships: For each pair of adjacent criteria in the ranking, the experts define the importance relationship:

$$r_{i,i+1} = \frac{w_i}{w_{i+1}} \quad for \quad i = 1,\dots,n-1 \tag{1}$$

Where w_i represents the weight of the criterion C_i.

- Calculation of weights: First, the weight (w_1) attributed to the main criterion C_1 is calculated using the following formula:

$$w_1 = \frac{1}{1 + \frac{1}{r_{1,2}} + \frac{1}{r_{1,2} * r_{2,3}} + \dots + \frac{1}{r_{1,2} * r_{2,3} * \dots * r_{n-1,n}}} \tag{2}$$

For $i = 2, \dots, n$, the other weights w_i are obtained using the formula:

$$w_i = \frac{w_1}{\prod_{j=1}^{i-1} r_{j,j+1}} \tag{3}$$

- Evaluation of the quality of defined relationships: To ensure the quality of the relationships between criteria, the deviation coefficient D_n of the criterion C_n is calculated according to the expression:

$$D_n = \left|1 - \frac{w_n}{w_n^k}\right| \quad \text{with} \quad w_n^k = \frac{w_n}{v_{1,n}} \tag{4}$$

It must be between 0 and 0.1 (a tolerance margin of 10%) and applies to the most and least important criteria. If this condition is not met, the relationships between adjacent criteria should be reviewed to ensure their consistency.

Definition of a single-valued neutrosophic fuzzy set

Consider a universe of discourse X. A single-valued neutrosophic fuzzy set on X is defined as follows:

$$A = \{(x, T_A(x), I_A(x), F_A(x)); x \in X\}$$

The functions $T_A(x), I_A(x)$ and $F_A(x)$ represent respectively the degrees of membership, indeterminacy, and non-membership of the element x to the set A.

These functions satisfy $0 \leq T_A(x), I_A(x), F_A(x) \leq 1$, and their sum is constrained by the relation: $0 \leq T_A(x), I_A(x), F_A(x) \leq 3$ (Zhou et al., 2023).

Definition of neutrosophic number (NN)

Let A be a single-valued neutrosophic fuzzy set on the set of real numbers. A is called a neutrosophic fuzzy number if it satisfies the following conditions (Wang et al., 2023):

(i) Normality of A: there exists $x_0 \in R$ such that

$$T_A(x_0) = 1, I_A(x_0) = 0 \text{ and } F_A(x_0) = 0$$

(ii) Convexity of T_A : for all $x_1 and\ x_2 \in R$ and $\lambda \in [0,1]$,

$$T_A(\lambda x_1 + (I - \lambda)x_2) \geq \min\{T_A(x_1); T_A(x_2)\} \tag{5}$$

(iii) Convexity of I_A : for all $x_1 and\ x_2 \in R$ and $\lambda \in [0,1]$,

$$I_A(\lambda x_1 + (I - \lambda)x_2) \leq \max\{I_A(x_1); I_A(x_2)\} \tag{6}$$

(iv) Convexity of F : for all $x_1 and\ x_2 \in R$ and $\lambda \in [0,1]$,

$$F_A(\lambda x_1 + (I - \lambda)x_2) \leq \max\{F_A(x_1); F_A(x_2)\} \tag{7}$$

Definition of triangular neutrosophic number (TNN)

Let $\tilde{T} = \left\langle (x, T_T(x), I_T(x), F_T(x)); (d_1, d_2, d_3, X_N, Y_N, Z_N) \right\rangle$ be a single-valued triangular neutrosophic number, where:

- $d_1, d_2, d_3 \in \mathbb{R}$ with $d_1 \leq d_2 \leq d_3$,
- $X_N, Y_N \; and \; Z_N \in [0,1]$ represent respectively the maximum degrees of truth, indeterminacy, and falsity.

The membership, indeterminacy, and non-membership functions, denoted respectively by $T_{\tilde{T}}(x)$, $I_{\tilde{T}}(x)$ and $F_{\tilde{T}}(x)$ are defined as follows:

$$T_T(x) = \begin{cases} X_N \dfrac{x - d_1}{d_2 - d_1} \; if \; d_1 \leq x \leq d_2 \\ X_N \; if \; x = d_2 \\ X_N \dfrac{d_3 - x}{d_3 - d_2} \; if \; d_2 \leq x \leq d_3 \\ 0 \; if \; elsewhere \end{cases} \tag{8}$$

$$I_T(x) = \begin{cases} \dfrac{(x - d_1)Y_N + (d_2 - x)}{d_2 - d_1} \; if \; d_1 \leq x \leq d_2 \\ Y_N \; if \; x = d_2 \\ \dfrac{(d_3 - x)Y_N + (x - d_2)}{d_3 - d_2} \; if \; d_2 \leq x \leq d_3 \\ 0 \; if \; elsewhere \end{cases} \tag{9}$$

$$F_T(x) = \begin{cases} \dfrac{(x - d_1)Z_N + (d_2 - x)}{d_2 - d_1} \; if \; d_1 \leq x \leq d_2 \\ Z_N \; if \; x = d_2 \\ \dfrac{(d_3 - x)Z_N + (x - d_2)}{d_3 - d_2} \; if \; d_2 \leq x \leq d_3 \\ 0 \; if \; elsewhere \end{cases} \tag{10}$$

with the condition: $0 \leq T_T(x) + I_T(x) + F_T(x) \leq 3; \forall x \in \mathbb{R}$ (Wang et al., 2023).

De-neutrosophication

De-neutrosophication consists of reducing a composite neutrosophic number to a single scalar value. This is essential due to the lack of a classical ordering relationship among neutrosophic values.

