SOIL SCIENCE ANNUAL
2023, 74(3), 175383

https://doi.org/10.37501/soilsa/175383

The influence of geological formations on soil characteristics and quality in the southeast region of Pacitan Regency, Indonesia

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Received: 2023-05-31
Accepted: 2023-11-17
Published online: 2023-11-17
Associated editor: J. Chojnicki

Keywords:

Geological condition
Soil bulk density
Cation exchange capacity
Soil porosity
Soil organic carbon

Abstract

The south eastern region of Pacitan Regency, East Java, Indonesia, is directly facing opposite the direction of the Indo-Australian plate movement, and has a diverse geological structure with different rocks occurring on land surface. This research aims to determine the influence of geological formations on soil characteristics and quality and the limiting factors of soil quality. Soil samples were taken from 40 sampling points from 10 geological formations from the topsoil (tillage layer) at a 0–30 cm depth. The number of sample points is adjusted to the area of the geological formation, where the wider the geological formation, the more samples are taken. Soil characteristics data were analysed using Anova test and Duncan test to get information on the influence of geological formations on soil characteristics. Pearson correlation test and principal component analysis (PCA) were used to calculate the soil quality index, and the Kruskal-Wallis test to analyse the influence of geological formations on soil quality. The result shows that the soil mineral composition is mostly inherited from andesitic-basaltic parent rocks which has experienced weathering. Geological formation has an influence on bulk density, soil water content, porosity, cation exchange capacity and soil organic carbon content. The soil quality index value for various geological formations is in the range of 0.31–0.39, so it is included in the low to medium class. Jaten Formation and the Watupatok Formation do not have limiting factor on soil quality, base saturation (BS) is a limiting factor in Oyo Formation, and soil organic carbon (SOC) and total nitrogen (TN) are limiting factors in almost all geological formations..In conclusion, geological formations significantly influence several soil characteristic parameters but are not the dominant factor determining soil quality.

1. Introduction

Java Island is the southern most big island of the Indonesian archipelago and has unique geological characteristics due to the subduction plate zone. The interaction between the Eurasian Plate and the Indo-Australian Plate in the southern part of Java Island causes the emergence of very diverse geological formations. The northward movement of the Indo-Australian Plate subducts beneath the Eurasian Plate with a convergence rate of 67 mm per year (Simons et al., 2007) and a direction perpendicular to Java Island (Hall, 2012). This lateral pressure causes faults to occur in the southern part of Java and causes the geological conditions in Central Java to become more complex (Satyana, 2007). This research was conducted in Pacitan, the southernmost region of Java Island which is directly opposite the direction of the Indo-Australian plate movement and has a high diversity of geological formations. Pacitan Regency which includes Tulakan, Ngadirojo and Sudimoro subdistricts has ten different geological formations, formed from surface deposits, sedimentary rocks, volcanic rocks, and breakthrough rocks (Samoedra et al., 1992). The high diversity of geology formation has become interesting to study the formation's influence on the soil quality.

Soil formation is largely determined by the forming factors, including parent material (Jenny, 1941). Geological formations influence the diversity of soil characteristics (Toure et al., 2015). In terms of geology, the main factor in soil condition is the parent material (Mocek and Owczarzak, 2011; Djodjic et al., 2021). Anderson (1988) stated that parent material is one of the most influential soil-forming factors. However, soil properties and chemical composition are also influenced by the parent material (Brady and Weil, 2014; Wilson, 2019; Gruber et al., 2019). A homogeneous unit of parent material in an area is called a geological formation (Igwe and Egbueri, 2018). Soil functions as a life support (Lehmann et al., 2020), and has different characteristics depending on its physical, chemical and biological properties (Zalamea et al., 2016).

Wilson (2019) states that there are differences in the properties of soil formed from mafic and felsic rocks. Mafic rocks contain 45 and 55% silica, while felsic rocks contain more than 65% silica, the highest of all types. Mancini et al. (2020) stated that soils formed from mafic rocks show a high iron and other metal elements content, while soils formed by felsic rocks show a relatively higher quartz content.

Soil parent materials influence soil properties and soil quality (Legaz et al., 2017). Soil quality is related to soil function because of its role as an ecosystem service (Drobnik et al., 2018). Soil quality plays a major role in land resource management (Zhang et al., 2022), so determining the soil quality of land is very important (Bünemann et al., 2018). Soil quality is influenced by several indicators, especially parent material (Liu et al., 2018). Soil quality indicators are a collection of measurable parameters that reflect soil quality (Acton and Padbury, 1993). Minimum data sets (MDS) are selected physical, chemical, and biological soil properties used to determine soil quality (Doran and Parkin, 1996). However, only a few studies have discussed the influence of geological formations on soil characteristics and quality today. The aim of this research is to determine the influence of geological formations on soil characteristics, soil quality index in the southeastern region of Pacitan Regency, and to determine the limiting factors of soil quality in each geological formation in the southeastern region of Pacitan Regency.

2. Materials and methods

2.1. Study area

This research was conducted on ten geological formations in the southeastern region of Pacitan Regency, East Java Province, Indonesia, including Tulakan District at coordinates 8°10'13" N and 111°16'39" E, Ngadirojo District at coordinates 8°13'0 "N and 111°19'0"E and Sudimoro District at coordinates 8°13' 38"N and 111°22' 10"E. The geological formation of the research area is explained in Table 1. Based on the World Reference Base for Soil Resources, the predominating soil type in the research area is Lithosol (IUSS Working Group WRB, 2022). The ten geological formations at the research location have soil parent materials as listed in Table 1.

