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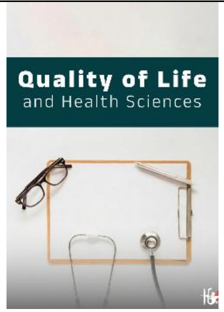

Explainable XGBoost Modeling of Quality of Life Among Patients with Fibromyalgia Using Pain, Sleep, and Psychological Flexibility Variables

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ABSTRACT

Objective: This study aimed to develop and interpret an explainable XGBoost model for predicting quality of life among patients with fibromyalgia based on pain intensity, sleep quality, psychological flexibility, and relevant demographic and clinical variables.

Methods and Materials: This cross-sectional predictive modeling study was conducted among 318 patients with fibromyalgia receiving services from rheumatology and pain management clinics in Tehran, Iran. Data were collected using a demographic and clinical information form, the Short Form Health Survey for quality of life, the Visual Analog Scale for pain intensity, the Pittsburgh Sleep Quality Index for sleep quality, and the Acceptance and Action Questionnaire-II for psychological flexibility. After data screening and preprocessing, quality of life was considered the continuous outcome variable. Predictive modeling was performed using XGBoost regression, and model performance was compared with linear regression, support vector regression, and random forest regression. Model accuracy was evaluated using mean absolute error, root mean square error, coefficient of determination, and cross-validation. SHAP analysis was used to explain the final XGBoost model.

Findings: Correlation analysis showed that quality of life was significantly and negatively associated with pain intensity ($r = -0.58$, $p < 0.01$) and poor sleep quality ($r = -0.52$, $p < 0.01$), while it was significantly and positively associated with psychological flexibility ($r = 0.49$, $p < 0.01$). The XGBoost model demonstrated the strongest predictive performance, with a test MAE of 7.84, test RMSE of 10.18, test R^2 of 0.66, and cross-validated R^2 of 0.63. SHAP analysis identified pain intensity as the most influential predictor, followed by poor sleep quality and psychological flexibility.

Conclusion: The findings indicated that quality of life among patients with fibromyalgia can be predicted with acceptable accuracy using an explainable XGBoost model, with pain intensity, sleep quality, and psychological flexibility emerging as the most important predictors.

Keywords: *Fibromyalgia; Quality of Life; XGBoost; Explainable Artificial Intelligence; Pain Intensity; Sleep Quality; Psychological Flexibility.*

1. Introduction

Fibromyalgia is a chronic and complex pain condition characterized by persistent widespread pain, fatigue, sleep disturbance, cognitive complaints, emotional distress, and reduced functional capacity. Its clinical significance extends beyond the presence of pain alone, because patients frequently experience a multidimensional burden that affects daily activity, social participation, occupational functioning, psychological well-being, and overall quality of life. Contemporary perspectives increasingly conceptualize fibromyalgia as a heterogeneous condition in which biological, psychological, behavioral, and contextual factors interact to shape symptom severity and functional outcomes. This biopsychosocial understanding is particularly important because many patients with fibromyalgia present with overlapping symptom clusters rather than a single dominant clinical complaint. The heterogeneity of fibromyalgia has been emphasized in research identifying subgroups of patients based on physical symptoms and cognitive-affective variables related to pain, suggesting that different patients may experience distinct pathways toward disability and quality-of-life impairment (Pilar Martínez Narváez-Cabeza de et al., 2021). Similarly, broader work on chronic pain psychology in neurology practice highlights that chronic pain conditions require assessment models that integrate sensory, emotional, cognitive, and behavioral dimensions rather than limiting clinical interpretation to nociceptive intensity alone (Serdarević, 2024).

Quality of life is one of the most clinically meaningful outcomes in fibromyalgia because it reflects the cumulative effect of pain, impaired sleep, psychological distress, physical limitations, and social disruption. Although pain is the most visible feature of fibromyalgia, quality of life is not determined only by the magnitude of pain. Patients with similar pain intensity may differ substantially in functioning, emotional adjustment, sleep restoration, and ability to remain engaged in valued activities. This variability indicates that quality of life should be examined through integrated models capable of capturing nonlinear and interactive relationships among symptom and psychological variables. Research in chronic pain populations has shown that pain intensity is strongly associated with diminished quality of life, but this relationship is often shaped by cognitive and emotional processes such as catastrophizing, emotional regulation, and coping capacity (Anagnostopoulos et al., 2022). In fibromyalgia, this issue is especially relevant because the syndrome commonly involves central sensitization, emotional distress, fatigue, and reduced restorative sleep, all of which may amplify the perceived burden of pain and reduce adaptive functioning (Galvez-Sánchez et al., 2021).

Pain remains a central determinant of health-related quality of life among individuals with fibromyalgia. The persistent and widespread nature of fibromyalgia pain disrupts movement, reduces physical activity, interferes with social and occupational roles, and increases psychological strain. Recent consensus and review literature emphasizes that therapeutic approaches to fibromyalgia should combine pharmacological and non-pharmacological strategies, reflecting the complexity of symptom mechanisms and the limitations of relying on a single treatment pathway (Devigili et al., 2025). The continued attention to controversies in fibromyalgia diagnosis, mechanisms, and management also shows that the condition remains clinically challenging and requires refined approaches to assessment and intervention planning (Ablin & Sarzi-Puttini, 2024). Non-pharmacological interventions for pain relief have gained increased attention because many patients require long-term strategies that address both pain reduction and functional restoration (Wang et al., 2025). Evidence from rehabilitation and nonpharmacological intervention research further supports the importance of exercise, education, behavioral strategies, and multidisciplinary care in improving fibromyalgia-related outcomes (Kundakci et al., 2021; Pathak et al., 2023).