For a triangular neutrosophic number (TNN), various de-neutrosophication algorithms can be applied to extract distinct characteristic values. The method proposed here, called the Area of

Withdrawal (AW) method (or Area of Removal/Retirement), calculates this single value by combining geometric parameters (distances) and the Truth, Indeterminacy, and Falsity components according to the given formula (11), thus ensuring a faithful and usable synthesis of the neutrosophic number (Chakraborty et al., 2018).

$$D(\tilde{T}) = \left[\frac{d_1 + 2d_2 + d_3}{5}\right](3X_N - Y_N - 2Z_N) \quad (11)$$

The CODAS method for decision support

The CODAS method (COmbinative Distance-based ASsessment), developed by Ghorabaee (2016), is designed to evaluate and rank alternatives according to multiple conflicting criteria by combining Euclidean and Taxicab (Manhattan) distances from a negative ideal solution (NIS), thereby ensuring a robust and accurate ranking. Since its introduction, CODAS and its fuzzy extensions have been applied across various domains: Mishra (2021) used intuitionistic fuzzy CODAS to rank low-carbon suppliers in the maritime sector; and Ashofteh (2023) integrated CODAS with SWARA to optimize reservoir management using performance indicators. Thus, CODAS has established itself as a flexible and reliable multi-criteria approach, suitable for complex decision-making contexts such as human resource management, energy sustainability, and hydrology.

The different steps of this method can be summarized as follows (Ghorabaee et al., 2016):

- Define the decision matrix $X = (x_{ij})_{m\times n}$, where a set of alternatives $a_1, a_2, \ldots, a_m$is evaluated according to criteria $c_1, c_2, \ldots, c_n$.
- Normalize the matrix *X* to obtain the normalized matrix $R = (r_{ij})_{m\times n}$

$$r_{ij} = \begin{cases} \frac{x_{ij}}{\max\limits_i x_{ij}}, & if j \in N_b \\ \frac{\min\limits_i x_{ij}}{x_{ij}}, & if j \in N_c \end{cases} \quad (12)$$

where N_b and N_c denote the sets of benefit and cost criteria, respectively.

- Calculate the weighted normalized matrix $V = (v_{ij})_{n\times m}$,

$$v_{ij} = \pi_j \times r_{ij} \quad (13)$$

where $\pi_j$represents the weight assigned to criterion $c_j$by the decision makers, such that $\sum_{j=1}^{n} \pi_j = 1$.

- Determine the negative-ideal solution $NS = \{NS_1, NS_2, \ldots, NS_m\}$:

$$NS_j = min_{1\le i\le n}\{v_{ij}\} \quad (14)$$

- Calculate the Euclidean (E_i) and Taxicab (Manhattan) (T_i) distances of each alternative from the negative-ideal solution:

$$E_i = \sqrt{\sum_{j=1}^{n}(v_{ij} - NS_j)^2} \quad (15), \qquad T_i = \sum_{j=1}^{n} | v_{ij} - NS_j | \quad (16)$$

- Compute the assessment score H_i for each alternative:

$$H_i = \sum_{k=1}^{n}[(E_i - E_k) + (\psi(E_i - E_k) \times T_i)] \quad (17)$$

where $\psi(E_i - E_k)$ is an indicator function defined as:

$$\psi(E_i - E_k) = \{1, if \ | E_i - E_k | \geq \tau \ 0, otherwise \quad (18)$$

where τ is a threshold parameter (typically $\tau = 0.02$).

- Alternatives are ranked in descending order of their H_i values, with the highest CODAS score indicating the best option.

Physicochemical characteristics of mineral water and spring water in Algeria

Tables 1 and 2 present the physicochemical properties of the waters considered. These characteristics, obtained through the labelling of different products, are in agreement with the results of analyses performed in officially accredited laboratories (Khelifa et al., 2024).

Table 1 - Physicochemical characteristics of natural waters in Algeria

Water	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^{+} mg/l	K^{+} mg/l	Cl^{-} mg/l	SO_4^{-2} mg/l	HCO_3^{-} mg/l	NO_3^{-} mg/l	NO_2^{-} mg/l	Dry residue at 180°C
Saïda	68	50	58	2	81	65	376	15	0	478
Messerghine	52	42	45	3	78	50	260	5	0	320
Sfid	74	35	28	2	68	91	268	27	0	650
Mouzaïa	136	75	145	3	150	120	60	20	0.02	1280
Ifri	99	24	15.8	2.1	72	68	265	15	<0.02	380
Guedila	78	37	29	2	40	95	/	4.5	<0.01	564
Toudja	56.6	15.2	36	0.7	54.6	19.6	/	2.55	<0.02	256
Mansourah	85	37	30	1	48	53	362	12	0	660
Lalla khedidja	53	7	5.5	0.54	11	7	160	0.42	0	187
Batna	59	45	15	2	22	40	378.2	0	0	650
Texanna	30	9.1	11	1	28.4	11	60	0	0	152
Thevest	89.95	34	47.25	0.99	65	188	231.8	2.35	0.01	
El Goléa	35	16	36	5	21	32	118	2.4		180
N'Gaous	143	65.4	63.4	3.76	75	44.4		2.07	0	962
Youkous	77.4	14.5	13.4	4.65	25.7	35.8	218	2	0	231
Sidi Okba	143	65.4	63.4	3.76	75	445	213	2.07	0	425
Sidi Idris	38.87	3.16	7.14	0.72	16.97	10	127.95	0.15	0.02	202
Milok	62.6	5.5	5.7	3.7	13	72	118.95	16.36		180
Daouia	31.9	19.9	75	0.7	40.4	18.3	288	0.4		325
Alma	91	37	31	2	55	87	350	15	0.01	682

