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Evaluation of Quarry Rehabilitation Status Using Soil Physico-chemical and Soil Enzyme Activity in Tezo Ward, Kilifi County, Kenya

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Abstract Quarrying activities create significant health, environmental and visual impacts which require to be addressed through the implementation of some rehabilitation practices. The process usually starts and proceeds using key steps following a decision to reach a targeted desired final ecosystem. As the processes progresses however, the most important factor considered to affect ecosystem integrity, is soil quality which is determined using the physicochemical and biological characteristics for ecosystem structure and function. Literature has indicated that most past ecosystem rehabilitation research has been using inaccurate, time consuming and costly methods. This study evaluated the changes among selected soil physicochemical properties and enzyme activity as measures of the quarry rehabilitation status. The study analyzed the soil bulk density (BD), organic matter (OM), pH, nitrates (NO_3^--N), nitrites (NO_2^--N), ammonium ion (NH_4^+), phosphates (PO_4^{3-}) and Cation Exchange Capacity (CEC) of the Tezo rehabilitated quarry sites in Kilifi County, Kenya. In addition, amylase, cellulase and protease enzyme activities were also evaluated. Soil samples were collected from early (< 10 years), intermediate (11 – 20 years) and mature (> 20 years) rehabilitation plots. Undisturbed virgin plots and abandoned plots which were recovering naturally represented the control plots. Findings showed that soil bulk density was significantly different *($P < .0001$)* and was highest among the intermediate and early plots while the mature plots had the lowest BD values. Relative to soil organic matter, the study results showed that BD decreased as OM increased among all the plots. Additionally, soil OM revealed significant difference *($P < .0001$)* among all plots while reporting a general increase with rehabilitation stages. All the selected soil chemical parameters revealed significant differences *($P < .0001$)* across all rehabilitation stages. Both nitrates and nitrites ions were highest within intermediate plot but on the contrast, nitrates were lowest within early plots while nitrites were lowest within the virgin plots. The highest ammonium ion levels were reported in mature plot which were twice that of the early plots while phosphate levels were however, highest among the natural sites but similarly lowest within the early plots. Virgin plots reported CEC levels that were about 2.5 times higher than the early sites. Soil pH measurements were within a narrow range of between 7.7 and 8.6 between the lowest and highest value. Except protease enzyme activity, which had significant differences *($P < .02$)* only among the naturally recovering plots, amylase and cellulase were significantly different across all plots at different rehabilitation stages. There were, in addition, strongly to moderately positive correlations between amylase and cellulase with organic matter, nitrates, nitrites ammonium and phosphate ions. Protease activity however, revealed negative correlations with organic matter. The study therefore identified, due to their consistent trend, OM, CEC, ammonium phosphate ions as well as amylase and cellulase activity as being the most reliable soil quality indicators that can be used to predict the rehabilitations status of quarries.

Keywords: *Rehabilitation, physicochemical properties, ecosystem integrity, enzyme activity*

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1. Introduction

Construction works require cement and concrete which are produced using carbonate rocks from open pit quarry mines. The worldwide production of carbonate rocks ranks third in terms of volume and fourth in terms of value compared to all non-fuel mineral products [1]. The extraction of limestone and other quarrying activities create significant health, environmental and visual impacts due to wastes and the alteration of the original topography and soil profiles. In addition, large ugly and sterile sites are usually left behind, stripped of all their living materials, which in most cases do not support any life [2,3].

Quarry rehabilitation is a process that aims at creating a self-supporting ecosystem that will be resilient to perturbations [4]. The process requires the application of technical measures in order to increase the speed of regeneration and the development of site specific and self-sustaining plant communities and ecosystems. To achieve this, soil ecology knowledge is useful, depending on the severity of the original disturbance and the goals of the quarrying rehabilitation project [5]. The process usually starts and proceeds using key steps following the selection of a desired target ecosystem and its successional phase. For instance, the process can begin with land form modeling, substrate preparation, plant species selection, revegetation and post-plantation interventions [6]. Due to variations in the degree of ecosystem degradation, specificity of restoration goals can challenge rehabilitationists in making generalizations with regard to the approaches that lead to successful rehabilitation [5]. Many studies have concentrated on a single rehabilitation method while a few experimental studies have so far tested the efficacy of different restoration approaches and in particular the use of different plant species for re-vegetation [6,7].

During quarry rehabilitation, the most important factors affecting ecosystem integrity is soil quality which is determined by the physical, chemical and biological support characteristics for ecosystem structure and function. The specific soil properties on rehabilitated land will determine the level of ecosystem development and the extent to which development will progress [8]. Rehabilitation efforts should recognize the integral role of soil physical and chemical properties in successful re-vegetation of degraded sites. The main challenge in rehabilitation success is the failure to understand the link between ecosystem degradation and specific restoration goals [5]. Initiation of quarry rehabilitation plans should therefore be based on a clear set of objectives, reflecting the legislative requirements, local social, economic and environmental considerations for future use of the site, which should be technically and financially sustainable (Wbcsd, 2011). Plans to rehabilitate quarry mines need to be developed prior to mining of new sites and operating the quarries accompanied by a plan to monitor and manage the corrective measures, including measurement of performance against objectives [9,10].

