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Research Article

Adaptive neuro-fuzzy inference system approach for sustainability assessment in paper industry

Salman Akhoundzadeh [1], Mansour Soufi [1, *], Seyedeh Ameneh Sajjad [2], Mehdi Fadaei [1]

1. Department of Industrial Management, Ra.C., Islamic Azad University, Rasht, Iran
2. Department of Agronomy, Ra.C., Islamic Azad University, Rasht, Iran

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Abstract

The paper industry, as one of the largest consumers of natural resources, faces growing pressure to adopt sustainable practices that balance economic growth, environmental responsibility, and social well-being. Traditional evaluation methods often fail to capture the sector's complex interdependencies and nonlinear dynamics. This study introduces a hybrid framework based on the Adaptive Neuro-Fuzzy Inference System (ANFIS) to assess the sustainability performance of Iranian paper production companies. A comprehensive set of 93 indicators across three sustainability dimensions—economic, environmental, and social—was identified through literature review and expert consultation. Principal Component Analysis (PCA) refined these into 24 critical indicators, which structured the ANFIS model in MATLAB. The model was trained and validated using survey data from 144 industry professionals across four companies, with Gaussian membership functions applied to all input and output variables. Fuzzy rules were developed to link the sustainability dimensions, forming one main model and three sub-models (social: 5 inputs; environmental: 10 inputs; economic: 9 inputs). Using a hybrid learning algorithm, the model achieved convergence after 60 epochs with testing and validation errors of 0.00163 and 0.00097, respectively, while boundary tests confirmed logical system behavior. The model's application to Setareh Shomal Company yielded sustainability scores of 0.58 (social), 0.61 (environmental), and 0.65 (economic), highlighting strengths in customer satisfaction and operational efficiency and weaknesses in energy consumption and employee safety. Future organizational strategies should prioritize improving workplace conditions, optimizing energy and water usage, and reducing environmental pollutants to achieve balanced and sustainable performance

Keywords:
Sustainability, Paper Industry, Adaptive Neuro-Fuzzy Inference System (ANFIS), Sustainable Production

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*** Corresponding Author:**
Mansour Soufi
Department of Industrial Management, Ra.C., Islamic Azad University, Rasht, Iran
E-Mail: **ms.soufi@iau.ac.ir**

1. Introduction

In recent decades, marked by escalating challenges such as climate change, resource depletion, and social inequality, industries have been compelled to embed sustainability principles into their operations (Kazemi et al., 2024). Beyond traditional financial performance, long-term success and integration into global trade networks now require compliance with technical standards, enhanced competitiveness, attention to environmental indicators, and the promotion of social welfare and development (Soufi et al., 2025; Soltanifar et al., 2022). Although awareness of sustainable development has grown—supported by environmental education and policy initiatives—many industries remain in the early stages of balancing economic, social, and environmental goals, with practical implementation often lagging behind conceptual adoption (Salahi et al., 2023; Attar et al., 2016).

The adoption of sustainable business models is therefore essential for generating effective solutions and tangible benefits for both customers and stakeholders (Homayounfar et al., 2018a,b). Central to this transformation is the integration of environmental requirements into production processes, which fosters cleaner production strategies. Equally important are human resources, operational efficiency, and technological innovation, all of which are pivotal for achieving sustainable production (da Silva Junior et al., 2024; Kharaghani et al., 2024). Research has increasingly emphasized the interconnectedness of sustainability dimensions. Baghersad and Zobel (2021) highlighted the importance of extending operations management beyond environmental and human resource concerns to include stakeholder engagement, while Tang et al. (2023) underscored the need to address economic, social, and environmental pillars simultaneously. Sustainable production thus demands holistic strategies in product design, processes, supply chains, and end-of-life management, ensuring minimized environmental harm, efficient resource use, workplace safety, and long-term viability (Homayounfar et al., 2018c).

These global imperatives are particularly acute in resource-limited contexts such as Iran's wood and paper sector, where sustainability initiatives have focused on raw material optimization, agricultural residue utilization, recycling programs, fast-growing forestry, and cultural awareness campaigns (Chavooshi et al., 2012; Shafieyan et al., 2017; Quintana et al., 2024).

Against this backdrop, systematic sustainability appraisal emerges as a strategic necessity. It not only ensures compliance with international standards but also enhances corporate reputation and competitiveness in global markets increasingly sensitive to environmental performance. For developing economies such as Iran, where paper companies face raw material shortages, outdated technologies, and weak recycling infrastructures, sustainability assessment is more than an environmental safeguard—it is a pathway toward innovation, resilience, and long-term growth. By embedding robust appraisal mechanisms, the industry can transition toward circular economy principles, conserving resources while creating sustainable value for future generations.

