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Research Article

Soil Quality Index Mapping Using GIS and Sentinel-2 Image In Jember, East Java

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Abstract
Soil is a solid mineral and organic matter from weathering rocks over the years. The current condition shows many productive lands that are of low quality. Soil quality must be a top priority in land management efforts to support the sustainability of ecology. This study proposes to soil quality index (SQI) assessment of paddy fields in Jember Regency, Indonesia, using the principal component analysis (PCA) method based on spatial data. The research procedure consists of (1) making land units, (2) soil sampling, (3) laboratory analysis, (4) principal component analysis (PCA), (5) assessment of soil quality index (SQI), and (6) Thiessen polygon analysis. The correlation results show the average correlation value < 0.5 (not significant). The soil quality is determined by three main components: total P, silt fraction, and clay fraction. The results of the soil quality analysis showed that 68,888 Ha was in the very low-quality category, and 39,948 Ha was in the low-quality category. Meanwhile, paddy fields included in the medium category are only 3,513 Ha. The addition of organic matter can improve the quality of paddy fields.

Keywords: Soil degradation; soil quality index; mapping; irrigated paddy

1. Introduction

Soil is a solid mineral and organic matter resulting from weathering rocks over the years (Schoonover & Crim, 2015). Natural Resources Conservation Service (1999) also defines soil as solids (minerals and organic matter), liquids, and gases occupying space and having a horizon or layer due to the influence of the loss or addition of a specific substance. The change in the horizon is influenced by the type of soil minerals, climate, temperature, macroorganisms, and soil microorganisms. Different soil conditions will affect its functioning.

In general, soil serves as a place to live for humans, animals, and plants. According to Tahat et al. (2020), soil functions to (1) ensure the sustainability of animal and plant production, (2) maintain and improve water quality, and (3) improve animal and plant health. Soil quality must be a top priority in land management. Soil quality is a dynamic interaction between physical, chemical, and biological properties. It influences external factors such as land use, land management, and the socio-economic conditions of the community (Ghimire et al., 2018; Triantafyllidis et al., 2018).

Research in Malaysia shows that 36 out of 61 respondent farmers practice intensive agriculture [A1] (Terano et al., 2015; Fesyuk et al., 2021), with no exception in Indonesia. Most of the soil in Indonesia is of low quality (Lantoi et al., 2016; Supriyadi et al., 2018). It causes the high intensity of chemical inputs in agricultural practices. Rahman and Zhang (2018) stated that more than half of

China's agricultural production increase is based on the high consumption of chemical fertilizers. Using chemical fertilizers and pesticides can increase the availability of soil nutrients and negatively impact the soil (Kobua et al., 2021).

Chemical fertilizers produce residues that can last decades in the soil (Baghdadi et al., 2018). This residue causes the soil to become acidic, causes soil compactions, reduces the number of microorganisms, and reduces the availability of soil nutrients (Rahman & Zhang, 2018). Mahmood et al. (2017) also stated that intensive application of chemical fertilizers causes land degradation and leaching of nutrients into groundwater, which poses a risk to human and animal health. Evaluation of the soil quality index (SQI) is needed to determine the existing condition of the soil. Soil quality index assessment aims to assess the distribution of soil nutrients (N, P, K, C-organic, and pH) (Nepal and Asheshwar, 2018). Information on nutrient distribution is expected to be the initial data for planning more sustainable land management.

Many soil quality indicators make it difficult to determine the main components(Edrisi et al., 2019). Principal Component Analysis (PCA) is the right method to determine the main components. PCA analyzes the correlation between each component and determines the weight of each principal component through the minimum data set (MDS) (Supriyadi et al., 2019). The use of the PCA method in quality assessment has been carried out in several areas, i.e., Mexico (Bedolla-Rivera et al., 2020), Greece (Vassilios Triantafyllidis et al., 2018), Egypt (Shokr et al., 2021), Wonogiri (Indonesia) (Supriyadi et al., 2019). In general, procedures of PCA analysis consist of (1) determining the leading component of each indicator that affects soil quality; (2) calculating the weight of each principal component, and (3) calculating the SQI value by calculating the weight of the principal component multiplied by the eigenvactor value. PCA will reduce data redundancy, where soil indicators with eigenvalues >1 will be selected as the main component. Each main component is then weighted (Wi) by dividing the % of variance by the % of the total variance listed in the MDS table. The SQI calculation is done by adding up the product of the principal component values and their weights.