The research area based on Schmidt–Ferguson is included in climate D (moderate) with a Q value of 67.02% (Q value is between 60% and 100%). The Q value is the ratio (comparison) of the average dry and wet months. Total annual rainfall is around 2796 mm/year. The soil type of the research location is dominated by Tropopsamment 49.9%, Dystropept 12.7%, Dystrandept 16.3, Tropaquept 11.6%, Tropaquept 2.1%, Millisols 5.6%, Haplorthox 1.5% and Tropudult 0.2% (Pacitan district Government, 2005).

2.2. Soil sampling

The research was conducted through field study and laboratory analysis. Determination of sample points was carried out through purposive sampling based on geological map references of the research area. The number of sample points was adjusted to the extent of geological formations in the study area, and a total of 40 sample points were taken for soil samples (Fig. 1). Soil samples were taken at a depth of 0-30 cm as a tillage layer, covering two land uses, namely dry land and rice fields (Table 1).

2.3. Analytical methods

The parameters observed include soil physical properties, soil chemistry, soil biology, and soil mineralogy. Analysis of soil physical, chemical, and biological properties was carried out based on Balittanah (2009). Soil mineralogy on geological formations were carried out based on Mange and Maurer (1992), texture analysis was carried out using the pipette method; bulk density (BD), porosity and soil water content (SWC) using the gravimetric method; soil organic carbon (SOC) was done by Walkey and Black method (Nelson and Sommers, 1983); pH H_2O by potentiometric method; electrical conductivity (EC_e) using the conductometric method; cation exchange capacity (CEC), base saturation (BS), and available potassium (AK) with the ammonium acetate extraction method; available P (AP) by Olsen method from Olsen (1954) and total nitrogen (TN) by Kjeldahl method from Bremner (1996), microbial biomass carbon (MBC) by fumigation method; and mineral sand fraction using line measurement and polarization microscope methods.

Table 1
Regional conditions at the soil sampling location

Geological Formation	District	Elevation (MASL)	Land use	Sampling Location		Geological Condition
				Latitude	Longitude	
Alluvial	Ngadirojo	4	Rice paddy	8° 14' 38" S	111° 16' 2" E	Gravel, gravel, sand, silt, clay, mud and locally coral fragments. This unit is river and coastal deposits, spread in lowlands along rivers and locally in coastal areas
	Ngadirojo	8	Dryland	8° 14' 58" S	111° 18' 34" E	
	Ngadirojo	15	Dryland	8° 12' 26" S	111° 19' 57" E	
	Sudimoro	7	Rice paddy	8° 15' 17" S	111° 22' 50" E	

Table 1, continue

Geological Formation	District	Elevation (MASL)	Land use	Sampling Location		Geological Condition
				Latitude	Longitude	
Arjosari	Tulakan	805	Dryland	8° 7’ 25” S	111° 20’ 28” E	Conglomerates of various materials, sandstone, siltstone and claystone; local limestone, sandy marl and gravelly pumice sandstone; inserts of volcanic breccia, lava and tuff
	Ngadirojo	721	Dryland	8° 7’ 49” S	111° 21’ 11” E	
	Ngadirojo	51	Dryland	8° 10’ 51” S	111° 19’ 58” E	
	Ngadirojo	490	Dryland	8° 11’ 30” S	111° 18’ 28” E	
	Ngadirojo	14	Rice paddy	8° 12’ 01” S	111° 19’ 50” E	
	Sudimoro	267	Dryland	8° 10’ 52” S	111° 22’ 37” E	
	Sudimoro	315	Dryland	8° 10’ 16” S	111° 23’ 53” E	
	Sudimoro	267	Dryland	8° 12’ 38” S	111° 23’ 5” E	
Intrusive rocks	Tulakan	569	Dryland	8° 12’ 34” S	111° 13’ 32” E	Andesite, dacite, diorite, and basalt
	Tulakan	550	Dryland	8° 11’ 39” S	111° 15’ 15” E	
	Ngadirojo	192	Dryland	8° 12’ 14” S	111° 18’ 19” E	
	Sudimoro	556	Dryland	8° 11’ 43” S	111° 21’ 51” E	
Jaten	Tulakan	481	Dryland	8° 8’ 37” S	111° 12’ 55” E	Conglomerate, conglomerate sandstone, quartz sandstone, tuff sandstone, mudstone, siltstone, lignite and tuff, locally containing sulfur
	Tulakan	359	Dryland	8° 10’ 53” S	111° 17’ 13” E	
	Tulakan	247	Rice paddy	8°10’49” S	111°16’47” E	
	Tulakan	587	Dryland	8° 8’ 13” S	111° 17’ 13” E	
Mandalika	Tulakan	386	Dryland	8° 12’ 1” S	111° 14’ 36” E	Is an interbed of lava, volcanic breccia and tuff; interbedded with tuffaceous sandstone, siltstone and claystone
	Ngadirojo	718	Dryland	8° 9’ 31” S	111° 20’ 50” E	
	Sudimoro	390	Dryland	8° 10’ 1” S	111° 23’ 44” E	
	Sudimoro	291	Dryland	8° 13’ 29” S	111° 21’ 34” E	
	Sudimoro	13	Rice paddy	8°14’44” S	111°23’4” E	
Nampol	Tulakan	401	Dryland	8° 9’ 49” S	111° 14’ 17” E	Tuffaceous sandstone, siltstone, tuffaceous limestone, claystone, locally lensed or thinly layered lignite; inserts of conglomerate and conglomerate sandstone
	Tulakan	338	Rice paddy	8°10’2,3” S	111°16’46” E	
Oyo	Tulakan	426	Dryland	8° 13’ 7” S	111° 13’ 46” E	Calcareous sandstone, tuffaceous sandstone, calcareous siltstone, tuffaceous limestone, sandy marl, and tuffaceous marl
	Tulakan	163	Dryland	8°14’37” S	111°14’19” E	
Watupatok	Tulakan	495	Dryland	8° 5’50” S	111°20’29” E	Includes lava, interbedded sandstone, claystone and chert
	Tulakan	544	Dryland	8° 5’54” S	111°20’15”E	
Wonosari	Tulakan	397	Dryland	8° 10’ 23” S	111° 15’ 28” E	Reef limestone, layered limestone, chipping limestone, sandy limestone, and marl
	Ngadirojo	172	Dryland	8° 13’ 19” S	111° 16’ 25” E	
	Ngadirojo	8	Rice paddy	8° 15’ 5” S	111° 18’ 58” E	
	Ngadirojo	91	Dryland	8°14’7,4” S	111°18’59” E	
	Sudimoro	183	Dryland	8° 14’ 25” S	111° 20’ 41” E	
	Sudimoro	194	Dryland	8°15’0.9” S	111°23’46” E	
Wuni	Tulakan	560	Dryland	8° 9’ 23” S	111° 11’ 49” E	Volcanic breccia, tuff, tuff sandstone, interbed sandstone, and siltstone; locally inlaid with lignite, lensed with limestone, and containing eroded wood
	Tulakan	334	Rice paddy	8° 9’ 48” S	111° 16’ 50” E	
	Tulakan	457	Dryland	8° 9’ 22” S	111° 16’ 8” E	