This study advances the sustainability literature by addressing critical gaps. First, while environmental, social, and economic dimensions have often been studied independently, few attempts have integrated them into a comprehensive framework tailored to the paper industry. Second, existing research largely depends on generic sustainability indicators, overlooking sector-specific metrics that reflect the unique challenges of this industry. To address this, the present study develops refined, industry-specific indicators that more accurately capture sustainability realities in paper manufacturing. Third, the study introduces the Adaptive Neuro-Fuzzy Inference System (ANFIS) as a novel appraisal methodology rarely applied in this context. Unlike conventional static or linear approaches, ANFIS can model complex, nonlinear relationships, delivering more accurate and dynamic evaluations of sustainability performance. This innovation improves predictive precision, accounts for uncertainty in human judgment, and enhances interpretability for managerial decision-making. Collectively, these contributions establish a robust, data-driven framework that bridges theoretical models of sustainability with practical application, enabling paper companies to benchmark performance, identify weaknesses, and design actionable strategies for long-term competitiveness and resilience.

2. Literature Review

The paper industry, spanning the entire value chain from raw material sourcing to the production of paper, cardboard, and related products, plays a critical role in global economies, especially in resource-constrained contexts such as Iran (Verma et al., 2024). Effective supply chain management is a cornerstone of sustainable development in this sector, as inefficiencies often exacerbate operational and environmental challenges (Saberifard et al., 2024). As argued by Carolin et al. (2023), many of the industry's persistent issues stem from insufficient attention to resilience dimensions, which are vital for balancing economic viability, environmental stewardship, and social responsibility.

Mounting concerns over non-biodegradable pollutants have further intensified the search for eco-friendly and biodegradable alternatives (Teixeira et al., 2025). Among these, nanocellulose has emerged as a promising solution. Derived from natural cellulose—the most abundant biopolymer on Earth with an annual production exceeding 110 million tons—nanocellulose is renewable, biodegradable, and biocompatible. It exhibits superior characteristics such as high tensile strength, stiffness, thermal resistance, and surface reactivity, making it a versatile nanomaterial with applications across industries ranging from papermaking and packaging to healthcare, construction, and electronics (Babaei and Patel, 2025). Recent advances underscore its potential in sustainable packaging, where it improves barrier properties and reduces dependence on petroleum-based plastics. Additionally, agro-industrial residues are increasingly recognized as viable feedstocks for nanocellulose extraction, aligning with circular economy principles while minimizing waste (Wang et al., 2024).

A major challenge, however, lies in securing affordable and sustainable raw materials. Beyond wood, alternative sources such as cotton, flax, hemp, bagasse, ramie, wheat straw, and rice husks have been explored (Teng et al., 2020). Waste streams from wood and paper industries—including MDF residues and recycled paper—also hold significant potential for nanocellulose production (Guan et al., 2021). Given that global paper consumption generates over 400 million tons of waste annually, recycling has become urgent to mitigate impacts such as greenhouse gas emissions, deforestation, and resource depletion (Abaei, 2024). Encouragingly, recycling rates rose from 31 million tons in 1970 to 210 million tons in 2010, reaching a global recovery rate of 57.9% (FAO, 2018). Life cycle assessments further demonstrate that cellulose extraction from fruit and vegetable wastes can significantly lower energy use and environmental footprints (Foroughi et al., 2021).

Nevertheless, waste paper recycling faces inherent limitations: fibres can only be reused 3–4 times (theoretically 6–7) before degradation reduces strength and bonding capacity (Zachariah et al., 2025). These constraints highlight the need for higher-value alternatives such as nanocellulose, ethanol, and organic acids. In papermaking, nanocellulose has already proven effective in enhancing mechanical and barrier properties, allowing paper to compete with synthetic, non-sustainable materials (Balea et al., 2020). These material innovations underscore the growing need for advanced modelling tools to assess their lifecycle sustainability impacts and guide evidence-based decision-making in the paper industry.

At the organizational level, sustainability research emphasized that strategic orientation plays a decisive role. Shou et al. (2019) found that sustainability orientation fosters sustainable supply management (SSM), whereas purely operational orientation can hinder it, yielding mixed performance outcomes. Earlier, Veleva and Ellenbecker (2001) proposed sub-indicators for cleaner production, including certified raw materials, optimized formulations, process controls, cultural alignment, and continuous employee empowerment—factors that significantly improve production sustainability (Carolin et al., 2023).

In Iran, however, the paper industry continues to face deep-rooted challenges: chronic raw material shortages, rising substitution by alternative packaging, limited technical expertise, outdated technologies, obsolete equipment, and financial barriers to modernization (Pourmousa, 2019; Roshanro et al., 2016). Heavy dependence on imports further undermines domestic output, while inadequate recycling infrastructure hampers effective waste paper recovery. To address these issues, recent studies have applied multi-criteria decision-making approaches. For instance, Mehri Charvadeh et al. (2024) employed the VIKOR method to identify and prioritize 11 core components and 30 sub-components for resilient and sustainable cellulose supply chains. Similarly, Mehri Charvadeh and Pourmousa (2023) utilized hybrid methods such as AHP, BWM, and ARAS to rank sustainability priorities, providing valuable insights for strategic planning in the sector.Despite the expanding body of research on sustainability, there remains a notable gap in the application of advanced analytical tools tailored to specific industrial contexts such as the paper industry. Most existing studies rely on conventional assessment methods that struggle to capture the complexity of sustainability dynamics, while the influence of social and cultural factors—particularly in regions like Iran—has been insufficiently addressed in the literature.