Sleep disturbance is another core feature of fibromyalgia and a major contributor to diminished quality of life. Many patients report non-restorative sleep, insomnia symptoms, frequent awakenings, daytime fatigue, and reduced energy. Sleep problems may worsen pain sensitivity, impair emotional regulation, increase fatigue, and reduce the capacity for daily activity. In chronic pain populations, insomnia and poor sleep quality are not merely consequences of pain but may also intensify pain and delay recovery, creating a reciprocal cycle of symptom amplification (Sipilä & Kalso, 2021; Wiklund, 2021). Systematic review evidence on non-pharmacological sleep interventions for people with chronic pain indicates that sleep-focused strategies may have value for improving both sleep and pain-related outcomes (Whale et al., 2022). Acceptance and commitment therapy has also been investigated in relation to insomnia and sleep quality, suggesting that psychological flexibility-based interventions may influence sleep outcomes through changes in avoidance, distress tolerance, and acceptance of difficult

internal experiences (Salari et al., 2020). In fibromyalgia specifically, resistance training and broader exercise-based approaches have been reviewed as potential strategies for improving sleep and symptom management (Ana Cecília Rosatelli de Freitas et al., 2023; Silva et al., 2024). Although evidence from other clinical populations, such as epilepsy, also supports the role of exercise in sleep improvement, its relevance to fibromyalgia lies in the broader principle that physical and behavioral interventions can influence sleep regulation and health functioning (Mueller et al., 2024).

Psychological flexibility is increasingly recognized as a key psychological process in chronic pain and fibromyalgia. Psychological flexibility refers to the ability to remain open to unpleasant internal experiences, such as pain, fatigue, anxiety, or negative thoughts, while continuing to act in accordance with personal values. In chronic pain, psychological inflexibility and experiential avoidance can intensify disability by narrowing behavioral repertoires, increasing fear-based avoidance, and reducing engagement in meaningful activity. Meta-analytic evidence indicates that psychological flexibility and inflexibility are associated with important outcomes among chronic pain patients, including emotional distress, disability, pain interference, and quality of life (Fang & Ding, 2022). New-generation psychological treatments in chronic pain increasingly emphasize acceptance, mindfulness, values-based action, and flexible responding rather than exclusive attempts to eliminate pain sensations (McCracken et al., 2022). These approaches are particularly relevant to fibromyalgia because complete symptom elimination is often difficult, whereas improved functioning and quality of life may be achieved by modifying the relationship between patients and their symptoms.

Acceptance and commitment therapy and related approaches have gained prominence in fibromyalgia and chronic pain research because they directly target psychological flexibility. Evidence suggests that acceptance and commitment therapy may be effective in central pain sensitization syndromes, where symptom burden is maintained by complex interactions between pain processing, emotional distress, behavioral avoidance, and reduced activity engagement (Galvez-Sánchez et al., 2021). Systematic reviews and meta-analyses have examined cognitive-behavioral therapy and acceptance and commitment therapy for anxiety and depression among patients with fibromyalgia, supporting the relevance of psychological interventions in addressing the emotional burden of the condition (Cojocaru et al., 2023). The contribution of psychologists in fibromyalgia assessment and treatment has also been emphasized, particularly in relation to identifying maladaptive pain responses, emotional difficulties, and behavioral patterns that contribute to reduced functioning (Luciano et al., 2023). Mindfulness-based strategies and mind-body interventions have similarly been described as relevant symptom management approaches for fibromyalgia, especially because they may influence pain perception, stress reactivity, emotional regulation, and quality of life (Gordon et al., 2022; Islam et al., 2022).

The increasing availability of digital and remote interventions has further expanded the treatment landscape for fibromyalgia and chronic pain. Telerehabilitation has been investigated for fibromyalgia and may provide accessible strategies for symptom management, exercise guidance, and continuity of care, especially for patients who face mobility limitations or barriers to in-person services (Wu et al., 2023). E-health interventions targeting pain-related psychological variables have also been systematically reviewed, indicating growing interest in technology-supported approaches for addressing psychological and behavioral mechanisms in fibromyalgia (Donisi et al., 2023). Digital acceptance and commitment therapy protocols for fibromyalgia reflect this shift toward scalable, self-guided, and personalized care models that target psychological flexibility and symptom adaptation (Gallego et al., 2024). Internet-delivered acceptance and commitment therapy has also shown relevance for chronic pain management, including models designed as microlearning interventions with extended follow-up (Rickardsson et al., 2021). Related evidence from internet-delivered acceptance and commitment therapy in cancer populations and digital behavioral therapy in axial spondyloarthritis demonstrates that remote psychological and behavioral treatments may improve outcomes across chronic illness contexts marked by persistent symptoms and reduced quality of life (García-Torres et al., 2024; Kiefer et al., 2025). These developments strengthen the rationale for identifying which symptom and psychological variables most strongly predict quality of life, because such information can guide individualized and digitally supported intervention planning.

