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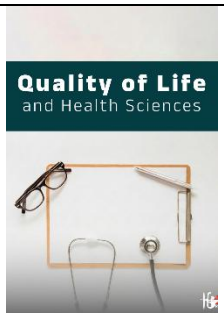

Elastic Net Regression and Gradient Boosting for Predicting Health-Related Quality of Life Among Patients With Chronic Obstructive Pulmonary Disease

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A B S T R A C T

Objective: This study aimed to develop and compare Elastic Net Regression and Gradient Boosting Regression models for predicting health-related quality of life among patients with chronic obstructive pulmonary disease in Tehran.

Methods and Materials: This cross-sectional predictive modeling study was conducted on 286 patients with chronic obstructive pulmonary disease who were receiving outpatient pulmonary care in Tehran, Iran. Data were collected using a demographic and clinical information form, spirometric indices, the St. George's Respiratory Questionnaire, the COPD Assessment Test, the modified Medical Research Council dyspnea scale, the Hospital Anxiety and Depression Scale, and physical activity assessment. The total score of the St. George's Respiratory Questionnaire was considered the primary outcome variable. After data screening, preprocessing, standardization of continuous predictors, and coding of categorical variables, two predictive models were developed: Elastic Net Regression and Gradient Boosting Regression. The dataset was divided into training and testing subsets, and model performance was evaluated using root mean squared error, mean absolute error, and coefficient of determination.

Findings: Bivariate analyses showed that poorer health-related quality of life was significantly associated with higher COPD Assessment Test scores, greater dyspnea severity, lower FEV1 percentage predicted, lower FEV1/FVC ratio, more frequent exacerbations, more hospitalizations, higher anxiety and depression scores, lower physical activity, longer disease duration, higher body mass index, and older age. In the testing dataset, Elastic Net Regression explained 61.9% of the variance in health-related quality of life, with RMSE = 10.12 and MAE = 7.81. Gradient Boosting Regression demonstrated superior predictive performance, explaining 70.4% of the variance, with RMSE = 8.91 and MAE = 6.83. The most important predictors across models were symptom burden, dyspnea, lung function, depression, exacerbation frequency, anxiety, and physical activity.

Conclusion: Gradient Boosting Regression provided more accurate prediction of health-related quality of life than Elastic Net Regression, although both models identified clinically meaningful predictors. These findings support the use of multidimensional predictive modeling to identify chronic obstructive pulmonary disease patients at greater risk of poor quality of life.

Keywords: *Chronic obstructive pulmonary disease; health-related quality of life; predictive modeling; dyspnea; psychological distress.*

1. Introduction

Chronic obstructive pulmonary disease is a progressive, heterogeneous, and burdensome respiratory condition characterized not only by persistent airflow limitation but also by a broad set of physical, psychological, behavioral, and social consequences that substantially reduce health-related quality of life. Although spirometric impairment remains central to diagnosis and staging, the lived burden of chronic obstructive pulmonary disease extends far beyond pulmonary function indices. Patients frequently experience dyspnea, fatigue, cough, sputum production, recurrent exacerbations, sleep disruption, reduced physical activity, anxiety, depression, social restriction, and loss of independence. Consequently, health-related quality of life has become one of the most clinically meaningful outcomes in chronic obstructive pulmonary disease because it captures the patient-centered impact of the disease on daily functioning and perceived well-being. Recent studies from different clinical and geographic settings have repeatedly shown that quality of life among patients with chronic obstructive pulmonary disease is determined by a complex interaction of respiratory severity, symptom burden, behavioral patterns, psychosocial status, treatment access, and contextual factors rather than by lung function alone (Shahid et al., 2024; Sharma et al., 2021; Tekobo et al., 2025; Ying et al., 2024).

The importance of health-related quality of life in chronic obstructive pulmonary disease is especially evident because patients with similar spirometric profiles may report markedly different levels of functional limitation, emotional distress, and perceived health. This discrepancy demonstrates that physiological measurements, although indispensable, are insufficient for representing the full burden of the disease. Quality-of-life assessment provides a broader clinical lens through which respiratory symptoms, physical limitations, psychological responses, and social consequences can be integrated into a single patient-centered outcome. Studies examining determinants of quality of life among chronic obstructive pulmonary disease patients have identified dyspnea, exacerbation history, comorbid conditions, smoking-related behaviors, reduced exercise tolerance, psychological distress, and socioeconomic disadvantage as major contributors to poorer outcomes (Cao et al., 2023, 2024; Rehman et al., 2021; Ying et al., 2022). These findings support the need for analytic approaches capable of modeling multidimensional predictors and identifying which combinations of variables are most strongly associated with quality-of-life impairment.

The burden of chronic obstructive pulmonary disease is also shaped by the chronicity of the condition and the cumulative effect of repeated disease-related disruptions. Frequent exacerbations, hospitalizations, and ongoing symptom instability can accelerate functional decline and reinforce a cycle of inactivity, fear of breathlessness, psychological distress, and worsening quality of life. Severe chronic obstructive pulmonary disease often requires integrated care approaches, including pharmacological management, rehabilitation, palliative support, education, and self-management strategies. Practice reviews and palliative care literature emphasize that patients with advanced chronic obstructive pulmonary disease frequently present with refractory symptoms, unmet supportive care needs, and multidimensional suffering that cannot be fully addressed through disease-centered treatment alone (Fu et al., 2022; Gonçalves et al., 2025; Guler et al., 2025; Madiraca et al., 2023). These perspectives highlight the need to detect patients at risk of poor quality of life earlier and more accurately, so that clinical support can be matched to the actual burden experienced by the patient.

Psychological and psychosocial factors are particularly important in explaining health-related quality of life among patients with chronic obstructive pulmonary disease. Anxiety may increase symptom vigilance, intensify perceptions of dyspnea, and reduce engagement in physical and social activities. Depression may reduce motivation for self-care, pulmonary rehabilitation participation, medication adherence, and physical activity, thereby worsening both perceived and objective health outcomes. Evidence has shown that depression and autonomic dysfunction may be associated with reduced lung function in chronic obstructive pulmonary disease, supporting the close interconnection between psychological status and physiological functioning (Li & Rong, 2025). Pulmonary rehabilitation literature further emphasizes psychosocial support as a core component of comprehensive care, particularly because emotional distress can influence coping, participation, and perceived benefit from rehabilitation interventions (Yohannes, 2024). In advanced disease, psychosocial burden may become even more pronounced, especially when breathlessness, dependency, uncertainty, and fear of deterioration affect daily life and personal identity (Gonçalves et al., 2025; Madiraca et al., 2024).