The key attributes used in measuring rehabilitation progress for most past research have focused on vegetation structure, species diversity, species abundance, ecological functions and socio-economic factors [11]. These approaches have proved to be inaccurate, time consuming and costly. Literature review shows that there are only a few published studies that address the use of soil quality indicators as measures of ecosystem integrity and their relationship with the diversity of plant communities.

This study therefore, examined the status of soil physical, chemical and microbial enzyme activities as measures of ecosystem recovery status within rehabilitated quarry in Tezo ward in Kilifi County, Kenya. The most suitable soil physicochemical and soil activity data for evaluation of rehabilitation status were established by examining their trends across different stages of rehabilitated quarry study sites.

2. Materials and Methods

2.1. Study Area

This study was conducted in Tezo ward (TZ), in Kilifi County along the coast of Kenya. Soil samples were collected form plots that were formerly limestone quarries which had undergone post closure revegetation using nitrogen fixing casuarina trees. Three plots measuring thirty meters by thirty meters (30 m x 30 m) were identified based on their rehabilitation stage which were categorized as early (E; <10), Intermediate (I; 11 - 20) and mature (M; > 20) years. To enable establishment of baseline and to allow for comparison of effect of rehabilitation, an undisturbed virgin plot and an abandoned naturally recovering pot of similar size were also identified and sampled to represent the negative and positive control plots.

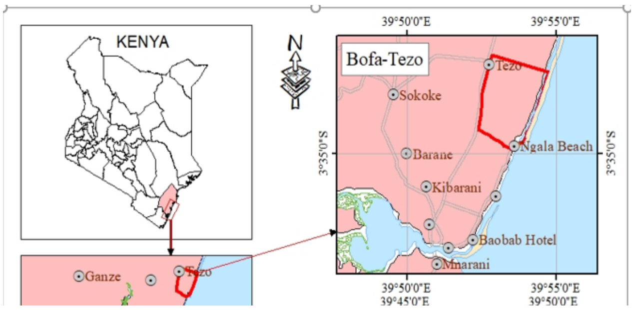


Figure 1. Map showing the study site. (Source: Author's construct)

2.2. Soil Sampling

Soil samples were collected using core rings along six transects measuring 30 m long from each of the five plots. These samples were collected at 0 to 15 cm depth around the root zones underneath the growing trees at 0, 10, 20 and 30 m along the transects. A composite soil sample from each plot was then made by thoroughly mixing the individual samples in order to minimize within plot soil spatial heterogeneity. The composite samples were thereafter separated into three replicate batches for laboratory tests and sealed in aseptic plastic bags. Some samples were taken for soil moisture content analysis while others were air dried for analysis of physicochemical and enzyme activities after they had been sifted to remove gravel and undecomposed litter.

2.3. Soil Physicochemical and Enzyme Activity Analysis

Different laboratory soil analysis protocols were used to determine the different soil physicochemical properties and enzyme activities. The thermogravimetric method was used for determination of soil water content where the content was expressed as a mass per unit volume [12]. Soil bulk density was determined as a ratio between the dry weight to soil volume (g/cm^3) [13]. Determination of soil organic matter was done using the wet oxidation method [12] while soil textural classes were determined using the USDA soil texture calculator for the soil particle size distribution. Soil pH was measured using a pH meter after allowing the soil suspension to settle for 30 minutes [12]. Available Orthophosphate ions (PO_4^{3-}) determination was done by the micro-kjeldahl protocols [14] in which is a colorimetric procedure followed after the samples were digested at 360°C for 2 hours. Ammonium ion (NH_4^+-N) measurement was done using the micro-Kjeldahl colorimetric method after extraction using 2 M KCl solution [12]. The cadmium reduction method was used for determination of nitrate nitrogen in which nitrates were first reduced to nitrites. Determination of CEC was done by extraction method with 1M neutral NH_4AC [14]. Amylase and Cellulase activity were determined by the modified dinitrosalicylic by acid Miller (1959) while protease activity was determined by the trichloroacetic acetic acid by Ladd and Butler (1986).

2.4. Statistical Analysis

Sample means for each of the three batches of soil physicochemical properties and enzyme activity analyzed for each rehabilitation stage and the control plots were compared using a One-way Analysis of Variance (ANOVA) computed using Statistical Analysis System (SAS). This computation was done after data had been tested for normality using the Shapiro Wilk normality test ($P > .05$). The treatment groups in this analysis were therefore the different rehabilitation stages and the control groups were used to determine any significant changes over the rehabilitation period on the soil properties of the quarry soil materials. Treatment means were separated using the Tukey Honest Significant Difference Test (HSD). The Pearson correlation coefficients (r) between physico-chemical properties and enzyme activities were determined using the Microsoft excel function.

3. Results

3.1. Effect of Soil Physico-chemical Properties Following Rehabilitation

3.1.1. Soil Physical Properties Following Rehabilitation

Results for soil physical properties for Tezo early (TZE), Tezo intermediate (TZI), Tezo mature (TZM), Tezo naturally recovering (TZN) and Tezo virgin (TZV) plots are summarized in Table 1 and Figure 2 below.

