FUZZY ANALYTIC HIERARCHY PROCESS: A COMPREHENSIVE LITERATURE REVIEW

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ABSTRACT

This literature review explores the advancements and applications of the Fuzzy Analytic Hierarchy Process (FAHP) technique between 2019 and 2024, in addition to studies that combined or compared FAHP with other methods. The FAHP integrates the Analytic Hierarchy Process (AHP) with fuzzy set theory to manage uncertainty and imprecision in Multi-Criteria Decision-Making (MCDM) problems. This review covers 85 articles from prominent journals using well-known databases. It introduces a novel taxonomy that categorizes FAHP research into three main categories: outcome types, methodological variations, and application domains, with additional subcategories. This article highlights diverse applications of the FAHP across many fields and domains, proving the method's effectiveness in addressing complex decision problems. Observations reveal the FAHP's strength in uncertainty problems, while gaps in the literature call for further exploration in less applied fields like agriculture and healthcare. Other future research directions also are discussed

Keywords: Fuzzy Analytic Hierarchy Process (FAHP); Fuzzy AHP; Multi-Criteria Decision-Making (MCDM)

1. Introduction

Decision-making techniques and processes have been widely investigated, developed, and applied in various industries and fields. This shows the importance of integrating them into all operational levels within a field to reach the best decision among different alternatives.

Decision-making in complex scenarios often entails evaluating multiple criteria which are often desirable and conflicting in their importance, values, priorities, impacts, and effects. This challenge is addressed by applying Multi-Criteria Decision-Making (MCDM), where each criterion should be assigned an importance weight. Therefore, each alternative will have a specific value (Hwang, 1981). MCDM provides a structured approach for dealing with decisions involving multiple alternatives and competing criteria with different weights that should be considered. MCDM is designed to capture the trade-offs between different decision attributes to help Decision-Makers (DMs) reach the most satisfactory decision among various alternatives.

The MCDM process consists of several steps. The step that weights each criterion is called the weighting step. A famous method used in weighting attributes/criteria is the AHP (Saaty, 1977; Saaty, 1980). The AHP is primarily used to weight criteria in decision-making processes to help determine the relative importance of different criteria through pairwise comparisons (Saaty, 1980). The weights derived from these comparisons are used to prioritize and evaluate the decision criteria, which will help score alternatives pairwise under each criterion. Applying this method will assist in ranking and selecting alternatives based on those weighted criteria, which leads to the appropriate decision (Saaty, 1980).

The AHP always relies on crisp values or precise numerical judgments, which may not be helpful when encountering uncertainties and the subjective nature of human assessments. To address this challenge, fuzzy set theory introduced by Zadeh (1965) was incorporated with the AHP to develop the Fuzzy AHP (FAHP) by Van Laarhoven and Pedrycz (1983). Fuzzy set theory provides a mathematical way to represent the vagueness and imprecision in human thought processes, as it modifies the traditional binary logic to accommodate degrees of uncertainty and partial truth (Zadeh, 1965). Incorporating fuzzy set theory with the AHP is critical for dealing with real-world complexities and ambiguities in decision-making, which allows the decision-makers to more flexibly express their preferences (Van Laarhoven & Pedrycz, 1983).

In the FAHP approach, pairwise comparison judgments are represented as fuzzy numbers, such as Triangular or Trapezoidal fuzzy numbers (Van Laarhoven & Pedrycz, 1983). An example is provided in Table 1. This modification allows for a more detailed expression of preferences, minimizing the effects of uncertainty, thus providing a more realistic reflection of the decision-makers' true intentions.

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Table 1
Fuzzy triangular membership function for measuring importance levels

Importance	Fuzzy Membership Function
Equal	(1, 1, 1)
Moderate	(2, 3, 4)
Strong	(4, 5, 6)
Very Strong	(6, 7, 8)
Extremely Strong	(9, 9, 9)
Intermediate Values	(1, 2, 3)
	(3, 4, 5)
	(5, 6, 7)
	(7, 8, 9)

The FAHP follows the same hierarchical structure as the AHP but replaces crisp numbers with fuzzy values throughout the pairwise comparisons. The procedure for deriving weights involves computing fuzzy geometric means across each row of these fuzzy comparison matrices and normalizing these means to obtain fuzzy priority vectors (Van Laarhoven & Pedrycz, 1983). By incorporating these fuzzy priorities into the structured MCDM process, the method becomes a robust tool for managing uncertainties and conflicting priorities in the decision-making process. This integration enhances MCDM's adaptability and facilitates a comprehensive analysis (Van Laarhoven & Pedrycz, 1983).

The steps or process of the FAHP begin with structuring the problem into a hierarchy of criteria and sub-criteria. Next, decision-makers use linguistic terms to assess the importance of criteria, forming a fuzzy pairwise comparison matrix. These judgments are then synthesized to derive fuzzy priorities. Fuzzy weights are calculated from the matrix, representing the relative importance of each criterion. To obtain crisp values, the fuzzy weights are defuzzified. Finally, the consistency of the comparisons is checked to ensure reliable results (Van Laarhoven & Pedrycz, 1983).

