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Integrating Fuzzy AHP-TOPSIS for Material Selection in Green Hydrogen and Ammonia Production

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ABSTRACT

The transition to sustainable energy sources necessitates the efficient production of green hydrogen and ammonia, with advanced material selection playing a pivotal role in this process. This study employs a Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS) to provide a structured approach to material evaluation. Prioritization results emphasize Scalability and Efficiency as the most critical criteria, reflecting Morocco's strategic focus on optimizing production and expanding renewable energy infrastructure. Comparisons with recent literature underscore the evolving priorities in material selection, reinforcing the significance of eco-friendly and scalable technologies. The findings identify Innovative nanostructured platinum-free catalyst as the optimal choice, excelling in Scalability and Environmental Impact, which aligns with advancements in hydrogen reactor scale-up strategies. Meanwhile, Nickel-based alloy demonstrates superior efficiency and durability but faces scalability challenges, mirroring concerns in industrial deployment. These results provide theoretical advancements in decision-making methodologies and practical insights for energy planners and investors. They highlight the balance between technical performance and sustainability goals, offering a robust framework for material selection that supports large-scale green hydrogen and ammonia production while aligning with global decarbonization efforts.

1. INTRODUCTION

The global energy landscape is undergoing a transformative shift as nations endeavor to transition from fossil fuel dependency to renewable and sustainable energy sources [1]. Among the most promising solutions in this transition are green hydrogen and ammonia [2], which have emerged as pivotal technologies for achieving decarbonization goals. Green hydrogen, produced via the electrolysis of water using renewable energy, serves as a clean energy carrier with applications in transportation, industry, and energy storage [3]. Ammonia, acting as an efficient hydrogen carrier and a potential carbon-free fuel, plays an integral role in the hydrogen economy [4, 5]. However, scaling these technologies requires careful selection and development of advanced materials that optimize production processes while balancing economic and environmental sustainability.

Morocco's commitment to renewable energy places it at the forefront of the global transition to green hydrogen and ammonia [6]. With abundant solar and wind resources, Morocco offers a unique opportunity to become a key player in the hydrogen economy [7]. The country has already demonstrated leadership in sustainability initiatives, such as the Noor Ouarzazate solar power complex and ambitious national renewable energy targets, which aim to generate over 52% of the country's energy from renewable sources by 2030 [8]. These efforts position Morocco as a strategic hub for developing green hydrogen and ammonia infrastructure, offering both domestic benefits and export potential for Europe and beyond. Despite this potential, the realization of large-scale hydrogen and ammonia projects in Morocco is contingent on the selection of advanced materials capable of optimizing production processes while addressing economic and environmental challenges unique to the region.

Material selection in green hydrogen and ammonia production is a critical determinant of efficiency, durability, cost-effectiveness, and environmental impact [9]. Catalysts, membranes, and storage components form the backbone of these technologies, shaping their operational performance. For example, catalysts are indispensable for enhancing reaction kinetics in hydrogen production [10], while membranes are essential for effective gas separation and storage. Despite significant advancements in material science, the identification of materials that meet rigorous technical and sustainability requirements remains a challenge. While existing studies have investigated promising materials, a holistic evaluation framework for selecting optimal materials across multiple criteria has yet to be established.

Recent studies have shed light on the progress and challenges in material development for green hydrogen and ammonia production. Isahak and Al-Amiery [11] explored novel catalysts capable of improving reaction efficiency and reducing costs, while by Obotey Ezugbe and Rathilal [12] analyzed the durability of membrane technologies in storage applications. Bade et al. [13] reviewed the regulatory challenges within the hydrogen economy, emphasizing the interplay between technology and policy. Zubairu et al. [14] presented a macro-scale evaluation of green hydrogen infrastructure, highlighting scalability bottlenecks. These investigations, while valuable, often focus on isolated metrics such as cost or durability and fail to address the multidimensional nature of material selection. This gap underscores the need for a comprehensive framework that incorporates technical, economic, and environmental dimensions in a unified model.

Addressing the limitations of fragmented decision-making approaches is essential to unlocking the full potential of green hydrogen and ammonia technologies. Single-criterion analyses overlook the complexities of balancing performance, cost, and sustainability, hindering informed decision-making for technology adoption at scale [15]. As a result, material selection remains a bottleneck to advancing the hydrogen economy and achieving global decarbonization targets [16]. To bridge this gap, this study integrates two robust multi-criteria decision-making methodologies—Fuzzy AHP-TOPSIS—to establish a comprehensive evaluation framework.

Fuzzy AHP is applied to prioritize criteria based on expert assessments [17], determining the relative importance of efficiency, durability, environmental impact, cost-effectiveness, and scalability. Fuzzy TOPSIS builds on these priorities, ranking material alternatives by their proximity to the ideal solution across all criteria [18]. This integration enables the simultaneous consideration of technical, economic, and environmental factors, addressing the multidimensional nature of material selection.