Table 1. Summary of physical properties of samples from Tezo quarry site

Parameter	TZE	TZI	TZM	TZN	TZV
BD	1.064^b	1.224^a	0.642^e	0.996^c	0.812^d
OM	0.245^d	1.375^b	1.375^b	0.480^c	1.790a
MC	0.04588^e	0.3536^d	1.0091^a	0.4351^c	0.6302^b
TC	Sandy loam	Loamy sand	Loamy sand	Loamy sand	Sandy loam

Mean values (n =3) in each row with the same letter are not significantly different at α = 0.05
Bulk Density, BD; Organic Matter, OM; Moisture Content, MC; and Textural Class, TC.

The soil physical property values among all rehabilitation plots were significantly different ($P < .0001$).

Soil bulk density values in the early plots were about 1.5 times (1.064 g/cm^3) higher than the lowest (0.642 g/cm^3) recorded among the mature sites. Soil organic matter content was lowest (0.245 %) within the early sites while the virgin sites had the highest (1.79 %). Soil moisture was highest within the mature plots (1.009 %) while the early sites had the lowest values (0.046 %). The intermediate, mature and natural sites had loamy sand soils while the early and virgin site soils were sandy loam.

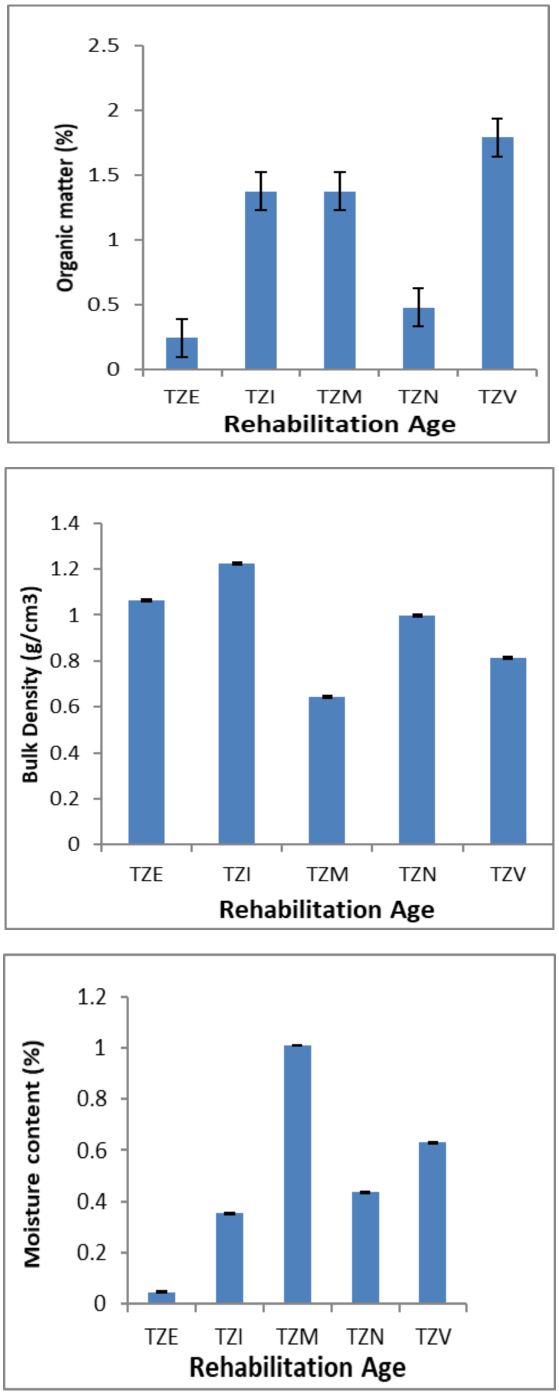


Figure 2. Soil physical properties for samples from Tezo site

3.1.2. Soil Chemical Properties Following Rehabilitation

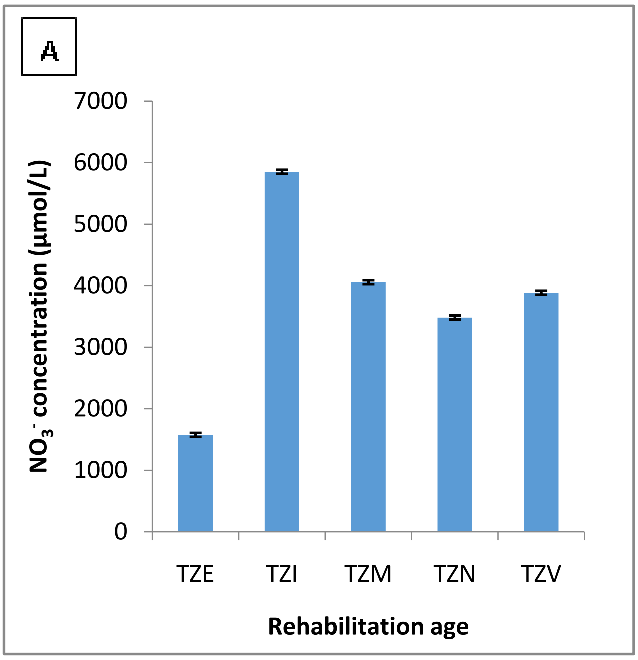
Results for soil chemical properties for rehabilitation plots are presented in Table 2 and Figure 3 below.