This literature review comprehensively examines the studies and advancements on the FAHP technique and its applications over six years, from 2019 to 2024. This review incorporates multiple dimensions, focusing on the key contributions within various fields and industries by applying the FAHP technique, theoretical advancements on the FAHP, and other studies comparing different techniques with the FAHP.

A total of 85 papers were selected from various journals through extensive searches in multiple databases, including Scopus, ScienceDirect, Taylor and Francis, Springer Nature Link. This review also includes all published literature review papers in this area within the past six years, ensuring a thorough coverage of the subject. The keywords include Fuzzy Analytic Hierarchy Process, FAHP, Fuzzy AHP, Multi-Criteria Decision Making, and MCDM.

This literature review has some novel contributions. First, as a critical contribution, this review article presents a novel taxonomy that offers a new way to categorize and

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understand developments in the FAHP and its applicability. Second, this review is distinguished by being alone in its coverage of FAHP studies and applications between 2019 and 2024.

2. Taxonomy

This literature review employs a novel structured taxonomy to categorize articles on the FAHP from 2019 to 2024, dividing the literature into three main categories, where articles are analyzed from multiple perspectives. The first category, outcome types, includes literature review articles that consolidate existing knowledge and provide an overview of FAHP applications and developments, as well as theoretical advances proposing improvements or adjustments to the FAHP methodology. The second category, methodological variations, encompasses studies that integrated the FAHP with other techniques to enhance its utility and adaptability, alongside comparative methodology articles that evaluate the FAHP against other methods, highlighting strengths and weaknesses. Lastly, the application domains category includes various fields and industries that have applied the FAHP technique, which shows its broad applicability across diverse sectors.

2.1. Outcome type

This category of articles is critical to understanding the advancements of FAHP research and its impact on many other methodologies from 2019 to 2024, and includes two subcategories: literature review articles and theoretical advances of the FAHP. Each of these subcategories provides a unique perspective on the evolution of the FAHP. In addition to summarizing the literature review articles published between 2019 and 2024, this category also includes the articles that contribute to the theoretical advancements of the FAHP technique.

2.1.1. Literature review articles

To the best of our knowledge, only two literature review articles on the FAHP were published between 2019 and 2024. Liu et al. (2020) conducted a comprehensive review of 109 articles on the FAHP published between 2008 and 2019. The article highlighted various FAHP techniques including the steps and notes about each technique's unique strengths and weaknesses, depending on the nature of the decision problem. It also discussed significant research gaps in exploring FAHP's different methods and detailed each method's advantages and scope. Liu et al. (2020) classified the various FAHP techniques into four categories based on the steps involved in developing an FAHP model: representation of pairwise comparisons, aggregation of fuzzy sets for group decisions and weight derivation, defuzzification of fuzzy sets to crisp values, and consistency measurement of judgments. Each category was thoroughly explored to identify the specific methodologies used and their computational implications, which assists researchers and practitioners in facilitating the selection of the appropriate techniques based on their specific decision-making problems.

Castelló-Sirvent et al. (2022) published a literature review article about the FAHP that covered the period between 1994 and 2022. The article analyzed 2,086 articles using VOSViewer 1.6.17 software. The authors provided a bibliometric analysis of the FAHP literature and traced its evolution, thematic clusters, and main collaboration networks over three decades. This analysis can assist in selecting the most suitable FAHP

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methodologies, considering their mathematical complexity and the precision required for specific applications. They identified some gaps in the literature, such as the shortage of studies comparing different FAHP methodologies to assess their effectiveness across various contexts. The other gaps identified were the under-exploration of the FAHP in certain industries and contexts and the lack of geographical diversity. Therefore, they suggested a need for broader application studies, and the expansion of studies into new cultural and economic areas. Castelló-Sirvent et al. (2022) also encouraged researchers to develop new FAHP methodologies, specifically integrating the FAHP with other decision-making techniques like fuzzy TOPSIS, fuzzy Delphi, ELECTRE, DEMATEL, and defuzzification processes (transforming fuzzy numbers into crisp values).

2.1.2. Theoretical advances

This subcategory includes articles that conducted theoretical improvements or adjustments to the FAHP methodology. Table 2 shows the key theoretical advancements in the method, and illustrates a range of enhancements and developments to the FAHP, such as Intuitionistic and Spherical FAHP, to refine consistency measurement and introduce advanced methods for dealing with eigenproblems associated with triangular fuzzy multiplicative preference relations. These developments of innovative algorithms and FAHP models ensure greater accuracy and applicability of FAHP in complex decision-making scenarios.