Despite substantial evidence regarding pain, sleep, and psychological factors in fibromyalgia, there remains a methodological need for predictive models that can estimate quality of life while also explaining the relative contribution of each predictor. Traditional statistical models are useful for

testing linear associations, but they may be limited when relationships are nonlinear, threshold-based, or dependent on interactions among variables. Fibromyalgia is particularly suited to advanced predictive modeling because pain, sleep, psychological flexibility, illness duration, demographic factors, and comorbidity may jointly influence quality of life in complex ways. Explainable machine learning approaches can address this issue by combining predictive accuracy with interpretability. XGBoost is a gradient boosting algorithm capable of capturing nonlinear patterns and interaction effects, while explainability methods such as SHAP can clarify how each variable contributes to individual and overall predictions. This is especially important in clinical research, where prediction alone is insufficient unless the model also provides interpretable information that can inform assessment, treatment prioritization, and patient-centered care.

The need for integrative predictive modeling is also supported by the broader literature on multicomponent and self-management approaches to fibromyalgia. Multicomponent interventions have been evaluated against other therapeutic approaches, reflecting the understanding that fibromyalgia management usually requires simultaneous attention to physical, psychological, and behavioral domains (Araya-Quintanilla et al., 2025). Evidence-based self-management strategies provide a foundation for digital therapeutic applications and emphasize the importance of active patient involvement in symptom monitoring, behavior change, pacing, and coping skill development (Foustoukos et al., 2024). Emerging integrative medicine approaches also encourage multimodal disease management, combining conventional care with behavioral, psychological, lifestyle, and complementary strategies when appropriate (Carlson et al., 2025). In related chronic health conditions, psychological interventions have shown potential for improving symptom-related distress and functioning, as observed in endometriosis and cancer populations, further reinforcing the relevance of psychological adaptation in quality-of-life outcomes (Jiang et al., 2024; Pino-Sedeño et al., 2024). Stress-related mechanisms are also relevant because chronic illness and persistent pain can interact with physiological and emotional stress systems, contributing to symptom persistence and functional decline (D'Andre et al., 2024). Moreover, research on hypermobility spectrum disorders demonstrates that chronic musculoskeletal and pain-related conditions often have broad biopsychosocial effects, including physical limitation, emotional burden, and social disruption, which parallels many challenges experienced by patients with fibromyalgia (Clark et al., 2023).

Taken together, the existing literature suggests that pain intensity, sleep quality, and psychological flexibility are theoretically and clinically important determinants of quality of life among patients with fibromyalgia. However, most previous studies have relied on conventional associative designs or intervention-focused outcomes, leaving a gap in the use of explainable machine learning models that can predict quality of life and simultaneously identify the most influential predictors. An explainable XGBoost approach can provide clinically useful information by estimating the relative importance and directional influence of pain, sleep, psychological flexibility, and related covariates. Such an approach may help clinicians identify patients at greater risk of poor quality of life, prioritize intervention targets, and support more personalized care planning. Therefore, the aim of this study was to develop and interpret an explainable XGBoost model for predicting quality of life among patients with fibromyalgia in Tehran using pain intensity, sleep quality, psychological flexibility, and relevant demographic and clinical variables.

2. Methods and Materials

2.1. Study Design and Participants

This study was conducted using a cross-sectional predictive modeling design to examine the extent to which pain, sleep quality, and psychological flexibility variables could predict quality of life among patients with fibromyalgia through an explainable XGBoost approach. The study population consisted of adult patients with fibromyalgia who were receiving diagnostic or follow-up services in rheumatology and pain management clinics in Tehran, Iran. A total of 318 patients with fibromyalgia participated in the study. Participants were selected through convenience sampling from specialized outpatient clinics in Tehran after confirmation of eligibility based on the study criteria. Inclusion criteria were being 18 years of age or older, having a confirmed diagnosis of fibromyalgia by a rheumatologist according to accepted clinical criteria, having at least six months of illness duration, being able to read and complete the questionnaires independently, and providing informed consent to participate in the study. Patients were excluded if they had severe neurological disorders, active inflammatory rheumatic disease, uncontrolled psychiatric disorders requiring urgent intervention, severe cognitive impairment, or incomplete

questionnaire data that could not be handled through the planned data preprocessing procedures. Before data collection, the objectives of the study were explained to all participants, and they were assured that participation was voluntary and that their information would remain confidential. The final dataset included demographic and clinical information as well as standardized measures of quality of life, pain intensity, sleep quality, and psychological flexibility, which were used for statistical analysis and machine learning modeling.

2.2. Measures

Demographic and clinical information was collected using a researcher-developed form designed to record the background characteristics of the participants. This form included age, gender, marital status, educational level, employment status, duration of fibromyalgia, medication use, history of comorbid chronic disease, and frequency of clinical visits. These variables were collected to describe the sample and to provide additional contextual information for interpreting the quality of life profile of patients with fibromyalgia. Clinical information was obtained through patient self-report and review of available medical records when necessary. The demographic and clinical form was reviewed by specialists in health psychology and rheumatology to ensure that the collected information was relevant to the aims of the study.

Quality of life was assessed using the Short Form Health Survey, which is one of the most widely used standardized instruments for evaluating health-related quality of life in clinical populations. The questionnaire evaluates different dimensions of physical and mental health, including physical functioning, role limitations due to physical problems, bodily pain, general health, vitality, social functioning, role limitations due to emotional problems, and mental health. Items are scored according to the standard scoring procedure, and higher scores indicate better perceived quality of life and health functioning. In the present study, the total transformed quality of life score was used as the main outcome variable for XGBoost modeling. The use of this instrument was appropriate because fibromyalgia affects both physical and psychological domains of functioning, and the scale provides a comprehensive estimate of health-related quality of life. The Persian version of the questionnaire has been used in previous health-related studies and has demonstrated acceptable validity and reliability.