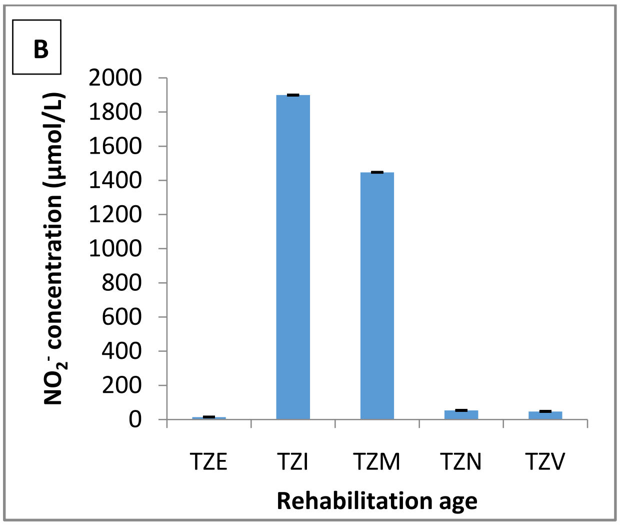
Within all plots of the study the site, the soil chemical parameters revealed significant differences *(P <.0001)* across all rehabilitation stages. Both nitrates and nitrites ions were highest within intermediate plot (5850.47 and 1899.6 µmol/l respectively) while nitrates were lowest within early plots (1574 µmol/l) while nitrites were lowest within the virgin sites (47.103 µmol/l). The highest ammonium ion levels were reported in mature plot (10517.6 µmol/l) which were twice that of the early sites (5011.1 µmol/l). On the contrast, phosphate levels were however, highest among the natural sites (112.07 µmol/l) while they were similarly lowest within the early sites (1.64933 µmol/l). The virgin study sites reported CEC levels that were about 2.5 times higher than the early sites. Soil pH measurements were within a narrow range of between 7.7 and 8.6 for the natural and early plots respectively.

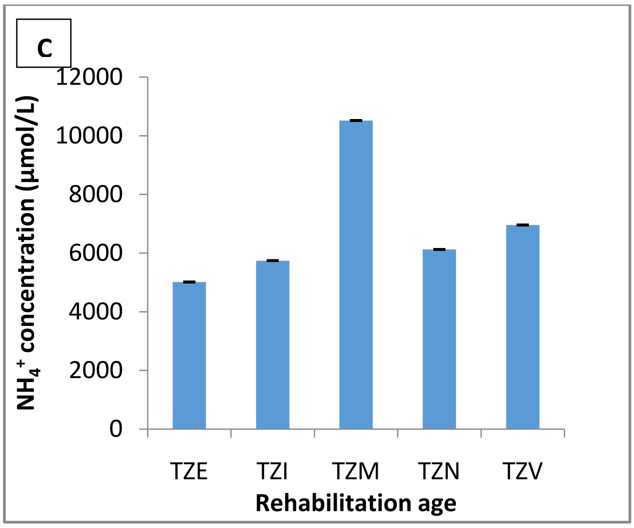
Table 2. Summary of chemical properties of samples from Tezo quarry site

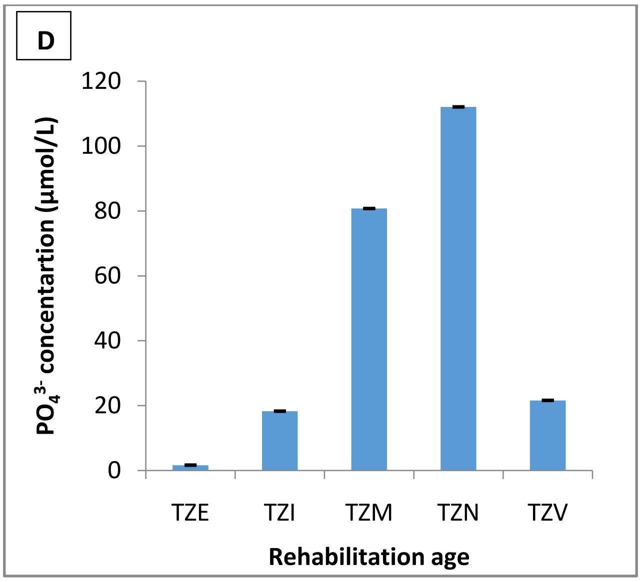
Parameter	TZE	TZI	TZM	TZN	TZV
NO_3^--N	1574^e	5850.47^a	4056.93^b	3481.3^d	3883.39^c
NO_2^--N	14.063^b	1899.6^a	1446.901^d	53.216^c	47.103^e
NH_4^+	5011.119^e	5740.676^d	10517.59^a	6125.552^b	6956.227^c
PO_4^{3-}	1.64933^e	18.286^d	80.75^b	112.07^a	21.608^c
CEC	19.104^d	18.781^e	23.604^c	35.672^b	46.076^a
PH	8.6^a	8.1^c	8.3^b	7.7^e	7.8^d