Table 2 - Physicochemical characteristics of spring waters in Algeria

Water	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^{+} mg/l	K^{+} mg/l	Cl^{-} mg/l	SO_4^{2-} mg/l	HCO_3^{-} mg/l	NO_3^{-} mg/l	NO_2^{-} mg/l	Dry residue at 180°C
Besbassa	54.16	2.64	5	2	10	4	164.7	9	0.01	206
Messad	79	27	50	2	40	156	275	23	0.01	611
Tazliza	48	20	48	8	76	96	104	19.97	0.01	407
Ain Bouglez	4.6	3.75	29	1	30	10	48.8	9	0.06	140
Sidi rached	134.38	6.69	29.21	2.45	50	139	235	21.8	0	610
Taya	42.75	12.48	55	1	110	82		17.37	0.01	400
Star	115	33	30	1.8	82	95	330	37.2	<0.02	490
Ayris	65.6	6.8	28.5	1.9	37	75	234.24	2.7	0.01	276
Qniaa	111.66	26.97	48.22	2.48	92.12	66.66	259.02	12.39	0.01	602
Guerioune	72	27	11	2	21	11	336	20.2	<0.01	475
Ovitale	91	14	30	1	50	86	214	14	0	420
Ichemoul	101	2	10	0.6	10	54	262	13	<0.01	344
Arwa	120	23	56	1	100	104	256	46.5	<0.01	450
Soumam	114	32	71	2	78	196	293	19.2	0.01	755
Hirouche	107.4	18.2	22.2	1.6	62.2	54	262.8	32.8	<0.01	550.8
Ifren	68.8	10.69	32	2.4	17.04	62.5	283.04	3.22	<0.01	300
Ariaf	102.4	29.16	88.8	1.4	196.32	175.43	200.08	5.31	<0.01	732
Mont Djurjura	103	28	54	1	97	56	357	30	<0.01	700
Fezguia	35.23	13.44	31	1	30	28	305	19	0	412
Ouwis	106	25	60	2	48.59	117	261	18.3	0	724
Nestle	55	17	> 12	0.5	15	33	210	4.6	< 0.01	372

Results and discussion

Water quality indicators

Although all bottled waters comply with health standards and are therefore safe to drink, their quality assessment was based on taste preference, the ability to be consumed regularly without discomfort, and their potability in a broad sense, including long-term health implications.

For this purpose, the expert group identified four essential criteria:

❖ Nitrate content (C_1) is an essential criterion due to the health risks posed by high concentrations, especially for infants and pregnant women. Even if the samples meet the standards, a lower content remains preferable for safe and sustainable daily consumption (Jensen et al., 2023; Bryan et al., 1973).

❖ Hardness (C_2), which reflects the concentration of calcium and magnesium salts influencing the taste of water (Rosen and Booth, 1971), is measured in mg/L of CaCO3, a unit equivalent to French degrees (°f), where 1°f corresponds to 10 mg/L of CaCO3. This parameter directly affects the taste and digestibility of water: excessive hardness can impart a chalky taste and a "heavy" water sensation, while moderate hardness is

generally perceived as more pleasant and better assimilated by the body (Bryan et al., 1973; Galan et al., 2002).

❖ Water mineralization (C_3), essential for a balanced mineral intake and daily nutritional needs, influences long-term health depending on its excess or deficiency; it is generally classified according to the total dissolved solids concentration (in mg/L): low mineralization with a dry residue at 180°C below 50 mg/L, weak mineralization between 50 and 500 mg/L, moderate mineralization between 500 and 1500 mg/L, and high mineralization above 1500 mg/L (Kamalapriya et al., 2023).

❖ The hydrochemical nature (C_4) is a key indicator of the geological origin of the water. Its analysis reveals the underground path, the rocks encountered, and can highlight specific characteristics or risks related to its stability over time (Patel et al., 2023).

Establishing criteria weights

A weighting system, established by consensus among four experts, was used to prioritize the major health and organoleptic issues. The DIBR II method was applied to assess the importance of each criterion, whose relationships are presented in the following table.

Table 3 - Importance relationships defined by the experts

	Importance relationship of the criteria			
Experts	r_{12}	r_{23}	r_{34}	r_{45}
E 1	1.33	1.50	2.00	4.00
E 2	2.00	0.67	3.00	4.00
E 3	1.40	1.43	2.00	4.00
E 4	1.33	3.00	0.5	2.00

Equations (1) to (4) were used to calculate the weights of the criteria for each expert, as presented in Table 4.

Table 4 - Criteria weights according to each expert

	Criteria weights				
Experts	w_1	w_2	w_3	w_4	D_n
E 1	0.399	0.300	0.200	0.100	0
E 2	0.401	0.200	0.299	0.100	0
E 3	0.406	0.101	0.290	0.203	0
E 4	0.399	0.300	0.100	0.200	0

All deviations D_n are less than 0.1, therefore the evaluations are consistent.

Aggregation of expert opinions using the Bonferroni operator

In this study, the Bonferroni $BM^{p,q}$ operator (Zhou et al., 2019) was applied to aggregate experts' opinions and determine the criteria weights under the DIBR II method, as defined by:

$$BM^{p,q}(x_1, x_2, ..., x_m) = \left[\frac{1}{m(m-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{m} (w_i^e)^p (w_j^u)^q \right]^{\frac{1}{p+q}} \quad (19)$$

Here, m denotes the number of experts, p,q ≥ 0 are the stabilization parameters, and e and u respectively represent the e-th and u-th experts, with 1≤e,u ≤ m.

The aggregation of opinions, performed using equation (19) with m = 4 and p= q = 1, yielded the final criteria weights presented in Figure 2.