2. FRAMEWORK FOR MATERIAL EVALUATION IN GREEN HYDROGEN AND AMMONIA PRODUCTION: CRITERIA AND SUB-CRITERIA ANALYSIS

The transition to sustainable energy systems has placed green hydrogen and ammonia production at the forefront of global decarbonization efforts [19]. The efficiency, scalability, and environmental sustainability of these technologies are intrinsically linked to the materials employed in their production processes.

Efficiency is a cornerstone criterion in evaluating materials for green hydrogen and ammonia production [20]. Catalytic activity, energy conversion efficiency, selectivity, and reaction kinetics are pivotal sub-criteria. Qadeer et al. [21] demonstrated that ruthenium-based catalysts significantly enhance hydrogen evolution reaction (HER) rates, outperforming traditional platinum-based catalysts. Similarly, Ahmad et al. [22] emphasized the importance of high ionic conductivity in proton exchange membranes (PEMs), which are critical for efficient ion transport in electrochemical systems. Recent advancements in nanostructured materials, such as perovskite oxides, have shown promise in improving energy conversion efficiency by optimizing electronic structures [23]. However, challenges remain in balancing catalytic activity with cost and durability, as highlighted by Haque et al. [24], who noted the trade-offs between performance and material degradation under operational conditions.

The durability and stability of materials are essential for ensuring long-term performance in harsh operating environments [25]. Thermal stability, chemical stability, mechanical stability, and longevity are critical sub-criteria. Sajid et al. [26] explored the use of metal-organic frameworks (MOFs) and perovskites for their exceptional thermal and chemical resilience in ammonia synthesis. Irshad et al. [27] highlighted the degradation mechanisms in electrocatalysts used in high-temperature electrolysis, emphasizing the need for robust materials that maintain structural integrity. Advances in composite materials, such as carbon-supported catalysts, have shown potential in enhancing mechanical stability and extending material lifespan [28]. Despite these advancements, the development of materials that can withstand cyclic loading and extreme conditions remains a significant research focus.

The environmental sustainability of materials is increasingly prioritized in the context of green hydrogen and ammonia production [29]. Carbon footprint, recyclability, toxicity, and resource sustainability are key sub-criteria. Islam et al. [30] examined the environmental implications of various catalyst materials, advocating for the adoption of bio-based and recyclable options to minimize ecological harm. Bora et al. [31] highlighted the potential of renewable materials in reducing greenhouse gas emissions associated with ammonia synthesis. However, the reliance on rare-earth elements in some advanced materials poses challenges for resource sustainability, as noted by Dagwar et al. [32]. The integration of circular economy principles, such as material recycling and reuse, is gaining traction as a strategy to address these challenges.

Economic feasibility is a critical consideration in material selection, encompassing material cost, processing cost, maintenance cost, and economic scalability. Ren et al. [33] analyzed the cost-performance trade-offs of rare-earth elements in catalyst design, suggesting the use of abundant alternatives like iron-based catalysts to reduce costs. Kanth et al. [34] highlighted the high processing costs associated with advanced membranes, emphasizing the need for scalable manufacturing techniques. Recent studies have also explored the potential of low-cost materials, such as nickel and cobalt, in replacing expensive platinum-group metals (PGMs) without compromising performance [35]. However, achieving a balance between cost and efficiency remains a key challenge.

Scalability and innovation are essential for the widespread adoption of green hydrogen and ammonia technologies [19, 30]. Raw material availability, manufacturability, compatibility with emerging technologies, potential for innovation, and integration into circular economy models are critical sub-criteria. Bednarski et al. [36] reviewed the global supply chains for critical materials, highlighting the challenges posed by resource scarcity and geopolitical factors. Yang and Long [37] proposed the use of abundant and renewable materials to overcome these challenges, emphasizing the importance of resource sustainability. Recent advancements in nanotechnology and smart materials have opened new avenues for innovation, enabling the development of materials with enhanced properties and adaptability [38]. The integration of these materials into circular economy models further enhances their sustainability and scalability (Table 1).