Table 2
Articles that contributed to theoretical improvements in FAHP

References	**Brief description of the theoretical improvements/adjustments**
Wang (2019)	Developed a representable uninorm-based Intuitionistic Fuzzy AHP (IFAHP)
Wang (2020)	Developed methods for enhancing the transitivity and consistency measurement of Triangular Fuzzy Multiplicative Preference Relations (TFMPRs)
Kutlu Gündoğdu and Kahraman (2020)	Developed a novel Spherical Fuzzy Analytic Hierarchy Process (SF-AHP)
Kinay and Tezel (2022)	Introduced Magnitude-based Fuzzy AHP (MFAHP) and Total Difference-based Fuzzy AHP (TDFAHP)
Sam’an et al. (2021)	Developed a new interval type-2 trapezoidal fuzzy AHP
Wang (2021)	Introduced new methods for solving eigenproblems associated with triangular fuzzy multiplicative preference relation matrices
Chen et al. (2022b)	Represented an advancement in FAHP by incorporating intuitionistic fuzzy elements
Sakhardande and Gaonkar (2022)	Developed a novel approach for handling large data matrix problems

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References	Brief description of the theoretical improvements/adjustments
Arman (2023)	Developed four new FAHP methods that incorporate Pentagonal Fuzzy Numbers (PFNs)

2.2. Methodological variations

The methodological variations category has two subcategories. First, the "Combination with other techniques" subcategory highlights studies that combine the FAHP with other methodologies. The second subcategory is "Comparative methodology" which lists articles that compare the FAHP technique to other decision-making methods to examine its strengths and weaknesses in various scenarios. These subcategories help illustrate how the FAHP is being investigated and tested to meet the challenges of complex decision-making environments.

2.2.1. Combination with other techniques

As shown in Table 3, many studies have integrated the FAHP technique with other techniques and methodologies, such as Aggregation of Individual Judgment and Quality Function Deployment, to enhance decision-making precision across different fields. These integrations demonstrate the ability and versatility of the FAHP in optimizing and adapting to diverse analytical needs by incorporating other techniques to reach the final objectives.

Table 3
References based on techniques and methodologies that have been combined or integrated with FAHP

References	Techniques/methodologies combined/integrated with FAHP
Abdul et al. (2023)	Spherical FAHP (SFAHP) and Pythagorean FAHP (PFAHP)
Al-Araidah et al. (2020)	Aggregation of Individual Judgment (AIJ)
Alhadidi and Alomari (2024)	VIKOR "VlseKriterijumska Optimizacija I Kompromisno Resenje"
Ashour et al. (2022)	Parsimonious-Cybernetic Fuzzy Analytic Hierarchy Process (P-CFAHP)
Ayalew et al. (2022)	Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS)
Ayalew et al. (2023)	Exploratory Factor Analysis (EFA)
Ayyildiz et al. (2023)	Quality Function Deployment (QFD), Pythagorean Fuzzy AHP (PFAHP)
Bakhtari et al. (2021)	Interpretive Structural Modeling (ISM) and MICMAC analysis. MICMAC : "Matrice d'Impacts Croises Multiplication Appliquee aun Classement"
Buran and Erçek (2022)	Spherical Fuzzy AHP (SF-AHP) and Intuitionistic Fuzzy AHP (IF-AHP)
Chen and Wu (2021)	Alpha-Cut Operations (ACO) method
Dhumras and Bajaj (2024)	Weighted Aggregated Sum Product Assessment (WASPAS)

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References	Techniques/methodologies combined/integrated with FAHP
Dong et al. (2021)	Linguistic Distribution Assessment (LDA) and Bidirectional Projection Method
Fu et al. (2023)	Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS)
Jawad et al. (2023)	Spherical Fuzzy Sets (SFS)
Kutlu Gündoğdu and Kahraman (2020)	Spherical Fuzzy Sets (SFS) - Spherical Fuzzy TOPSIS - Spherical Fuzzy WASPAS - Spherical Fuzzy VIKOR
Karatop et al. (2021)	Evaluation Based on Distance from Average Solution (EDAS) - Fuzzy Failure Mode and Effect Analysis (Fuzzy FMEA)
Kazemi et al. (2020)	Fuzzy Cognitive Map (FCM)
Kong and Zhang (2024)	Interval Technique for Order Preference by Similarity to an Ideal Solution (I-TOPSIS)
Lakshmi and Kumara (2024); Leung et al. (2021); Raja et al. (2024); Li et al. (2023); Yousefzadeh et al. (2020); Sirisawat and Kiatcharoenpol (2018)	Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)
Nazari et al. (2018)	Fuzzy Inference System (FIS)
Olabanji and Mpofu (2020)	Fuzzy Weighted Average (FWA)
Rajput et al. (2024)	Spherical Fuzzy Analytic Hierarchy Process (SFAHP) - Linear Assignment Model (LAM)
Singh (2021)	Elimination and Choice Translating Reality (ELECTRE-I)
Tasnuva and Bari (2024)	Machine learning algorithms
Wang et al. (2020)	SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis
Wang et al. (2021)	Multi-choice Goal Programming (MCGP)
Wattanasaeng and Ransikarbum (2024)	Multi-objective optimization methodology
Yang et al. (2019)	Multi-objective Disassembly Fruit Fly Optimization Algorithm (MDFOA)
Zhu et al. (2022)	Entropy method and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations)

2.2.2. Comparative methodology

This subcategory discusses the studies that compare other techniques and methodologies with the FAHP, as shown in Table 4. This helps to better illustrate the method's efficiency, strengths, and weaknesses compared to other alternative methodologies.