Beyond anxiety and depression, broader contextual and existential dimensions may also influence quality of life in

chronic obstructive pulmonary disease. Spiritual concerns, meaning, dignity, and emotional adjustment have been discussed as important but often underrecognized aspects of care among individuals with advanced chronic obstructive pulmonary disease (Kotlińska–Lemieszek et al., 2022). Caregiver and dyadic factors may further shape patient outcomes, as chronic obstructive pulmonary disease often affects not only the individual patient but also the family system involved in daily care, symptom management, and emotional support. Dyadic evidence suggests that self-care and quality of life should be understood within the relational context of patients and caregivers rather than as isolated patient-level phenomena (Cai et al., 2025). Similarly, research on caregiver health in chronic obstructive pulmonary disease and related serious pulmonary conditions indicates that caregiver burden and patient illness experience are closely connected, particularly when palliative care needs are present (Marić et al., 2021). These findings reinforce the multidimensional nature of health-related quality of life and justify the inclusion of psychosocial and behavioral predictors in predictive modeling studies.

Self-management, integrated care, rehabilitation, and digital health strategies have increasingly been examined as mechanisms for reducing disease burden and improving quality of life in chronic obstructive pulmonary disease. Blended self-management interventions have been studied as approaches for reducing disease burden among patients with chronic respiratory diseases, and systematic reviews from low- and middle-income countries suggest that structured self-management interventions may improve chronic obstructive pulmonary disease outcomes when adapted to local health system capacities (Adhikari et al., 2025; Song et al., 2021). Integrated disease management programs have also demonstrated relevance for chronic obstructive pulmonary disease outcomes, with program duration and continuity of care potentially influencing clinical and patient-reported results (Lin et al., 2023). Technological advances, including digital monitoring, telehealth, and mobile-supported interventions, have been proposed as tools for improving quality of life among older adults with chronic obstructive pulmonary disease by supporting monitoring, feedback, adherence, and access to care (Lippi et al., 2023). More recently, longitudinal evidence on Internet-of-Things-driven dynamic pulmonary function monitoring has further emphasized the potential relationship between continuous respiratory monitoring and quality of life in community-dwelling chronic obstructive pulmonary disease patients (Zhao et al., 2026).

The clinical heterogeneity of chronic obstructive pulmonary disease also requires attention to comorbidities and co-occurring health conditions. Nutritional status, for example, may influence exacerbation risk, prognosis, physical performance, and quality of life in patients with complex chronic obstructive pulmonary disease, and malnutrition has been described as a clinically relevant predictor of adverse outcomes (Raimondo et al., 2024). Periodontal disease has also been discussed in relation to chronic obstructive pulmonary disease, suggesting possible bidirectional associations between oral health and respiratory disease pathways (Tamiya et al., 2023). Alpha-1 antitrypsin deficiency represents another disease-related context in which respiratory burden, systemic effects, and quality-of-life impairment may be substantial (Miravitlles et al., 2022). Sexual dysfunction has also been identified as an underexamined but important dimension of quality of life among patients with chronic obstructive pulmonary disease, indicating that intimate and relational domains may be affected by respiratory symptoms, fatigue, psychological distress, and medication-related factors (Rahman et al., 2026). These diverse findings demonstrate that quality of life is influenced by a broad clinical ecology that includes pulmonary, systemic, functional, psychological, and social domains.

Environmental and behavioral exposures further complicate the prediction of quality of life in chronic obstructive pulmonary disease. Smoking behavior remains a central disease-related factor, but contemporary research has also examined switching behavior and electronic cigarette use patterns in relation to symptom burden and health-related quality of life (Cao et al., 2023, 2024). Climate-related stressors may also affect patient well-being, as emerging work has examined climate anxiety and its association with quality of life among patients with chronic obstructive pulmonary disease (Asal et al., 2025). These lines of evidence indicate that quality-of-life prediction should not be restricted to conventional clinical variables but should also consider behavioral and contextual factors that may influence symptom perception, health behavior, and psychological well-being. Differences in chronic obstructive pulmonary disease management across clinician types further suggest that care patterns, treatment habits, and patient characteristics vary in real-world practice, which may affect symptom control and patient-reported outcomes (Castro et al., 2025).

The measurement of disease burden and quality of life is another important methodological issue. In chronic

conditions, patient-reported outcome measures are essential because they provide direct evidence about the burden patients experience in daily life. Instruments that evaluate symptom burden, activity limitation, psychosocial impact, and treatment burden can complement physiological indicators and help clinicians identify needs that may not be visible through standard clinical evaluation. Work on the validity and reliability of chronic condition burden scales supports the broader movement toward structured assessment of patient-perceived burden in chronic disease management (Claessens et al., 2023). Similar arguments have been made in other chronic inflammatory and respiratory-related conditions, where quality of life can reveal unmet needs that conventional biomedical indicators may fail to capture (Enrique Gómez de la et al., 2023). Rehabilitation research in malignant pleural mesothelioma, although focused on a different pulmonary condition, also underscores the importance of functioning and quality of life as central outcomes in chronic and serious respiratory disease contexts (Lippi et al., 2024). These perspectives support the use of health-related quality of life as a primary outcome in predictive studies of chronic obstructive pulmonary disease.

Despite the expanding literature on determinants of quality of life, many existing studies rely primarily on traditional statistical methods that estimate average associations between predictors and outcomes. These methods are valuable for hypothesis testing, but they may be limited when predictors are numerous, correlated, nonlinear, or interactive. In chronic obstructive pulmonary disease, variables such as lung function, dyspnea, symptom burden, physical activity, anxiety, depression, exacerbation frequency, and hospitalization history often overlap conceptually and statistically. Standard regression models may be vulnerable to multicollinearity, overfitting, or inadequate modeling of nonlinear patterns. Elastic Net Regression is useful in this context because it combines variable selection and coefficient shrinkage, allowing correlated predictors to be handled more effectively while maintaining interpretability. Gradient Boosting, in contrast, is a machine-learning approach that can capture nonlinear relationships and interaction effects through sequential tree-based learning. These two methods therefore offer complementary advantages: Elastic Net provides a parsimonious and interpretable regularized regression framework, while Gradient Boosting provides a flexible predictive model capable of detecting complex patterns in multidimensional clinical data.