This study seeks to bridge these gaps by employing the Adaptive Neuro-Fuzzy Inference System (ANFIS) as a robust framework for sustainability appraisal in the paper industry. ANFIS combines the strengths of fuzzy logic and neural networks, enabling the modelling of complex, nonlinear relationships and accommodating the uncertainty inherent in sustainability evaluations. By overcoming the limitations of traditional linear approaches, it provides a more accurate and dynamic understanding of sustainability performance.

Furthermore, the research explores how socio-economic and cultural conditions in Iran shape organizational sustainability, offering context-sensitive insights that are often overlooked in globalized frameworks. This dual contribution—introducing ANFIS as an advanced appraisal methodology and integrating contextual factors—positions the study as a novel step toward more holistic sustainability evaluation. Ultimately, the findings are expected to support more informed decision-making, foster stakeholder engagement, and guide paper companies in developing adaptive strategies that enhance resilience, competitiveness, and long-term sustainability. Research

3. Methodology

This study aims to assess sustainability of paper production companies employing a mixed-method approach that integrates qualitative and quantitative techniques. Principal component analysis (PCA) was used to identify and refine sustainability indicators specific to the paper industry, while ANFIS was used to assess the sustainability.

The study participants comprise experts from the paper industry and academic specialists in sustainability. Selected experts met the following criteria: (1) at least 15 years of professional experience, (2) a minimum of 5 years in managerial position, (3) a relevant postgraduate degree, and (4) knowledge of sustainability concepts and indicators. Based on these criteria, 13 experts were chosen, including 5 academics and 8 industry professionals.

The sustainability appraisal system for paper companies, focusing on industry-specific indicators, was modeled using ANFIS in MATLAB software. The ANFIS model's key parameters, such as the number of membership functions and the training algorithm, were established through an iterative process that optimized both prediction accuracy and computational efficiency. A backpropagation-based learning algorithm was used to fine-tune the fuzzy inference system's parameters, adjusting membership function parameters during training to reduce the mean squared error (MSE) between predicted and actual resilience values. The Gaussian membership function was selected for its smooth, bell-shaped curve, which effectively models uncertainty and handles imprecise data. This function is particularly suitable for capturing the fuzzy nature of human judgment in assessing sustainability factors. *Fig. 1* illustrated the research framework.

The Adaptive Neuro-Fuzzy Inference System (ANFIS), introduced by Jang (1993), combines the strengths of fuzzy logic and artificial neural networks to create a powerful hybrid system for data-driven modeling (Homayounfar et al., 2018). ANFIS leverages fuzzy if-then rules alongside neural network learning capabilities to map input data to desired outputs efficiently. This approach transforms numerical inputs into outputs through interconnected neural processing units and weighted pathways, offering a flexible and robust framework for handling complex, non-linear relationships

(Arslankaya, 2023). By employing neural network-based learning algorithms, ANFIS dynamically optimizes the parameters of its fuzzy inference system, enhancing prediction accuracy (Daneshvar et al., 2021). The choice of membership functions depends on the problem's characteristics, with this study utilizing Gaussian membership functions due to their smooth, bell-shaped curves, which effectively map crisp inputs to fuzzy sets and capture uncertainty (Govindharaj et al., 2024).

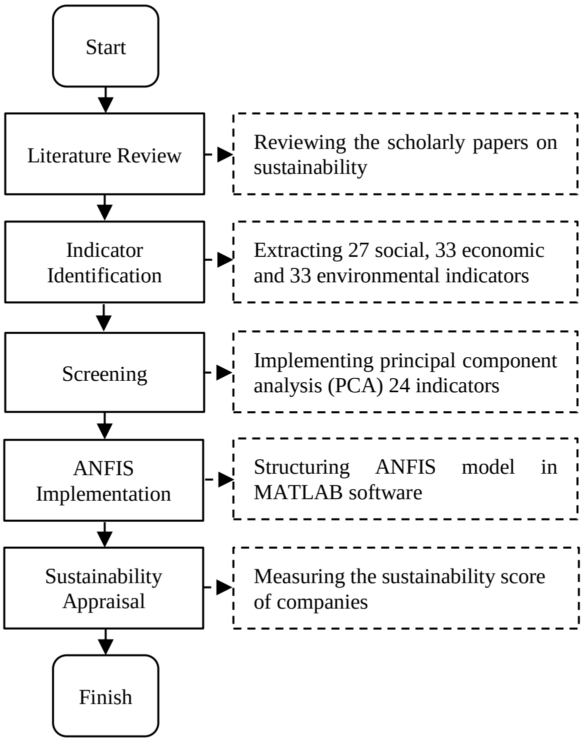


Fig 1.Research framework

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is highly effective due to its ability to handle complex datasets, offer a diverse range of membership functions, provide robust generalization, and enhance interpretability through fuzzy rules. By seamlessly integrating linguistic and numerical information, ANFIS facilitates efficient problem-solving across various applications (Ghasemi Hamedan et al., 2025). The architecture of ANFIS, consisting of six operational layers, is detailed below, with each layer contributing to the system's ability to map inputs to outputs accurately. The six-layer structure of ANFIS, as described by Ghasemi Hamedan et al. (2025), ensures precise processing of input data through fuzzy logic and neural network principles:

Layer 1: This layer consists of input nodes that receive raw input variables and pass them directly to the next layer without any processing. It serves as the entry point for data into the ANFIS system, facilitating seamless data transfer to subsequent layers.