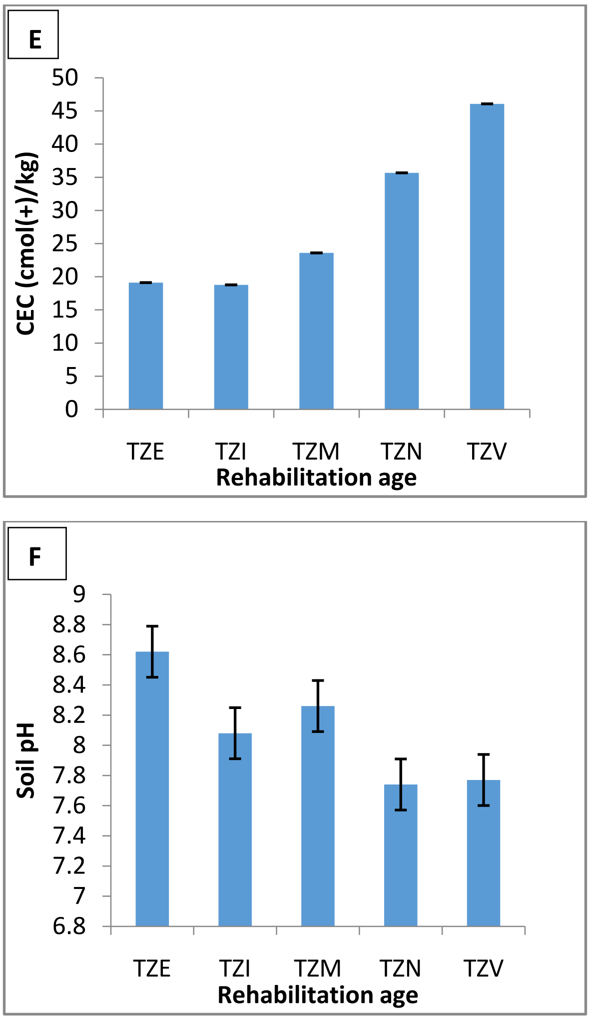
Mean values (n =3) in each row with the same letter are not significantly different at α = 0.05
Nitrates, NO_3^--N; Nitrites, NO_2^--N; Ammonium ion, NH_4^+; Phosphate ion, PO_4^{3-}; Cation Exchange Capacity; CEC and pH











A) NO_3^--N; B) NO_2^--N; C) NH_4^+; D) PO_4^{3-}; E) CEC; F) pH

Figure 3. Soil chemical properties for samples for different rehabilitation plots

3.2. Effect of Soil Enzyme Activity and their Correlation with Physico-chemical Properties Following Rehabilitation

3.2.1. Effect of Rehabilitation on Soil Enzyme Activity

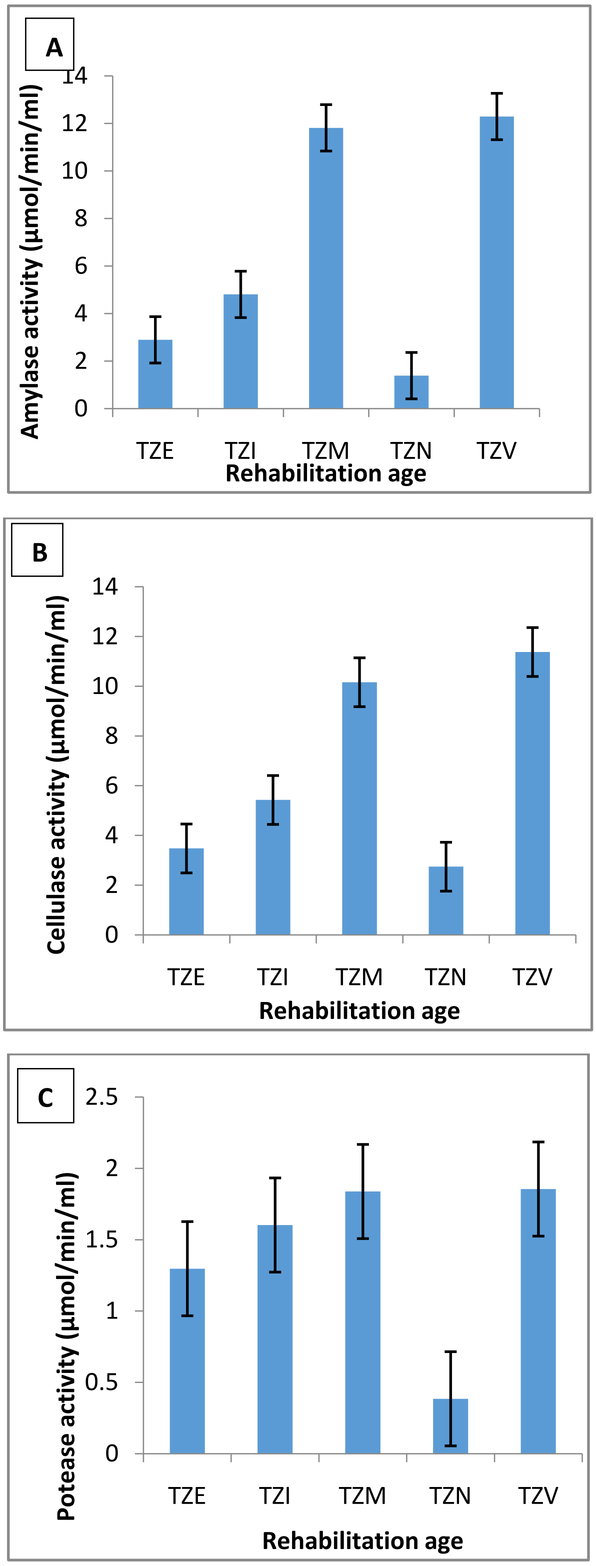
Table 3 and Figure 4 below presents the microbial enzyme activities for soil samples collected from Tezo quarry site.