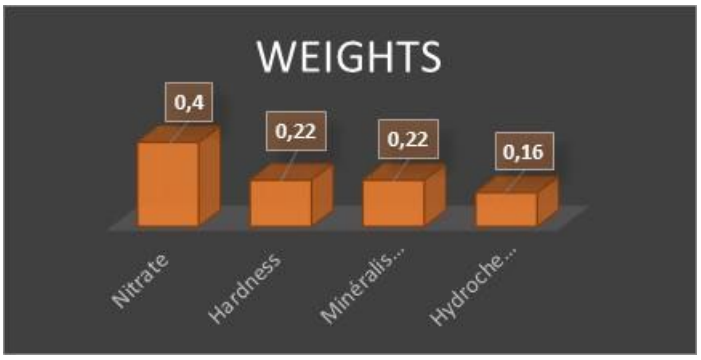


Figure 2 - Weights associated with the criteria

The final (de-neutrosophic) decision matrix

The final (de-neutrosophic) decision matrix is obtained by consolidating the m criteria evaluations for n alternatives, initially expressed by decision-makers in the form of triangular neutrosophic numbers (TNN).

To do this, the following procedure was followed:

Construction of individual neutrosophic decision matrices

Each decision-maker α ($\alpha = 1, \ldots, k$) develops a decision matrix

$$\tilde{D}_\alpha = \left[(\tilde{B}_{ij})_\alpha \right]_{n \times m} \quad \text{with}$$

$$(\tilde{B}_{ij})_\alpha = \left((d_1)_{ij}^\alpha, (d_2)_{ij}^\alpha, (d_3)_{ij}^\alpha, (X_N)_{ij}^\alpha, (Y_N)_{ij}^\alpha, (Z_N)_{ij}^\alpha \right) \quad (20)$$

where the element $\left(\tilde{B}_{ij}\right)_{\alpha}$ represents the evaluation of alternative i with respect to criterion j by decision-maker α.

Tables 5 and 6 illustrate these evaluations for mineral and spring waters, based on the criteria of hardness, mineralization, nitrate content, and hydrochemical nature, as provided by two experts.

Table 5 - Neutrosophic decision matrix (NNT) of mineral waters

	EXPERT 01												EXPERT 02											
Water	C1			C2			C3			C4			C1			C2			C3			C4		
Saida	1	1	2	1	1	2	3	4	5	5	6	7	1	1	1	1	2	3	3	5	6	7	8	10
Messerghine	5	6	7	1	2	5	7	9	9	5	6	7	5	7	7	1	2	4	7	9	10	7	8	10
SFID	1	1	1	1	1	3	6	7	9	5	6	7	1	1	1	1	2	5	6	7	8	6	6	8
Mouzaia	1	1	1	1	1	1	4	4	5	2	3	4	1	1	1	1	1	1	4	4	4	2	4	5
Ifri	1	1	1	1	1	4	7	8	9	5	6	7	1	1	2	1	2	3	7	9	9	6	6	8
Guedila	6	6	7	1	2	3	2	3	3	3	3	3	6	7	7	1	2	2	3	3	3	2	3	3
Toudja	7	7	8	3	3	5	1	1	2	2	3	4	7	8	8	5	6	8	1	1	2	2	4	5
Mansourah	2	3	3	1	1	2	5	6	7	5	6	8	3	3	3	1	1	4	6	7	8	5	6	8
Lala khedidja	8	9	9	4	6	7	1	2	2	5	6	7	8	9	9	4	6	8	2	2	1	6	6	8
Batna	9	9	10	1	1	2	8	8	8	5	6	7	8	9	10	2	2	5	8	8	9	7	8	10
Texanna	8	9	9	7	8	8	1	1	1	5	6	7	8	9	10	7	7	8	1	1	1	6	6	8
Thevest	7	7	9	1	2	2	5	6	7	3	3	3	7	8	9	2	2	2	6	6	7	2	3	3
El Goléa	7	7	8	5	6	7	2	2	3	5	6	8	7	8	9	6	7	8	2	2	2	7	6	8
N'Gaous	7	7	8	1	1	1	5	6	7	2	3	4	7	8	9	1	1	1	4	6	6	2	4	5
Youkous	7	7	8	3	3	7	5	5	6	5	6	7	8	9	9	2	3	7	5	6	6	6	6	8
Sidi Okba	7	7	8	1	1	1	4	4	5	3	3	3	7	8	9	1	1	1	4	5	5	2	3	3
Sidi Idris	8	8	10	7	7	8	1	2	2	5	6	7	9	9	10	7	8	9	1	1	2	6	6	8
Milok	1	1	1	3	4	7	2	3	4	4	5	6	1	1	2	5	7	9	2	3	3	4	7	9
Daouia	7	9	10	5	6	7	6	7	8	4	4	6	8	9	10	7	7	7	7	8	9	3	5	5
Alma	1	1	1	1	1	2	5	6	7	5	6	8	1	1	2	2	2	3	6	6	7	6	6	8