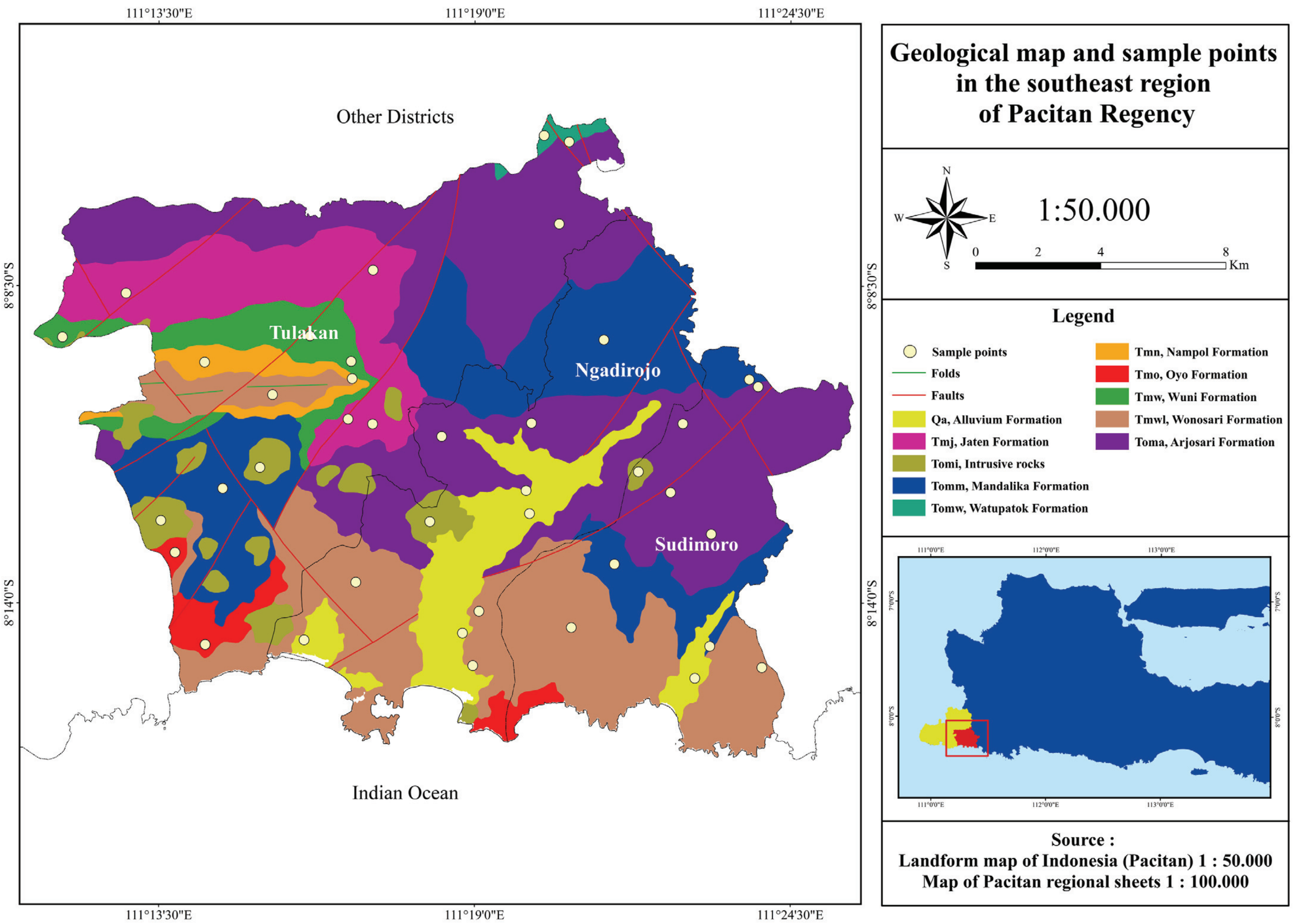

Fig. 1. Geological map and sample points in the study area.

2.4. Analysis of soil characteristics

Data on soil properties is obtained from the analysis of soil samples in the laboratory. Data obtained from the laboratory is then broken down into original samples from geological formations. The diversity of soil characteristics from various geological formations was analysed using the Anova test. To obtain the influence of geological formations on soil characteristics, the Duncan test was carried out.