Table 3. Summary of microbial enzyme activity in soil samples from Tezo quarry site

Parameter	TZE	TZI	TZM	TZN	TZV
A. Amylase	2.89^{bc}	4.8^{b}	11.81^{a}	1.38^{c}	12.28^{a}
B. Cellulase	3.48^{bc}	5.42^{a}	10.16^{a}	2.74^{c}	11.37^{a}
C. Protease	1.29^{a}	1.6^{a}	1.83^{a}	0.38^{b}	1.85^{a}

Mean values (n =3) with the same letter in each row are not significantly different at α = 0.05
Enzyme activity is expressed in Units as µmol/min/ml

Amylase activity results indicated a significant difference *(P = .0004)* between the virgin and mature sites, while there was no significant difference within the early, intermediate and naturally recovering sites. The naturally recovering site had the lowest level of activity (1.38 µmol/min/ml) while the virgin site recorded the highest values (12.28 µmol/min/ml). Similarly, cellulase activity among the intermediate, mature and virgin sites showed significant differences *(P = .0011)* within the early and naturally recovering plots. On the contrary, protease activity levels revealed significant differences *(P = .02)* only among the naturally recovering plots compared to the rest of the plots.



Amylases activity; B) Cellulase activity; C) Protease activity

Figure 4. Microbial enzyme activity in soil samples from Tezo site

3.2.2. Correlation between Soil Physico-chemical Properties and Enzyme Activity

A correlation analysis between soil microbial enzyme activity and selected physicochemical properties was computed using the raw triplicate data values. This arrangement resulted into a sample size of 15 data values across rehabilitation stages and the controls plots. The Microsoft Excel correlation function was used to carry out the correlation analysis. Other than establishing the strength of the linear relationships between any two categories of variables, the correlation results further enabled the identification of variables that can be tied together and more reliably used as rehabilitation monitoring indicators.

The results of the correlation analysis are presented in the Table 4 below and discussed individually in the subsequent sections. The directions of correlation are represented by blue colour (positive), red colour (negative), and white colour (neutral) while the intensity of the colour indicates the level of strength or weakness of the correlation.

Table 4. Pearson correlation coefficients between soil physico-chemical Properties and microbial enzyme activities

	Amylase	Cellulase	Protease
Organic Matter	0.83	0.81	0.56
Moisture	0.78	0.53	0.73
CEC	0.35	0.45	0.53
PH	-0.14	-0.16	-0.29
Nitrates	0.26	0.19	0.05
Nitrites	0.21	0.054	-0.08
Ammonium	0.73	0.44	0.67
Phosphates	-0.09	-0.36	0.23

4. Discussion

4.1. Effect of Quarry Rehabilitation on Soil Bulk Density, Organic Matter and Moisture Content

Soil bulk density, which affects root growth, increases with compaction and is also affected by the soil's particle size distribution. Conventionally, the bulk density critical values indicate that any value less than 1.5g/cm^3 is generally considered as low. In this study, all rehabilitation stages generally reported low values which were significantly different at different rehabilitation stages. Although the results did not reveal clearly distinct trends, bulk densities were generally higher within the early rehabilitation stages and lower within the mature stages. As expected, soil organic matter levels were generally lowest within early rehabilitation plots which corresponded with high bulk density levels and vice versa (Table 1 and Figure 2). The observed soil physical property trends in this study were in agreement with the results of a study by Pittarello et al. (2021). Similar study results published by Gajda, Czyz, and Dexter (2016) indicated that farming systems based on less invertible management resulted in a decrease in soil bulk density. In addition, Pittarello et al. (2021) confirmed that the amount of crop residues incorporated into soils also influences the bulk density changes. Organic matter contents were about 7 times higher among virgin sites and 5 times higher within the mature plot. A significant negative correlation between organic matter and bulk density was also reported by Nabayi et al. (2021) which signifies the importance of organic matter in improving the physical conditions of soils. Any contradicting result therefore, may be associated with differences in crop species composition, other soil properties and the complex interactions of all these soil factors [18]. Soil organic matter has long been considered the key quality factor affecting physical, chemical and biological properties of soil within rehabilitation sites [19].

Unlike other physical properties, soil moisture is usually replenished by rainfall input into the soil profile within the top surface layer rather than being influenced by rehabilitation stage of quarry plots. Evaporation, on the other hand, accounts for large proportions of the total water loss from soil while mulching practices play an important role in reducing it [20]. In this study site, the average soil moisture levels were 4.9 % where the highest moisture levels occurred within the virgin plot (10%). Further, soil moisture conservation is also generally influenced by soil management practices. According to results published by Ding, Wang, and Jin (2023) soil moisture can greatly vary in the surface layer due to the influence of plant characteristics and changes in the hydrological processes of rainfall in the soils.

