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Soil Quality Index and Its Determining Factors in Shrub Vegetation: Implications for Sustainable Land Management in Aceh Besar, Indonesia

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Abstract: Soil Quality Index (SQI) is an important indicator for evaluating soil functions and supporting sustainable land management. However, information on the relationships between SQI and soil properties under tropical shrub vegetation remains limited. This study aimed to analyze the correlation between SQI and selected soil physical and chemical properties under shrub vegetation in Aceh Besar Regency, Indonesia. Soil samples were collected using purposive sampling from shrubland sites and analyzed for nine soil variables, including rooting depth, silt and clay fractions, bulk density, porosity, soil pH, total nitrogen, available phosphorus, exchangeable potassium, and soil organic carbon. The SQI was determined using a scoring-based index approach, and Pearson correlation analysis was performed using IBM SPSS Statistics 25. The average SQI was 0.4381, indicating moderate soil quality. Soil physical properties were the primary determinants of SQI, with the silt and clay fractions showing the strongest positive correlation ($r = 0.993$), followed by porosity ($r = 0.934$) and rooting depth ($r = 0.790$). Among the chemical properties, exchangeable potassium exhibited the strongest positive correlation ($r = 0.870$). These findings indicate that improving soil physical conditions, particularly soil texture and porosity, while maintaining potassium availability, should be prioritized to enhance soil quality and support sustainable management of shrubland ecosystems in Aceh Besar Regency.

Keywords: Chemical properties of soil; Correlation analysis; Physical properties of soil; Shrub vegetation; SQI

Introduction

Soil is a fundamental component of terrestrial ecosystems that supports plant productivity, regulates nutrient cycling, stores carbon, and maintains environmental sustainability. The capacity of soil to perform these ecological and agronomic functions is commonly evaluated using the Soil Quality Index (SQI), which integrates multiple soil properties into a single quantitative indicator that represents overall soil condition (Chaudhry et al., 2024; Munnaf & Mouazen, 2021). The SQI approach has become increasingly important because soil degradation caused by land-use change, intensive land exploitation, erosion, and climate-related disturbances has reduced soil fertility and ecosystem resilience worldwide (Mukhopadhyay et al., 2016). Consequently, identifying the key soil properties controlling SQI is essential for developing sustainable land management strategies and maintaining ecosystem functions.

Vegetation type is one of the major factors influencing soil quality because it regulates litter production, root development, nutrient cycling, soil aggregation, and organic matter accumulation. Shrub vegetation is particularly important in tropical ecosystems because it commonly develops on abandoned agricultural land, degraded forests, and areas undergoing secondary succession. Shrubs may

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improve soil quality through litter deposition, root turnover, and localized nutrient accumulation, creating so-called "fertility islands" that enhance soil fertility and ecosystem recovery (Kooch & Sohrabzadeh, 2024; Kartalaei et al., 2023). However, the effects of shrub vegetation on soil quality vary considerably depending on species composition, soil characteristics, and local environmental conditions.

Previous studies have extensively investigated soil quality under different vegetation and land-use systems. Research conducted in wetlands demonstrated significant differences in SQI among tree, shrub, and grass vegetation, with soil organic carbon, texture, and porosity identified as important indicators of soil quality (Zhang et al., 2022; Zhou et al., 2020). Similarly, studies in agricultural and forest ecosystems reported that land-use change substantially alters soil physical and chemical characteristics, thereby influencing soil quality (Kahsay et al., 2025; Kahsay et al., 2023). Other investigations have developed comprehensive SQI frameworks by integrating multiple soil indicators to evaluate land degradation and ecosystem sustainability (Lenka et al., 2022; Vasu et al., 2024). Recent reviews also highlighted soil organic carbon, total nitrogen, soil texture, bulk density, and nutrient availability as among the most reliable indicators for assessing soil quality across diverse ecosystems (Abshiba et al., 2025; Fan et al., 2025; Marion et al., 2022).