2.5. Soil quality analysis

Soil quality index analysis was carried out in three stages; MDS selection through the Pearson correlation test, the PCA main test, and then the PCA test result data was selected into the MDS (Andrews et al., 2004). Principal components (PC) with eigenvalues ≥ 1 are selected into MDS, then the weighting index (Wi) is searched for the selected data. The final stage is that the selected indicators are given a score based on their scoring value. The BD and MBC parameters were weighted using scoring from Lal (1994); porosity and pH parameters with scoring from Wander et al. (2002); and SOC, EC_e, CEC, BS, AK, AP, and TN parameters using scoring Balittanah (2009). Data analysis is complete, followed by calculating the soil quality index using the formula:

$$SQI = \sum_{i=1}^{n} Wi \times Si$$

Explanation:
SQI : Soil quality index
Si : Score on selected MDS
Wi : Weighting index
n : Total soil quality MDS

The soil quality index values were matched with Cantú et al. (2007) soil quality classes (Table 2). Analysis of the effect of geological formations on soil quality was conducted using the Kruskal-Wallis test. Determining the limiting factors of soil quality was carried out using the method of Rachman (2021) in the form of a scoring method, where parameters with a score equal to or less than 2 were used as limiting factors of soil quality.

Table 2
Soil quality class (according to Cantú et al., 2007)

Soil Quality	Range	Class
Very high	0.80-1	1
High	0.60-0.79	2
Medium	0.35-0.59	3
Low	0.20-0.34	4
Very low	0-0.19	5

3. Results and Discussion

3.1. Soil characteristics

Table 3 shows that the mineral composition of the soil in each geological formation is almost the same. The mineral composition from Table 3 shows that the rocks that dominate in the research area are andesitic-basaltic (intermediate-mafic) rocks. These results are almost the same as Purwanto et al. (2020). These andesite-basaltic rocks are caused by the formation of rocks in Pacitan influenced by ancient volcanic activity (Samoedra et al., 1992). The results of the mineral composition analysis show that the pyroxene mineral content, namely augite and hypersthene, is higher than the amphibole content. Pyroxene minerals have the potential to contribute Ca and Mg nutrients through rock weathering and produce high soil pH values and base saturation (Singh and Schulze, 2015). The pH value and base saturation of the geological formations in this study are quite high.

The rocks in the geological formation of this study may have experienced weathering to form sedimentary rocks such as conglomerate, breccia and sandstone. However, the easily weathered mineral content in this study was quite high (Table 3). According to Aini et al. (2016), soil that contains a lot of easily weathered minerals indicates that the soil is still in the initial development stage and has not advanced further weathering. Because the soil still contains quite a lot of easily weathered minerals, the soil in the research area is still not very developed. The analysis results show that the weathered minerals are dominated by opaque minerals (Table 3). Opaque minerals are minerals that do not emit light and are usually dark or metallic in colour (Pichler and Schmitt-Riegraf, 1997). The presence of opaque minerals will affect rock weathering, where a rock that have a high opaque content may be more resistant to weathering.

Table 4 shows differences in soil bulk density (BD) between intrusive alluvial rock Formations and the Nampol Formation, Wuni Formation, Oyo Formation and Watupatok Formation. The Mandalika Formation and Arjosari Formation have a different BD from the Watupatok Formation. The Jaten Formation and Wonosari Formation do not have differences in BD from other formations (Table 4). Bulk density in the research area is included in the high to very high category. Soils with high BD are very difficult to manage in agriculture (Mukhopadhyay et al., 2019). There are differences in porosity between the Watupatok Formation, Nampol Formation and Jaten Formation, Wonosari Formation, Intrusive Rock Formation, Alluvial Formation, and Mandalika Formation (Table 4). Porosity in this research area is in the medium to high category. Medium to high porosity results from soil that has not been intensively compacted (Shaheb et al., 2021). There are differences in soil water content between the Oyo Formation, Jaten Formation and Wuni Formation with the Arjosari Formation and intrusive rock formations. The Alluvial Formation has different soil water content from the Oyo and Jaten Formations. High soil water content indicates that the soil's capacity to hold water for plant growth is also high (Banjarnahor et al., 2018). The soil texture at this research location is dominated by sandy clay loam, and this texture is almost the same in all geological formations (Table 4). Datta et al. (2017) reported that soil with a sandy clay loam texture was able to retain water better than soil with a sandy texture.

Table 3
Mineral sand fraction composition of various geological formations in the study area

Geological Formation	Mineral Sand Fraction																				
	Op	Zi	Cq	Crq	Ic	Mw	Rf	Vg	Al	An	La	By	At	Or	Gh	Au	Hp	Ep	To	Di	Rt+An
Alluvial	19		3	2		5	56		sp	sp	5	1				2	7	sp			
Arjosari	5		5	4	sp	14	67								sp	2	3				
Intrusive rock	25	1	1	5	1	8	45			sp	2	1				3	7	1			sp
Jaten	42		2	3		6	17				1	7			2	5	15	sp			
Mandalika	35		3	5	4	6	26					2			3	6	10				
Nampol	31		2	6	1	5	12			2	7	11			5	4	14	sp		sp	
Oyo	59		sp	3		3	6				2	3			4	7	13	sp		sp	
Watupatok	62		sp	1	sp	8	15				2	3				2	7	sp		sp	
Wonosari	32		2	6	2	5	14			1	1	6	sp	sp	2	14	15	sp	sp		
Wuni	33		sp	9	sp	11	8	sp		1	sp	sp			3	12	22	1			

Explanations: Op = Opaque, Zi = Zircon, Cq = Cloudy quartz, Crq = Clear quartz, Ic = Iron concretions, Mw = Mineral weathering, Rf = Rock fragments, Vg = Volcanic glass, Al = Albite, An = Andesine, La = Labrodorite, By = Bytownite, At = Anorthite, Or = Orthoclase, Gh = Green horblende, Au = Augite, Hp = Hypersthene, Ep = Epidote, To = Tourmaline, Di = Diopside, Rt+An = Rutile + Anatase, sp = sporadic