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Table 4
Techniques and methodologies compared with the FAHP

References	Techniques/methodologies compared with FAHP	Overall better method
Chan et al. (2019)	AHP	Depends on the context or the complexity of the decision problem.
Kutlu Gündoğdu and Kahraman (2020)	Compared Spherical FAHP with Neutrosophic sets AHP	Both methods were effective. The choice depends on the specific needs for handling uncertainty.
Bostancioglu (2021)	AHP	FAHP is more effective in uncertain problems.
Coffey and Claudio (2021)	Compared Group FAHP with Group AHP	GFAHP is better with significant uncertainty and multiple stakeholders or decision-makers.
Chen et al. (2022b)	Compared Intuitionistic Fuzzy (IF) AHP with AHP	IFAHP is better in ambiguous decision problems.
Jbaihi et al. (2024)	AHP	FAHP is more reliable in high-level uncertainty and imprecision.

2.3 Applications domains

This category includes the FAHP application domains between 2019 and 2024. This category has explored diverse areas where FAHP has been successfully implemented. It highlights the FAHP's capability to handle the complexities and uncertainties inherent in various MCDM problems, which have been applied across various fields, as shown in Table 5. In many fields, ranging from strategic management and engineering to healthcare and environmental sustainability, the FAHP has been successfully proven to support the decision-making process, resulting in more accurate and reliable decisions under uncertainty.

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Table 5
Applications domains and fields of FAHP

Domain or field	Specific decision	References
Additive manufacturing	Selection of 3D printers	Chen and Wu (2021)
	Optimal printing parameters	Raja et al. (2024)
Agricultural production	Cultivation of hazelnuts	Ayyildiz et al. (2023)
Architectural engineering and design management	Sustainable interior design	Ashour et al. (2022)
	Optimal double-skin facades	Bostancioglu (2021)
	Selecting designs and elements	Gupta and Lee (2023)
	Historic masonry buildings	Lallam et al. (2023)
	Laminate flooring materials	Singer and Özşahin (2022)
	Wooden outdoor furniture	Singer and Özşahin (2023)
Construction management / Infrastructure engineering	Building construction projects	Ayalew et al. (2023)
	Construction quality control	Getawa Ayalew et al. (2024)
	Road maintenance management	Ayalew et al. (2022)
	Tunnel water inrush	Kong and Zhang (2024)
	Metro tunnel construction	Lyu et al. (2020)
	Metro rail construction	Sarkar and Singh (2021)
Medical equipment	Microscope usability design	Chen et al. (2022a)
Engineering design	Assembly fixture design	Olabanji and Mpofu (2020)
Environmental engineering management	Wetland health assessment	Das et al. (2022)
	Suitable backfill materials	Fu et al. (2023)
	Characterizing soil erosion risk	Kaya et al. (2023)
	Groundwater potential zones	Kumar et al. (2022)
	Forest management strategies	Mostafa et al. (2022)
	Petroleum soil phytoremediation	Wang et al. (2019)
Facilities planning	Layout sustainable design	Wattanasaeng and Ransikarbum (2024)
Food quality assurance	Fresh produce quality assurance	Leung et al. (2021)
Freight transportation	Safety for dangerous goods	Huang et al. (2020)

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Domain or field	Specific decision	References
	Business analytics for freight	Rabia and Bellabdaoui (2023)
Healthcare management	Hospital ward system maturity	Li et al. (2023)
	Effects of rising heart diseases	Nazari et al. (2018)
	Service quality performance	Singh (2021)
Human resource management	Attraction of high-tech talent	Shi and Lai (2023)
Mining engineering	Process mining technology	Dogan (2021)
	Minerals processing plant	Kazemi et al. (2020)
	Acid mine drainage treatment	Lorio et al. (2023)
Finance and investments	Portfolio for stock exchange	Jawad et al. (2023); Lakshmi and Kumara (2024)
Judicial systems	Legal judgment summarization	Bansal et al. (2019)
Livelihood disaster management	livelihood vulnerability	Tasnuva and Bari (2024)
Manufacturing operations	Industry 4.0 implementation	Bakhtari et al. (2021)
	Green manufacturing indicators	Sharma et al. (2021)
	Fixing agricultural machinery	Yang et al. (2019)
Maritime operations	Safety for Arctic shipping	Wan et al. (2024)
Natural gas management	Supply security of natural gas	Zhu et al. (2022)
Natural hazards and risks management	Mitigating landslide-prone areas	Sur et al. (2020)
	Geohazard risks for railway	Zheng et al. (2021)
Health & safety management	Health risks with nanomaterial	Salari et al. (2024)
Economic developments	Business climate and investment	Rajput et al. (2024)
Public transportation management	Public transport business models	Buran and Erçek (2022)
	Transit service quality attributes	Verma and Rastogi (2024)
Recycling management	Copper recovery method	Yousefzadeh et al. (2020)
Renewable energy development	Renewable energy promotion	Abdul et al. (2023)