So far, soil quality research has only been carried out quantitatively through laboratory analysis without being based on spatial data (Nepal and Asheshwar, 2018; Ghimire et al., 2018). The novelty of this research is to present a map of the distribution of soil quality based on principal component analysis. Spatial data information is needed to determine site-specific nutrient availability management. Because the land has various spatial variability, it is not accurate if one location area only relies on the analysis results from one sampling point (Shokr et al., 2021). This study aims to assess the soil quality index (SQI) of paddy fields in Jember Regency, Indonesia, using the principal component analysis (PCA) method based on spatial data. [A1]I think it is important to avoid qualitative data

2. Methods

2.1. Study Area

The research was conducted in irrigated paddy fields in Jember Regency, East Java, Indonesia (Fig. 1).

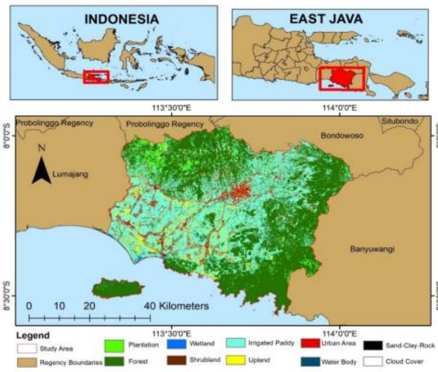

Figure 1. Study area

2.2. Input Data and Tool Used

The primary input data used for this study are (1) Paddy Map, (2) Soil Map, and (3) Slope Map. Table 1. explains the data source used for this study.

Table 1. Material resources

Material	Sources
Paddy Map	Sentinel 2A satellite image data processing (USGS, 2019)
Soil Map	Indonesian Soil Research Institute (Balai climatology)
Slope Map	Derived from DEMNAS (BIG, 2019)

Making a paddy map begins with an inventory of image data. The primary input data is the Spot image of the study area, selected based on the minimum cloud cover in the 2017-2020 period). Image classification is processed using Multispec TM software. This study uses the Gaussian maximum likelihood to obtain the maximum likelihood classification (MLC). Next, a guided classification was created by creating 200 ground control points or training areas. In the final process, an accuracy test is carried out, provided that if the accuracy test value is more than 80%, then the land use map is acceptable. Fig. 1. Explain the results of land use classification in the Jember Regency.

The soil map was extracted from a soil-type map from the Soil research institute. The layer is then overlayed with a regency boundary. The slope is derived from DEMNAS. The DEMNAS (Digital elevation model at the national level) was downloaded from the official website of the National Geospatial Agency (BIG)(National Geospatial Agency (BIG), 2019). The DEMNAS has a spatial pixel resolution similar to sentinel images (~± 10m). Furthermore, the equipment used for : (1) soil sampling, (2) laboratory analysis, and (3) data processing are listed in (Table 2).

Table 2. List of tools used

Tool	function
Soil drill	soil samples
Shovel	soil samples
AAS (atomic absorption spectrophotometer)	Soil Pottasium Availability
Spectrofotometer	Soil Phosporus Total
SPSS	Principal component analysis
Musltispec	Land use analysis
QGIS	Soil Quality Index (SQI) assessment

2.3. Procedure

The research procedure consists of (1) determination of land unit, (2) soil sampling, (3) laboratory analysis, (4) principal component analysis (PCA), (5) assessment of soil quality index (SQI), and (6) Thiessen polygon analysis (Fig 2). Firstly, Land units are determined by overlaying a map of paddy fields, slopes, and soil types. Each Land unit represents different soil characteristics and slopes. The overlay process produces six land units can be seen in Table 3. Then, Soil sampling was carried out on each land unit. For each land unit, soil samples were taken in 4 locations. Four locations are chosen to improve the accuracy of the data obtained. Figure 3 shows the sampling locations of paddy fields. Figure 4 shows the difference in soil color at several sampling locations.

Furthermore, the soil was air-dried to a moisture content of <5% and then pulverized. The soil was sieved with a 2 mm sieve for analysis of the physical, chemical, and biological properties of the soil. Table 4 shows the methods used in the analysis of soil properties. Soil property values were used for correlation and principal component analysis (PCA). The stages of PCA analysis are (1) determining the leading component of each indicator that affects soil quality, (2) calculating the weight of each principal component, and (3) calculating the SQI value by calculating the weight of the principal component multiplied by the eigenvactor value.