Table 4
Analysis of soil physical properties in various geological formations

Geological Formation	BD (g cm^{-3})	Porosity (%)	SWC (%)	Texture (USDA, 2017)			
				Sand (%)	Silt (%)	Clay (%)	Texture Class
Alluvial	1.32^{a}	39.68^{b}	6.18^{bc}	41.37	31.43	27.19	Clay Loam
Arjosari	1.26^{ab}	44.42^{ab}	4.29^{c}	49.82	25.20	24.98	Sandy Clay Loam
Intrusive rocks	1.35^{a}	40.59^{b}	5.53^{c}	47.71	21.93	30.36	Sandy Clay Loam
Jaten	1.11^{abc}	53.11^{b}	13.65^{a}	34.26	28.46	37.28	Clay Loam
Mandalika	1.25^{ab}	38.07^{b}	10.53^{abc}	45.24	24.16	30.60	Sandy Clay Loam
Nampol	1.06^{bc}	53.11^{a}	8.61^{abc}	55.07	17.84	27.10	Sandy Clay Loam
Oyo	1.02^{bc}	46.51^{ab}	13.17^{a}	55.75	10.53	33.72	Sandy Clay Loam
Watupatok	0.95^{c}	53.43^{a}	7.35^{abc}	49.51	20.37	30.12	Sandy Clay Loam
Wonosari	1.20^{abc}	42.01^{b}	9.37^{abc}	40.87	32.13	27.55	Clay Loam
Wuni	1.06^{bc}	44.16^{ab}	12.01^{ab}	44.96	29.17	25.86	Loam

Explanations: BD = Bulk density, SWC = Soil water content, Letter symbol = Mean with same column who follow by same letter is not significant difference by Duncan test at the 5% level.

Table 5 shows that there are no significant differences in soil pH in various geological formations. Intrusive rock formations have a lower soil pH than other formations. Zhang et al. (2019) reported that mineral composition of parent material influences the pH value of soil. There is no difference in EC_e in the various geological formations in this study and the values are very low. Thus, the influence of salinity in this study area is negligible (Supriyadi et al., 2016). According to Noviyanto et al. (2017), high EC_e will result in a decrease in soil productivity. Variability in soil chemical properties between geological formations exists in the CEC parameters. The CEC values of the Jaten, Oyo and Wuni Formations are different from the CEC values of the Arjosari Formation. The CEC of the Jaten and Oyo Formations is also different from the CEC of the Alluvial, Mandalika and Intrusive Rock Formations. The CEC of soil samples in the study area is classified as medium to high. According to Adam et al. (2021), CEC has a relationship with the availability of nutrients in the soil. The CEC value in the research area shows that the nutrients are in good condition.

Soil base saturation (BS) in the study area is low to high, and there is no difference in soil BS between geological formations. BS is closely related to soil pH (Havlin, 2013). The relatively low BS value in the Oyo Formation has a pH of 6.53, while the relatively high BS value in the Alluvial Formation has a pH of 6.84. Ouimet et al. (1996) and Rawal et al. (2019) stated that lower BS will more affect soil acidity. However, soil pH does not always affect BS, because the presence of bases in the clay sorption complex is not only influenced by H pressure but is dynamic and influenced by the environment, climate and geochemistry (Osman 2012). Table 5 shows that total nitrogen (TN)

Table 5
Analysis of soil chemical and biology properties in various geological formations

Geological Formation	pH	EC_e (dS/m)	CEC cmol^{+}kg^{-1}	BS (%)	TN (%)	AP (ppm)	AK (cmol^{+} kg^{-1})	SOC (%)	MBC (mg g^{-1})
Alluvial	6.84^{a}	0.126^{a}	21.20^{bc}	72.25^{a}	0.17^{a}	2.29^{a}	0.32^{a}	0.99^{b}	0.29^{a}
Arjosari	7.00^{a}	0.077^{a}	19.86^{c}	63.73^{a}	0.20^{a}	3.81^{a}	0.36^{a}	1.11^{b}	0.57^{a}
Intrusive rocks	6.45^{a}	0.058^{a}	21.82^{bc}	39.57^{a}	0.18^{a}	1.64^{a}	0.32^{a}	1.13^{b}	0.43^{a}
Jaten	6.86^{a}	0.103^{a}	37.08^{a}	56.19^{a}	0.28^{a}	6.18^{a}	0.44^{a}	2.13^{ab}	0.61^{a}
Mandalika	6.60^{a}	0.077^{a}	21.40^{bc}	55.59^{a}	0.22^{a}	2.71^{a}	0.35^{a}	1.88^{ab}	0.68^{a}
Nampol	7.05^{a}	0.084^{a}	33.44^{abc}	69.56^{a}	0.18^{a}	6.67^{a}	0.28^{a}	2.76^{a}	0.47^{a}
Oyo	6.53^{a}	0.112^{a}	38.60^{abc}	29.11^{a}	0.19^{a}	3.09^{a}	0.25^{a}	2.68^{a}	0.51^{a}
Watupatok	7.08^{a}	0.136^{a}	38.37^{a}	51.53^{a}	0.30^{a}	2.45^{a}	0.43^{a}	2.06^{ab}	0.48^{a}
Wonosari	7.09^{a}	0.104^{a}	28.45^{abc}	64.78^{a}	0.24^{a}	2.35^{a}	0.34^{a}	1.42^{ab}	0.90^{a}
Wuni	6.75^{a}	0.059^{a}	37.14^{bc}	50.58^{a}	0.20^{a}	3.43^{a}	0.37^{a}	1.91^{ab}	0.43^{a}

Explanations: EC_e = Electrical conductivity, BS = Base saturation, CEC = Cation exchange capacity, TN = Total nitrogen, AP = Available P, AK = Available K, SOC = Soil organic carbon, MBC = Microbial biomass carbon, Letter symbol = Mean with same column who follow by same letter is not significant difference by Duncan test at the 5% level.

in the study area is classified as low to medium and there is no difference in the average for each geological formation. Alluvial formations have relatively low TN. Low TN formation in alluvial formations can be caused by runoff (Verrina et al., 2013; Wang et al., 2015).