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Domain or field	Specific decision	References
	Offshore wind energy develops	Dhingra et al. (2022)
	Location for wind power farms	Kutlu Gündoğdu and Kahraman (2020)
	Renewable energy investments	Karatop et al. (2021)
	Clean energy virtual enterprises	Liu et al. (2019)
	Renewable energy adoption	Shah et al. 2019
	Resources for electricity	Wang et al. (2020)
Internal audit planning	Optimizing project selection	Wang et al. (2021)
Corporate social responsibility	Ranking CSR drivers in supply	Moktadir et al. (2018)
Sustainable supply chain management	Selecting sustainable suppliers	Arman (2023); Tavana et al. (2021)
	Green supply chain framework	Dhumras and Bajaj (2024)
	Risks in clothing supply mgt.	Majumdar et al. (2020)
	Reverse logistics barriers	Sirisawat and Kiatcharoenpol (2018)
Sustainability development within enterprises	Entrepreneurial ecosystems	Aliabadi et al. (2019)
	Industrialization performance	Candan and Toklu (2022)
	Evaluating companies	Dağıdır and Özkan (2024)
	Ranking sustainable enterprises	Dong et al. (2021)
Textile industry	Sustainable production indicator	Hashim et al. (2021)
	Indigo dyeing process	Fidan et al. (2021)
Transportation planning / Urban development	Single point urban interchanges	Alhadidi and Alomari (2024)
	Path-level walkability index	Dasari and Gupta (2023)
Waste management	Waste disposal site alternatives	Kahraman (2024)
	Demolition waste management	Khoshand et al. (2020); Past et al. (2023)
Water desalination and treatment	Osmosis desalination membrane	Al-Araidah et al. (2020)
	Carbon adsorbent for color	Azari et al. (2022)
	Wastewater treatment tech.	Ho et al. (2021)

3. Observations and results

This section illustrates the results and the key observations of the comprehensive review of the FAHP technique between 2019 and 2024.

3.1. Most applied application domains

Between 2019 and 2024, the FAHP technique was applied in 33 different fields. Table 5 illustrates the application domains. This study observed the key objectives that decision-makers have decided on using the FAHP within various domains. It was observed that the top field adopting the FAHP in its studies is renewable energy development.

The renewable energy development sector has widely applied the FAHP, with seven articles included in this review. They include prioritizing barriers to ecopreneurship for renewable energy promotion (Abdul et al., 2023), selecting the optimal location for wind power farms (Kutlu Gündoğdu & Kahraman, 2020), selecting renewable energy resources for electricity generation (Wang et al., 2020), prioritizing barriers to offshore wind energy development (Dhingra et al., 2022), selecting an optimal renewable energy alternative for investment (Karatop et al., 2021), assessing risks in clean energy virtual enterprises (Liu et al., 2019), and prioritizing barriers to renewable energy adoption (Shah et al., 2019).

The next three fields that have applied the FAHP technique in many studies are Architectural Engineering, Construction/Infrastructure Engineering, and Environmental Engineering Management. Each of these three fields has six papers included in this review, as demonstrated in Table 5.

The fields with the lowest FAHP adoption in their studies are Agricultural Production, Medical Equipment, Engineering Design, Food Quality Assurance, Human Resource Management, Judicial Systems, Livelihood Disaster Management, Maritime Operations, Natural Gas Management, Health and Safety Management, Economic Development, Recycling Management, Internal Audit Planning, and Corporate Social Responsibility.

Figure 1 shows the application domains that applied the FAHP, and the number of articles included in this review.