Pain intensity was measured using the Visual Analog Scale for pain. This instrument consists of a continuous line ranging from no pain to the worst imaginable pain, on which participants indicate the average intensity of pain they experienced during the previous week. The score is usually converted into a numerical value from 0 to 10 or 0 to 100, with higher scores representing greater pain intensity. In this study, pain intensity was entered into the predictive model as one of the main clinical predictors because persistent widespread pain is a central feature of fibromyalgia and is strongly associated with reduced physical functioning, emotional distress, and impaired quality of life. The Visual Analog Scale has been widely used in chronic pain research and has shown acceptable sensitivity for assessing perceived pain severity.

Sleep quality was assessed using the Pittsburgh Sleep Quality Index. This questionnaire evaluates subjective sleep quality during the previous month and includes components related to sleep duration, sleep latency, sleep disturbances, habitual sleep efficiency, use of sleep medication, daytime dysfunction, and overall subjective sleep quality. The total score reflects global sleep quality, with higher scores indicating poorer sleep quality. Because sleep disturbance is one of the most common and disabling symptoms among patients with fibromyalgia, the Pittsburgh Sleep Quality Index was selected as a key predictor in the present study. Poor sleep may intensify pain perception, increase fatigue, reduce emotional regulation capacity, and contribute to lower quality of life. The Persian version of this questionnaire has been used in clinical and non-clinical populations and has demonstrated satisfactory psychometric properties.

Psychological flexibility was measured using the Acceptance and Action Questionnaire-II. This instrument assesses the degree to which individuals are able to remain in contact with difficult internal experiences, such as pain, distress, fear, and negative thoughts, while continuing to engage in meaningful and value-based actions. The questionnaire contains items scored on a Likert-type scale, and higher scores generally reflect greater psychological inflexibility or experiential avoidance, depending on the scoring direction used. In the present study, scores were interpreted so that higher psychological flexibility represented better adaptive functioning after reverse scoring where necessary. Psychological flexibility was included as a psychological predictor because fibromyalgia is not only characterized by physical symptoms but also by the patient's ability to cope with persistent discomfort, tolerate

unpleasant internal experiences, and maintain meaningful activities despite pain. The scale has been widely applied in studies based on acceptance and commitment therapy and has shown acceptable validity and reliability in previous research.

2.3. Data Analysis

Data analysis was conducted in two main stages, including conventional statistical preprocessing and machine learning-based predictive modeling. Initially, the collected data were examined for accuracy, missing values, outliers, and distributional characteristics. Descriptive statistics, including mean, standard deviation, frequency, and percentage, were used to describe the demographic and clinical characteristics of the participants. Missing values were evaluated before model development, and cases with extensive incomplete responses were removed from the dataset, whereas minor missing values were handled using appropriate imputation procedures based on the type and distribution of the variable. Continuous variables were inspected for extreme values, and implausible responses were checked against the original questionnaires. The outcome variable was the total quality of life score, and the main predictor variables included pain intensity, global sleep quality, psychological flexibility, and relevant demographic and clinical covariates. Before entering the variables into the machine learning model, all variables were coded consistently, and categorical variables were transformed into machine-readable formats.

The predictive analysis was performed using the Extreme Gradient Boosting algorithm. XGBoost was selected because it is a powerful ensemble learning method capable of modeling complex, nonlinear, and interactive relationships among clinical and psychological variables. The model was trained to predict quality of life scores among patients with fibromyalgia based on pain, sleep, and psychological flexibility variables. The dataset was divided into training and testing subsets, with 70% of the data used for model training and 30% reserved for final model evaluation. To reduce overfitting and improve generalizability, hyperparameters such as learning rate, maximum tree depth, number of estimators, subsample ratio, column sampling ratio, and regularization parameters were optimized using cross-validation within the training set. Model performance was evaluated using regression-based indices, including mean absolute error, root mean square error, and coefficient of determination. These indices were selected to determine both the average prediction error and the proportion of variance in quality of life explained by the model.

To enhance the interpretability of the XGBoost model, explainable artificial intelligence procedures were applied after model training. SHapley Additive exPlanations values were calculated to identify the relative contribution of each predictor to the prediction of quality of life. Global SHAP analysis was used to determine the overall importance of pain intensity, sleep quality, psychological flexibility, and demographic or clinical covariates in the model. In addition, local SHAP explanations were used to examine how specific variables contributed to predicted quality of life scores for individual patients. This explainability approach made it possible to move beyond prediction accuracy and clarify the direction and strength of the association between each predictor and the model output. The final analysis therefore provided both predictive performance indicators and clinically interpretable information about the variables most strongly associated with quality of life among patients with fibromyalgia. All statistical and machine learning analyses were conducted using appropriate statistical software and Python-based machine learning packages.

3. Findings and Results

A total of 318 patients with fibromyalgia from Tehran were included in the final analysis. The mean age of the participants was 42.68 years with a standard deviation of 9.74 years, and the age range was from 22 to 67 years. Most participants were female, with 267 women representing 84.0% of the sample, while 51 participants were male, representing 16.0% of the sample. Regarding marital status, 231 participants were married, 49 were single, 24 were divorced, and 14 were widowed. In terms of education, 37 participants had less than a high school diploma, 86 had completed high school or diploma-level education, 126 had a bachelor’s degree, and 69 had postgraduate education. With respect to employment status, 114 participants were employed, 96 were homemakers, 47 were self-employed, 38 were retired, and 23 were unemployed. The mean duration of fibromyalgia diagnosis was 6.18 years with a standard deviation of 4.07 years. A total of 277 participants reported current use of medication for pain or fibromyalgia-related symptoms, and 125 participants reported at least one additional chronic medical condition. Overall, the demographic and clinical profile of the sample indicated that the study included a predominantly middle-aged and female

clinical group with a moderate duration of fibromyalgia and substantial symptom burden.