Despite these advances, studies specifically evaluating the relationships between Soil Quality Index and individual soil physical and chemical properties in tropical shrubland ecosystems remain limited, particularly in Indonesia. Most previous investigations have focused on cropland, forests, wetlands, or grassland ecosystems, while shrub vegetation has received relatively little scientific attention. This knowledge gap limits the understanding of which soil properties predominantly determine soil quality under shrub vegetation and consequently restricts the development of effective management strategies for these ecosystems (Reis & Dindaroğlu, 2024; Abdullah et al., 2024b).

Aceh Besar Regency represents an important case study because it exhibits considerable land-use dynamics, including abandoned agricultural land, secondary shrub vegetation, and degraded landscapes undergoing natural regeneration. The region is also characterized by diverse soil orders, including Ultisols, Inceptisols, and Entisols, which differ substantially in nutrient availability, weathering intensity, and physical characteristics. These heterogeneous environmental conditions are expected to generate substantial variation in soil quality, making Aceh Besar an appropriate location for evaluating the relationships between SQI and soil properties (Fawaid et al., 2026). Improving knowledge of soil quality under shrub vegetation is therefore important for supporting land rehabilitation, sustainable management of marginal lands, and long-term ecosystem restoration in tropical environments (Yu et al., 2023).

The present study addresses these knowledge gaps by evaluating the relationships between Soil Quality Index and selected soil physical and chemical properties under shrub vegetation using Pearson correlation analysis. Unlike previous studies that primarily emphasized overall SQI assessments across different land-use types, this research identifies the dominant soil properties that contribute to SQI in tropical shrubland ecosystems and provides location-specific evidence from Aceh Besar Regency, Indonesia, where comparable studies remain scarce. The findings are expected to improve the scientific understanding of soil quality assessment in shrub vegetation and provide useful information for sustainable land management and ecosystem rehabilitation. Therefore, this study aims to analyze the correlation between the Soil Quality Index (SQI) and selected soil physical and chemical properties under shrub vegetation in Aceh Besar Regency, Indonesia.

Method

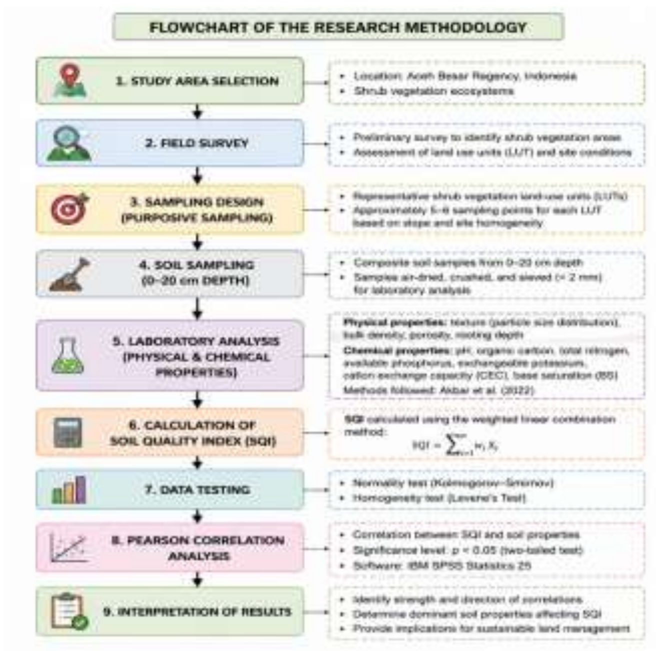

Figure 1. Flowchart of the research methodology

The shrub vegetation environment in Aceh Besar Regency, Aceh, covering an area of about 96,962.2 ha, was the study site. In addition to fieldwork, analyses were conducted at the Soil and Plant Research Laboratory of the Faculty of Agriculture, Universitas

Syiah Kuala. GPS, soil drills, sample rings, pH meters, tape measures, plastic bags, rubber bands, knives, hoes, and an Abney level were among the tools used in the field. Analytical balances, pH meters, ovens, shakers, hot plates, homogenizers, distillation units, burettes, beakers, spectrophotometers, and atomic absorption spectrophotometers (AAS) were among the tools used in laboratory analysis.