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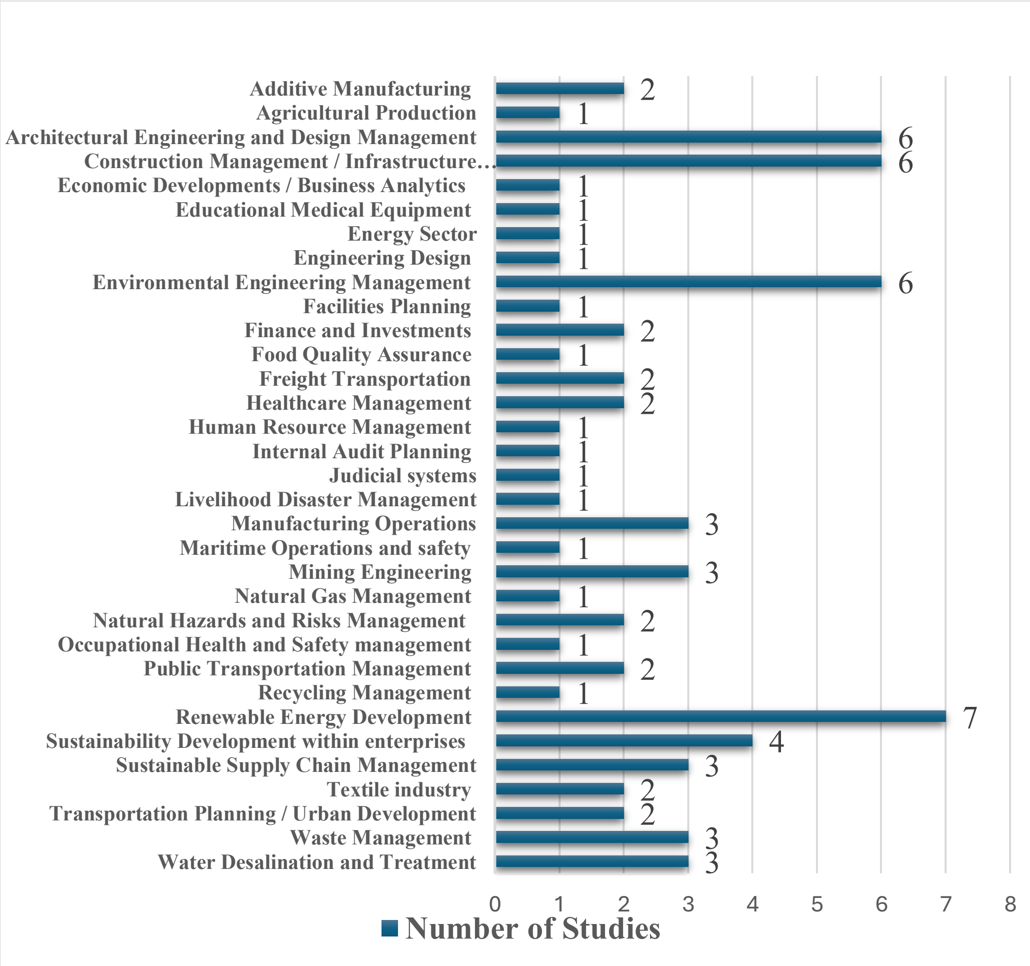

Figure 1 Application domains of FAHP and the number of studies

3.2. Incorporating FAHP with sustainability studies

FAHP studies adopted the sustainability trend widely and in-depth. Many studies across various fields focused on incorporating sustainability measures with their optimization problems. This integration demonstrates the applicability of FAHP to the sustainable advancements of other operations and problems. For example, a study by Wattanasaeng and Ransikarbum (2024) applied the FAHP to optimize the eco-industrial park layout's sustainable design. Another study was performed by Hashim et al. (2021) on the prioritization of sustainable production indicators in the textile industry. Also, Ho et al. (2021) applied FAHP in weighting sustainability criteria and selecting the optimal wastewater treatment process technologies and suppliers within the water desalination and treatment sector.

3.3. Databases usage

In this study, multiple databases were used to search for FAHP-related papers. As shown in Figure 2, four databases were used. The database that had the most related articles was ScienceDirect, with 41 articles. The second and third databases were Taylor

& Francis and Scopus, with 31 and 12 articles, respectively. The database with the lowest number of articles was Springer Nature Link, with only one article.

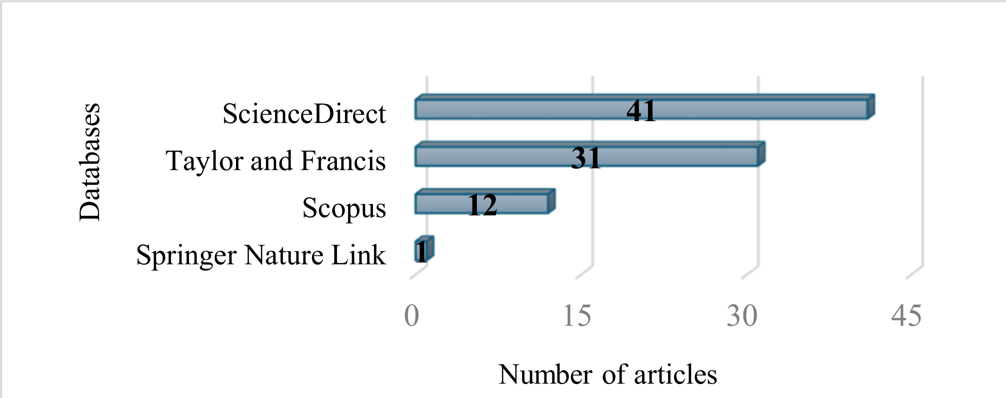

Figure 2 Number of articles in each database accessed

3.4. Associated journals

The 85 articles found were sourced from 48 journals, as shown in Table 7. The top FAHP publisher was the *Journal of Cleaner Production*, with 15 articles. The second most dominant journal was *Expert Systems with Application*, with 13 papers. Table 6 ranks the top four journals based on their ratio of total articles included in the study.