Applying Elastic Net Regression and Gradient Boosting to health-related quality-of-life prediction in chronic obstructive pulmonary disease can help address several clinically relevant gaps. First, it can clarify which predictors contribute most strongly to quality-of-life impairment when demographic, clinical, respiratory, psychological, and behavioral factors are considered simultaneously. Second, it can compare the performance of a regularized linear model with a nonlinear machine-learning model, thereby informing whether the quality-of-life burden in chronic obstructive pulmonary disease is better explained through additive linear effects or more complex predictive structures. Third, it can generate clinically interpretable evidence that may assist in screening patients at risk of poor health-related quality of life and prioritizing interventions such as pulmonary rehabilitation, self-management support, psychological care, nutritional assessment, symptom control, and palliative care. Such an approach is aligned with the broader movement toward patient-centered, data-informed, and individualized chronic disease management.

In the context of Tehran, the development of predictive evidence is particularly important because chronic obstructive pulmonary disease care occurs within a dynamic urban environment where air pollution, smoking exposure, socioeconomic variation, healthcare access, comorbidities, and family caregiving patterns may all influence patient outcomes. Local predictive models can provide context-sensitive evidence rather than relying exclusively on findings from other healthcare systems. Given that quality of life is shaped by symptom burden, psychological distress, activity limitation, exacerbation history, treatment patterns, and contextual conditions, a predictive modeling approach can offer a more integrated understanding of chronic obstructive pulmonary disease burden in this population. The present study was therefore designed to combine clinically meaningful predictors with modern statistical learning methods to estimate health-related quality of life and identify the most important determinants of poorer outcomes among patients with chronic obstructive pulmonary disease.

The aim of this study was to develop and compare Elastic Net Regression and Gradient Boosting models for predicting health-related quality of life among patients with chronic obstructive pulmonary disease in Tehran using demographic, clinical, respiratory, psychological, and functional predictors.

2. Methods and Materials

2.1. Study Design and Participants

This study was designed as a cross-sectional predictive modeling study conducted among patients with chronic obstructive pulmonary disease in Tehran, Iran. The target population consisted of adult patients with a confirmed clinical diagnosis of chronic obstructive pulmonary disease who were receiving outpatient pulmonary care in specialized respiratory clinics and pulmonary departments affiliated with hospitals in Tehran. A total of 286 patients with chronic obstructive pulmonary disease participated in the study. Participants were recruited through convenience sampling from patients who attended clinical visits during the data collection period and met the eligibility criteria. Inclusion criteria were age 40 years or older, confirmed diagnosis of chronic obstructive pulmonary disease by a pulmonologist based on clinical evaluation and spirometric evidence of persistent airflow limitation, clinical stability at the time of assessment, ability to read and understand Persian, and willingness to provide informed consent. Patients were excluded if they had an acute exacerbation during the previous four weeks, severe cognitive impairment, active malignancy, advanced heart failure, severe psychiatric disorder, or any other medical condition that could interfere with questionnaire completion or substantially affect health-related quality of life independent of chronic obstructive pulmonary disease.

Before data collection, the objectives and procedures of the study were explained to all eligible patients. Participation was voluntary, and all participants provided written informed consent. The confidentiality of patient information was protected throughout the research process, and all data were analyzed anonymously. Demographic and clinical information was obtained during the same assessment session, and questionnaire data were collected in a quiet clinical setting under the supervision of trained research staff. The final analytic sample included 286 patients after screening for eligibility and completeness of the main outcome variable. This sample size was considered sufficient for predictive modeling because it provided an adequate number of observations for training and testing regression-based and machine-learning models while allowing stable estimation of prediction error through resampling procedures.

2.2. Measures

Data were collected using a structured demographic and clinical information form and standardized self-report instruments related to health-related quality of life, respiratory symptoms, psychological status, and functional condition. The demographic section included age, sex, marital status, educational level, employment status, body mass index, smoking status, duration of chronic obstructive pulmonary disease, medication use, history of hospitalization, number of exacerbations during the previous year, and presence of major comorbid conditions. Clinical information included disease severity indicators, spirometric indices, oxygen therapy status, and physician-reported disease stage when available. Forced expiratory volume in one second, forced vital capacity, and the ratio of forced expiratory volume in one second to forced vital capacity were recorded from the most recent spirometry results documented in the patient's medical file.

Health-related quality of life was assessed using the St. George's Respiratory Questionnaire, which is a disease-specific instrument designed to evaluate quality of life among individuals with chronic respiratory diseases. The questionnaire measures the impact of respiratory symptoms and disease-related limitations on daily functioning and well-being. It includes symptom, activity, and impact domains, and produces a total score representing overall respiratory-related quality of life. Higher scores indicate poorer health-related quality of life. In the present study, the total score of the St. George's Respiratory Questionnaire was considered the primary outcome variable for predictive modeling. The use of a disease-specific quality-of-life instrument was appropriate because chronic obstructive pulmonary disease affects patients not only through physiological impairment but also through limitations in physical activity, social participation, emotional functioning, and perceived health status.

Respiratory symptom burden was measured using the COPD Assessment Test and the modified Medical Research Council dyspnea scale. The COPD Assessment Test was used to quantify the overall impact of chronic obstructive pulmonary disease symptoms on daily life, including cough, sputum production, chest tightness, breathlessness, activity limitation, sleep disturbance, and energy level. The modified Medical Research Council dyspnea scale was used to assess perceived breathlessness during physical activity. Psychological status was assessed using the Hospital Anxiety and Depression Scale, which evaluates symptoms

of anxiety and depression in medically ill populations. Physical activity was assessed using the short form of the International Physical Activity Questionnaire, and functional limitation was also evaluated through patient-reported activity restriction related to respiratory symptoms. These variables were selected because health-related quality of life in chronic obstructive pulmonary disease is commonly influenced by a combination of respiratory severity, symptom burden, psychological distress, physical inactivity, and clinical history.

2.3. Data Analysis

Data analysis was performed in several consecutive stages, including data screening, descriptive analysis, preprocessing, model development, model validation, and interpretation of predictive features. Initially, all variables were examined for missing values, coding errors, outliers, and distributional characteristics. Continuous variables were described using means and standard deviations, and categorical variables were described using frequencies and percentages. Missing values were evaluated according to their frequency and pattern. When missingness was limited and judged to be random, missing continuous predictors were imputed using median values and categorical predictors were imputed using the most frequent category. The outcome variable was not imputed, and participants with missing health-related quality-of-life scores were excluded from the final modeling dataset. Continuous predictors were standardized before Elastic Net Regression to ensure comparability of coefficients and to prevent variables with larger scales from having disproportionate influence on model estimation. Categorical predictors were transformed into dummy variables before modeling.