Layer 2: Fuzzification occurs in this layer, where input variables from the first layer are mapped to fuzzy sets using adjustable membership functions. Each node computes the membership degree of the inputs, denoted as Eq. (1). Common membership functions include triangular, trapezoidal, generalized bell, and Gaussian, with the latter preferred for its smooth, bell-shaped curve that effectively models uncertainty (Ghasemi Hamedan et al., 2025).

$$O_{2,i} = \mu_{A_i}(x) \qquad O_{2,j} = \mu_{B_i}(y) \tag{1}$$

Layer 3: This layer, also known as the product layer, *represents* the fuzzy rules. Each node, labeled with the product operator (Π\PiΠ), computes the firing strength of a rule by multiplying the membership degrees from the fuzzy layer, as shown in Eq. (2). This calculates the weight of each rule based on the input variables.

$$w_i = \mu_{A_i}(x)\mu_{B_i}(y) \ldots \tag{2}$$

Layer 4: In this layer, the firing strengths from the rule *layer* are normalized. Each node calculates the normalized firing strength for a rule by dividing its firing strength by the sum of all firing strengths, as given by Eq. (3). This ensures that the contribution of each rule is proportional to the total firing strength.

$$\overline{w}_i = \frac{w_i}{\sum_{n=1}^{k} w_k} \tag{3}$$

Layer 5: This layer computes the weighted output for each rule. Each node multiplies the normalized firing strength ($\overline{w}_i$) by the rule's output function, typically a linear combination of inputs, as expressed in Eq. (4), where p_i, q_i, and r_i are adjustable parameters of the Takagi-Sugeno fuzzy system.

$$O_{4i} = \overline{w}_i f_i = \overline{w}_i(p_i x + q_i y + r_i) \tag{4}$$

Layer 6: The final layer aggregates all weighted outputs from the defuzzification layer to produce the system's overall output. The output is computed as Eq. (5), representing the final crisp output of the ANFIS model.

$$f_{cikis} = \sum_{i=1}^{n} \overline{w}_i f_i = \sum_{i=1}^{n} \overline{w}_i\,(p_i x + q_i y + r_i) \tag{5}$$

4. Results and Discussion

To develop, validate and use the ANFIS model within the practical context of paper industry, the group of experts was asked to participate in analytical phase. In this research, sustainability indicators first identified through a qualitative method, and listed in Table (1).

Table 1
Main indicators of organizational sustainability

	Indicators	Authors
Social	Employee training and development	Alfi et al., 2022; Homayounfar et al., 2018a; Saberifard et al., 2024; Alfi et al., 2023; Kamali Chirani and Homayounfar, 2023
	Employee satisfaction	
	Customer satisfaction	
	Corporate accountability	
	Employee exposure to chemicals	
Environmental	Energy consumption rate	Soufi et al., 2025; Soltanifar et al., 2022; Fadaei Eshkiki and Homayounfar (2024), Alfi et al., 2022; Alfi et al., 2023; Homayounfar et al., 2018b; Attar et al., 2016; Razavinasab et al., 2024; Shafieyan et al., 2017
	Energy waste reduction	
	Hazardous waste management	
	Recyclability capability	
	Reduction of environmental pollutants	
	Use of recycled materials	
	Sludge management	
	Air pollution	
	Use of greywater	
	Wood consumption rate	
Economic	Production cost	Shafieyan et al., 2017; Alfi et al., 2022; Salahi et al., 2023; Alfi et al., 2023; Kharaghani et al., 2023;
	Paper price	
	Company profitability	
	Operational efficiency	
	Paper Quality	
	Akhal Price	

	Machine breakdown and downtime	
	Revenue from by-products	
	Recycling costs	

The research process is described in following:

4.1. System configuration

- *Defining input variables*

According to the classification indices presented in Table (1), the sustainability system is defined with three input dimensions—social sustainability, environmental sustainability, and economic sustainability—and one output dimension, namely organizational sustainability. The structure of the main fuzzy system is presented in *Fig. 2*. As previously mentioned, the main fuzzy system considers three inputs, based on them rules have been defined.