Table 6 - Neutrosophic decision matrix (NNT) of spring waters

	EXPERT 01												EXPERT 02											
Water	C1			C2			C3			C4			C1			C2			C3			C4		
Besbassa	3	1	2	5	6	7	1	1	3	5	6	7	3	4	5	6	7	8	1	2	3	5	7	7
Messad	1	1	1	1	2	5	5	6	7	5	6	7	1	1	1	1	2	4	6	7	7	5	7	7
Tazliza	1	1	1	4	4	5	4	5	8	2	3	7	1	1	2	5	6	6	7	8	9	2	3	5
Ain bouglez	4	4	5	8	9	9	1	1	1	1	1	2	3	4	5	9	9	9	1	1	1	1	1	4
Sidi rached	1	1	1	1	2	2	5	6	7	5	6	7	1	1	1	1	2	2	8	9	9	5	7	7
Taya	1	1	1	5	6	8	2	3	5	1	1	2	1	1	2	5	6	7	4	5	5	1	1	4
Star	1	1	1	1	1	3	3	5	5	6	7	1	1	1	1	1	2	1	5	6	8	5	7	7
Ayris	6	7	9	3	4	5	6	7	5	5	6	7	6	7	8	5	6	8	5	9	8	5	7	7
Qniaa	2	3	3	1	1	3	5	6	7	5	6	7	3	3	3	1	1	2	6	7	8	5	7	7
Guerioune	1	1	1	2	2	2	7	8	8	5	6	7	1	1	1	2	2	6	7	8	9	5	7	7
Ovitale	1	1	2	2	2	2	7	7	8	5	6	7	2	2	5	2	3	5	7	8	9	5	7	7
Ichemoul	1	2	5	2	3	4	6	7	9	5	6	7	1	2	4	2	3	6	6	7	8	5	7	7
Arwa	1	1	1	1	1	3	3	3	4	5	6	7	1	1	1	1	1	2	5	6	8	5	7	7
Soumam	1	1	1	1	1	1	3	4	5	5	6	7	1	1	2	1	1	2	3	5	6	5	7	7
Hirouche	1	1	1	1	1	4	7	8	9	5	6	7	1	1	1	1	2	4	7	9	10	5	7	7
Ifren	6	7	9	2	3	5	7	7	8	5	6	7	6	7	8	5	6	8	7	8	9	5	7	7
Ariaf	5	6	7	1	2	2	3	5	6	2	3	7	6	6	7	1	2	2	3	4	5	2	3	5
Mont djurdjura	1	1	1	1	2	2	3	3	5	5	6	7	1	1	1	1	2	2	5	6	8	5	7	7
Fezguia	1	1	2	3	6	8	6	7	9	5	6	7	1	1	1	6	9	9	7	7	8	5	7	7
Ouwis	1	1	2	1	2	2	6	6	7	5	6	7	1	1	1	2	2	2	6	7	7	5	7	7
Nestlé	6	6	7	3	3	5	3	4	6	5	6	7	6	7	7	5	6	8	2	3	7	5	7	7

Aggregation of decision matrices

The individual matrices are combined into a single aggregated global matrix (Lan et al., 2023):

$$\tilde{D} = \left[(\tilde{B}_{ij}) \right]_{n \times m}$$

Where $\tilde{B}_{ij} = \left((d_1)_{ij}, (d_2)_{ij}, (d_3)_{ij}, (X_N)_{ij}, (Y_N)_{ij}, (Z_N)_{ij} \right)$ (21)

And

$$\begin{cases} (d_1)_{ij} = \min_{\alpha} (d_1)_{ij}^{\alpha} \\ (d_2)_{ij} = \sqrt[k]{\prod_{\alpha=1}^{k} (d_2)_{ij}^{\alpha}} \\ (d_3)_{ij} = \max_{\alpha} (d_3)_{ij}^{\alpha} \\ (X_N)_{ij} = \min_{\alpha} (X_N)_{ij}^{\alpha} \\ (Y_N)_{ij} = \max_{\alpha} (Y_N)_{ij}^{\alpha} \\ (Z_N)_{ij} = \max_{\alpha} (Z_N)_{ij}^{\alpha} \end{cases} \quad (22)$$

The Tables 7 and 8 present the result of this step for the two water sets (mineral and spring), with

$$(X_N)_{ij}^{\alpha} = 0.60; (Y_N)_{ij}^{\alpha} = 0.15 \text{ and } (Z_N)_{ij}^{\alpha} = 0.20$$

Table 7 - The aggregated matrix for mineral waters

	Nitrate			Hardness			Mineralization			Hydro-Chemical Nature		
Saida	1	1.000	2	1	1.41	3	3	4.472	6	5	6.928	10
Messerghine	5	6.481	7	1	2.00	5	7	9.000	10	5	6.928	10
Sfid	1	1.000	1	1	1.41	5	6	7.000	9	5	6.000	8
Mouzaia	1	1.000	1	1	1.00	1	4	4.000	5	2	3.464	5
Ifri	1	1.000	2	1	1.41	4	7	8.485	9	5	6.000	8
Guedila	6	6.481	7	1	2.00	3	2	3.000	3	2	3.000	3
Toudja	7	7.483	8	3	4.24	8	1	1.000	2	2	3.464	5
Mansourah	2	3.000	3	1	1.00	4	5	6.481	8	5	6.000	8
Lala khedidja	8	9.000	9	4	6.00	8	1	2.000	2	5	6.000	8
Batna	8	9.000	10	1	1.41	5	8	8.000	9	5	6.928	10
Texanna	8	9.000	10	7	7.48	8	1	1.000	1	5	6.000	8
Thevest	7	7.483	9	1	2.00	2	5	6.000	7	2	3.000	3
El Goléa	7	7.483	9	5	6.48	8	2	2.000	3	5	6.000	8
N'Gaous	7	7.483	9	1	1.00	1	4	6.000	7	2	3.464	5
Youkous	7	7.937	9	2	3.00	7	5	5.477	6	5	6.000	8
Sidi Okba	7	7.483	9	1	1.00	1	4	4.472	5	2	3.000	3
Sidi Idris	8	8.485	10	7	7.48	9	1	1.414	2	5	6.000	8
Milok	1	1.000	2	3	5.29	9	2	3.000	4	4	5.916	9
Daouia	7	9.000	10	5	6.48	7	6	7.483	9	3	4.472	6
Alma	1	1.000	2	1	1.41	3	5	6.000	7	5	6.000	8