Table 1

Descriptive Statistics and Correlations Among Main Study Variables

Variable	Mean	Standard Deviation	Minimum	Maximum	1	2	3	4
1. Quality of life	42.86	15.37	11.20	82.40	1.00			
2. Pain intensity	7.06	1.63	2.00	10.00	-0.58**	1.00		
3. Poor sleep quality	10.88	3.42	3.00	20.00	-0.52**	0.46**	1.00	
4. Psychological flexibility	33.74	8.91	12.00	49.00	0.49**	-0.41**	-0.38**	1.00

The descriptive findings showed that patients with fibromyalgia reported a relatively low mean quality of life score, indicating considerable impairment in perceived physical and psychological functioning. The mean pain intensity score was high, suggesting that most participants experienced moderate to severe pain during the assessment period. The mean sleep quality score also indicated clinically meaningful sleep disturbance, which is consistent with the symptom pattern commonly observed in fibromyalgia. Psychological flexibility showed moderate variability across participants, suggesting that patients differed substantially in their ability to remain engaged in meaningful activities despite pain and distress. The correlation matrix showed that quality of life had a strong negative relationship with pain intensity, meaning that patients with higher pain severity tended to report lower quality of life. Quality of life also had a strong negative association with poor sleep quality, indicating that more disturbed sleep was related to poorer functioning and well-being. In contrast, psychological flexibility was positively associated with quality of life, showing that greater flexibility was related to better perceived health and functioning. Pain intensity was positively correlated with poor sleep quality and negatively correlated with psychological flexibility, suggesting that patients with more severe pain also tended to report poorer sleep and lower adaptive coping capacity. These results supported the relevance of pain, sleep, and psychological flexibility as core predictors in the subsequent machine learning model.

Table 2

Predictive Performance of Regression Models for Quality of Life

Model	Training MAE	Training RMSE	Training R^2	Test MAE	Test RMSE	Test R^2	Cross-Validated R^2
Linear regression	9.74	12.81	0.47	10.21	13.26	0.43	0.41
Support vector regression	7.96	10.34	0.66	8.91	11.61	0.57	0.55
Random forest regression	6.21	8.14	0.78	8.67	11.34	0.59	0.57
XGBoost regression	5.62	7.18	0.82	7.84	10.18	0.66	0.63

The model performance results showed that XGBoost regression provided the strongest prediction of quality of life among the evaluated models. Compared with linear regression, support vector regression, and random forest regression, the XGBoost model produced the lowest test mean absolute error and root mean square error, indicating that its predictions were closer to the observed quality of life scores. The test R^2 value for XGBoost was 0.66, showing that the model explained 66% of the variance in quality of life in the unseen test data. This level of performance indicates that the combination of pain intensity, sleep quality, psychological flexibility, and selected demographic and clinical covariates had substantial predictive value for estimating quality of life among patients with fibromyalgia. The difference between the training and testing performance was acceptable, suggesting that the model did not merely memorize the training data and retained adequate generalizability. The cross-validated R^2 value of 0.63 further supported the stability of the XGBoost model across repeated data partitions. Overall, these findings indicated that a nonlinear ensemble-based approach was better suited than conventional linear modeling for capturing the complex pattern of relationships among fibromyalgia-related symptoms, psychological adaptation, and quality of life.

Table 3

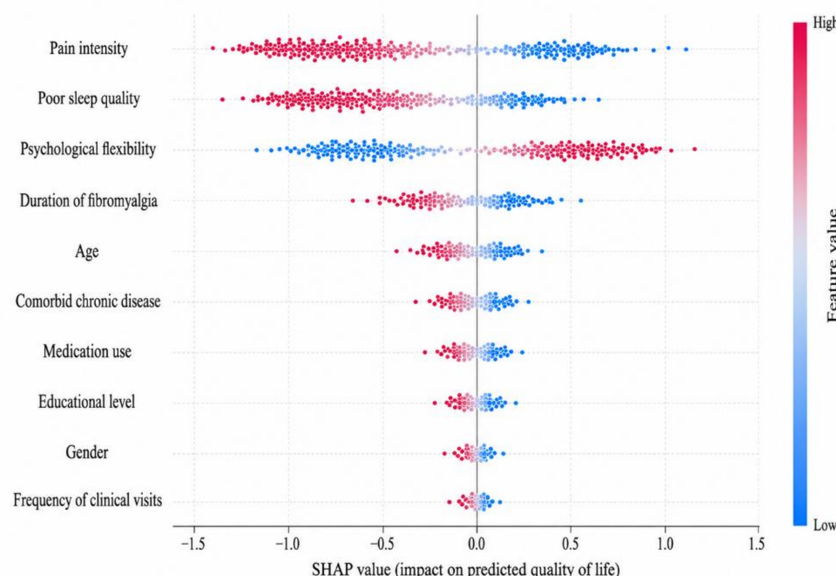
SHAP-Based Importance of Predictors in the Final XGBoost Model