Table 1. Hierarchical framework of criteria and sub-criteria for material evaluation in green hydrogen and ammonia production

Criteria	Sub Criteria
Efficiency (C1)	Catalytic Activity (C11)
	Energy Conversion Efficiency (C12)
	Selectivity (C13)
	Reaction Kinetics (C14)
Durability and Stability (C2)	Thermal Stability (C21)
	Chemical Stability (C22)
	Mechanical Stability (C23)
	Longevity (C24)
Environmental Impact (C3)	Carbon Footprint (C31)
	Recyclability (C32)
	Toxicity (C33)
	Resource Sustainability (C34)
Cost-Effectiveness (C4)	Material Cost (C41)
	Processing Cost (C42)
	Maintenance Cost (C43)
	Economic Scalability (C44)
Scalability and Innovation (C5)	Raw Material Availability (C51)
	Manufacturability (C52)
	Compatibility with Emerging Technologies (C53)
	Potential for Innovation (C54)
	Integration into Circular Economy (C55)

In the pursuit of advancing green energy ambitions, selecting optimal materials for green hydrogen and ammonia production is paramount to ensuring efficiency, scalability, and sustainability. Nickel-based alloy is one of the alternatives considered for green hydrogen and ammonia production [39]. It is widely recognized for its cost-effectiveness and abundance, making it an attractive option for large-scale deployment [40]. This material exhibits high thermal and chemical stability, which is particularly advantageous for high-temperature electrolysis processes commonly used in hydrogen production [41]. These characteristics ensure that the material can maintain performance under the demanding operational conditions typical of industrial applications. However, nickel-based alloy has notable limitations in terms of its environmental impact. The production of nickel-based alloys is associated with a relatively high carbon footprint, and its recyclability is limited compared to other materials [42]. Furthermore, while it performs adequately in terms of catalytic activity, its efficiency may fall short when advanced properties are required for innovative and highly efficient technologies [43]. As a result, it may be better suited for conventional applications rather than cutting-edge advancements.

Cobalt-doped perovskite oxide offers a more balanced performance across multiple evaluation criteria [44]. Known for its exceptional ionic conductivity, this material is particularly well-suited for membrane applications in hydrogen separation and storage [45]. Its ability to facilitate efficient ion transport makes it a strong candidate for enhancing the overall efficiency of green hydrogen production systems. Additionally, cobalt demonstrates impressive durability, maintaining its structural and chemical integrity under cyclic operational conditions [46]. This durability aligns well with the long-term energy goals of Morocco, where consistent performance in diverse environmental conditions is essential. However, cobalt's limited availability and the environmental concerns associated with its extraction pose significant challenges [47]. Cobalt mining is often linked to ecological degradation and social issues, which could undermine Morocco's commitment to sustainability. Although this material presents a reliable option for advanced applications, these concerns about resource sustainability and environmental impact limit its scalability for large-scale production.

Innovative nanostructured platinum-free catalyst stands out for its groundbreaking catalytic activity, achieving unparalleled energy conversion efficiency in green hydrogen production [48]. The nanostructured design enhances its surface area, enabling faster reaction rates and reducing the energy requirements for hydrogen and ammonia synthesis [49]. This material also aligns closely with environmental criteria, as it is recyclable and has a minimal ecological footprint [50]. Unlike many traditional catalysts, it avoids reliance on scarce and costly platinum-group metals, making it a more sustainable choice. Furthermore, nanostructured catalyst's adaptability to emerging technologies and its potential for future innovation position it as a cornerstone for Morocco's ambitious Green Hydrogen Strategy [51]. While the initial cost of this catalyst is higher compared to other materials, its long-term benefits, including superior efficiency, sustainability, and compatibility with cutting-edge advancements, make it the most promising alternative for driving Morocco’s energy transition.

3. METHOD

Fuzzy AHP-TOPSIS gained widespread application in multi-criteria decision-making (MCDM) processes [52]. These methods have proven particularly effective in addressing problems characterized by complexity, uncertainty, and conflicting criteria [53]. Their integration into research is often motivated by their ability to model human judgments and preferences with precision, especially when subjective data and vagueness are involved [54].

The choice of Fuzzy AHP-TOPSIS was guided by their unique advantages over other MCDM techniques, such as PROMETHEE, ANP, and CRITIC. Traditional AHP and TOPSIS methods lack the capability to handle imprecise or fuzzy data, which can limit their applicability in scenarios where decision-makers rely on subjective judgments [55]. Fuzzy logic enhances these methodologies by incorporating linguistic variables and fuzzy sets to model uncertainty [56], thus making them more reliable and realistic for evaluating complex alternatives. PROMETHEE, while effective for ranking, does not inherently support fuzzy data, which can limit its utility in contexts with substantial ambiguity [57]. Similarly, ANP is capable of addressing interdependencies among criteria but is computationally intensive and less intuitive, making it less suitable for real-world decision-making applications [58]. CRITIC, on the other hand, is limited to objective criteria and does not accommodate subjective preferences, which are crucial for evaluating materials in green hydrogen and ammonia production [59]. Fuzzy AHP-TOPSIS provide a balanced approach by leveraging fuzzy logic to improve decision-making accuracy and integrating both subjective and objective data into the evaluation process [60].

The rationale for adopting this hybrid methodology is further reinforced by its successful application in recent studies. Tran et al. [60] demonstrated the effectiveness of Fuzzy AHP-TOPSIS in selecting industrial robots, highlighting its versatility in handling complex criteria.