The primary outcome variable was the total score of the St. George's Respiratory Questionnaire. Two predictive models were developed: Elastic Net Regression and Gradient Boosting Regression. Elastic Net Regression was selected because it combines the advantages of ridge and lasso regularization and is useful when predictors are correlated, as is commonly observed among clinical, behavioral, and psychological variables in chronic obstructive pulmonary disease. This model allowed simultaneous variable selection and shrinkage of regression coefficients, thereby reducing overfitting and improving prediction stability. The regularization parameters were tuned using cross-validation, and the optimal combination of penalty strength and mixing parameter was selected based on the lowest cross-validated prediction error.

Gradient Boosting Regression was used as a nonlinear machine-learning approach to capture complex and potentially non-additive relationships between predictors and health-related quality of life. The model was trained through sequential decision trees in which each new tree attempted to reduce the residual error of the previous trees. Important hyperparameters, including the number of estimators, learning rate, maximum tree depth, minimum samples per split, and subsampling rate, were tuned using cross-validation within the training dataset. To evaluate model generalizability, the dataset was randomly divided into a training set comprising 80% of the participants and a testing set comprising 20% of the participants. Model tuning was conducted only on the training data, and final performance was evaluated on the independent testing data.

Predictive performance was assessed using root mean squared error, mean absolute error, and coefficient of determination. Root mean squared error was used to evaluate the magnitude of prediction error with greater sensitivity to large errors, mean absolute error was used to provide an interpretable estimate of average absolute prediction deviation, and coefficient of determination was used to determine the proportion of variance in health-related quality of life explained by the models. The performance of Elastic Net Regression and Gradient Boosting Regression was compared based on these indices. In addition to predictive accuracy, model interpretability was examined. For Elastic Net Regression, standardized regression coefficients were reviewed to identify predictors retained by the penalized model. For Gradient Boosting Regression, variable importance values were extracted to determine the relative contribution of each predictor to the prediction of health-related quality of life. Where appropriate, partial dependence patterns were inspected to understand the direction and form of associations between key predictors and predicted quality-of-life scores.

All analyses were conducted using statistical and machine-learning procedures suitable for predictive modeling. The analytic strategy emphasized both prediction accuracy and clinical interpretability. The final models were evaluated with attention to overfitting, generalizability, and the practical relevance of predictors. A significance level of 0.05 was used for conventional descriptive and inferential procedures, while machine-learning model selection was based primarily on cross-validated prediction error and testing-set performance.

3. Findings and Results

The final sample consisted of 286 patients with chronic obstructive pulmonary disease who were receiving outpatient pulmonary care in Tehran. The mean age of the participants was 63.47 years with a standard deviation of 8.92 years, and the age range was 42 to 82 years. Of the participants, 172 were men, representing 60.1% of the sample, and 114 were women, representing 39.9%. Most participants were married, with 226 patients reporting married status, while 60 patients were single, divorced, or widowed. Regarding education, 79 participants had primary education or lower, 128 had secondary or high-school education, and 79 had university-level education. In terms of occupational status, 83 participants were employed, 117 were retired, and 86 were unemployed or homemakers. The mean body mass index was 26.38 kg/m² with a standard deviation of 4.57, indicating that, on average, the sample was in the overweight range. With respect to smoking status, 121 participants were current smokers, 126 were former smokers, and 39 had never smoked. The average duration of chronic obstructive pulmonary disease was 7.18 years with a standard deviation of 4.64 years, showing that most participants had lived with the disease for several years before participation in the study. Overall, the demographic profile of the sample reflected a clinically relevant group of middle-aged and older adults with established chronic obstructive pulmonary disease and varying levels of disease burden, psychological symptoms, and functional limitation.

Table 1

Clinical, respiratory, psychological, functional, and health-related quality-of-life characteristics of the participants

Variable	Mean ± SD or n (%)	Minimum	Maximum
Duration of COPD, years	7.18 ± 4.64	1.00	24.00
FEV1, % predicted	51.86 ± 16.72	22.00	88.00
FVC, % predicted	68.43 ± 15.91	34.00	104.00
FEV1/FVC ratio	56.28 ± 9.74	34.00	69.00
Number of exacerbations during the previous year	1.64 ± 1.18	0.00	6.00
Number of hospitalizations during the previous year	0.48 ± 0.72	0.00	4.00
Long-term oxygen therapy	54 (18.9%)	—	—
GOLD stage I	41 (14.3%)	—	—
GOLD stage II	112 (39.2%)	—	—
GOLD stage III	94 (32.9%)	—	—
GOLD stage IV	39 (13.6%)	—	—
COPD Assessment Test score	21.73 ± 7.12	5.00	38.00
Modified Medical Research Council dyspnea score	2.31 ± 1.03	0.00	4.00
Hospital Anxiety and Depression Scale anxiety score	8.92 ± 4.21	1.00	20.00
Hospital Anxiety and Depression Scale depression score	9.36 ± 4.38	1.00	21.00
Physical activity, MET-minutes/week	1248.55 ± 702.38	210.00	3480.00
SGRQ symptoms score	55.84 ± 18.61	12.00	94.00
SGRQ activity score	62.43 ± 17.52	18.00	96.00
SGRQ impact score	47.92 ± 18.14	9.00	91.00
SGRQ total score	53.76 ± 16.87	14.00	92.00

As shown in Table 1, the participants demonstrated moderate to severe respiratory impairment and a substantial level of disease-related burden. The mean FEV1 percentage predicted was 51.86, indicating that many patients had clinically meaningful airflow limitation. Distribution across GOLD stages showed that the largest proportion of participants were classified in stage II, followed by stage III, while smaller proportions were classified in stages I and IV. This pattern indicates that the sample included patients with a broad clinical spectrum of chronic obstructive pulmonary disease rather than being restricted to either mild or advanced disease. The mean COPD Assessment Test score was 21.73, reflecting a considerable perceived impact of respiratory symptoms on everyday life. The mean modified Medical Research Council dyspnea score was 2.31, suggesting that breathlessness during physical activity was a frequent and functionally relevant complaint among participants. Psychological symptoms were also evident, as the mean anxiety and depression scores were close to the commonly used clinical threshold range on the Hospital Anxiety and Depression Scale. Physical activity levels varied widely, but the average value indicated that many

participants had relatively limited activity engagement. The mean total score of the St. George's Respiratory Questionnaire was 53.76, showing impaired health-related quality of life. Among its domains, the activity score was the highest, suggesting that activity limitation was the most pronounced aspect of quality-of-life impairment in this sample. The symptoms and impact domains were also elevated, indicating that respiratory symptoms and broader psychosocial consequences of the disease contributed substantially to poorer health-related quality of life.