Predictor	Mean Absolute SHAP Value	Relative Importance	Predominant Direction of Association With Quality of Life
Pain intensity	6.42	100.0%	Higher pain intensity predicted lower quality of life
Poor sleep quality	5.76	89.7%	Poorer sleep quality predicted lower quality of life
Psychological flexibility	4.91	76.5%	Higher psychological flexibility predicted higher quality of life
Duration of fibromyalgia	2.12	33.0%	Longer illness duration predicted lower quality of life
Age	1.66	25.9%	Older age predicted slightly lower quality of life
Comorbid chronic disease	1.13	17.6%	Presence of comorbidity predicted lower quality of life
Medication use	0.92	14.3%	Association was small and variable across patients
Educational level	0.75	11.7%	Higher educational level predicted slightly higher quality of life
Gender	0.48	7.5%	Contribution was weak and showed no stable directional pattern
Frequency of clinical visits	0.43	6.7%	Contribution was weak and varied across patients

The explainability analysis showed that pain intensity was the most influential predictor in the final XGBoost model. Patients with higher pain intensity scores were consistently predicted to have lower quality of life, confirming the central role of pain burden in fibromyalgia-related functional impairment. Poor sleep quality was the second most important predictor and had a clear negative contribution to predicted quality of life, meaning that greater sleep disturbance lowered the model's estimated quality of life score. Psychological flexibility was the third strongest predictor and showed a protective direction; patients with higher psychological flexibility were more likely to receive higher predicted quality of life scores, even when pain and sleep problems were present. Among the clinical and demographic covariates, illness duration and age contributed modestly to the model, with longer duration of fibromyalgia and older age generally associated with poorer predicted quality of life. Comorbid chronic disease also had a negative effect, although its contribution was smaller than the main pain, sleep, and psychological flexibility variables. Medication use, education, gender, and clinical visit frequency had relatively weak contributions, indicating that these variables were less central to prediction once symptom and psychological variables were included. These findings demonstrate that the model's predictions were primarily driven by clinically meaningful and theoretically relevant variables rather than by demographic characteristics.

Figure 1

SHAP Summary Plot of Predictors of Quality of Life Among Patients With Fibromyalgia



The SHAP summary plot confirmed the ranking and direction of predictors observed in the tabular explainability results. Pain intensity appeared as the strongest driver of lower predicted quality of life, with high pain values shifting predictions downward across a large number of patients. Poor sleep quality showed a similar pattern, indicating that higher sleep disturbance contributed to lower estimated quality of life. Psychological flexibility showed the opposite pattern, with higher levels shifting predictions toward better quality of life. The figure also indicated that the effect of the predictors was not uniform across all participants, which supports the use of a nonlinear machine learning model. For example, the negative contribution of pain intensity became especially pronounced among patients with both high pain and poor sleep quality, whereas psychological flexibility appeared to partially offset the negative predictive influence of symptom burden in some patients. This pattern suggests that quality of life in fibromyalgia is shaped by an interaction of symptom severity and psychological adaptation rather than by any single factor alone. Therefore, the explainable XGBoost model provided not only accurate prediction but also clinically interpretable evidence showing that pain reduction, sleep improvement, and enhancement of psychological flexibility may be key targets for improving quality of life in patients with fibromyalgia.

4. Discussion

The present study developed and interpreted an explainable XGBoost model for predicting quality of life among patients with fibromyalgia using pain intensity, sleep quality, psychological flexibility, and relevant demographic and clinical variables. The findings showed that participants experienced a substantial quality-of-life burden, with relatively low mean quality of life, high pain intensity, and clinically meaningful sleep disturbance. Correlational results indicated that quality of life was negatively associated with pain intensity and poor sleep quality, while it was positively associated with psychological flexibility. The predictive modeling results further demonstrated that XGBoost outperformed linear regression, support vector regression, and random forest regression, explaining 66% of the variance in quality of life in the test set. The SHAP-based explainability analysis showed that pain intensity was the strongest predictor of quality of life, followed by poor sleep quality and psychological flexibility. Duration of fibromyalgia, age, comorbid chronic disease, medication use, educational level, gender, and frequency of clinical visits contributed less strongly to prediction. These findings suggest that quality of life in fibromyalgia is mainly shaped by the combined burden of pain and sleep disturbance, while psychological flexibility functions as a protective psychological resource that may reduce the functional impact of chronic symptoms.

The finding that pain intensity was the strongest predictor of quality of life is consistent with the central clinical role of persistent widespread pain in fibromyalgia. Fibromyalgia is a condition in which pain is not only a sensory experience but also a functional, emotional, and behavioral burden that interferes with daily life, activity tolerance, social functioning, and self-perceived health. The strong negative contribution of pain intensity in the SHAP analysis indicates that as pain severity increased, the predicted quality of life score declined substantially. This aligns with contemporary views of chronic pain as a multidimensional condition that requires psychological, behavioral, and neurological interpretation rather than a purely biomedical explanation (Serdarević, 2024). The result is also compatible with research showing that pain intensity is associated with quality of life in chronic pain populations and that this association is often amplified by cognitive-affective processes such as catastrophizing, emotional distress, and reduced coping resources (Anagnostopoulos et al., 2022). In fibromyalgia, the importance of pain is further supported by evidence emphasizing the need for comprehensive pharmacological and non-pharmacological treatment approaches because no single intervention fully addresses the complexity of pain, fatigue, sleep disturbance, and psychological distress (Ablin & Sarzi-Puttini, 2024; Devigili et al., 2025).