The main material used in this research is soil samples taken from the top layer (0–20 cm depth) to analyze soil fertility. Area maps, Google Maps imagery, soil type maps, observation point maps, and chemical materials required during the field survey, including 10% H_2O_2, 10 N HCl, and distilled water, were also used. Other reagents required for laboratory analysis included 10% H_2O_2, 10 N HCl, and distilled water.

The research method used was a descriptive approach, based on field surveys and laboratory analyses. Field surveys were conducted to obtain primary data on the general biophysical conditions of an area, as well as the physical & chemical characteristics of the soil. This data was obtained through direct field observation and laboratory analysis of soil quality indicators.

Sampling points were selected using purposive sampling, targeting locations considered representative of shrub conditions in Aceh Besar Regency. Soil samples for chemical analysis were collected using a soil auger, and soil solum thickness was also measured. Sampling focused on the topsoil at a depth of 0–20 cm. Approximately 5–6 sample points were taken from each shrub vegetation land-use unit (LUT), which were then analyzed in the laboratory. The resulting data were used to determine the soil fertility status for each land-use type. Field observations and sampling were conducted at each observation point, which represented the scrub vegetation in the study area. Soil samples were collected from slopes ranging from 0–15% (flat to slightly steep), representing several soil types: Entisols, Ultisols, and Inceptisols.

Soil sample analysis was carried out in the laboratory to obtain information about the chemical & physical properties of the soil at the research site. The chemical parameters analyzed included pH (H_2O), organic carbon content, total nitrogen, available phosphorus, and exchangeable potassium. In addition, cation exchange capacity (CEC) & base saturation (BS) were used as supporting data for soil classification. For physical soil properties, analysis was conducted on undisturbed soil samples, including particle size distribution (texture), bulk density, and porosity. Parameters and methods for soil property analysis, including physical and chemical properties, as well as rooting depth (Akbar et al., 2022).

SQI analysis uses a method that has been modified by several researchers (Emami et al., 2024; Şeker et al., 2017; Mausbach & Seybold, 1998; Partoyo, 2005). The SQI is determined based on 9 soil property criteria. Modifications were made in several areas to reflect the conditions of the research area (Kusumawati et al., 2023; Partoyo, 2005; Arifin, 2011). The criteria for the soil quality index are divided into very good, good, medium, low, and very low categories.

The data were processed using SPSS version 25. The direction & strength of the relationship between 2 or more variables are represented by a numerical value called correlation. A correlation coefficient, which ranges from -1 to +1, is used to quantify this relationship. A direct relationship is denoted by a positive sign (+), whereas an inverse relationship is shown by a negative sign (-). The correlation coefficient, represented by the letter "r," is typically used to express the degree of relationship between variables. Pearson correlation analysis was performed using IBM SPSS Statistics version 25. Statistical significance was evaluated using a two-tailed probability test (Sig. 2-tailed). Correlations were considered statistically significant when $p < 0.05$, then:

$$r = \frac{n\sum XY - (\sum X)(\sum Y)}{\sqrt{(n\sum X^2 - (\sum X)^2)(n\sum Y^2 - (\sum Y)^2)}} \quad (1)$$

The strength and direction of the linear relationship between variables X and Y can be determined using the Pearson correlation coefficient. In this formula, n denotes the number of data pairs; $\sum XY$ is the sum of the products of X and Y; and $\sum X$ and $\sum Y$ are the sums of X and Y, respectively. $\sum X^2$ and $\sum Y^2$ represent the sums of squares for each variable. Interpretation of the correlation test results is then grouped into several categories, namely no correlation, very weak correlation, moderately strong, strong, perfect positive, and perfect negative (Abdullah et al., 2024a; Kadam et al, 2019; Mukherjee & Lal, 2014).