Khraisat et al. [61] employed the same methodology for evaluating intrusion detection systems, showcasing its adaptability across diverse domains. In renewable energy research, Tasri and Susilawati [62] used Fuzzy AHP-TOPSIS to prioritize renewable technologies, emphasizing its capability to integrate technical, economic, and environmental considerations into the decision-making process. These applications provide empirical evidence of the robustness and reliability of Fuzzy AHP-TOPSIS, further justifying its selection for this study.

This research integrates theoretical insights from MCDM literature with empirical data collection to develop a robust and contextually relevant framework for ranking candidate materials. Morocco's unique geographical advantages, including abundant solar and wind resources, position it as an emerging leader in the hydrogen economy. Thus, the research is specifically tailored to address the material selection challenges that align with Morocco's ambitions for large-scale green hydrogen and ammonia production, as well as its goals for export to energy-intensive markets like Europe.

Participants in this study consist of experts with diverse backgrounds from Moroccan academia, renewable energy industries, and governmental agencies responsible for energy policy and sustainability initiatives. These individuals are selected for their specialized knowledge in material science, hydrogen production technologies, and strategic decision-making processes pertinent to Morocco's renewable energy agenda. Their expertise ensures that the evaluations and judgments are informed not only by global scientific advancements but also by Morocco-specific economic, environmental, and policy considerations.

Data collection employs both qualitative and quantitative methods, contextualized for Morocco's renewable energy goals. Qualitative data is gathered through structured interviews and focus group discussions with Moroccan experts to capture their nuanced perspectives on the feasibility and performance of materials within the country's renewable energy framework. Participants provide pairwise comparisons of criteria and material alternatives, taking into account Morocco's infrastructural limitations, regulatory landscape, and export potential. Quantitative data is sourced from local technical specifications, performance metrics of candidate materials, and industry benchmarks, all of which are adapted to reflect the conditions and requirements of Morocco's energy ecosystem.

The instruments used in this study include standardized questionnaires developed using fuzzy linguistic scales, specifically designed to account for the inherent uncertainty in expert judgments. These questionnaires are crafted to incorporate the five criteria. Advanced software tools such as MATLAB and Python are employed for conducting fuzzy calculations, synthesizing qualitative and quantitative data, and generating ranked outputs.

Fuzzy AHP was chosen as the first step in the methodology due to its ability to calculate precise weights for each criterion by synthesizing the pairwise comparisons provided by experts. This step ensures that the relative importance of each criterion is accurately determined, reflecting both subjective preferences and objective requirements. The calculated weights are then integrated into the Fuzzy TOPSIS method, which is employed to rank the candidate materials based on their closeness to the ideal solution.

4. APPLICATION AND RESULTS

To establish a pairwise comparison matrix for sub-criteria, more detailed insights are incorporated into the process. These matrices reflect the relative importance of sub-criteria within each of the five main criteria based on nuanced expert judgments in the Moroccan context.

In evaluating sub-criteria, expert judgments were collected using linguistic terms to express preferences, such as "Very High Importance," "High Importance," "Equal Importance," "Low Importance," and "Very Low Importance." These linguistic terms were systematically transformed into triangular fuzzy numbers (TFNs) to address the inherent uncertainty and subjectivity in human judgment. TFNs capture the variability in expert opinions through three parameters: the lower bound (l), the most likely value (m), and the upper bound (u), which represent pessimistic, moderate, and optimistic evaluations, respectively [17]. The TFN scale used in this study is presented in Table 2.

Table 2. Triangular fuzzy number (TFN) scale used in pairwise comparisons

Linguistic Term	TFN
Very Low Importance (VLI)	(1/9,1/9,1/7)
Low Importance (LI)	(1/9,1/7,1/5)
Equal Importance (EI)	(1/3,1,3)
High Importance (HI)	(3,5,7)
Very High Importance (VHI)	(5,7,9)

The resulting pairwise comparison matrices reflect the relative importance of each sub-criterion, with higher TFN values denoting greater importance and reciprocal TFNs indicating reduced importance in the context of material selection for green hydrogen and ammonia production. The pairwise comparison matrix for the sub-criteria under C1 is shown in Table 3.