Available phosphate (AP) in the study area is at a very low to low level and there is no difference in the average of each geological formation (Table 5). According to Oliveira et al. (2022), AP in soil is influenced by the parent soil material. The relatively low AP content in intrusive rock formations can be caused by the mineral composition of the parent material that makes up the formation, namely felsic igneous rock, which causes a decrease in the availability of soil nutrients (Aji and Teapon, 2019). Low AP can also be caused by several factors such as organic matter content, soil management, pH and alkaline elements (Putri et al., 2019). The AK content of soil samples in the study area is at low to medium levels and there is no average difference in each geological formation. According to Portela et al. (2019), soil with high AK content is found in soil whose parent material is carbonate rock, gabbro, gabbro-diorite, and quartz-diorite. Wakeel and Ishfaq (2022), also say that AK is based on parent material. AK is also influenced by fertilization such as the addition of organic material (Bader et al., 2021).

There are differences in soil organic content (SOC) in the Nampol, Oyo, Alluvial rock, and Arjosari Formation as well as intrusive Formations. SOC in the study area is in the very low to medium range. The low SOC content in the Alluvial Formation is caused by frequent flooding in this area. Saint-Laurent et al. (2016) revealed that alluvial areas that are often flooded have lower SOC content than areas that are not flooded. Because SOC is dynamic and influences soil quality, assessments of changes in soil quality need to be carried out repeatedly over time (Chaudhuri et al., 2013; Mukhopadhyay et al., 2014). MBC in the study area has a very low value and there is no difference in the average for each geological formation. The low accumulation of organic carbon in each formation causes low MBC values (Bastida et al., 2021). Alluvial formations have relatively low MBC. The low MBC of alluvial formations can be caused by low SOC. Mangungsong et al. (2020) stated that soil in alluvial areas has problems in the form of low SOC content.

3.2. Soil quality index

Soil quality index assessment was carried out using the PCA test (Table 7). Only PCs with eigenvalues >1 are taken as an index (Andrews et al., 2002). Soil quality parameters were analyzed using Pearson correlation test to determine the strength of the relationship (Shao et al., 2020). In determining MDS, the parameter chosen is the highest Loading Factor on each PC. The correlation of each parameter is considered (Table 6). If more than one factor is retained in the PC, then correlation is used to determine which parameters are considered redundant and potentially removed from the MDS (Andrews and Carroll, 2001).

Based on the results of PCA analysis (Table 7), there are four PCs (main components) with eigenvalues > 1 and are considered to represent 84.44% of the total data. In PC 1, the parameters with the highest loading factor values and potential to become MDS are BD, porosity, SOC, and CEC. The parameters BD, SOC, and CEC were significantly correlated with each other, but only BD and SOC were chosen as MDS because of their large role. Meanwhile, porosity is only correlated with BD so it is not selected as MDS. In PC 2, the parameters that have the highest loading factor values are pH, BS, and AK. pH and BS were significantly correlated with each other so they were selected as MDS. Meanwhile AK is not significantly correlated so it is not included in the MDS. On PC 3, the parameters with the highest loading factors are BS and TN. However, only TN was selected to be MDS because BS had already been selected to be MDS. PC 4 has two parameters with the highest factor loading, namely EC_e and MBC, but only EC_e is used as MDS because it has a higher factor loading value. Thus, there are a total of six MDS, namely BD, SOC, pH, BS, TN, and EC_e. Complete MDS parameters represent soil physical, chemical and biological indicators (Andrés et al., 2022), and the six selected parameters are completely representative.

Table 6
Correlation analysis of soil quality parameters

Parameters	BD	Porosity	pH	EC_e	SOC	CEC	BS	TN	AP	AK
Porosity	**–0.79****									
pH	–0.31	0.52								
EC	–0.37	0.32	0.39							
SOC	**–0.82****	0.62	0.02	0.15						
CEC	**–0.84****	0.50	0.06	0.17	**0.80****					
BS	0.27	–0.02	**0.72***	0.12	–0.30	–0.37				
TN	–0.49	0.26	0.42	0.44	0.19	0.30	–0.25			
AP	–0.39	0.41	0.36	–0.06	0.59	0.49	0.31	0.10		
AK	–0.17	–0.04	0.36	0.16	–0.18	0.44	0.18	**0.82****	0.09	
MBC	0.00	–0.19	0.27	–0.09	0.03	0.01	0.09	0.43	–0.01	0.16

Explanations: BD = Bulk density, EC_e = Electrical conductivity, BS = Base saturation, CEC = Cation exchange capacity, TN = Total nitrogen, AP = Available P, AK = Available K, SOC = Soil organic carbon, MBC = Microbial biomass carbon

Table 7
Principal component analysis (PCA)

Eigenvalue	4.024	2.460	1.596	1.208
Proportion	36.586	22.362	14.507	10.986
Cummulative	36.586	58.948	73.455	84.441
Variable	PC1	PC2	PC3	PC4
BD	**–0.942**	0.202	0.113	0.097
Porosity	**0.800**	–0.097	0.289	–0.261
pH	0.490	**0.720**	0.398	–0.043
EC_e	0.433	0.296	–0.084	**–0.675**
SOC	**0.798**	–0.488	0.067	0.181
CEC	**0.805**	–0.398	–0.130	0.146
BS	–0.058	**0.709**	**0.659**	0.062
TN	0.591	0.547	**–0.571**	0.024
AP	0.588	–0.016	0.504	0.456
AK	0.278	**0.671**	–0.442	0.048
MBC	0.094	0.393	–0.320	**0.637**