The data obtained from the field were then tested for normality and homogeneity. Then, if the data were normally distributed & homogeneous, the analysis continued with statistical correlation analysis (Abdullah et al., 2025). Where: Y = Soil Quality Index, X_1 = Rooting depth, X_2 = Sit and Clay Fractions, X_3 = Bulk density, X_4 = Porosity, X_5 = pH (H_2O), X_6 = Total N, X_7 = Available P, X_8 = Exchangeable K, and X_9 = Organic C.

The analysis of the relationship between the SQI (Y) and variables X_1–X_9 was carried out using Pearson (Product-Moment) correlation. The Pearson method was used because the data are on a ratio/continuous scale, aims to measure the strength and direction of the linear relationship between variables, and is commonly used in soil quality index (SQI) studies and soil indicator selection. Correlation analysis is an important initial stage in identifying dominant indicators and understanding relationships among soil properties before further analysis (PCA/regression) (Askari & Holden, 2014; Carabassa et al., 2019).

Figure 2. Research locations on Shrub vegetation in Aceh Besar District

Result and Discussion

The average results of chemical and physical analysis and the SQI category of shrub vegetation obtained values: X_1 = 37.43, X_2 = 70.25, X_3 = 1.59, X_4 = 41.18, X_5 = 6.24, X_6 = 0.08, X_7 = 1.26, X_8 = 0.7, X_9 = 0.73, and Y = 0.4381 (moderate SQI category). The average SQI value of 0.4381 indicates that shrub vegetation in Aceh Besar falls within the moderate soil quality category. This suggests that the soil still retains sufficient ecological functions but requires improved nutrient management and soil conservation to enhance long-term sustainability.

Table 1. Correlation analysis of factors influencing SQI values

Variable	r (Y with Xi)	Direction	Strength
X_1 (Rooting depth)	0.790	Positive	Strong
X_2 (Soil and Clay Fractions)	0.993	Positive	Very strong
X_3 (Bulk density)	-0.770	Negative	Strong
X_4 (porosity)	0.934	Positive	Very strong
X_5 (pH)	0.413	Positive	Moderate
X_6 (Total N)	0.640	Positive	Strong
X_7 (Available P)	0.690	Positive	Strong
X_8 (Exchangeable K)	0.870	Positive	Very strong
X_9 (Organic C)	0.638	Positive	Strong

Regarding soil morphological and physical properties, rooting depth (X1) showed a strong positive correlation with SQI (r = 0.790), and root depth (X1) showed a strong positive correlation (r = 0.790). This indicates that the deeper the root system, the better the soil quality. Roots play a role in improving soil structure, increasing microbial activity, and improving nutrient cycling (Marschner, 2023; Richardson et al., 2009).

Among the evaluated variables, silt and clay fractions (X2) and porosity (X4) exhibited the strongest positive correlations with SQI, indicating that soil physical conditions play an important role in determining soil quality in the study area. Soil texture (X_2) – r = 0.993 (very strong). This is the most dominant factor. This means that the higher the silt and clay fraction, the better the soil quality. Fine-textured soil has high water-holding capacity, high cation exchange capacity, and better nutrient retention. This is in accordance with the concept that soil texture strongly influences the soil's ability to provide water and nutrients (Dexter, 2004; Brady & Weil, 2016). Bulk density (X_3) – r = -0.770 (strong negative). This indicates that the higher the bulk density, the lower the soil quality. Dense soil can cause root penetration barriers, poor aeration, and decreased microbial activity (Widjajanto et al., 2025; Shukla, 2023; Hillel, 2004). Porosity (X_4) – r = 0.934 (very strong). These results indicate that increased porosity is associated with an increase in SQI in shrub vegetation. High porosity increases water infiltration, soil aeration, root system development, and microbial activity, thereby improving the soil's physical, chemical, and biological functions (Nasution & Fitria, 2023). Therefore, porosity is a physical indicator that significantly improves soil quality and the sustainability of ecosystem functions. This finding is consistent with research (Vasu et al., 2024; Kusumawati et al., 2023; Hillel, 2004; Askari & Holden, 2014), which reported that porosity is a key indicator in evaluating soil quality and significantly influences the Soil Quality Index value. High porosity increases infiltration, aeration, and root development.