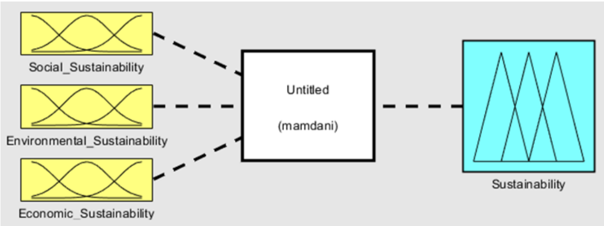
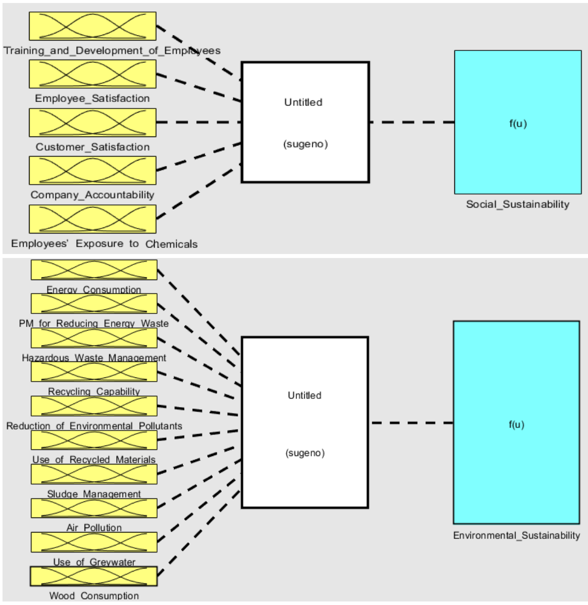


Fig 2. Structure of the main FIS model

The social sustainability input is characterized by factors such as employee training and development, employee satisfaction, customer satisfaction, corporate accountability, and employee exposure to chemicals.

The environmental sustainability input is determined by indicators including energy consumption, preventive maintenance planning for energy efficiency, hazardous waste management, recycling capability, reduction of environmental pollutants, use of recycled materials, sludge management, air pollution, utilization of greywater, and wood consumption.

The economic sustainability input is measured through factors such as production cost per ton of paper, product pricing, company profitability, operational efficiency, paper quality, cost of recycled paper procurement, breakdown and downtime rates, revenue from by-products, and recycling costs. The structures of the sub-FISs are illustrated in *Fig. 3*.



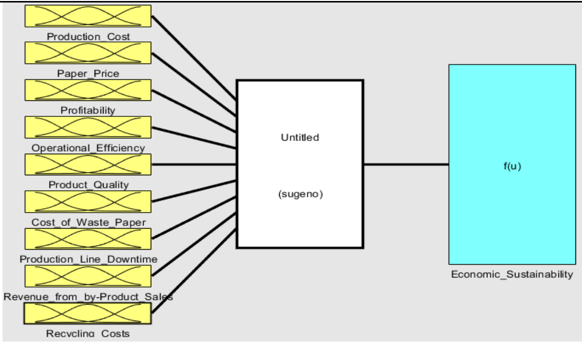


Fig 3. Structure of the Sub- FISs indicators

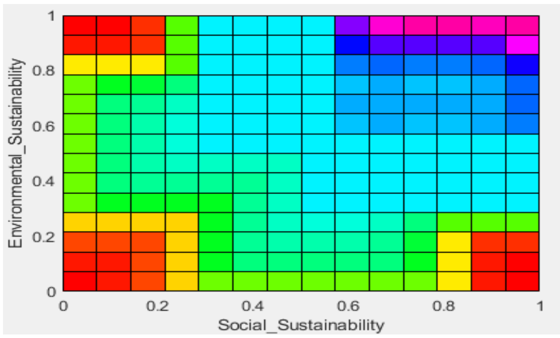
- Defining membership functions

In this study, among the various available membership functions, the *Gaussian function* was selected for all input and output variables. This choice ensures differentiability, which is essential for the Adaptive Neuro-Fuzzy Inference System (ANFIS), given the continuous nature of the input and output data. Linguistic terms were defined as *Very Low (VL), Low (L), Medium (M), High (H),* and *Very High (VH)*, with numerical values specified within the normalized range of [0, 1]. It should be emphasized that the range of variation for both input and output variables was determined using a *Likert scale* derived from the questionnaire responses.

- *Setting* fuzzy rules

During the rule-generation stage, fuzzy rules were developed to represent the relationships between different combinations of input and output variables. Based on the number of membership functions assigned to each input, the total possible rules can be calculated. For example, in the main fuzzy inference system (FIS) designed in this study, three dimensions of sustainability (social, environmental, and economic), each with five membership functions, theoretically yield 5×5×5=125 rules. However, guided by expert judgment, the final model included 49 rules, which were implemented in MATLAB. The user interface developed for the main FIS allows prediction values to be obtained by manually entering input variables, as shown in *Fig. 4*. The general structure of the fuzzy rules follows the template below:

If Social Sustainability = "..." and Environmental Sustainability = "..." and Economic Sustainability = "...", Then Organizational Sustainability = "...".