4.2. Effect of Quarry Rehabilitation on Soil Chemical Properties

4.2.1. Soil Nitrates (NO_3^--N), Nitrites (NO_2^--N) and Ammonium Ions (NH_4^+N)

Nitrogen exits in different oxidation states in the soil, this study, examined the trends of three oxidation states across rehabilitation stages. Plants normally take up nitrogen in form of nitrates or ammonium ion while nitrites, needed in relatively small quantities, are an intermediate product in the conversion of ammonium ion to nitrates. Forest restoration is important in determining the changes in soil concentration of nitrogen and available phosphorous. Nitrates were reported to be two times higher among the intermediate plots compared with the early stage (Table 2 and Figure 3). Because the rehabilitation process involved the introduction of nitrogen fixing plants, this observation could be associated with the ability of casuarina trees to fix nitrates together with the decomposition of organic residues. It was also reported that nitrate supply within the root zone relied upon N_2-fixing ability of the leguminous trees such as casuarina and the microbe-driven litter return [20,22]. Soil nutrients ions, especially nitrates, can however also become deficient due to differences in soil management practices, leaching from soil and denitrification. Denitrification alone has been reported to cause up to 30% of the total loss of nitrates which is favoured by warm and wet conditions with large amounts of decomposable matter [23]. Nitrogen from both enzymatic degradation and nitrogen fixation contribute to the total nitrogen and ammonium ion. It was also suggested by some research studies that the differences in root densities, from early to mature stages, could explain differences in nutrient supply. For instance, the turnover rate of fine roots, which is generally high in mature stages, could result in higher soil organic carbon and nitrates concentration in the soil [24].

Nitrites, just like nitrates, in this study, similarly recorded highest levels within the intermediate plot although there were no clear nitrites trends established in reference to rehabilitation stages (Figure 3). Nitrites are a transition product formed when ammonium ions are being converted into nitrates. The rate of conversion could however be affected by a number of factors such as soil aeration and climatic factors including soil temperature. It was reported in a study that most of the soils recording high nitrites levels also similarly have high nitrate amounts [25].

Ammonium ion, one of the most preferred forms of nitrogen by plants, is easily oxidized into nitrate ions under aerobic conditions. In this study, the mature plot recorded the highest (twice) levels while the lowest levels of ammonium ion were recorded among the early plot (Table 2 and Figure 3). These results are similar to a study which reported that restoration is a critical factor in determining changes in soil nitrogen and phosphates, and as it proceeds, the concentration of these nutrients and stocks also increase [24]. Usually, ammonium ions are formed following the decomposition of protein macro molecules in organic matter by aerobic microorganisms. This ion is highly soluble and is usually attached and held on colloidal exchange sites which are favoured by low pH levels [26]. Ammonium ion is also relatively unstable and therefore easily oxidized to form nitrate ions in the soil.

4.2.2. Soil available phosphates (PO_4^{3-})

Weathering, sorption and precipitation are essential geochemical processes that control phosphorous dynamics and speciation in the soil. The major mobile forms of phosphates are dihydrogen phosphate, hydrogen phosphate and the fully dissociated orthophosphate ions. Orthophosphate ion levels evaluated revealed that the mature and natural plots had about 70 times higher phosphates than the early rehabilitation plots (Figure 3). These high levels could be attributed to the extended period of rock weathering where the phosphate ions were still in available states. However, studies by Brown and Grant (2000), showed that the availability of phosphates in soils can be reduced when it combines with other ions such as iron to form some insoluble precipitates. Phosphate compounds differ significantly in their contribution to phosphate availability due to their chemical and biological nature. There availability is however, also determined by a balance between adsorption and desorption, which govern the equilibrium with phosphate in solution and the buffer capacity in soils [27].

4.2.3. Soil Cation Exchange Capacity (CEC)

The Cation Exchange Capacity (CEC) values were found to be highest among the virgin and mature plots which were about two and a half times higher than the early plot which recorded the lowest level (Table 2 and Figure 3). Maturity of rehabilitation plots is closely associated with abundance of soil organic matter which increases the availability of cation exchange sites in soils. In a similar study, soil organic matter was reported to be significantly related to CEC by Harada and Inoko (1975). Additionally, the study also confirmed that when the pH of soil solution decreased from 7.0 to 6.0, the CEC decreased from 40% to 30%. This relationship between CEC and organic matter was however shown to be weaker in soils that are more acidic [29]. The same study by Solly et al (2020) also concluded that the significant influence of CEC by organic matter content evolved as a function of soil pH. These patterns can be explained by the fact that more cation exchange sites are provided by soil organic matter. An et al. (2020), in their study, also reported that the concentration of base cations, CEC and electrical conductivity decreased with time due to root absorption by vegetation and soil pH could be decreased by the decomposing plant residues [31].

4.2.4. Soil pH

Soil pH affects the form and solubility of nutrients and therefore the amount of nutrients available for plant absorption. In this study, the pH range was observed to be close to neutral to a weak base value (Figure 3) and therefore the values were not very different among the rehabilitated quarry study plots. The early plot however, had slightly higher pH values while the virgin sites reported the lowest values These results generally meant that the mature the vegetation with the accompanied decomposition of litter, the lower the soil pH will be. This observation was in agreement with the values reported by An et al. (2020), where they found a decrease in soil pH in some vegetated restoration areas which they argued could be due to uptake of cations by roots which require the reverse influx of H^+. Soil pH was also noted to resist drastic changes with afforestation but rather, it changes slowly over a prolonged period of time. Dignam et al. (2018), in their study report, agreed that pH values in the same region, with different land use types, did not also differ significantly. They further argued that some unaccounted variations can be attributed to bacterial community structure changes and other factors not directly measured in their study.