Table 8 - The aggregated matrix for spring waters

Water	Nitrate			Hardness			Mineralization			Hydro-Chemical Nature		
Besbassa	3	4	5	5	6.481	8	1	1.414	3	5	6.481	7
Messad	1	1	1	1	2.000	5	5	6.481	7	5	6.481	7
Tazliza	1	1	2	4	4.899	6	4	6.325	9	2	3.000	7

Table 8 –(continued)

Water	Nitrate			Hardness			Mineralization			Hydro-Chemical Nature		
Ain bouglez	3	4	5	8	9.000	9	1	1.000	1	1	1.000	4
Sidi rached	1	1	1	1	2.000	2	5	7.348	9	5	6.481	7
Taya	1	1	2	5	6.000	8	2	3.873	5	1	1.000	4
Star	1	1	1	1	1.414	1	3	4.243	8	5	6.481	7
Ayris	6	7	9	3	4.899	8	5	7.937	8	5	6.481	7
Qniaa	2	3	3	1	1.000	3	5	6.481	8	5	6.481	7
Guerioune	1	1	1	2	2.000	6	7	8.000	9	5	6.481	7
Ovitale	1	1.414	5	2	2.449	5	7	7.483	9	5	6.481	7
Ichemoul	1	2	5	2	3.000	6	6	7.000	9	5	6.481	7
Arwa	1	1	1	1	1.000	3	3	4.243	8	5	6.481	7
Soumam	1	1	2	1	1.000	2	3	4.472	6	5	6.481	7
Hirouche	1	1	1	1	1.414	4	7	8.485	10	5	6.481	7
Ifren	6	7	9	2	4.243	8	7	7.483	9	5	6.481	7
Ariaf	5	6	7	1	2.000	2	3	4.472	6	2	3.000	7
Mont djurdjura	1	1	1	1	2.000	2	3	4.243	8	5	6.481	7
Fezguia	1	1	2	3	7.348	9	6	7.000	9	5	6.481	7
Ouwis	1	1	2	1	2.000	2	6	6.481	7	5	6.481	7
Nestlé	6	6.481	7	3	4.243	8	2	3.464	7	5	6.481	7

De-neutrosophication of the aggregated matrix

The final step consists of converting the aggregated NNT matrix into a final decision matrix $\widetilde{D}$ with unique scalar values, obtained by formula (11). Table 9 presents the consolidated and precise values resulting from this step, constituting the final decision matrix.

Table 9 - De-neutrosophic valued decision matrix for mineral and spring water

Mineral water	C1	C2	C3	C4	Spring water	C1	C2	C3	C4
Saida	1.400	1.912	5.024	8.080	Besbassa	4.480	7.269	1.912	6.989
Messerghine	6.989	2.800	9.800	8.080	Messad	1.120	2.800	6.989	6.989
SFID	1.120	2.472	8.120	7.000	Tazliza	1.400	5.543	7.182	4.200
Mouzaia	1.120	1.120	4.760	3.900	Ain bouglez	4.480	9.800	1.120	1.960
Ifri	1.400	2.192	9.232	7.000	Sidi rached	1.120	1.960	8.035	6.989
Guedila	7.269	2.240	3.080	3.080	Taya	1.400	7.000	4.129	1.960
Toudja	8.391	5.456	1.400	3.900	Star	1.120	1.352	5.456	6.989
Mansourah	3.080	1.960	7.269	7.000	Ayris	8.120	5.823	8.085	6.989
Lala khedidja	9.800	6.720	1.960	7.000	Qniaa	3.080	1.680	7.269	6.989
Batna	10.080	2.472	9.240	8.080	Guerioune	1.120	3.360	8.960	6.989
Texanna	10.080	8.391	1.120	7.000	Ovitale	2.472	3.332	8.671	6.989
Thevest	8.671	1.960	6.720	3.080	Ichemoul	2.800	3.920	8.120	6.989
El Goléa	8.671	7.269	2.520	7.000	Arwa	1.120	1.680	5.456	6.989
N'Gaous	8.671	1.120	6.440	3.900	Soumam	1.400	1.400	5.024	6.989
Youkous	8.925	4.200	6.147	7.000	Hirouche	1.120	2.192	9.512	6.989
Sidi Okba	8.671	1.120	5.024	3.080	Ifren	8.120	5.176	8.671	6.989
Sidi Idris	9.792	8.671	1.632	7.000	Ariaf	6.720	1.960	5.024	4.200
Milok	1.400	6.323	3.360	6.953	Mont Djurdjura	1.120	1.960	5.456	6.989

Table 9 –(continued)

Mineral water	C1	C2	C3	C4	Spring water	C1	C2	C3	C4
Daouia	9.800	6.989	8.391	5.024	Fezguia	1.400	7.475	8.120	6.989
Alma	1.400	1.912	6.720	7.000	Ouwis	1.400	1.960	7.269	6.989
					Nestlé	7.269	5.456	4.460	6.989

Water classification

Based on the weights shown in Figure 2 and the scores from the final decision matrix (Table 9), the CODAS method is applied to classify mineral waters and spring waters. The results obtained are presented in the table below.