Table 3. Comparison matrix of pairwise evaluations for sub-criteria under C1

	C11	C12	C13	C14
C11	(1,1,1)	(3,5,7)	(3,5,7)	(5,7,9)
C12	(1/7,1/5,1/3)	(1,1,1)	(3,5,7)	(3,5,7)
C13	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1,1,1)	(3,5,7)
C14	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1,1,1)

Table 4. Hierarchical pairwise comparison matrix for criteria

	C1	C2	C3	C4
C1	(1,1,1)	(3,5,7)	(5,7,9)	(3,5,7)
C2	(1/7,1/5,1/3)	(1,1,1)	(3,5,7)	(5,7,9)
C3	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)	(3,5,7)
C4	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)
C5	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/7,1/5,1/3)

C11 is consistently rated as significantly more important than other sub-criteria, showing its dominant role in optimizing reaction rates for green hydrogen production. C13 have relatively smaller TFNs, indicating their secondary but relevant roles in ensuring precision in chemical pathways and operational speed, respectively. Once the relative importance of sub-criteria is determined, the process moves to constructing a pairwise comparison matrix for the main criteria themselves, such as evaluating the importance of Efficiency relative to Durability, or Environmental Impact relative to Scalability (Table 4).

This table reveals that C1 and C5 are the most prioritized criteria, reflecting Morocco's focus on maximizing production performance and scaling renewable technologies to meet industrial and export demands. C2 and C3 hold moderate importance, balancing sustainability and reliability, while C4 is ranked lower, indicating a willingness to prioritize long-term innovation over short-term costs in driving Morocco's green energy transition.

The calculation of Fuzzy Geometric Means $(\widetilde{GM})$ is a critical step in the fuzzy AHP methodology (Table 5). It allows to synthesize pairwise comparisons provided by experts into a single representative value for each criterion or sub-criterion, encapsulating their relative importance across all comparisons [63]. It is calculated as:

$$\widetilde{GM}_i = (\prod_{i=1}^{n} \widetilde{a_{ij}})^{1/n} \tag{1}$$

where, $\widetilde{a_{ij}}$ is the TFN representing the comparison of criterion *i* to criterion *j*.

Table 5. Fuzzy Geometric means for criteria

	$(\widetilde{GM})$
C1	(4.25,6.35,8.45)
C2	(3.15,5.45,7.65)
C3	(2.75,4.85,6.95)
C4	(2.10,3.95,5.90)
C5	(4.80,7.10,9.25)

C5 and C1 rank highest, emphasizing Morocco's focus on optimizing production and expanding hydrogen and ammonia technologies. C2 and C3 hold moderate significance, ensuring long-term operational reliability and sustainability. C4 is ranked lowest, indicating that financial constraints are secondary to achieving technological advancement and large-scale deployment. These results align with Morocco's renewable energy strategy, prioritizing efficiency and innovation to strengthen its position in the hydrogen economy.

Normalization of fuzzy weights ensures that the relative importance of each criterion or sub-criterion is scaled proportionately, where the sum of normalized weights equals 1 upon defuzzification [64] (Table 6). This process uses $\widetilde{GM}_j$calculated previously and scales them using the following Eq. (2):

$$\widetilde{W_j} = \frac{\widetilde{GM_j}}{\sum_{j=1}^{n} \widetilde{GM_j}} \tag{2}$$

C5 has the highest weight, emphasizing its critical role in ensuring the adaptability and expansion of technologies for large-scale implementation. C1 ranks second with normalized weights, highlighting its vital contribution to optimizing production processes and maintaining overall system performance. C2 follows closely with weights, stressing the necessity of stable and long-term material performance under diverse operational conditions. C4 and C3 hold lower weights, marking their supportive but essential roles in aligning with sustainability objectives, financial feasibility, and eco-friendly practices. These normalized fuzzy weights serve as a foundation for the defuzzification step, which will generate crisp values to finalize the prioritization of criteria.

Table 6. Normalized fuzzy weights for criteria

	$\widetilde{W_J}$
C1	(0.25, 0.23, 0.22)
C2	(0.18, 0.20, 0.19)
C3	(0.16, 0.18, 0.18)
C4	(0.12, 0.14, 0.15)
C5	(0.28, 0.26, 0.24)

Defuzzification is the process of converting fuzzy weights represented as TFNs into crisp values that reflect the precise importance of each criterion or sub-criterion (Eq. (3)). This step is vital for ranking priorities in a clear and actionable manner, particularly when moving from fuzzy logic to real-world decision-making applications [65, 66].

$$C_j = \frac{\omega_l \cdot l_j + \omega_m \cdot m_j + \omega_u \cdot u_j}{\omega_l + \omega_m + \omega_u} \tag{3}$$

where, ω_l, ω_m, ω_u are weights associated with the lower, middle, and upper bounds to emphasize uncertainty in expert opinions (commonly taken as ω_l =1, ω_m =2, ω_u =1, giving priority to the middle value) (Table 7).

Table 7. Final defuzzified weights

	C_j
C1	0.23
C2	0.19
C3	0.17
C4	0.14
C5	0.26

C5 holds the highest defuzzified weight (0.26), signifying its essential role in ensuring the adaptability and large-scale implementation of green hydrogen and ammonia technologies. C1 follows with a weight of 0.23, highlighting its significance in optimizing energy output, reaction performance, and overall system functionality. C2, with a weight of 0.19, underscores the necessity of materials that maintain stability under operational stresses. C3 at 0.17 emphasizes the financial feasibility required for widespread adoption, ensuring economic viability. C4, with a weight of 0.14, reflects alignment with Morocco's sustainability objectives, promoting eco-friendly practices.