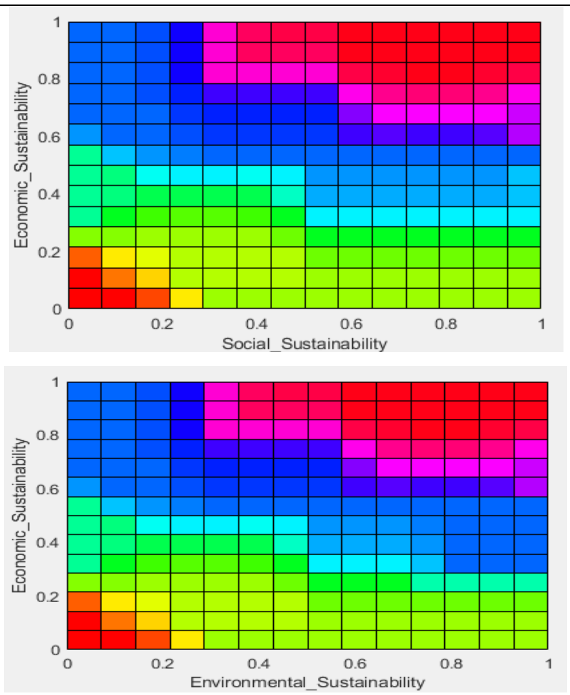


Fig 4 .Graphical view of the FIS rules

4.2. *ANFIS model development*

- *Model Structuring*

Structure of the ANFIS network is composed of nodes and interconnecting links that map the model's input variables to its output. The output of each node is determined by the parameters associated with it, while a learning rule governs the adjustment of these parameters during the training process. According to the research framework, four distinct ANFIS structures were developed and fitted to the data. The configuration of the sustainability's ANFIS architecture and Dimensions' ANFIS architectures are illustrated in *Fig. 5*.

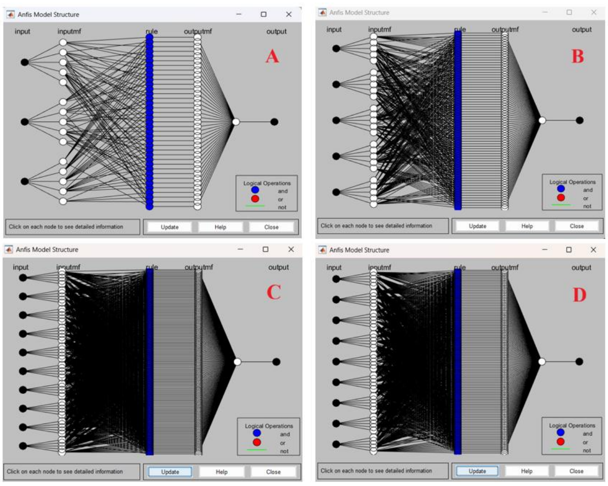


Fig. 5. ANFIS structures: (A) Sustainability, (B) Social sustainability, (C) Environmental sustainability, and (D) Economic sustainability

In the *Fig 5*, section B illustrates the structure of the ANFIS for social sustainability, which is designed with five inputs. Section (C) presents the ANFIS structure for environmental sustainability, comprising ten inputs. Finally, section (D) shows the ANFIS structure for economic sustainability, which includes nine inputs.

- *Data gathering*

To train the Fuzzy Inference System (FIS), a structured questionnaire was designed based on the dimensions of sustainability and their corresponding indicators. Senior managers, department heads, and employees involved in the organizational processes of Chouka Company, Setareh Shomal, Delta Cellulose Sefidrud, and the Gilan Khazar Cooperative Paper Company were invited to complete the questionnaire. Responses were collected using a five-point Likert scale, ranging from "Strongly Disagree" (1) to "Strongly Agree" (5). In total, 144 qualified respondents participated, including 5 senior managers, 17 department heads, and 122 employees actively engaged in organizational processes. The dataset was then divided into three subsets: 70% for training, 15% for testing, and 15% for validation.

- *Training the system*

In the first stage, the ANFIS model was trained using a supervised learning approach based on data from 110 completed questionnaires. This procedure gradually reduced the training error, optimized most of the initial membership functions, and integrated them into the ANFIS structure. To update the parameters of the membership functions, a hybrid learning method was applied, combining backpropagation with the least squares estimator (LSE) to improve computational efficiency. Because error variation is directly proportional to error magnitude, this measure was used as the stopping criterion for the training process. After 60 training epochs, both the main ANFIS model and the Sub-ANFIS models achieved an acceptable error threshold. The error rates calculated for the ANFIS model in the training, testing, and validation phases are summarized in Table (2):

Table 2
Calculated MSE

ANFIS Model	Training Error $(\times 10^{-3})$	Testing Error $(\times 10^{-3})$	Validation Error $(\times 10^{-3})$
Social Sustainability	3.41	2.02	1.77
Environmental Sustainability	0.97	0.85	0.54
Economic Sustainability	1.88	2.64	1.39

- *Model Validation and Testing*

To validate the model, the generalization capability of the fuzzy inference system was assessed, with particular attention to the risk of overfitting. Comparative graphs of predicted versus actual values for the training and validation datasets across all ANFIS structures demonstrate strong alignment, confirming the model's reliability.
As shown in the *Figs. 6* and 7, the alignment of the testing and validation data with the results of the main ANFIS system has been confirmed. The calculated error rates for these datasets were 0.00163 and 0.00097, respectively. Model validation and testing were also carried out for all three ANFIS subsystems in order to optimize the weights of fuzzy rules, enhance model accuracy based on input–output relationships, and establish a more robust index for assessing sustainability.