3.5. Countries that applied/developed the FAHP

Figure 3 shows that the application of the FAHP and the contribution to the FAHP technique were limited to around 20 countries between 2019 and 2024. Table 8 ranks the top four countries producing FAHP publications. Only six countries contributed to the advancements of FAHP during the covered period, and they are ranked in Table 9.

Table 6
Dominant journals in the FAHP field

Rank	Journals	Ratios of papers
1	*Journal of Cleaner Production*	18%
2	*Expert Systems with Applications*	15%
3	*Architectural Engineering and Design Management*	4%
4	*Cogent Engineering*	4%

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Table 7
Journals with FAHP articles

Journal	Number of papers
Architectural Engineering and Design Management	3
Cogent Business & Management	1
Cogent Engineering	3
Computers & Industrial Engineering	2
Cybernetics and Systems	1
Decision Support Systems	1
Desalination and Water Treatment	1
Enterprise Information Systems	1
Expert Systems with Applications	13
Fuzzy Information and Engineering	1
Geocarto International	2
Geomatics, Natural Hazards and Risk	2
Heliyon	1
IEEE Transactions on Fuzzy Systems	2
Information Sciences	1
International Journal of Architectural Heritage	1
International Journal of Construction Management	1
International Journal of Environmental Analytical Chemistry	1
International Journal of Healthcare Management	1
International Journal of Production Research	1
International Journal of Sustainable Development & World Ecology	1
International Journal of Sustainable Engineering	1
International Journal of Systems Science: Operations & Logistics	1
Journal of Cleaner Production	15
Journal of Construction Engineering and Management	1
Journal of Forest Science	1
Journal of Industrial and Production Engineering	1
Journal of International Maritime Safety, Environmental Affairs, Shipping	1
Journal of Management Analytics	1
Journal of the Air & Waste Management Association	1
Journal of the Operational Research Society	2
Journal of Transportation Safety & Security	1
Mathematical Problems in Engineering	1
Medicine	1
Minerals Engineering	2
Regional Studies in Marine Science	1
Rendiconti Lincei. Scienze Fisiche e Naturali	1
Results in Engineering	1
Scientific Reports	1
Small Enterprise Research	1
Soft Computing	2

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Journal	Number of papers
Sustainable Cities and Society	1
Sustainable Energy Technologies and Assessments	1
Technological Forecasting & Social Change	1
Urban, Planning and Transport Research	1
Waste Management & Research	1
Wood Material Science & Engineering	1
Total	84