The high predictive importance of pain intensity also supports the broader evidence base on non-pharmacological and rehabilitation-oriented interventions for fibromyalgia. Systematic reviews have shown that rehabilitation strategies and nonpharmacological interventions can improve important outcomes in primary fibromyalgia syndrome, suggesting that symptom management should involve physical, psychological, and behavioral components rather than medication alone (Kundakci et al., 2021; Pathak et al., 2023). Recent updates on non-pharmacological pain relief have similarly emphasized the value of approaches that target pain modulation, behavior change, and functional restoration (Wang et al., 2025). The finding that pain remained the most influential predictor even after including sleep and psychological flexibility indicates that pain burden continues to be a primary clinical marker of impaired quality

of life. However, the model also showed that pain does not operate in isolation; its predictive effect was accompanied by strong contributions from sleep quality and psychological flexibility, supporting the view that fibromyalgia is best understood as a heterogeneous and biopsychosocial condition (Clark et al., 2023; Pilar Martínez Narváez-Cabeza de et al., 2021).

Poor sleep quality emerged as the second most influential predictor of quality of life. This finding is clinically important because sleep disturbance is one of the most common and disabling complaints among patients with fibromyalgia. The negative SHAP pattern showed that higher sleep disturbance shifted predictions toward lower quality of life, indicating that impaired sleep may intensify the overall burden of fibromyalgia beyond pain alone. Sleep disturbance can worsen fatigue, increase pain sensitivity, impair cognitive functioning, reduce emotional regulation, and decrease motivation for physical and social activity. Previous research on chronic pain and sleep supports this interpretation, showing that insomnia symptoms and poor sleep quality are closely connected to pain experience, recovery, and functional outcomes (Sipilä & Kalso, 2021; Wiklund, 2021). Evidence from systematic reviews of non-pharmacological sleep interventions in chronic pain further suggests that sleep should be treated as a core therapeutic target rather than as a secondary symptom (Whale et al., 2022). In the context of fibromyalgia, the present findings reinforce the need to assess sleep quality routinely, because sleep disturbance appears to have a strong and independent contribution to patients' perceived quality of life.

The sleep-related findings are also consistent with intervention literature showing that behavioral and physical approaches may improve sleep and symptom regulation. Resistance training has been reviewed as a potential method for improving sleep among patients with fibromyalgia, and broader exercise training has been recommended for women with fibromyalgia because of its potential effects on physical function, symptom control, and health-related outcomes (Ana Cecília Rosatelli de Freitas et al., 2023; Silva et al., 2024). Although evidence from epilepsy is not specific to fibromyalgia, systematic review findings on exercise and sleep in neurological populations further support the general principle that structured physical activity may contribute to improved sleep regulation (Mueller et al., 2024). The current model's identification of poor sleep quality as a major predictor therefore supports multicomponent interventions that combine pain management, sleep hygiene, physical activity, and psychological coping strategies. It also suggests that quality-of-life improvement in fibromyalgia may require direct intervention on sleep rather than assuming that sleep will improve only after pain reduction.

Psychological flexibility was the third most important predictor and showed a positive association with quality of life. This means that patients who were more able to remain engaged in meaningful actions despite pain, fatigue, and distress were predicted to have better quality of life. This finding is highly consistent with the theoretical foundation of acceptance and commitment therapy and newer psychological treatments for chronic pain, which emphasize flexible responding, acceptance of unpleasant internal experiences, values-based behavior, and reduced experiential avoidance (McCracken et al., 2022). Meta-analytic evidence indicates that psychological flexibility and inflexibility are associated with important outcomes in chronic pain patients, including pain interference, emotional distress, disability, and quality of life (Fang & Ding, 2022). The present results extend this evidence by showing that psychological flexibility remains influential within a machine learning model that also includes pain intensity, sleep quality, and clinical covariates. In other words, psychological flexibility was not merely correlated with quality of life; it contributed meaningfully to prediction after accounting for other symptom variables.

The importance of psychological flexibility is also supported by studies of acceptance and commitment therapy, mindfulness, and mind-body interventions in fibromyalgia and related conditions. Systematic review evidence suggests that acceptance and commitment therapy may be effective in central sensitization syndromes, including fibromyalgia, where symptom severity is often linked to avoidance, emotional distress, and reduced functional engagement (Galvez-Sánchez et al., 2021). Reviews of cognitive-behavioral therapy and acceptance and commitment therapy for anxiety and depression in fibromyalgia further show that psychological interventions can improve emotional and functional outcomes in this population (Cojocaru et al., 2023). The contribution of psychologists in fibromyalgia care has been emphasized because psychological assessment can identify patterns of fear, avoidance, distress, and coping that influence disability and treatment response (Luciano et al., 2023). Similarly, mindfulness and mind-body interventions have been proposed as relevant symptom management strategies for fibromyalgia, particularly because they may improve attention regulation, distress tolerance, body awareness, and adaptive coping (Gordon et al., 2022; Islam et al., 2022). The present findings support

these perspectives by showing that psychological flexibility has a clinically meaningful role in predicting quality of life.