Table 2

Bivariate associations between predictor variables and total health-related quality-of-life score

Predictor variable	Pearson correlation with SGRQ total score	95% CI	p-value
COPD Assessment Test score	0.68	0.61 to 0.74	<0.001
Modified Medical Research Council dyspnea score	0.61	0.53 to 0.68	<0.001
FEV1, % predicted	-0.58	-0.65 to -0.49	<0.001
FEV1/FVC ratio	-0.42	-0.52 to -0.32	<0.001
Number of exacerbations during the previous year	0.43	0.33 to 0.52	<0.001
Number of hospitalizations during the previous year	0.36	0.25 to 0.46	<0.001
Hospital Anxiety and Depression Scale anxiety score	0.48	0.38 to 0.57	<0.001
Hospital Anxiety and Depression Scale depression score	0.55	0.46 to 0.63	<0.001
Physical activity, MET-minutes/week	-0.37	-0.47 to -0.26	<0.001
Duration of COPD	0.29	0.18 to 0.39	<0.001
Body mass index	0.18	0.06 to 0.29	0.003
Age	0.22	0.10 to 0.33	<0.001

Table 2 presents the bivariate relationships between the candidate predictor variables and the total health-related quality-of-life score. Because higher St. George's Respiratory Questionnaire scores indicate poorer health-related quality of life, positive correlations represent associations with worse health-related quality of life, whereas negative correlations represent associations with better health-related quality of life. The strongest positive association was observed for the COPD Assessment Test score, indicating that patients who reported greater overall symptom burden also reported substantially poorer health-related quality of life. Dyspnea severity was also strongly associated with the outcome, showing that breathlessness during daily activities was one of the most important clinical correlates of reduced quality of life. Lung function indices were negatively associated with the total quality-of-life score, meaning that lower FEV1 percentage predicted and lower FEV1/FVC ratio were related to poorer health-related quality of life. Psychological variables were also meaningfully associated with the outcome. Depression showed a moderate-to-strong positive relationship with poorer quality of life, while anxiety had a moderate positive relationship. Exacerbation frequency and hospitalization history were positively associated with poorer quality of life, suggesting that recent disease instability was clinically relevant to patients' perceived health status. Physical activity was negatively associated with the outcome, indicating that patients with higher activity levels tended to report better health-related quality of life. Although age, body mass index, and disease duration showed weaker associations than symptom burden and lung function, their statistically significant relationships supported their inclusion as candidate predictors in the subsequent predictive models.

Table 3

Predictive performance of Elastic Net Regression and Gradient Boosting Regression models

Model	Cross-validated RMSE	Cross-validated MAE	Cross-validated R^2	Testing RMSE	Testing MAE	Testing R^2
Elastic Net Regression	9.84	7.63	0.642	10.12	7.81	0.619
Gradient Boosting Regression	8.73	6.69	0.711	8.91	6.83	0.704

Table 3 shows the comparative predictive performance of the Elastic Net Regression and Gradient Boosting Regression models. Both models demonstrated acceptable predictive accuracy for estimating health-related quality of life among patients with chronic obstructive pulmonary disease. The Elastic Net Regression model achieved a testing

RMSE of 10.12 and a testing MAE of 7.81, indicating that its average prediction error was clinically interpretable and relatively stable between the cross-validated training results and the independent testing results. The testing R^2 value of 0.619 showed that the Elastic Net model explained approximately 61.9% of the variance in the total health-related quality-of-life score in the testing dataset. The Gradient Boosting Regression model performed better across all evaluation indices. It achieved a lower testing RMSE of 8.91, a lower testing MAE of 6.83, and a higher testing R^2 of 0.704. This indicates that the Gradient Boosting model explained approximately 70.4% of the variance in health-related quality of life in the testing dataset. The superiority of Gradient Boosting suggests that the relationship between clinical, respiratory, psychological, and functional predictors and health-related quality of life was not entirely linear. The improvement in prediction may reflect the ability of Gradient Boosting to capture nonlinear patterns and interaction effects, particularly between symptom burden, dyspnea, lung function, psychological distress, and physical activity.

Table 4

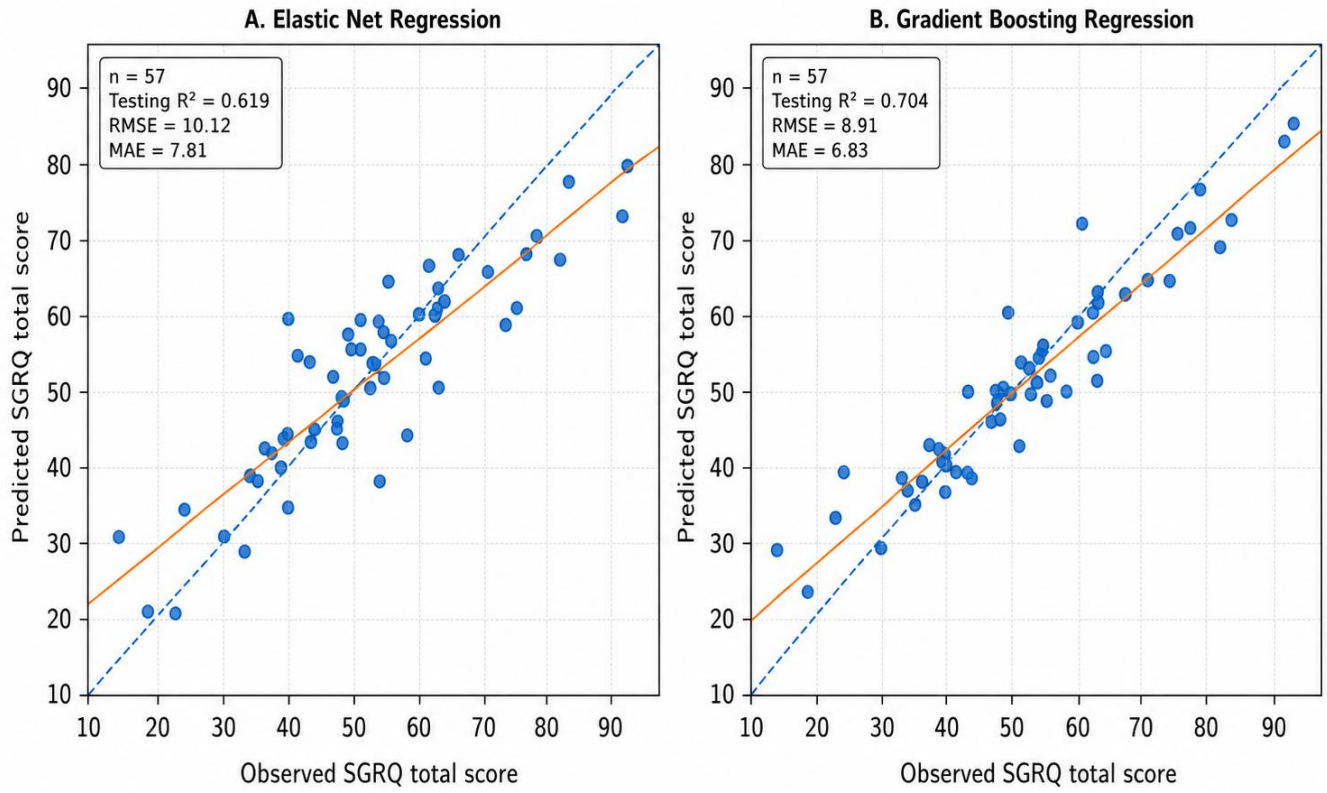
Most important predictors identified by Elastic Net Regression and Gradient Boosting Regression