Explanations: BD = Bulk density, EC_e = Electrical conductivity, BS = Base saturation, CEC = Cation exchange capacity, TN = Total nitrogen, AP = Available P, AK = Available K, SOC = Soil organic carbon, MBC = Microbial biomass carbon

Index calculations are based on calculations by Mukhopadhyay et al. (2014). This calculation is based on the principle that if there is more than one MDS in one PC, it is seen based on their correlation, if they are correlated, then the weight is divided based on the correlated MDS, while full weight is given to the uncorrelated MDS. Based on Table 8, it is known that the SQI in the ten formations is in the low to medium class with a value range of 0.31–0.39. Intrusive rock formations have the lowest SQI, while the highest SQI is found in the Watupatok and Jaten Formation. In general, the SQI values for the ten formations have values that are not much different.

The contribution of each MDS to SQI in the study area is quite varied (Fig. 2). BD is the parameter that makes the most significant contribution to the SQI calculation with a total value of 1.05. BD is very important because of its ability to determine soil structure, transport of water and dissolved nutrients, and air flow in the soil (Meng et al., 2023). According to Xu et al. (2016), BD also determines soil quality and soil fertility. pH and EC_e then contribute with values of 0.66 and 0.53. According to Smith and Doran (1997), pH and EC_e are important in SQI calculations because pH is used to measure soil acidity and EC_e as an estimate of salt concentration. SOC contributes to SQI with a value of 0.50. SOC is very important for soil quality. According to Rice et al. (2021), SOC influences almost all soil properties and nutrient cycles. BS contributes to SQI with a value of 0.43. Ac-

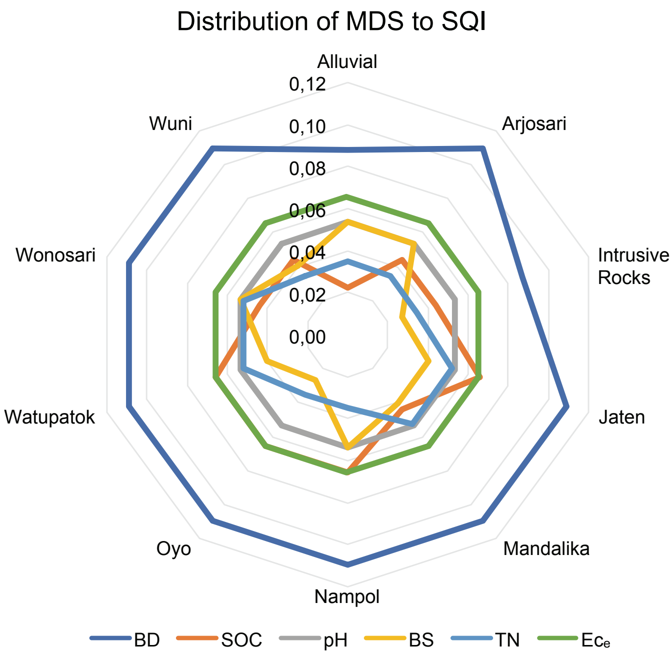

Fig. 2. Contribution of each MDS to soil quality index.

Table 8
Soil quality index assessment

MDS	Wi	Si									
		Alluvial	Arjosari	Intrusive rock	Jaten	Mandalika	Nampol	Oyo	Watupatok	Wonosari	Wuni
		Score	Score	Score	Score	Score	Score	Score	Score	Score	Score
BD	0.15	4	5	4	5	5	5	5	5	5	5
SOC	0.15	1	2	2	3	2	3	3	3	2	2
pH	0.13	4	4	4	4	4	4	4	4	4	4
BS	0.13	4	4	2	3	3	4	2	3	4	3
TN	0.17	2	2	2	3	3	2	2	3	3	2
EC_e	0.13	5	5	5	5	5	5	5	5	5	5
	SQI	0.32	0.36	0.31	0.39	0.36	0.38	0.36	0.39	0.38	0.35
	Score	2	3	2	3	3	3	3	3	3	3
	Class	Low	Medium	Low	Medium	Medium	Medium	Medium	Medium	Medium	Medium

Explanations: BD = Bulk density, SOC = Soil organic carbon, BS = Base saturation, TN = Total nitrogen, EC_e = Electrical conductivity cording to Wu and Liu (2019), BS has an influence on assessing soil quality because sufficient BS in the soil can influence soil pH so that it is optimal for plant growth and microbial life. TN contributes to SQI with a value of 0.42. According to Simfukwe et al. (2021), nitrogen is important because nitrogen is needed for the growth of plant and soil microbes, as well as soil productivity.

3.3. Influence of geological formations on soil characteristics

Table 9 shows that geological formations have a significant effect on BD, porosity, SWC, CEC and SOC. BD in the study area ranged from 0.95–1.32 g cm^{-3} (Table 4). BD can be influenced by parent materials which mostly come from volcanic rocks and a little carbonate. According to Verheye (2009), soil derived from volcanic parent material has a low BD making it ideal for plant growth. Zhou et al. (2022), stated that the BD of soil on carbonate rocks ranges from 1.04–1.22 g cm^{-3}. The BD value in Zhou et al. (2022) research has the same range as the BD in this research area. Porosity in this study area ranges from 38.07–53.43% (Table 4). Soil porosity is influenced by geological formations through interactions with parent materials (Schoonover and Crim, 2015). The highest porosity is found in the Jaten Formation which is mostly composed of tuff sandstone. Based on research by da Silva et al. (2022), higher porosity is found in soil derived from sandstone compared to basalt or lime. Soil water content (SWC) in the study area has a value range of 4.29-13.65% (Table 4). The water content in the soil is relatively low. However, the soil's ability to hold water is influenced by its texture (Datta et al., 2017). Geological formations also play a role in determining soil moisture content. They interact with factors like soil texture, which is formed due to the weathering of the parent material (Al Khoury et al., 2023; Okewale and Coop, 2017).