The results also have implications for digital and remote care models. The relevance of psychological flexibility, sleep, and pain as predictors is consistent with the growing body of evidence on e-health, telerehabilitation, and digitally delivered psychological interventions for fibromyalgia and chronic pain. Telerehabilitation has shown potential for fibromyalgia management, particularly by increasing access to structured care for patients who may face mobility, fatigue, or geographical barriers (Wu et al., 2023). E-health interventions targeting pain-related psychological variables in fibromyalgia also highlight the feasibility of addressing coping processes, distress, and behavioral adaptation through technology-supported formats (Donisi et al., 2023). Digital acceptance and commitment therapy protocols for fibromyalgia further demonstrate the relevance of scalable interventions that target psychological flexibility and self-management (Gallego et al., 2024). Related evidence from internet-delivered acceptance and commitment therapy for chronic pain, internet-delivered acceptance and commitment therapy for cancer patients and survivors, and digital behavioral therapy for axial spondyloarthritis indicates that digital psychological interventions can support patients living with persistent symptoms and reduced functioning (García-Torres et al., 2024; Kiefer et al., 2025; Rickardsson et al., 2021). Therefore, the present model may help identify patients who could benefit most from digitally supported pain, sleep, and psychological flexibility interventions.

The superior performance of XGBoost compared with conventional and alternative machine learning models indicates that the relationship between fibromyalgia-related predictors and quality of life is likely nonlinear and interactive. Linear regression explained less variance than XGBoost, suggesting that a purely linear framework may not fully capture how pain, sleep, psychological flexibility, illness duration, and comorbidity combine to shape quality of life. This finding aligns with the clinical reality of fibromyalgia, where patients with similar levels of pain may experience different quality-of-life outcomes depending on sleep disruption, psychological adaptation, illness duration, and coexisting conditions. The SHAP explanation further strengthened the clinical value of the model by identifying not only which predictors were important but also how they influenced predicted quality of life. This interpretability is especially important because predictive models in healthcare must be understandable to clinicians and researchers. The present findings are consistent with the logic of multicomponent treatment, self-management strategies, and integrative care models, which emphasize that fibromyalgia treatment should be individualized and should address multiple symptom domains simultaneously (Araya-Quintanilla et al., 2025; Carlson et al., 2025; Foustoukos et al., 2024).

5. Conclusion

Although the present study focused on fibromyalgia, the findings are also consistent with broader evidence from other chronic illness populations showing that psychological distress, stress processes, and adaptive coping influence quality of life. Systematic reviews of acceptance and commitment therapy in cancer populations and psychological interventions in endometriosis show that psychological processes can shape symptom burden and functioning across chronic health conditions (Jiang et al., 2024; Pino-Sedeño et al., 2024). Research on cancer and stress also emphasizes the close connection between chronic disease, stress responses, psychological adjustment, and intervention needs (D'Andre et al., 2024). These studies support the broader interpretation that pain and sleep symptoms should be understood alongside psychological flexibility and coping processes. In fibromyalgia, this integrated interpretation is particularly important because the condition involves persistent symptoms that may not be fully eliminated, making adaptive functioning, symptom self-management, and psychological resilience central to quality-of-life improvement.

6. Limitations & Suggestions

This study had several limitations that should be considered when interpreting the findings. First, the cross-sectional design prevents causal conclusions about the relationships among pain intensity, sleep quality, psychological flexibility, and quality of life. Although the XGBoost model showed strong predictive performance, prediction does not establish temporal or causal direction. Second, participants were selected from clinics in Tehran using convenience sampling, which may limit the generalizability of the findings to patients in other regions, rural settings, or different healthcare systems. Third, the study relied on self-report questionnaires, which may be influenced by recall bias, response style, current mood, or symptom fluctuation at the time of assessment. Fourth, although the model included key clinical and psychological variables, other potentially important predictors such as

fatigue severity, physical activity, medication type, depression, anxiety, pain catastrophizing, social support, and inflammatory or neurological markers were not included. Fifth, the model was internally validated using train-test splitting and cross-validation, but it was not externally validated in an independent sample.

Future studies should use longitudinal designs to examine whether pain intensity, sleep quality, and psychological flexibility predict changes in quality of life over time among patients with fibromyalgia. Longitudinal modeling would help clarify whether improvements in sleep or psychological flexibility lead to subsequent improvements in quality of life or whether these variables change together as part of a broader recovery process. Future research should also validate the present XGBoost model in independent samples from other cities, countries, and clinical settings to determine its generalizability. It would be valuable to compare XGBoost with other advanced machine learning approaches, such as neural networks, elastic net models, Bayesian models, and stacked ensemble models. Future studies should include broader biopsychosocial predictors, including fatigue, depression, anxiety, pain catastrophizing, physical activity, social support, body mass index, medication profile, and biological markers. In addition, future research should examine whether explainable machine learning models can be integrated into clinical decision-support systems for identifying high-risk patients and recommending individualized intervention targets.

The findings suggest that clinicians working with patients with fibromyalgia should assess pain intensity, sleep quality, and psychological flexibility as central components of routine care. Treatment planning should not focus only on reducing pain but should also include strategies for improving sleep and strengthening adaptive psychological functioning. Patients with high pain intensity and poor sleep quality may require more intensive, multicomponent interventions that combine medical management, physical activity, sleep-focused strategies, and psychological support. Psychological flexibility should be considered a practical intervention target, especially for patients who experience high distress, avoidance, reduced activity engagement, and difficulty maintaining valued life roles despite symptoms. Clinicians may benefit from using structured screening tools to identify patients at risk of poor quality of life and to prioritize treatment goals. The results also support the development of personalized care pathways in which patients receive targeted recommendations based on their dominant risk profile, such as pain-focused, sleep-focused, or psychological flexibility-focused intervention plans.

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Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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Authors' Contributions

All authors equally contributed to this article.

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