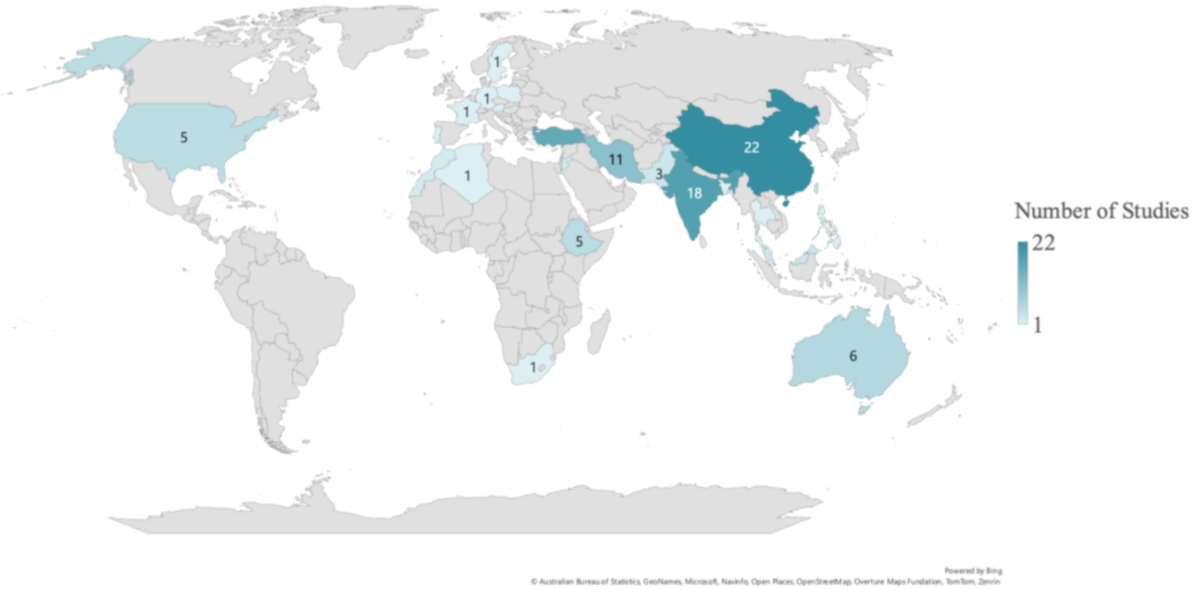

Figure 3 Countries that studied the FAHP

Table 8
Countries with the most FAHP publications

Rank	Country	Number of FAHP publications
1	China	22
2	India	18
3	Iran	11
4	Australia	6

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Table 9
Countries contributing to the advancement of the FAHP

Rank	Countries advancing FAHP	Number of studies
1	China	4
2	Turkey	2
3	Singapore “with China”	1
4	Iran	1
5	India	1
6	Malaysia	1

3.6. Observations on combining the FAHP with other techniques

It was clearly observed from the studies that compared the FAHP with other techniques, that the FAHP has better performance when dealing with ambiguity and vagueness in the uncertain problems. Most of the comparative studies mentioned in Table 4 compared the FAHP with the AHP technique. A study by Jbaihi et al. (2024) found that the FAHP is more reliable than the AHP in handling high levels of uncertainty and imprecision. In comparison, a study done by Chan et al. (2019) concluded that the choice of the FAHP or the AHP depends on the context and complexity of the decision problem.

3.7. Most common technique combined with FAHP

Between 2019 and 2024 over 20 different assessment and decision-making techniques were combined with the FAHP in various studies. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) was the decision-making technique most commonly combined with the FAHP with the most recent being Lakshmi and Kumara (2024). Table 3 shows other studies that combined different techniques with the FAHP.

3.8. Observations from the series of developments to the FAHP

Table 2 summarizes recent advancements in the FAHP method. Innovations include pentagonal fuzzy numbers (Arman, 2023), spherical fuzzy AHP (Kutlu Gündoğdu & Kahraman, 2020), and interval type-2 trapezoidal FAHP (Sam’an et al., 2021). Other improvements involve intuitionistic fuzzy elements (Chen et al., 2022b), and enhancing transitivity and consistency in triangular fuzzy preference relations (Wang, 2020; Wang, 2021). These advancements enhance the FAHP’s adaptability for complex decision-making processes.

The key observed advancement proposed by Sakhardande and Gaonkar (2022), involves a mapping method that simplifies the data input from experts by directly converting their opinions into a format suitable for FAHP calculations. This approach saves time and increases the consistency of the pairwise comparison matrices by automating much of the comparison process, which addresses major issues related to handling large datasets in FAHP.

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4. Conclusions and future works

This review article has introduced a new taxonomy for organizing the FAHP literature between 2019 and 2024 and has filled the gap in literature reviews during the past three years. A total of 85 articles were found and included in this review. This article explored the development and applications of the FAHP technique between 2019 and 2024 and clarified its applications in diverse fields and its combination with different decision-making methods. This review article demonstrated the FAHP's comparison with other techniques and has confirmed the high efficiency of the FAHP in contexts and environments with high uncertainty and imprecision.

Based on the reviewed articles, the following future research directions are suggested:

- Apply the FAHP in less explored fields like healthcare and agriculture. In healthcare, the FAHP could be used to enhance decision-making for patient prioritization and resource allocation, while in agriculture, to optimize crop management and supply chain efficiency. FAHP application could also be expanded to other new fields that have not yet been applied, such as digital marketing, sports management, oil discovery, space science, media, and cybersecurity sectors, which might lead to excellent results.
- Develop FAHP models that integrate machine learning techniques that can enhance predictive analytics and decision-making accuracy in complex scenarios. Combining the FAHP with blockchain technology could ensure transparency and security in decentralized decisions. This combination will support innovative applications in various fields driven by Artificial Intelligence (AI).
- Enhance FAHP models with real-time data analysis capabilities to improve decision-making processes. This is useful when applying the FAHP in dynamic environments such as stocks or financial markets, banks, and crisis or emergency management, where conditions change rapidly, and data is continuously updated. This real-time integration allows immediate responses and adjustments, which ensures that decisions remain effective as situations evolve.
- Explore the integration of the FAHP with Geographic Information Systems (GIS). This integration supports better decision-making in urban planning, environmental management, and resource allocation. Those fields rely on precise analysis of geographical data and spatial relationships to drive their strategies and actions.
- Develop hybrid models that use the FAHP as an MCDM tool and an optimization model. The outputs of the FAHP can serve as the values for specific parameters within the optimization model. This approach enables more precise and dynamic decision-making processes.

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