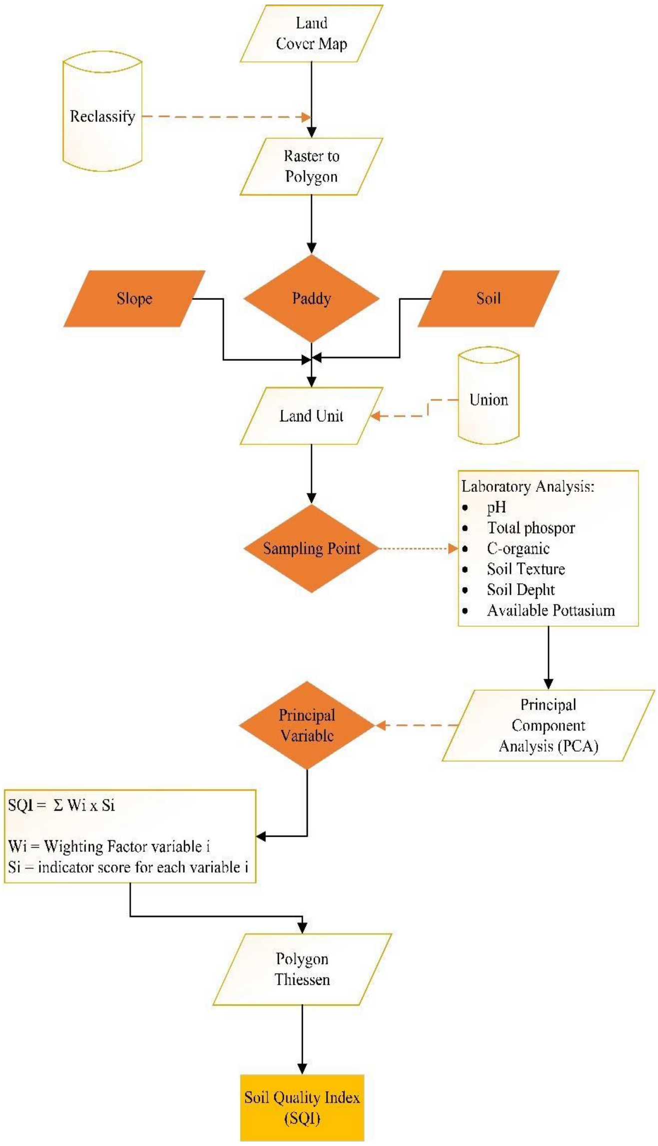

Figure 2. Procedure research

Table 3. Land unit

Soil Type	Slope
Inceptisols	slope > 15%
Entisols	slope > 15%
Andisols	slope > 15%
Entisols	slope 0 - 15%
Inceptisols	slope 0 - 15%
Alfisols	slope 0 - 15%