Cation exchange capacity in the study area is in the range of 19.86–38.60 $cmol^{+}\ kg^{-1}$ (Table 5). The presence of clay minerals may influence this. Chowdhury et al. (2021), found that clay minerals like montmorillonite, illite, and kaolinite can affect CEC. These minerals interact with CEC through isomorphic substitution, creating a negative charge on clay particles. This attracts positively charged cations, contributing to the soil's CEC (Ketterings et al., 2007). The study area has a soil organic carbon (SOC) content ranging from 0.99% to 2.76% (Table 6). Geological formations can influence SOC levels due to the properties of the parent material. Mao et al. (2020) found that variations in parent material can affect SOC content. Chen et al. (2022) found that parent material variations and their interaction with soil minerals can affect SOC content. This interaction is crucial for organic carbon stability as it mediates the absorption of diverse organic compounds (Zhao et al., 2022).

Table 9
The influence of geological formation on soil characteristics

Parameters	N	p-value
Bulk density	40	**0.01****
Porosity	40	**0.05***
Soil water content	40	**0.00****
pH	40	0.53
Electrical conductivity	40	0.29
Soil organic carbon	40	**0.05***
Cation exchange capacity	40	**0.00****
Base saturation	40	0.44
Total nitrogen	40	0.51
Available phospor	40	0.76
Available kalium	40	0.78
Microbial biomass carbon	40	0.54

3.4. The influence of geological formations on soil quality

In this study, the influence of each geological formation on the soil quality index was analysed using Kruskal-Wallis test. The Kruskal-Wallis test is used because it is an alternative to parametric statistical tests such as one-way ANOVA and does not require distribution assumptions and can be used on small samples (Nahm, 2016). The test results show that the asymp sig value is 0.437 (Table 10). This value is greater than the significance level used, namely 0.05. Thus, there is a real difference between geological formations and soil quality index values. The results of this test indicate that geological formation is not the dominant factor determining soil quality in the study area. According to Bünemann et al. (2018), soil quality is determined by three main factors, namely; extrinsic factors include parent material, climate, topography, and hydrology; Intrinsic factors include the physical, chemical and biological properties of soil; and anthropogenic factors include land use, management practices, pollution, and climate change. According to Karlen et al. (1994), soil management is one of the determinants of soil quality on land. Furthermore, according to Haberern (1992) in Karlen et al. (2003), soil quality focuses on the impact of soil management on environmental quality, human and animal health, as well as food safety and quality. Thus, the potential presence of other factors that influence soil quality apart from geological formations will also become increasingly diverse.

Table 10
Independent-samples Kruskal-Wallis test results

N	Statistic Test	df	Asymp. Sig
10	9.000[a,b]	9	0.437

3.5. Factors limiting soil quality

Based on Table 11, two geological formations do not have limiting factors on soil quality, namely the Jaten Formation and the Watupatok Formation. The soil quality parameters found in this formation are in moderate to very high condition. BS is a limiting factor in the Oyo Formation, while SOC and TN are limiting factors in almost all geological formations. Thus, three parameters were found to be limiting factors for SQI in the research area: SOC, TN and BS.

Table 11
Limiting factors of soil quality

Geological Formation	SQI	Limiting factors
Alluvial	0.32	SOC, TN
Arjosari	0.36	SOC, TN
Intrusive rocks	0.31	SOC, BS, TN
Jaten	0.39	–
Mandalika	0.36	SOC
Nampol	0.38	TN
Oyo	0.36	BS, TN
Watupatok	0.39	–
Wonosari	0.38	SOC
Wuni	0.35	SOC, TN

Explanations: SOC = Soil organic carbon, TN = Total nitrogen, BS = Base saturation

SOC is important in soil because of its relationship to other properties. According to Wiesmeier et al. (2016), a lack of SOC in the soil will reduce soil productivity. Nitrogen is a nutrient that plants really need. According to Sun et al. (2020), nitrogen content in the soil will affect plant productivity, soil properties and plant physiology. BS is a parameter that is closely related to soil fertility. According to González-Fontes et al. (2017), if the soil has low BS, the plant productivity decreases due to the lack of base cations. Soils with low BS conditions need to improve soil quality, such as improving SOC by adding organic matter (Corsi et al., 2012). Efforts to improve NPs can be carried out by carrying out crop rotation with leguminous plants (Bowles et al., 2022). Soil improvement with low BS can be done by fertilizing with calcium and magnesium based fertilizer (Antonius, 2019).

4. Conclusions

1. Geological formations influence soil mineral composition, especially in andesitic-basaltic rocks. The soil characteristics that influenced by geological formations are bulk density, porosity, soil water content, cation exchange capacity, and soil organic carbon
2. The soil quality index of various geological formations is in the range of 0.31–0.39 (low to medium class), and the geological formations in the research area are not the dominant factor influencing the soil quality index.
3. Factors limiting soil quality in the research area include soil organic carbon, total nitrogen and base saturation.

Acknowledgments

The researcher would like to thank Universitas Sebelas Maret Surakarta and Ministry of Education, Culture, Research and Technology for supporting this research. In addition, thanks also to the government of Pacitan Regency, East Java, Indonesia for allowing research to be carried out in their area.

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