Predictor variable	Elastic Net standardized coefficient	Direction in Elastic Net model	Gradient Boosting relative importance
COPD Assessment Test score	0.39	Positive	100.00
Modified Medical Research Council dyspnea score	0.29	Positive	82.60
FEV1, % predicted	-0.28	Negative	69.80
Hospital Anxiety and Depression Scale depression score	0.25	Positive	74.20
Hospital Anxiety and Depression Scale anxiety score	0.18	Positive	54.30
Number of exacerbations during the previous year	0.16	Positive	57.90
Physical activity, MET-minutes/week	-0.17	Negative	49.70
Number of hospitalizations during the previous year	0.11	Positive	36.40
Duration of COPD	0.08	Positive	32.40
Body mass index	0.05	Positive	20.10
Age	0.04	Positive	18.40
FEV1/FVC ratio	-0.10	Negative	41.60

Table 4 summarizes the most influential predictors identified by the two modeling approaches. In the Elastic Net Regression model, the COPD Assessment Test score had the largest standardized coefficient, indicating that overall respiratory symptom burden was the strongest linear predictor of poorer health-related quality of life. Dyspnea severity, lower FEV1 percentage predicted, and depressive symptoms were also retained as major predictors. The positive coefficients for COPD Assessment Test score, modified Medical Research Council dyspnea score, depression, anxiety, exacerbation frequency, hospitalization, disease duration, body mass index, and age indicate that higher values on these variables were associated with poorer health-related quality of life. In contrast, the negative coefficients for FEV1 percentage predicted, FEV1/FVC ratio, and physical activity indicate that better lung function and greater physical activity were associated with better health-related quality of life. The Gradient Boosting model produced a similar but more flexible predictive pattern. Symptom burden had the highest relative importance value, followed by dyspnea, depressive symptoms, lung function, exacerbation frequency, anxiety, physical activity, and FEV1/FVC ratio. This convergence between Elastic Net and Gradient Boosting strengthens the interpretation that health-related quality of life in chronic obstructive pulmonary disease is jointly shaped by respiratory symptoms, physiological disease severity, psychological distress, and functional behavior. The presence of physical activity among the important predictors is particularly notable because it suggests that functional engagement may contribute to quality-of-life differences beyond lung function alone.

Figure 1

Predicted versus observed health-related quality-of-life scores in the testing dataset for Elastic Net Regression and Gradient Boosting Regression



The pattern shown in Figure 1 indicated that predicted scores were more closely aligned with observed health-related quality-of-life scores in the Gradient Boosting Regression model than in the Elastic Net Regression model. In both models, most predicted values followed the general direction of the observed St. George's Respiratory Questionnaire total scores, confirming that the selected clinical, respiratory, psychological, and functional variables had meaningful predictive utility. However, the Elastic Net Regression model showed greater dispersion around the prediction line, particularly among patients with very poor health-related quality of life. This suggests that a strictly regularized linear model may underestimate or overestimate quality-of-life impairment in patients with more complex symptom profiles. By contrast, the Gradient Boosting model demonstrated tighter clustering of predicted values around the observed values, especially in the middle and upper ranges of the quality-of-life score distribution. This finding supports the quantitative performance indices reported in Table 3 and suggests that Gradient Boosting provided a more accurate representation of the multidimensional and potentially nonlinear determinants of health-related quality of life in patients with chronic obstructive pulmonary disease.

Overall, the findings showed that patients with chronic obstructive pulmonary disease in Tehran experienced substantial impairment in health-related quality of life, particularly in the activity domain. Symptom burden, dyspnea severity, reduced lung function, depressive symptoms, anxiety symptoms, exacerbation history, hospitalization, and reduced physical activity were all associated with poorer health-related quality of life. The predictive modeling results indicated that both Elastic Net Regression and Gradient Boosting Regression were useful for estimating health-related quality of life, but Gradient Boosting demonstrated superior predictive performance. The most important predictors were consistent across the two models, with respiratory symptom burden, dyspnea, lung function, depression, exacerbation frequency, anxiety,

and physical activity emerging as the central determinants of health-related quality-of-life variation in the sample.

4. Discussion

The present study examined the prediction of health-related quality of life among patients with chronic obstructive pulmonary disease using Elastic Net Regression and Gradient Boosting Regression. The findings showed that patients with chronic obstructive pulmonary disease in Tehran experienced a considerable impairment in health-related quality of life, as reflected by the elevated mean total score of the St. George's Respiratory Questionnaire. Among the quality-of-life domains, the activity domain had the highest mean score, indicating that limitations in physical activity and daily functioning were the most pronounced dimensions of disease burden in this sample. This result is consistent with the clinical nature of chronic obstructive pulmonary disease, in which dyspnea, fatigue, reduced exercise tolerance, and fear of symptom aggravation commonly restrict daily activity and participation. Previous studies have similarly emphasized that health-related quality of life in chronic obstructive pulmonary disease is strongly influenced by symptom burden, functional impairment, disease severity, and daily activity restriction (Sharma et al., 2021; Tekobo et al., 2025; Ying et al., 2024). The present findings also align with broader evidence showing that chronic obstructive pulmonary disease imposes both humanistic and socioeconomic burdens on patients and caregivers, making quality of life a central outcome for clinical assessment and disease management (Rehman et al., 2021).