Soil chemistry factors in shrub vegetation with exchangeable potassium (X_8) – r = 0.870 (very strong). This indicates that K availability increases SQI. K availability plays a role in plant water regulation, enzyme activation, and stress resistance (Wang & Wu, 2013; Zörb et al., 2014). Organic carbon (X_9) – r = 0.638 (strong). This indicates that organic matter contributes to soil quality, particularly by improving soil structure, increasing cation exchange capacity, and supporting microbial activity (Nuraya & Agawaman, 2025; Shahbaz et al., 2017; Six et al., 2002). pH (X_5) – r = 0.413 (moderate). pH affects nutrient availability (Sirait et al., 2020; Lee et al., 2021), but its effect is not dominant at this location. Similar findings were reported by Askari & Holden (2014), who identified exchangeable potassium as one of the principal indicators of soil quality in grassland ecosystems. Likewise, Vasu et al. (2024) emphasized that nutrient availability, particularly exchangeable bases, substantially contributes to SQI development.

Available phosphorus (X7) – r = 0.69 (strong). Phosphorus is the second most important factor. This indicates that increasing P can increase SQI. Available phosphorus plays a role in root growth and in the transfer of energy (ATP). Phosphorus is essential for plant metabolism and development (Lambers et al., 2018; Lambers et al., 2015; Vance et al., 2003). Total nitrogen (X_6) – r = 0.64 (strong). Nitrogen contributes significantly to soil fertility. N in soil acts as a major component of chlorophyll and can increase plant biomass (Mahboob et al., 2023; Xu et al., 2012). Based on the strength of the correlations, the principal soil properties associated with SQI were the silt and clay fractions (X2), porosity (X4), exchangeable potassium (X8), and rooting depth (X1), all of which exhibited strong to very strong positive relationships with SQI. This indicates that SQI in shrub vegetation is more controlled by soil physical properties (texture and structure) and specific nutrients (especially K and organic matter).

This study was limited to shrub vegetation and evaluated only selected physical and chemical soil properties. Biological indicators, such as microbial biomass and soil respiration, were not included. Future studies integrating biological parameters with multivariate analyses, such as Principal Component Analysis (PCA), are recommended to develop a more comprehensive Soil Quality Index.

Conclusion

The average Soil Quality Index (SQI) under shrub vegetation in Aceh Besar Regency was 0.4381, indicating a moderate level of soil quality. Pearson correlation analysis showed that soil physical properties were the primary determinants of SQI. The silt and clay fractions (X2) exhibited the strongest positive correlation with SQI (r = 0.993), followed by porosity (X4) (r = 0.934), while exchangeable potassium (X8) showed the strongest relationship among the chemical properties (r = 0.870). Rooting depth (X1) also had a strong positive correlation with SQI (r = 0.790). These findings indicate that improving soil physical conditions, particularly soil texture and porosity, while maintaining potassium availability, is essential for enhancing soil quality and supporting the sustainable management of shrubland ecosystems in Aceh Besar Regency. Future research should incorporate biological soil indicators and multivariate statistical approaches to develop a more comprehensive Soil Quality Index.

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Author Contributions

Conceptualization and design of research work, .RW.; implementation of field/laboratory experiments and data collection, data analysis and interpretation, manuscript preparation, R.W. and U.H.

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Conflicts of Interest

The researchers declare no conflict of interest.

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