Table 10 - Ranking of mineral and spring waters based on the CODAS method

Mineral waters				Spring waters			
Water	Rank	Water	Rank	Water	Rank	Water	Rank
Daouia	1	Messerghine	11	Taya	1	Qniaa	11
Mansourah	2	Lala khedidja	12	Ariaf	2	Ayris	12
Youkous	3	Guedila	13	Arwa	3	Fezguia	13
Alma	4	Batna	14	Sidi rached	4	Nestlé	14
N'Gaous	5	Toudja	15	Hirouche	5	Ovitale	15
El Goléa	6	Thevest	16	Soumam	6	Messad	16
Texanna	7	SFID	17	Ouwis	7	Ain bouglez	17
Sidi Idris	8	Sidi Okba	18	Besbassa	8	Mont Djurdjura	18
Ifri	9	Saida	19	Guerioune	9	Star	19
Mouzaia	10	Milok	20	Ichemoul	10	Ifren	20
						Tazliza	21

Sensitivity analysis

A sensitivity analysis was carried out to evaluate the robustness of the CODAS ranking results under variations in the criteria weights. Three alternative weighting scenarios (Case 1, Case 2, and Case 3) were compared with the main model to examine the impact of these changes on the final ranking of alternatives (Table12).

Table 11 - Criteria weights for the different scenarios of the sensitivity analysis

Scenario	W1(%)	W2(%)	W3(%)	W4(%)	Key observations on weighting
Main Model	40	22	22	16	W1 is the dominant criterion. W2 and W3 have the same weight.
Case 1	35	23.67	23.67	17.66	Decrease in W1, slight increase in the other criteria.
Case 2	41.7	23.65	23.65	11	Increase in W1, strong reduction in W4. W2 and W3 increase slightly.
Case 3	45.34	27.33	27.33	0	W1, W2, and W3 are strongly increased, W4 is completely eliminated (zero weight).

As shown in Table 11, each scenario applies a different distribution of weights among the four criteria.

Table 12 - Comparison of mineral water rankings obtained using the main model and different weighting scenarios

Mineral water	Main Model	Case 01	Case 02	Case 03
Daouia	1	1	1	1
Mansourah	2	15	2	2
Youkous	3	3	3	3
Alma	4	4	4	4
N'Gaous	5	6	5	5
El Goléa	6	5	6	6
Texanna	7	7	7	7
Sidi Idris	8	8	8	8
Ifri	9	9	9	9
Mouzaia	10	10	10	10
Messerghine	11	17	11	11
Lala khedidja	12	12	12	12
Guedila	13	13	13	13
Batna	14	14	14	14
Toudja	15	2	15	15
Thevest	16	16	16	16
Sfid	17	11	17	17
Sidi Okba	18	18	18	18
Saida	19	19	19	19
Milok	20	20	20	20

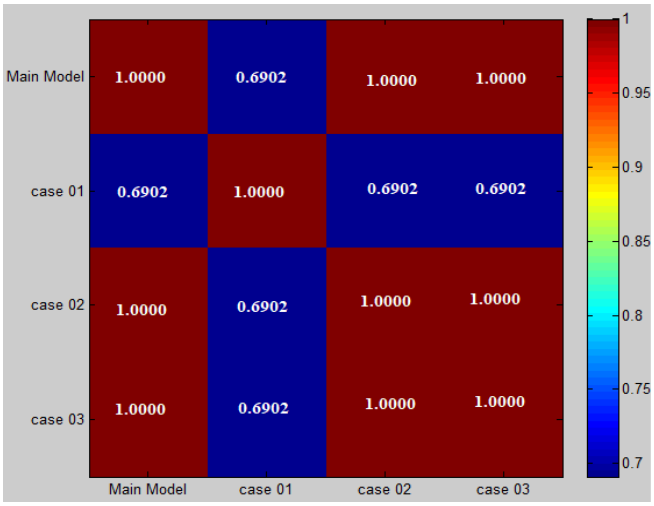


Figure 3 - Correlation matrix between the main model and different weighting scenarios

The correlation matrix in Figure 3 illustrates the level of agreement between the main model and the tested scenarios. Correlation values close to 1 indicate a strong consistency, confirming that the CODAS method provides stable and reliable results despite variations in weighting.

Comparative analysis

The comparative analysis in Table 13 demonstrates the consistency of rankings produced by the CODAS method relative to other multi-criteria decision-making (MCDM) approaches, including WASPAS, VIKOR, COPRAS, SAW, and MOORA. CODAS generally yields a coherent ranking pattern, particularly for top-performing brands such as Daouia, Alma, Youkous, and El Goléa. Some variation is observed for mid-ranked alternatives (Ifri, Mansourah, Toudja, and Mouzaïa), reflecting differences in criteria weighting and distance computation.

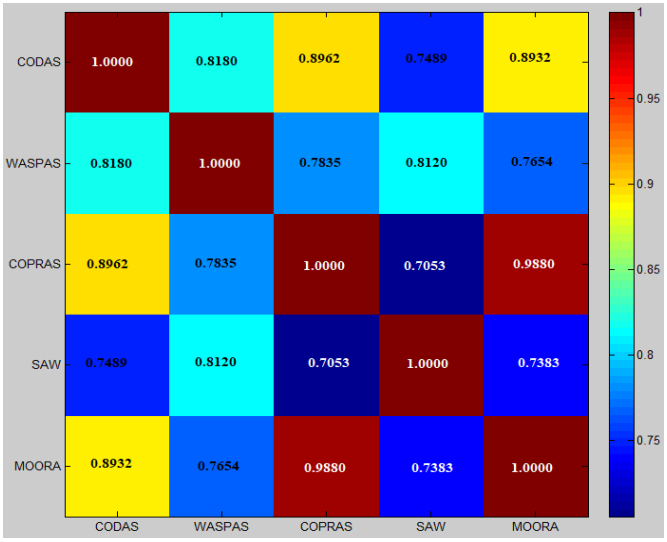


Figure 4 - Spearman correlation coefficient matrix for MCDM methods

The Spearman correlation matrix (Figure 4) indicates a strong positive correlation between CODAS and other MCDM methods, confirming the method's reliability and robustness. By effectively combining Euclidean and Taxicab distances, CODAS provides a discriminative ranking that clearly distinguishes closely ranked alternatives.