The bivariate findings indicated that higher COPD Assessment Test scores, greater dyspnea severity, more frequent exacerbations, more hospitalizations, higher anxiety and depression scores, longer disease duration, higher body mass index, and older age were associated with poorer health-related quality of life. In contrast, better lung function and higher physical activity were associated with better quality of life. These findings confirm that quality of life in chronic obstructive pulmonary disease is not determined by a single disease marker but by the accumulation of respiratory, psychological, clinical, and behavioral burdens. The strong positive association between COPD Assessment Test score and St. George's Respiratory Questionnaire total score indicates that general symptom burden is a core determinant of perceived health status. This supports previous evidence showing that symptom burden and patient-reported disease impact are closely tied to quality-of-life outcomes among chronic obstructive pulmonary disease patients (Shahid et al., 2024; Ying et al., 2022). Similarly, the strong association between dyspnea and poorer quality of life is consistent with the well-established clinical role of breathlessness as one of the most disabling symptoms of chronic obstructive pulmonary disease and one of the major drivers of activity limitation, emotional distress, and social withdrawal.

The negative relationship between FEV1 percentage predicted and health-related quality-of-life impairment shows that patients with poorer lung function tended to experience worse perceived health status. However, the strength of the association also suggests that lung function alone cannot fully explain quality-of-life differences. This interpretation is consistent with previous literature emphasizing that spirometric impairment is important but insufficient as a comprehensive indicator of patient burden. Studies on chronic obstructive pulmonary disease and related respiratory conditions have shown that quality-of-life outcomes are shaped by pulmonary function, symptoms, comorbidities, behavioral factors, and treatment context (Claessens et al., 2023; Miravitlles et al., 2022). The present findings therefore support a multidimensional approach to outcome assessment, in which physiological indices are combined with patient-reported measures to obtain a more complete representation of disease burden. Evidence from dynamic pulmonary function monitoring also suggests that repeated or continuous monitoring may provide clinically meaningful information about quality of life, especially when pulmonary function is interpreted in relation to daily symptoms and functioning (Zhao et al., 2026).

Psychological symptoms were also important predictors of health-related quality of life. Depression and anxiety were both positively associated with poorer quality of life, and depression emerged as one of the most influential variables in both predictive models. This finding supports the view that psychological distress is not a secondary or peripheral issue in chronic obstructive pulmonary disease but a central component of disease burden. Depression can reduce motivation, self-care behaviors, treatment adherence, physical activity, and participation in pulmonary rehabilitation, while anxiety may intensify breathlessness perception and avoidance behaviors. Previous studies have shown that comorbid depression and autonomic dysfunction may be associated with reduced lung function in patients with chronic obstructive pulmonary disease, which supports the close relationship between psychological and respiratory

functioning (Li & Rong, 2025). The result is also consistent with literature emphasizing psychosocial support as an essential component of pulmonary rehabilitation and chronic obstructive pulmonary disease management (Yohannes, 2024). In advanced disease, psychological and existential distress may become more prominent, reinforcing the importance of palliative and supportive care frameworks (Gonçalves et al., 2025; Guler et al., 2025; Madiraca et al., 2023).

The importance of exacerbation frequency and hospitalization history in the present study further indicates that disease instability contributes significantly to health-related quality-of-life impairment. Patients with more frequent exacerbations and hospitalizations may experience greater fear of future episodes, reduced confidence in physical activity, increased dependency, and worsening symptom perception. This finding is consistent with clinical and prognostic literature showing that exacerbations are major events in the course of chronic obstructive pulmonary disease and can affect symptom burden, functioning, healthcare utilization, and perceived health status. Malnutrition has also been identified as an important factor in predicting acute exacerbations and poor outcomes among patients with highly complex chronic obstructive pulmonary disease, suggesting that exacerbation risk is embedded in a broader clinical profile that includes nutritional and systemic vulnerability (Raimondo et al., 2024). The present findings therefore reinforce the need to identify patients at high risk of poor quality of life through models that include both stable disease characteristics and recent disease instability.

The predictive modeling results showed that both Elastic Net Regression and Gradient Boosting Regression were useful for estimating health-related quality of life, but Gradient Boosting demonstrated superior performance. The Elastic Net Regression model explained 61.9% of the variance in health-related quality of life in the testing dataset, while the Gradient Boosting model explained 70.4%. The lower testing RMSE and MAE in the Gradient Boosting model indicated better predictive accuracy and smaller average prediction errors. This finding suggests that the relationship between predictors and health-related quality of life in chronic obstructive pulmonary disease may include nonlinear and interactive patterns that are better captured by tree-based ensemble learning. For example, the effect of dyspnea on quality of life may depend on physical activity level, depressive symptoms, exacerbation history, or lung function. Similarly, the effect of pulmonary impairment may be more severe among patients with poor self-management capacity, psychological distress, or limited social support. The advantage of Gradient Boosting in the present study therefore reflects the complex clinical reality of chronic obstructive pulmonary disease, where multiple predictors interact to shape patient-reported outcomes.

At the same time, the Elastic Net Regression findings were clinically valuable because they provided an interpretable linear model with retained predictors and standardized coefficients. The strongest coefficient was observed for COPD Assessment Test score, followed by dyspnea severity, lower FEV1 percentage predicted, depressive symptoms, anxiety symptoms, exacerbation frequency, and physical activity. This pattern was highly consistent with the variable importance structure of the Gradient Boosting model, which also identified symptom burden, dyspnea, depressive symptoms, lung function, exacerbation frequency, anxiety, and physical activity as central predictors. The convergence between the two models strengthens the conclusion that quality of life in chronic obstructive pulmonary disease is primarily shaped by the combined influence of respiratory symptoms, physiological impairment, psychological distress, and functional behavior. Similar multidimensional interpretations are supported by studies on self-management, integrated disease management, and blended interventions, which show that improving chronic obstructive pulmonary disease outcomes requires attention to symptoms, behavior, psychological adaptation, and continuity of care rather than isolated biomedical treatment (Adhikari et al., 2025; Lin et al., 2023; Song et al., 2021).