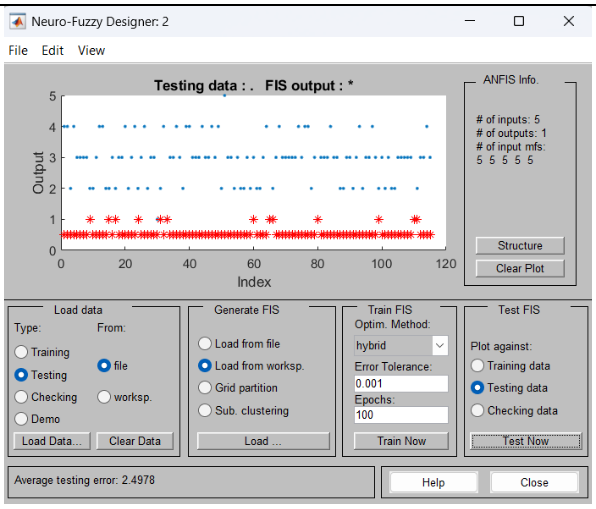


Fig 6.Comparison between ANFIS output and testing data

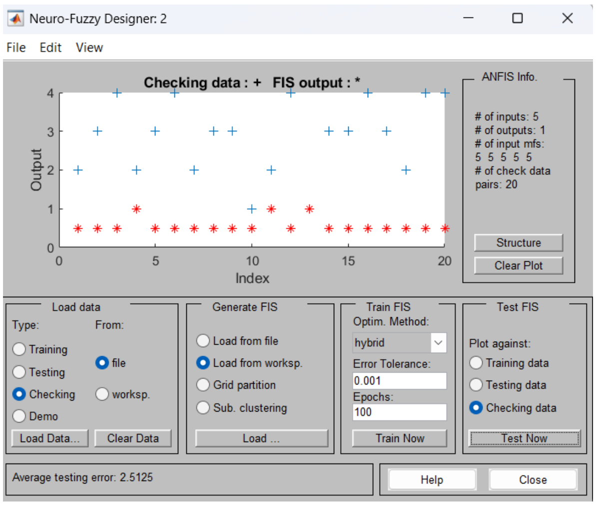


Fig 7.Comparison between ANFIS output and validation data

In addition, to examine the behavior of the model, a boundary condition test was performed. In this test, the designed FIS was evaluated under different extreme conditions (low, medium, and high), and the sensitivity of the model to input variations was analyzed. In this study, it was assumed that input values fall within the normalized range of 0 to 1. The boundary condition test for the main FIS illustrated in Table (3), which exhibits logical behavior in response to input variations.

Table 3
Extreme conditions test

Type	Indicator	Minimum	Mean	Maximum
Input	Social Sustainability	0.000	0.500	1.000
	Environmental Sustainability	0.000	0.500	1.000
	Economic Sustainability	0.000	0.500	1.000
Output	Organizational Sustainability	0.00178	0.506	0.994

For all three sub-FISs, this test was implemented, showing logical behavior.

4.3. Evaluation of sustainability

In this stage, the trained ANFIS model was applied to evaluate organizational sustainability using real data. For implementation, a questionnaire based on sustainability indicators was designed and distributed among industry experts. The questionnaire employed a normalized 0–1 scale to facilitate the assessment of organizational sustainability. Responses were aggregated and normalized using the geometric mean and then entered as inputs into the ANFIS subsystems. The outputs from these subsystems were subsequently fed into the main ANFIS model, which generated the final organizational sustainability score (see Table 4).

Table 4
Sustainability appraisal for Setareh Shomal company

Dim.	Indicators	Score	Score
Social	Employee training and development	0.62	0.58
	Employee satisfaction	0.54	
	Customer satisfaction	0.73	
	Corporate accountability	0.65	
	Employee exposure to chemicals materials	0.49	
Environmental	Energy consumption rate	0.44	0.61
	Energy waste reduction	0.70	
	Hazardous waste management	0.68	
	Recyclability capability	0.77	
	Reduction of environmental pollutants	0.48	
	Use of recycled materials	0.66	
	Sludge management	0.65	
	Air pollution	0.47	
	Use of greywater	0.40	
	Wood consumption rate	0.79	
Economic	Production cost	0.57	0.65
	Paper price	0.68	
	Company profitability	0.70	
	Operational efficiency	0.75	
	Paper Quality	0.72	
	Akhal Price	0.61	
	Machine breakdown and downtime rate	0.60	
	Revenue from by-products	0.42	
	Recycling costs	0.58	

According to Table (4), the model incorporates three main input dimensions, each consisting of multiple indicators that ultimately contribute to the overall sustainability score.
In the social dimension, the total score was 0.58, reflecting a moderate level of sustainability. Among the indicators, customer satisfaction (0.73) and corporate responsiveness (0.65) performed relatively well, underscoring the company's emphasis on external stakeholder relations. By contrast, employee exposure to chemicals and bleaching agents (0.49) and employee satisfaction (0.54) highlight ongoing challenges in improving workplace health and working conditions. Thus, while external relations appear comparatively stronger, greater attention is required to support and protect human capital.
In the environmental dimension, the score reached 0.61, which is slightly higher than the social dimension. Strengths include recycling capacity (0.77) and wood consumption management (0.79), indicating efforts to reduce pressure on natural resources. Hazardous waste management (0.68) and use of recycled materials (0.66) also received satisfactory scores. However, weak performance was recorded for energy consumption (0.44), pollution reduction (0.48), air pollution control (0.47), and especially gray water utilization (0.40). These results reveal that although the company demonstrates progress in raw material management and recycling,

significant gaps remain in energy efficiency, pollution control, and water resource management.