4.3. Effect of quarry Rehabilitation on Enzyme Activity and their Correlation with Physicochemical Properties

4.3.1. Effect of Rehabilitation on Enzyme Activity

Amylase and cellulase enzymes are responsible for catalyzing the hydrolytic depolymerization of starch and cellulose hydrolysis in soils respectively. Proteases on the other hand are a group of proteolytic enzymes that hydrolyze polypeptides and oligopeptides into amino acids. In this study, the activities of all the three enzymes in the virgin and mature plots were highest than within natural rehabilitation plot which recorded the lowest activity (Table 3 and Figure 4). The three enzyme activity trends revealed in the study was an indication that their activity generally increased with rehabilitation maturity and absence of soil disturbance among other factors. In their study, De Melo et al. (2002), reported that soil enzymes are generally not very different in their response to several soil factors that either activate or inhibit them. As reported by An et al. (2020), soil nutrient improvement is indicated by an increase in enzyme activity which helped in the survival of pioneering afforestation species and facilitated vegetation success. It was suggested that the influence of vegetation on soil enzyme amylase activity is mainly exerted by the presence of substrate contained in plant residues which then can induce amylase synthesis [31]. Restrained enzyme activities can occur due to lack of microorganisms appropriately adapted to the available substrate in soils [33].

4.3.2. The Correlation between Enzyme Activity and Physico-chemical Properties

In this study, the correlation results between amylase and cellulase activity and organic matter were reported to be strongly positive within all rehabilitation stages while protease and organic matter revealed a weak positive correlation (Figure 4). The occurrence of strong positive correlation between amylase and cellulase and organic matter generally implied that organic matter, which is a source of organic carbon, positively influenced the diversity of either individual or microbial communities. Although it is the soil organic matter quality and quantity that affects soil enzyme activity, it is most importantly, the extracellular enzyme activity which determined by the liter chemistry of the soil organic matter [31,33]. Similar research studies reported a positive correlation between soil organic carbon content and amylase activity [34]. Reports form a study by Fan et al. (2021) on the other hand revealed the existence of a strongly positive correlation between cellulase activity and carbon, indicating the enzyme's role in driving the carbon cycle. The reported weak positive correlation with protease activity is further in agreement with a study which also showed that consistent seasonal variations within different reforestation stages was due to differences in soil moisture [35].

A strong positive correlation between moisture and amylase activity was also observed while cellulase and protease had a moderately positive correlation. Soil moisture usually affects soil nutrient movement and substrate availability resulting into changes in microbial community composition and activity (Wang et al. 2023)

Cation Exchange Capacity (CEC) revealed a positive correlation with three enzyme activities (Figure 4). These results indicated that CEC, which usually increases with maturity and organic colloidal matter content results in increased microbial activity [31]. Correlations were moderately to strongly positive between nitrates, nitrites, ammonium and phosphate ions and all the three enzyme activities consistent with findings from a similar study [19]. These positive correlations agreed with reports that showed the existence of a positive relationship between soil organic carbon and plant root biomass with enzyme activity as afforestation progresses [37,38].

5. Conclusion

Soil quality monitoring is a complex concept because it is determined by multiple structural and functional parameters. This study was able to establish individual physicochemical parameter trends with the highest potential for use as indicators for monitoring rehabilitation status.

Soil bulk density and soil moisture content across rehabilitation stages and the virgin control site did not have clearly distinct trends. Soil bulk densities were however generally high within the early rehabilitation and lowest within the mature plots. Conversely, organic matter systematically increased with rehabilitation progress. As expected, soil moisture content is replenished by rainfall input into the soil profile rather than rehabilitation stage. These observations therefore indicated that among the physical properties evaluated, soil organic matter had the highest potential for use in monitoring rehabilitation status.

Whereas nitrates and nitrites revealed similar patterns with the highest levels occurring within mature plot, these two forms of nitrogen are however prone to leaching, denitrification losses and are also affected by other soil management practices. These dynamics makes their use for rehabilitation monitoring unreliable. Cation Exchange Capacity (CEC), ammonium ions and phosphates showed a consistent pattern where the mature plots recorded the highest levels while the lowest levels were within the early rehabilitation plots. This observation suggests that the three soil properties can be useful indicators for assessing rehabilitation status.

Finally, pH values ranged between close to neutral to a weak alkaline value. Although its changes affect the solubility of nutrients in soil and consequently the amount of nutrients available for plants, it does not drastically change with rehabilitation and therefore may not be considered as a sensitive indicator for rehabilitation status evaluation.

Recommendations

- Soil quality indicators can be used to complement the current restoration evaluation methods such as the use of vegetation structure, species diversity, abundance and ecological functions because as much as the soil factors influence vegetation performance, the vegetation is also influenced by the soils.
- There is need to establish standard practices that guide ecosystem restoration. It was observed that quarry mine closure and soil management plans differed and, in some instances, there was complete lack of knowledge of the same.
- The composition and diversity of soil microbial communities should also form part of the evaluation methods because they are influenced by both biotic and abiotic conditions and quantity and quality of substrate.

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