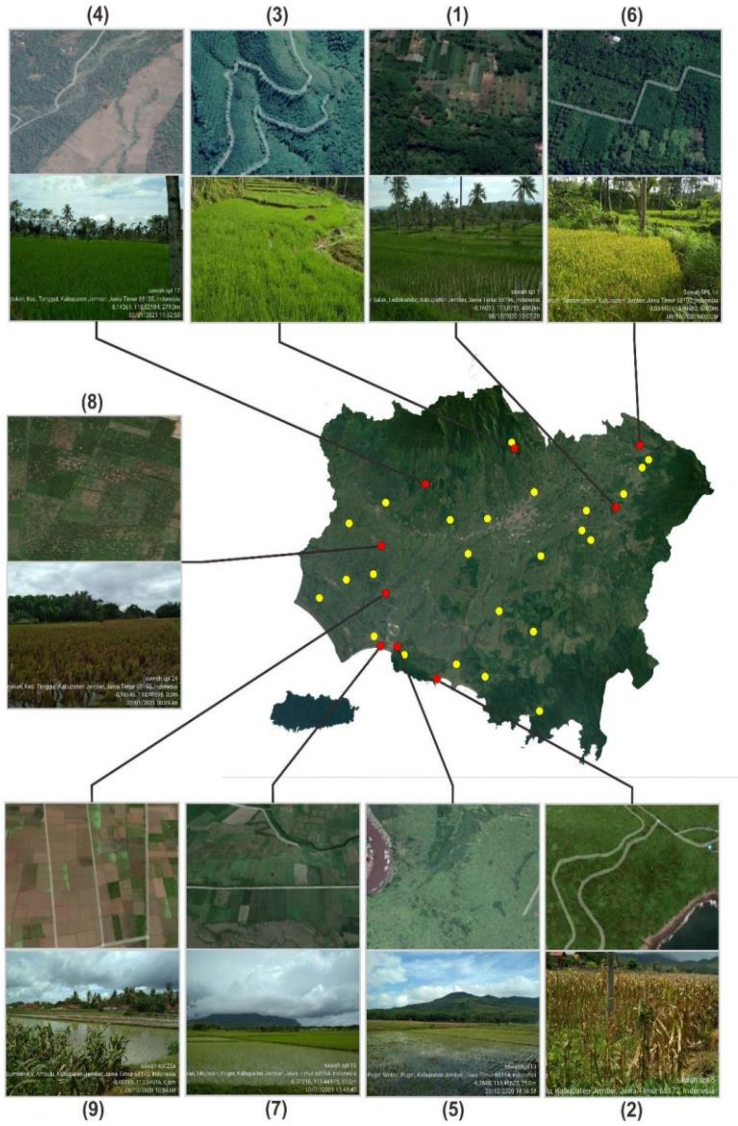

Figure 3. Sampling location

Note: The number above shows the research sampling point

Figure 4. Different colours of soil sampling

Table 4. Method of physical, chemical and biological properties

Variable	Method
pH	The soil-water suspension (1:25)
Total Phosphor	Percolation with HCl 25%
Available Potassium (K)	Neutral N NH_4OAc
% Sand	Pippet
% Silt	Pippet
% Clay	Pippet
Effective soil depth	Measurement
C-organic	Curmis

Sources: (Supriyadi et al., 2019)

The results of the calculation of soil properties are carried out by calculating the standard deviation to determine the variation of each data. The standard deviation calculation formula follows eq. 1:

$$S = \sqrt{\frac{\sum_{K=1}^{n}(X_k - \bar{X})^2}{n-1}} \quad \text{..................... (1)}$$

Where:
X_k is the observation value
$\overline{X}$ is the mean value
n is the number of observation
$\sum$ means to sum or add up

Assessment of Soil Quality Index (SQI)

The stages in assessing the soil quality index are (1) determining the leading component of each indicator that affects soil quality; (2) calculating the weight of each principal component, and (3) calculating the SQI value by adding the weight of the principal component multiplied by the eigenvactor value. The main components are obtained from the extraction of soil quality components. If the Eigenvalue > 1, then the component affects the quality of the soil. If the Eigenvalue <1, the component is considered unable to explain the variable properly. The eigenvalue is symbolized by λ with the equation (eq.2):Ax = λx……………………..(2)

a. λ1, λ2, λ3… λn is *eigen value* matrix A
b. x1, x2, x3… xn is eigenvector according eigenvalue (λn)

Then calculate the weight of the principal components using equation 3 (eq.3) (Jolliffe, 2002):

$$PC = \frac{\%\ of\ varians\ Eigen\ value\ (\lambda)}{Covariance\ Variance} \times 100\% \quad \text{.............(3)}$$

PC1, PC2, PC3,…… PCn is weight of the principal components

Then calculate SQI using equation 4 (eq.4):

SQI = (PC1 x A1) + (PC2 x A2) + (PC3 x A3) ....(4)

Table 5 shows the score and class used to determine the SQI.

Table 5. Class of soil quality index

No	Score	Class of Soil Quality Index
1	0.80 – 1.00	Very good
2	0.60 – 0.79	Good
3	0.40 – 0.59	Medium
4	0.20 – 0.39	Low
5	0.00 – 0.19	Very low

Sources: (Nusantara et al., 2018)

Thiessen Polygon Analysis

Thiessen Polygon process using GIS software. Thiessen polygon is an interpolation method by weighting the sampling location points (Arianti et al., 2018). Then, a triangular line will be made by drawing a line between the sampling points to form an area representing the SQI value at each sampling point.