In the economic dimension, the highest overall score of 0.65 was achieved, suggesting relatively stronger performance compared to the other two dimensions. Indicators such as operational efficiency (0.75), profitability (0.70), and product quality (0.72) reflect effective production management and solid economic outcomes. Nonetheless, weaknesses persist in revenue from by-products (0.42) and recycling costs (0.58), pointing to the need for stronger innovation strategies in value creation and more efficient management of environmental costs (see *Fig. 8*)

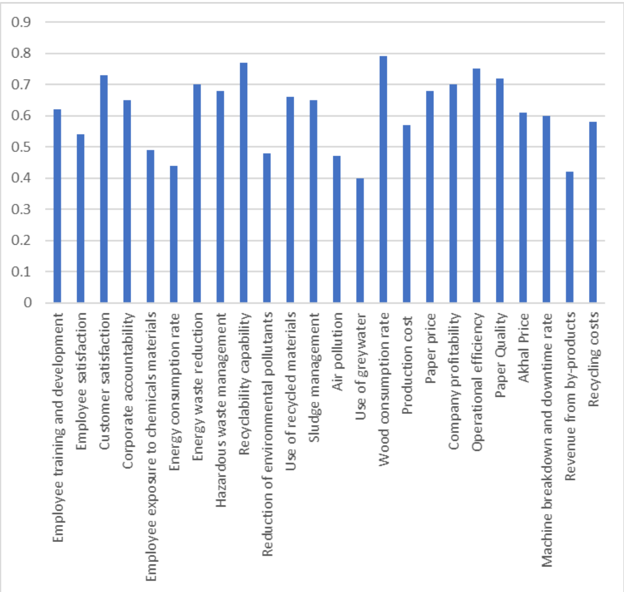


Fig. 8. Sustainability indicators diagram

In summary, the company's overall sustainability score was calculated as 0.63, indicating a moderate yet acceptable level of progress toward sustainable development. A comparison of the three dimensions shows that the company performed strongest in the economic domain and weakest in the social domain. Accordingly, it is recommended that future organizational efforts prioritize improving working conditions and employee health, optimizing energy and water consumption, and reducing environmental pollutants, in order to achieve greater balance across the three core pillars of sustainability.

5. Conclusion

This study employed an ANFIS model to evaluate sustainability in the paper industry. The findings indicate that human capital is a strategic priority, as the development of employees' skills and capabilities exerts the greatest impact on maintaining and enhancing sustainable performance. Following this, the indicators of wood consumption and corporate accountability ranked second in importance. The high significance of wood consumption, as the primary raw material in the paper industry, highlights natural resource and raw material management as critical concerns in sustainability assessment. Meanwhile, corporate accountability holds a prominent position within the social dimension, underscoring the necessity of transparency, responsibility, and stakeholder engagement.

In subsequent rankings, indicators such as employee satisfaction and company profitability emerge, illustrating the direct link between workforce motivation and economic sustainability. By contrast, indicators like air pollution and revenue from by-products occupy the lower end of the rankings. This suggests that, although these indicators possess intrinsic importance for sustainability, decision-makers within the company assign them lower priority compared to issues related to human and economic resources. A noteworthy observation is that most economic and social indicators occupy higher levels of importance, whereas certain environmental indicators—such as greywater use and energy consumption—receive less attention. This trend may reflect a short-term emphasis on economic and human factors alongside a relative neglect of environmental dimensions. However, such an approach may, in the long run, pose significant risks to the company's overall sustainability.

Practically, managers can use the ANFIS-based assessment to benchmark organizational performance against industry standards, set measurable sustainability goals, and monitor progress over time. This approach supports strategic planning by aligning sustainability initiatives with organizational objectives, ultimately enhancing competitiveness and stakeholder trust.

This study has several limitations. It relied on qualitative assumptions and a limited dataset, which may constrain the accuracy of its projections. All three dimensions of sustainability were treated with equal weight, even though firms may prioritize them differently. The simulation horizon was restricted to 60 months, potentially overlooking long-term dynamics. Moreover, factors such as organizational resistance, implementation risks, and external shocks were not explicitly modeled.

Future research should aim to integrate richer quantitative data, extend the time horizon, and incorporate stakeholder heterogeneity to capture more realistic dynamics. Expanding the model to different industries or regional contexts could also provide deeper insights into the adoption and effectiveness of sustainability strategies.

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