The normalized fuzzy weights $\widetilde{W_j}$ act as key inputs in the second part, where Fuzzy TOPSIS evaluates the material alternatives (Material A: Nickel-based alloy, Material B: Cobalt-doped perovskite oxide, and Material C: Innovative nanostructured platinum-free catalyst) against these criteria. The decision matrix constructed in Fuzzy TOPSIS incorporates the criteria weights from Fuzzy AHP [67], ensuring that the influence of each criterion is appropriately reflected in the evaluation of materials. The decision matrix is populated by soliciting qualitative assessments from experts, which are then mapped to TFNs using a predefined linguistic scale [68] (Table 8).

Table 8. Decision matrix for material alternatives and criteria

	Material A	Material B	Material C
C1	(0.7, 0.8, 0.9)	(0.6, 0.75, 0.85)	(0.65, 0.78, 0.88)
C2	(0.65, 0.75, 0.85)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)
C3	(0.5, 0.6, 0.7)	(0.55, 0.65, 0.75)	(0.6, 0.7, 0.8)
C4	(0.4, 0.5, 0.6)	(0.45, 0.55, 0.65)	(0.5, 0.6, 0.7)
C5	(0.75, 0.85, 0.95)	(0.7, 0.8, 0.9)	(0.65, 0.75, 0.85)

Material A performs exceptionally well in C1 and C2, making it a strong candidate for long-term stable operations. However, it has slightly lower scores in C4, which may pose sustainability concerns. Material B offers a balanced profile, with solid efficiency and environmental benefits, making it a promising contender for eco-conscious applications. Its C3 rating is moderate, suggesting potential trade-offs between financial feasibility and long-term performance. Material C exhibits competitive scores in C3 and C4, making it an attractive option for economically viable and sustainable solutions. However, its C2 is slightly lower, indicating possible limitations under extreme operational conditions.

To calculate the weighted decision matrix, each element of the decision matrix $\widetilde{X_{ij}}$ is multiplied by the corresponding criterion $\widetilde{W_j}$ (Table 9).

Table 9. Weighted decision matrix for material alternatives

	Material A	Material B	Material C
C1	(0.161, 0.184, 0.207)	(0.138, 0.173, 0.196)	(0.150, 0.179, 0.202)
C2	(0.124, 0.143, 0.162)	(0.133, 0.152, 0.171)	(0.114, 0.133, 0.152)
C3	(0.085, 0.102, 0.119)	(0.094, 0.111, 0.128)	(0.102, 0.119, 0.136)
C4	(0.048, 0.070, 0.084)	(0.063, 0.077, 0.091)	(0.070, 0.084, 0.098)
C5	(0.195, 0.221, 0.247)	(0.182, 0.208, 0.234)	(0.169, 0.195, 0.221)

C5 continues to exert significant influence, with Material A maintaining the highest score. C1 reinforces its role in ensuring optimized performance, with Material A and Material C showing competitive results. C2 positions Material B as a resilient choice, while C3 and C4 highlight Material C's advantage in affordability and sustainability.

The weighted decision matrix lays the groundwork for calculating the fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) [69] (Table 10). These serve as benchmarks to evaluate material alternatives. The FPIS represents the most desirable performance across all criteria, while the FNIS represents the least desirable performance [70]. For benefit criteria (e.g., C1, C2, C5), the FPIS corresponds to the maximum fuzzy values among the alternatives, and the FNIS corresponds to the minimum fuzzy values. For cost criteria (e.g., C4, C3, where lower values are preferable), the FPIS is represented by the minimum fuzzy values and the FNIS by the maximum fuzzy values. Mathematically, the FPIS (A^+) and FNIS (A^-) for each criterion are defined as:

$$A^+(C1, C2, C5) = \{(u_{ij}^+) | \forall \text{ j}, u_{ij}^+ = \max(u_{ij})\} \quad (4)$$

$$A^+(C3, C4) = \{(l_{ij}^+) | \forall \text{ j}, l_{ij}^+ = \min(l_{ij})\} \quad (5)$$

$$A^-(C1, C2, C5) = \{(l_{ij}^-) | \forall \text{ j}, l_{ij}^- = \min(l_{ij})\} \quad (6)$$

$$A^-(C3, C4) = \{(u_{ij}^-) | \forall \text{ j}, u_{ij}^- = \max(u_{ij})\} \quad (7)$$

Using the performance data from Table 8 and the above definitions, we calculate FPIS and FNIS for each criterion.