3. Result and Discussion

3.1. Soil Properties of Paddy Fields

Table 6 shows the soil properties analysis results from 24 sampling points. The observed variables included pH, total P, available K, soil texture, depth, and C-organic. The results of the pH analysis showed that the average paddy soil had a pH of 7.01. This value is neutral and suitable for plant growth (Lantoi et al., 2016). Nutrient availability increases as the soil pH become neutral. Soil with an acidic pH will increase the availability of Al and Fe. While the soil is alkaline, the availability of Ca and Mg increases. Elements of Al, Fe, Ca, and Mg will poison plants if absorbed in excessive amounts (Farooque et al., 2012).

Table 6. Soil properties

Variables		Total P (mg/100g)	Availaible K (me/100g)	Sand (%)	Silt (%)	Clay (%)	Soil Depth (cm)	C-organic (%)
Mean	1	12.29	;	48.10	24.39	27.50	36.36	2.42
SD	5	4.81	2	23.22	22.76	16.16	10.25	0.44
Min	4	4.86	7	4.97	1.85	5.22	25.00	1.28
Max	0	2.83	;	88.99	89.08	65.26	1.28	3.27

SD: Standart Deviation

The pH values ranged from 6.04 to 7.80, averaging 7.01. This value is still slightly acidic and alkaline (Li et al., 2018). pH is closely related to nutrient availability. The optimal pH for plant growth is between 6-7 (Karapouloutidou and Gasparatos, 2019). Soil with a low pH will contain a lot of Al and Fe, which threatens plants, while at a high pH, the soil will contain excess Ca and Mg (Hanafiah, 2018). PH also plays a role in the biodegradation of organic pollutants, nitrification processes, denitrification processes, microorganism activity, and mineralization of organic matter (Neina, 2019).

The average total P-value was 12.29 mg/100 g of soil. The highest value was 29.83 mg/100 g of soil, while the lowest was 4.86 mg/100 g. At the sampling point with a low total P-value, biochar can be added to increase the availability of nutrients, including P nutrients (Prasad et al., 2019). Phosphorus is an essential macronutrient needed by plants in the vegetative and generative phases. Phosphorus can stimulate roots to absorb nutrients and increase resistance to high-temperature areas (Szulc et al., 2020).

K analysis results are available between 0.47 – 1.25 me/100 g. This value is classified as moderate to high. Although the availability of potassium is high, it is easily leached, so the addition of organic matter is needed to hold K nutrients (Mahmood et al., 2017). Organic matter, after undergoing further weathering, will produce humus. This humus functions as an organic colloid that is negatively charged and has a clay-like role (binds nutrients).

The results of soil texture analysis showed that the paddy fields in Jember Regency were dominated by the sand fraction (48.10%). Meanwhile, clay and silt fractions have equal percentages (27.50% and 24.39%). This is in line with the C-organic analysis results, which are also included in the low category (Farooque et al., 2012). The value of the clay fraction, which is low and dominated by the sand fraction, indicates that the soil does not contain much organic matter. The adequate depth of the soil ranged from 25 - 70 cm, with an average of 36.36 cm. This value is quite good because the average annual plant has a root length of approximately 30 cm (Arunrat et al., 2020).

Paddy fields in Jember Regency also have varying soil depths (Table 6). The value of the adequate depth of soil ranges from 25 - 70 cm, with an average of 36.36 cm. This value is good. According to Arunrat et al. (2020), the adequate depth of paddy soil is between 0-40 cm. Adequate soil depth is the depth of soil that plant roots can penetrate (Tufaila & Alam, 2014). Rice fields are land managed intensively through the plowing process, causing silting of the adequate depth of the soil due to the formation of a plow tread layer. This plow tread layer is found at a depth of 25-40 cm with the potential for nutrient accumulation, especially P nutrients, due to the intensification of rice planting accompanied by excess synthetic fertilizers (Syafitri et al., 2020).

3.2. Principal Component Analysis Result

Table 7 shows the correlation analysis result among all variables. The correlation results show the average correlation value < 0.5, so the relationship between variables is insignificant (Bedolla-Rivera et al., 2020). Two associations have a correlation value > 0.5, namely (1) pH sand and clay; (2) C-organic and sand. The relationship between the sand and clay fraction is -0.836, meaning that if one-factor increases, the other factors will decrease in number. The relationship between C-organic and sand is -0.543, which means that if C-organic increases, sand will decrease.