The role of physical activity in the present study is particularly important. Higher physical activity was associated with better health-related quality of life and remained among the influential predictors in the modeling results. This finding suggests that physical activity may represent both a marker and a mechanism of better functioning. Patients who remain more active may have lower symptom avoidance, better physical conditioning, more confidence in daily activities, and fewer depressive symptoms. Conversely, inactivity may worsen deconditioning, increase dyspnea during exertion, and contribute to poorer perceived health. The finding aligns with rehabilitation-oriented evidence emphasizing functioning and quality of life as central outcomes in respiratory disease management (Lippi et al., 2024). It is also consistent with research on technological and digital solutions for older adults with chronic obstructive pulmonary disease, where digital monitoring and supportive

technologies are increasingly discussed as methods to improve functioning, engagement, and quality of life (Lippi et al., 2023). In this regard, predictive models may help identify patients whose quality of life is most affected by modifiable functional behaviors.

The findings also support the importance of broader social, relational, and contextual factors in chronic obstructive pulmonary disease. Although the present model focused primarily on patient-level clinical and psychological variables, the interpretation of quality of life should not be separated from family and care context. Dyadic research has shown that patient self-care and caregiver factors are linked to quality of life, indicating that chronic obstructive pulmonary disease is often managed within relational systems rather than by patients alone (Cai et al., 2025). Caregiver health and palliative care implementation are also relevant in chronic obstructive pulmonary disease and other serious pulmonary conditions, especially when the disease becomes advanced and daily support needs increase (Marić et al., 2021). Moreover, palliative care needs among women with advanced chronic obstructive pulmonary disease point to the importance of gender-sensitive and context-sensitive approaches to quality-of-life assessment and intervention (Madiraca et al., 2024). These findings help explain why clinical prediction should eventually move beyond symptom and lung function variables and include social support, caregiving burden, and access to supportive care.

The present findings can also be understood in relation to behavioral and environmental exposures. Smoking-related behavior and electronic cigarette use patterns have been linked to symptom burden and quality of life, suggesting that respiratory outcomes and patient-reported well-being are influenced by ongoing exposure and behavioral change (Cao et al., 2023, 2024). Climate-related concerns may also affect quality of life among patients with chronic obstructive pulmonary disease, especially in urban environments where air pollution, heat, and environmental uncertainty may intensify respiratory vulnerability and psychological burden (Asal et al., 2025). Differences in chronic obstructive pulmonary disease management across clinician types further indicate that patient outcomes may vary according to care patterns, maintenance treatment habits, and provider-level decision-making (Castro et al., 2025). In addition, high frequency chest wall oscillation and other symptom-focused therapeutic approaches may influence clinical symptoms, highlighting the importance of treatment modalities that address the daily symptom burden experienced by patients (Bruner et al., 2024). These findings collectively suggest that future prediction models may become more powerful if they integrate clinical variables with exposure history, care patterns, treatment modalities, and environmental indicators.

5. Conclusion

Finally, several domains of quality of life may remain underrecognized unless deliberately assessed. Sexual dysfunction, spirituality, oral health, and unmet needs are examples of areas that may affect well-being but are not always included in routine chronic obstructive pulmonary disease assessment. Evidence regarding sexual dysfunction and quality of life shows that intimate functioning may be impaired among patients with chronic obstructive pulmonary disease and may represent an important but overlooked component of patient-centered care (Rahman et al., 2026). Spirituality has also been discussed as a meaningful dimension for people with advanced chronic obstructive pulmonary disease, particularly in relation to coping, support, and healthcare education (Kotlińska–Lemieszek et al., 2022). Oral health may also be relevant, as literature on the bidirectionality between chronic obstructive pulmonary disease and periodontal disease points to the possible interaction of systemic inflammation, infection, and health behavior (Tamiya et al., 2023). In addition, quality-of-life research in other chronic inflammatory conditions has shown that patient-reported outcomes can reveal unmet needs that may not be captured by clinical indicators alone (Enrique Gómez de la et al., 2023). The present study contributes to this patient-centered perspective by demonstrating that health-related quality of life can be predicted with reasonable accuracy when multidimensional patient information is analyzed using appropriate predictive modeling techniques.

6. Limitations & Suggestions

This study had several limitations that should be considered when interpreting the findings. The cross-sectional design prevents causal interpretation, and the observed associations between predictors and health-related quality of life should be understood as predictive rather than causal relationships. Participants were recruited from outpatient pulmonary care settings in Tehran, which may limit the generalizability of the findings to patients in rural regions, other cities, hospitalized populations, or those with limited access to specialized care. Some variables, including psychological symptoms, physical activity, and quality of life, were measured through self-report instruments and may

therefore be affected by recall bias, response style, or temporary mood state. Although the sample size was adequate for the planned models, larger samples would allow more robust validation, subgroup analysis, and external testing. In addition, some potentially important predictors, such as air pollution exposure, medication adherence, social support, caregiver burden, sleep quality, nutritional biomarkers, and longitudinal exacerbation patterns, were not included in the final model.

Future studies should use longitudinal designs to examine whether Elastic Net Regression, Gradient Boosting, and other machine-learning models can predict future deterioration or improvement in health-related quality of life over time. External validation in independent samples from different regions and healthcare settings is needed to determine whether the present model performs reliably beyond the original study population. Future research should also include broader predictor domains, such as environmental exposure, air quality, treatment adherence, pulmonary rehabilitation participation, caregiver support, sleep quality, nutritional status, inflammatory markers, and digital monitoring data. Comparative studies may evaluate additional algorithms, including random forests, support vector regression, extreme gradient boosting, neural networks, and interpretable hybrid models. It would also be valuable to examine subgroup-specific models based on sex, age, disease severity, smoking status, exacerbation frequency, and comorbidity profiles to determine whether different predictors are more important for different patient groups.

The findings suggest that clinical assessment of patients with chronic obstructive pulmonary disease should include routine evaluation of health-related quality of life in addition to spirometry and standard symptom assessment. Clinicians should pay particular attention to patients with high symptom burden, severe dyspnea, reduced lung function, depressive symptoms, anxiety symptoms, frequent exacerbations, hospitalization history, and low physical activity, as these factors were central predictors of poorer quality of life. Predictive models such as Gradient Boosting may be used as decision-support tools to identify patients who require more intensive monitoring, pulmonary rehabilitation, psychological support, self-management education, nutritional assessment, or palliative care referral. At the same time, the interpretability of Elastic Net Regression can help clinicians understand which variables contribute most strongly to risk. In practice, quality-of-life prediction should support individualized care planning, earlier intervention, and integrated management rather than replacing clinical judgment.

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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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