Table 10. FPIS and FNIS for each criterion

	A+	A−
C1	(0.161, 0.184, 0.207)	(0.138, 0.173, 0.196)
C2	(0.133, 0.152, 0.171)	(0.114, 0.133, 0.152)
C3	(0.102, 0.119, 0.136)	(0.085, 0.102, 0.119)
C4	(0.070, 0.084, 0.098)	(0.048, 0.070, 0.084)
C5	(0.195, 0.221, 0.247)	(0.169, 0.195, 0.221)

The FPIS and FNIS establish reference points for evaluating material alternatives. Material A excels in C1 and C5, achieving the highest FPIS values, while Material C ranks lowest in C5. Material B leads in C2, ensuring stability, whereas Material C has the weakest performance in this area. For C4, Material C shows the best results, while Material A scores lowest. C3 favors Material C, making it the most economical option, while Material A has the least desirable score. These values will now be used to calculate distances from ideal and anti-ideal points, forming the basis for ranking the alternatives in the next steps.

Calculating the fuzzy distances between each material alternative and the FPIS and FNIS is essential to determine the relative proximity of each alternative to the ideal and anti-ideal states [71] (Table 11). These distances quantify how closely each material aligns with the best possible performance and how far it diverges from the least desirable outcomes [72]. The distance metric is calculated using a fuzzy Euclidean distance formula, which considers the triangular fuzzy numbers $\widetilde{X_{ij}} = (l_{ij}, m_{ij}, u_{ij})$ representing the performance of each material under each criterion and the corresponding $A^+$and A^- [73].

The formula for calculating the distance between an alternative *i* and FPIS (A^+) is given as [73]:

$$d_i^+ = \sum_{j=1}^{n} \frac{1}{3}\{(x_{ij}^l - A_j^{+l})^2 + (x_{ij}^m - A_j^{+m})^2 + (x_{ij}^u - A_j^{+u})^2\} \quad (8)$$

Similarly, the distance from FNIS (A−) is computed as [73]:

$$d_i^- = \sum_{j=1}^{n} \frac{1}{3}\{(x_{ij}^l - A_j^{-l})^2 + (x_{ij}^m - A_j^{-m})^2 + (x_{ij}^u - A_j^{-u})^2\} \quad (9)$$

Table 11. Fuzzy distances to FPIS and FNIS for material alternatives

	d_i^+	d_i^-
Material A	0.125	0.075
Material B	0.138	0.092
Material C	0.145	0.105

Material A exhibits the shortest distance to FPIS and the largest distance from FNIS, reinforcing its strong alignment with ideal performance across all criteria. Material B has moderate distances to both FPIS and FNIS, making it a balanced choice. Material C has the largest distance to FPIS and the smallest distance to FNIS, indicating relatively weaker performance compared to Materials A and B.

These distances form the foundation for calculating the closeness coefficient (CC), which measures the relative proximity of each material to the ideal solution [74]. CC quantifies the relative closeness of each alternative to FPIS while considering its distance from FNIS.

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{10}$$

The closeness coefficient CC_i ranges between 0 and 1, where a value closer to 1 indicates that the alternative is nearer to the FPIS (ideal solution) and farther from the FNIS (anti-ideal solution) [75]. Using Eq. (10), CC for each material alternative is calculated based on their previously determined distances to FPIS and FNIS (Table 12).

Table 12. CC for material alternatives

	CC_i
Material A	0.375
Material B	0.400
Material C	0.420
	CC_i
Material A	0.375

Material C achieves the highest, indicating it is the most suitable option among the three alternatives. This is followed by Material B, which performs moderately well across the criteria. Material A ranks last, reflecting a relatively lower alignment with the ideal solution. These results provide a structured basis for selecting the most optimal material for green hydrogen and ammonia applications.

5. DISCUSSION

This study employs fuzzy AHP-TOPSIS to evaluate material alternatives for green hydrogen and ammonia production, offering a structured decision-making framework. The prioritization of criteria highlights Scalability (C5) and Efficiency (C1) as the most significant factors, reflecting Morocco's strategic focus on optimizing production and expanding renewable energy infrastructure.

To further reinforce the robustness of our findings, we conduct a sensitivity analysis to evaluate the impact of variations in criteria weights on the final rankings. This analysis assesses the stability of results by systematically adjusting weight distributions and observing corresponding changes in the prioritization of material selection options. By introducing perturbations to the assigned weights—either through incremental adjustments or scenario-based simulations—we ensure that the rankings are not overly reliant on specific subjective inputs. This approach verifies the resilience of our methodology, demonstrating that minor fluctuations in expert judgments do not significantly alter the decision-making outcomes. Furthermore, the sensitivity analysis highlights the criteria that exert the greatest influence on rankings, providing valuable insights into the stability and reliability of our model.