Table 7. Correlation analysis

	Total P	**Available K**	**C-organic**	**Soil Depth**	**pH**	**Sand**	**Silt**	**Clay**
Total P	1.00							
Available K	0.20	1.00						
C-organic	0.22	0.26	1.00					
Soil Depth	-0.33	-0.24	-0.39	1.00				
pH	-0.06	0.04	0.02	0.11	1.00			
Sand	0.10	-0.14	-0.54*	0.26	-0.16	1.00		
Silt	0.12	0.05	0.13	-0.07	0.31	-0.21	1.00	
Clay	-0.16	-0,02	0.44	-0.10	0.37	-0.84*	0.25	1.00

Legend: * significant

Table 8. PCA result

Eigenvectors	**PC1**	**PC2**	**PC3**	**Eigenvalue**	**% Variance**	**Cumulative %**
Clay (%)	0.83*	-0.42	-0.16	2.58	1.68	1.16
Total P	0.12	0.70*	0.41	32.28	20.96	14.45
Silt (%)	0.41	-0.15	0.68*	32.28	53.24	67.68
Available K	0.30	0.49	0.18			
C_organic	0.74	0.31	-0.20			
Soil depth	-0.45	-0.62	0.08			
pH	0.34	-0.48	0.59			
Sand	-0.87	0.18	0.30			

Legend: * MDS variable

Table 8 shows the principal component analysis (PCA) results using SPSS. Three main components determine soil quality: total P, silt fraction, and clay fraction. It is in line with the results of the analysis of soil properties that these three factors have low values and need improvement. The importance of these three factors is determined based on the eigenvalue (Ghimire et al., 2018). The clay fraction has the highest importance value among the other two factors. The next position is the total P and silt fraction. The weighting factor for each component is based on the percent variance divided by the total variance. The weighting factor for Soil quality in paddy field has the following trend: PC1 (0.47) > PC2 (0.31) > PC3 (0.22). The score is then multiplied by the weighting factor derived from the PCA to obtain the index value for soil quality (SQI). The formula for determining the SQI is according to equation 4:

$$SQI = 0.47\ A1 + 0.31\ A2 + 0.22\ A3 \quad (4)$$

PC1 = Clay

PC2 = Total P

PC3 = Silt

The very good-quality soil will fulfill all the functions that are considered essential and will have a value of 0.80 – 1.00. Good quality has a value of 0.60 – 0.79, and medium quality has a value of 0.40 – 0.59. While low quality has a value of 0.20 – 0.39, and very low quality has a value of < 0.19. Soil quality has a significant influence on agricultural production. In this study, three indicators reflect the soil quality. Each parameter has a function supporting crop production. Clay minerals affect soil fertility by influencing soil acidity, controlling nutrient supply and availability, stabilizing soil organic matter by influencing micro aggregate formation, Soil aggregate stability, reducing erosion, and controlling soil microbial population and activity (Kome et al., 2019; Murphy, 2015). Clay content suitable for paddy fields is more than 37,5% (Ritung et al., 2011).

Elemental P is one of the primary macronutrients, so plants are needed in large quantities to grow and produce. The availability of P will supply plant nutrients (Schoonover & Crim, 2015). Phosphor will increase the number of flowers and fruit sets (Kurniadinata et al., 2018). The increase in total P in the soil will affect crop production by up to 13.9%. In this study, total P became an essential or limiting factor in soil quality. P deficiency will cause a decrease in plant productivity (Meena et al., 2021). The amount of 46.2% revealed significant P limitations on aboveground crop production (Hou et al., 2020). total P in suitable soil to support rice growth is more than 60 mg/100-gram soil (Ritung et al., 2011). In general, the P condition available on paddy fields in Jember Regency is still insufficient for optimum rice growth.

Silt is one of the main components that represent soil quality. The silt content will affect the ability of the soil to exchange cations. Silt content is the main contributor to CEC in silty soil (Liu et al., 2020). Silt will also affect soil erodibility, where the more significant the percentage of soil texture dust (silt), the greater the value of soil erodibility (Sulistyaningrum et al., 2012).

3.3. Assesment of Soil Quality Index (SQI)

The results of the soil quality analysis (SQI) contained three soil quality classes, namely (1) very low quality, (2) low quality, and (3) medium quality. This value was obtained based on three main components: clay fraction, total P, and silt fraction.