Table 13 - Comparison of CODAS with other MCDM methods

Mineral Water	CODAS	WASPAS	COPRAS	SAW	MOORA	Mineral Water	CODAS	WASPAS	COPRAS	SAW	MOORA
Daouia	1	1	1	1	1	Messerghine	11	10	10	10	10
Mansourah	2	11	2	13	2	Lala khedidja	12	12	12	12	12
Youkous	3	5	5	5	5	Guedila	13	9	13	15	15
Alma	4	4	4	4	4	Batna	14	14	7	14	7
N'Gaous	5	8	8	8	6	Toudja	15	13	15	2	13
El Goléa	6	6	6	6	8	Thevest	16	16	16	16	16
Texanna	7	7	14	7	14	SFID	17	15	17	17	17
Sidi Idris	8	3	3	3	3	Sidi Okba	18	18	18	18	18
Ifri	9	2	9	9	9	Saida	19	19	19	19	19
Mouzaia	10	17	11	11	11	Milok	20	20	20	20	20

Conclusion and perspectives

This study presents a hybrid DIBR II–CODAS approach integrating triangular neutrosophic numbers to classify bottled waters in Algeria. Water quality criteria - nitrate content, hardness, mineralization, and hydrochemical characteristics - were weighted based on expert opinions using the Bonferroni operator, and CODAS was applied to the de-neutrosophicated decision matrix to obtain proximity coefficients and final rankings. The top mineral waters were Daouia, Mansourah, Youkous, Alma, and N'Gaous, while the top spring waters were Taya, Ariaf, Arwa, Sidi Rached, and Hirouche.

Sensitivity analysis confirmed the model's robustness, with minor ranking changes, the nitrate criterion being the most influential. High correlation with other multi-criteria methods and the combination of Euclidean and Taxicab distances demonstrate that CODAS provides reliable and discriminative rankings.

This model provides a reliable decision-support tool for hydrochemical classification of bottled waters in Algeria. Additionally, this research creates new avenues for further studies, such as expanding the water sample size, incorporating additional criteria (like trace elements and stable isotopes), and monitoring water quality evolution over time. Ultimately, it forms a scientific basis for recommendations targeting industry stakeholders, regulatory bodies, and consumers aimed at sustainable and transparent water management.

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Višekriterijumska analiza primenjena na hidrohemijsku klasifikaciju flaširanih voda na tržištu u Alžiru

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OBLAST: nauka o odlučivanju, hidrologija
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Mineralne i izvorske vode imaju ključnu ulogu u svakodnevnoj ishrani zbog svog ukusa i zdravstvenih benefita. Tržište flaširane vode u Alžiru brzo raste, ali i dalje ne postoji dovoljno preciznih i objektivnih sistema za klasifikaciju voda na osnovu organoleptičkih svojstava i bezbednosti. Cilj ove studije je da razvije pouzdan numerički model za hidrohemijsku klasifikaciju flaširanih voda na tržištu u Alžiru.

Metode: U radu se koristi hibridni pristup višekriterijumskog odlučivanja koji integriše metodu DIBR II za određivanje težina kriterijuma na osnovu mišljenja eksperata i Bonferonijevu sredinu za agregaciju tih mišljenja. Radi efikasnog upravljanja neizvesnošću i nepreciznošću podataka, koriste se trougaoni neutrosofični brojevi (eng. TNN). Nakon toga, primenjuje se metoda CODAS (eng. COmbinative Distance-based ASsessment) za rangiranje brendova flaširane vode. Evaluacija obuhvata četiri ključna kriterijuma kvaliteta: koncentraciju nitrata, tvrdoću, ukupnu mineralizaciju i hidrohemijsku prirodu. Nakon konstruisanja i agregacije neutrosofičnih matrica odlučivanja i sprovođenja deneutrosofikacije, metodom CODAS je izračunat koeficijent blizine za svaki brend, što je dovelo do konačnog rangiranja.

Rezultati: U radu je identifikovano pet najboljih brendova mineralnih voda (Daouia, Mansourah, Youkous, Alma i N'Gaous) i izvorskih voda (Taya, Ariaf, Arwa, Sidi Rached i Hirouche). Analiza osetljivosti potvrdila je robusnost rangiranja, čime je validirana pouzdanost modela, i pokazala je da je sadržaj nitrata najuticajniji kriterijum, naglašavajući njegovu ključnu ulogu u proceni kvaliteta vode. Komparativna analiza je takođe pokazala da metoda CODAS daje konzistentna i pouzdana rangiranja u poređenju sa drugim višekriterijumskim metodama, uz dobru diskriminaciju između blisko rangiranih alternativa.

Zaključak: U studiji je razvijen inovativan i robustan numerički model koji kombinuje metode DIBR II i CODAS u neutrosofičkom okviru i pruža pouzdanu hidrohemijsku klasifikaciju flaširanih mineralnih i izvorskih voda u Alžiru. Model obuhvata težine zasnovane na mišljenju eksperata i uzima u obzir neizvesnost podataka kako bi generisao jasan i dosledan redosled brendova. Analiza osetljivosti potvrdila je stabilnost rangiranja, posebno naglašavajući dominaciju kriterijuma nitrata, čime se potvrđuje vrednost modela kao instrumenta za podršku odlučivanju različitim zainteresovanim stranama u ovom sektoru.

Ključne reči: višekriterijumska klasifikacija, mineralna voda, izvorska voda, DIBR II, CODAS, neutrosofični brojevi.

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