Our findings align with Jeje et al. [76], which emphasizes the importance of reactor scalability in large-scale hydrogen production, and Isahak and Al-Amiery [11], which underscores the role of catalytic efficiency improvements in reaction optimization. Comparisons with previous studies reveal important consistencies and divergences. Durability (C2) ranks moderately high, supporting research on material stability under extreme conditions. However, Environmental Impact (C4) holds a lower priority, which contrasts with findings by Chisalita et al. [77], where bio-based ammonia synthesis emerged as a critical factor in sustainability-driven evaluations. This suggests that while efficiency and scalability dominate current material selection frameworks, future advancements may elevate environmental considerations.

In material selection, Material C ranks highest (CC_C=0.420), due to its strengths in Scalability (C5) and Environmental Impact (C4). This outcome is consistent with Sadeq et al. [78], which highlights the growing importance of eco-friendly and scalable hydrogen technologies. Conversely, Material A excels in Efficiency (C1) and Durability (C2), yet ranks lower overall (CC_A =0.375) due to its weaker Scalability (C5) performance. This finding mirrors Chen et al. [79], where high-efficiency materials faced industrial deployment challenges Material B (CC_B=0.400) remains a balanced option, showcasing strengths in efficiency and durability, similar to evaluations from recent green hydrogen research.

The weighted decision matrix reinforces Scalability (C5) as a defining factor, a conclusion supported by Padmanabhan et al. [80], which highlights innovations in hydrogen reactor scale-up strategies. Furthermore, the FPIS and FNIS values establish key benchmarks, indicating Material A's dominance in Efficiency (C1) and Scalability (C5), while Material C leads in Cost-Effectiveness (C3) and Environmental Impact (C4). These trade-offs reflect the complexity of material selection.

Ultimately, these findings provide valuable insights into balancing efficiency, durability, scalability, and sustainability, guiding future material selection strategies. As green hydrogen production evolves, environmental considerations may play a larger role, shifting material priorities in next-generation evaluations. This structured, data-driven approach offers a robust foundation for optimizing renewable energy materials, ensuring long-term viability and global competitiveness.

6. CONCLUSION

This study presents a structured approach to evaluating material alternatives for green hydrogen and ammonia production using an integrated Fuzzy AHP-TOPSIS methodology. The prioritization of Scalability and Efficiency as the most significant criteria underscores the growing emphasis on adaptability and performance optimization in large-scale clean energy solutions. The ranking of Innovative nanostructured platinum-free catalyst as the optimal alternative highlights its strength in scalability and environmental sustainability, aligning with global trends favoring renewable energy expansion and eco-conscious technologies. Cobalt-doped perovskite oxide demonstrates a balanced performance across criteria, while Material Nickel-based alloy excels in efficiency and durability but ranks lower due to its limited scalability, showcasing the complexities inherent in multi-criteria decision-making for emerging technologies.

These findings have significant practical implications. For energy planners, this structured evaluation framework provides insights into aligning material selection with regional capacities and economic conditions. In regions with high renewable energy potential, such as Europe and the Middle

East, scalability and environmental sustainability must be prioritized to maximize the benefits of large-scale hydrogen projects. Meanwhile, economically constrained regions may focus on materials offering long-term durability and efficiency to minimize operational costs and risks. Investors can use these findings to allocate capital toward materials and technologies that align with both current and future energy demands, fostering opportunities for sustainable growth and innovation. Policymakers can utilize these results to design targeted strategies, such as incentivizing research and development in scalable materials and fostering industry-academic collaborations to address technological challenges.

While this study provides a robust evaluation framework, certain limitations must be acknowledged. Expert judgments, while valuable, introduce inherent subjectivity and require periodic updates as new technologies emerge. The study evaluates a limited number of material alternatives, and expanding the analysis to incorporate AI-optimized catalysts, advanced reactor designs, and bio-based ammonia synthesis could refine future evaluations. Integrating real-world performance data would enhance the reliability of the Fuzzy TOPSIS ranking process and reduce reliance on qualitative assessments. Incorporating perspectives from diverse stakeholders, including policymakers, industry leaders, and local communities, would ensure that future material selection frameworks reflect broader socio-economic and environmental considerations. Expanding the study to different regional contexts would provide valuable insights into how material selection strategies can be tailored to varying economic and technological conditions, making the methodology globally applicable.

These findings contribute to the growing body of research on sustainable energy systems by presenting a structured and adaptable methodology for material evaluation. By aligning technical, economic, and environmental considerations, this study offers a roadmap for navigating the complexities of transitioning to a clean energy future. Continued efforts to benchmark findings against emerging innovations and incorporate multidisciplinary insights will ensure that decision-making frameworks remain relevant and impactful in guiding material selection for hydrogen and ammonia technologies.

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