Based on figure 5, most of the rice fields in the Jember Regency are classified as having very low soil quality. Very few areas are of medium quality. About 68,887.65 Ha were included in the category of very low quality and 39,948.22 Ha in the category of low quality. Meanwhile, paddy fields included in the medium category are only 3,513.83 Ha. The low quality of the soil is due to the use of chemical fertilizers that are still very intensive and are not added to organic matter.

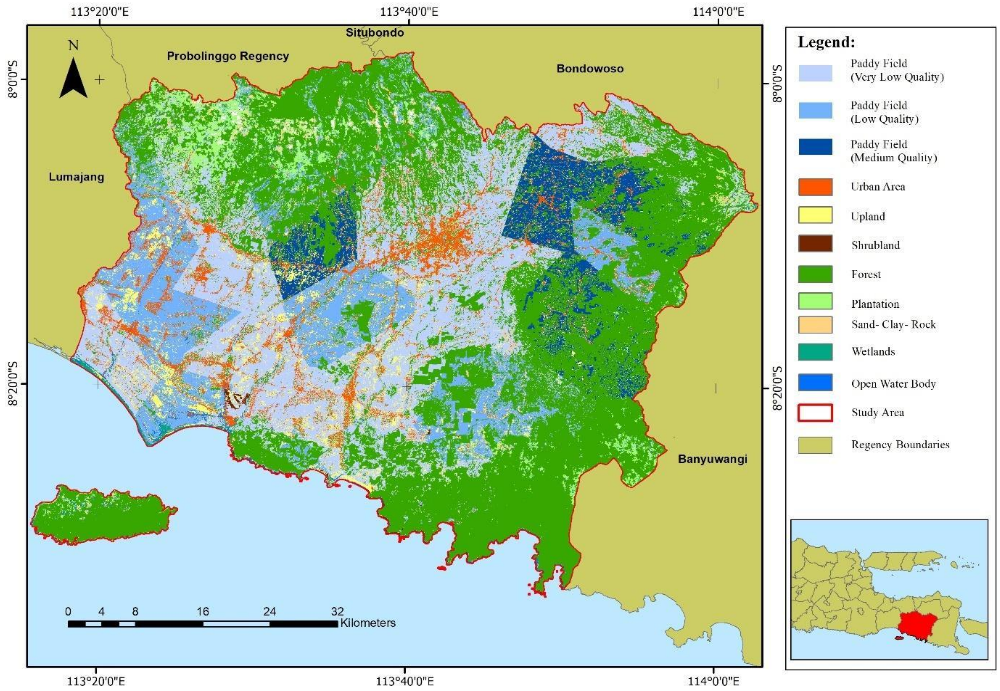

Figure 5. Map of soil quality index

The low soil quality index is spread in Ledokombo, Tempurejo, Mayang, Jelbuk, Sumberjambe, Tempurejo, and Sukorambi districts. The low soil quality index is spread in Ambulu, Umbulsari, Wuluhan, Rambipuji, Jombang, Puger, and Bangsalsari districts. The medium soil quality index is spread in Tanggul, Jenggawah, Mumbulsari, Semboro, and Kencong districts.

This condition reflects the need for site-specific soil management to improve soil quality to support plant survival. The limiting factors that need to be enhanced to enhance soil quality are P and soil texture availability. Both can be improved by adding organic matter rich in P and can improve soil texture (Bedolla-Rivera et al., 2020). Nutrient P includes slow-release nutrients from organic and inorganic fertilizers (Szulc et al., 2020). Application of P fertilization and organic matter can be made before planting so that its availability will increase along with plant growth.

Adding organic fertilizers can increase nutrient availability and improve soil's physical properties, especially texture (Kidinda et al., 2015). Adding organic matter in the long term will increase the formation of humus, an organic colloid with the same function as clay. Adding organic matter also significantly affected the increase in available P (Siregar et al., 2017).

4. Conclusions

The correlation analysis between factors showed that the average between elements did not have a significant relationship. The three main components determining paddy fields' soil quality index (SQI) are total P, clay, and silt fractions. More than half of the paddy fields in Jember Regency have very low soil quality. In addition, Organic matter and P fertilizer in the soil can improve soil quality. Management changes from intensive farming to organic farming will be able to increase soil capacity to support sustainability.

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