ASSESSING THE POTENTIAL OF LOCAL AMENDMENTS IN QUARRY SOIL RECLAMATION: AN AHP-DRIVEN ANALYSIS

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Abstract - This study investigated the potential of locally available organic amendments for the reclamation of quarry soil in Hoa Vang commune, Da Nang city, Vietnam. To identify promising amendments, semi-structured interviews were conducted with 20 local farmers to leverage their experiential knowledge. Five key soil quality criteria were considered: soil structure (C1), soil nutrient content (C2), soil microbial activity (C3), water retention capacity (C4), and cation exchange capacity (C5). The organic amendments evaluated included: domestic sludge (A1), organic waste (A2), livestock manure (A3), crop residues (A4), and rice husk ash (A5). Analytical Hierarchy Process (AHP) analysis of farmer responses revealed that soil nutrient content was perceived as the most important criterion for quarry soil reclamation, and consequently, livestock manure was identified as the amendment with the highest overall potential. Furthermore, laboratory experiments assessing water holding capacity indicated that rice husk ash exhibited the most significant improvement in this specific soil property.

Key words - Locally Organic Amendments; Solid Waste; Quarry Soil Restoration; AHP

1. Introduction

The socio-economic contributions of mining and quarrying are globally recognized. However, inadequately regulated or poorly managed extraction often results in significant environmental degradation and detrimental effects on human health [1]. While historical practices frequently overlooked environmental repercussions, a lack of corporate accountability unfortunately allows these issues to persist in several nations, including Vietnam. Generally, mining and quarrying operations exert direct pressures on landscapes, leading to soil erosion and the disruption of essential ecological functions, alongside indirect impacts such as air and water contamination and a reduction in biodiversity [2]. In Da Nang city, the extraction of construction materials through quarrying has grown substantially in comparison to neighboring provinces. Nevertheless, a considerable number of quarry sites implement environmental restoration efforts that do not adhere to established regulations. This often manifests as highly uneven terrain, extensive areas requiring leveling, and inappropriate excavation techniques, causing significant damage to the natural landscape and ecological integrity. Consequently, the quality of the soil environment remains severely compromised, rendering it unsuitable for viable crop cultivation. The operational phase of quarries has already precipitated numerous adverse environmental consequences for both natural ecosystems and human communities, disrupting ecological balance and contributing to multifaceted environmental pollution. Data from Da Nang's Department of Natural Resources and Environment (DONRE) indicate the presence of 13 active and 46 abandoned or inactive quarrying sites requiring restoration within the city. Despite efforts by local authorities and site owners to rehabilitate these areas, the severely degraded soil conditions at closed quarries often prove resistant to effective environmental restoration and sustainable agricultural use [3]. Therefore, mitigating the environmental impacts stemming from quarrying activities remains a critical challenge necessitating robust and innovative solutions. Organic and inorganic amendments are commonly employed to ameliorate the compromised physical, chemical, and biological characteristics of degraded soils and mine tailings, although the sustainability of their medium- and long-term efficacy remains a subject of ongoing investigation [4]. A substantial body of literature posits the pivotal role of organic matter in influencing virtually all key soil properties, leading to the widespread utilization of organic amendments. Historically, diverse organic materials such as domestic refuse, various forms of livestock manure (fresh, aged, composted), and plant residues have been applied, either as a superficial mulch or incorporated into the substrate requiring rehabilitation [5]. Fundamentally, organic amendments exert three primary beneficial effects in the remediation process: they enhance the physical structure of the substrate, provide essential organic matter and nutrients, and mitigate the bioavailability of potentially hazardous elements, particularly cationic contaminants [6]. Consequently, this often results in an increased water-holding capacity – a critical factor for facilitating ecological succession in water-limited environments – and the stimulation of seed germination, plant growth, and microbial activity [3, 5]. Given the challenges associated with restoring degraded quarry soils in Da Nang, Vietnam, understanding the specific potential of locally available organic amendments, such as domestic waste or agricultural residues, becomes paramount in developing effective and sustainable reclamation strategies.

The application of organic amendments, sourced from readily available biogenic resources like agricultural residues, animal waste, municipal organic waste, and urban domestic sludge, has consistently demonstrated proven efficacy in global contexts for the remediation and ecological restoration of degraded lands post-mineral extraction. These amendments not only furnish essential macro-, meso-, and micronutrients crucial for plant growth but also significantly enhance soil organic matter (humus), which is vital for sustaining edaphic fauna and microbial communities, thereby improving soil structure and porosity [6]. The rapid mineralization of nutrients from their organic components facilitates assimilation by vegetation, promoting vigorous plant establishment and contributing to restored soil biodiversity and vegetative cover. The cost-effectiveness of organic amendment production, coupled with their role in sustainable waste management, fosters an environmentally benign and economically viable pathway toward long-term sustainability. For instance, Grobelak et al.'s rigorous study in Silesia, Poland, highlighted the critical necessity of integrating diverse soil amendments (*e.g., dewatered municipal sewage sludge, stabilized compost, liming agents*) with appropriate vegetation (*Pinus sylvestris L., Miscanthus giganteus*) to optimize post-mining environmental recovery, demonstrating a compelling synergy between waste valorization and ecological restoration [7]. Similarly, Trinh et al.'s 2018 study in Highland, Vietnam, confirmed mining-induced adverse environmental impacts, advocating for robust, adaptable indigenous plant species and proposing afforestation or fruit/short-term crop cultivation as primary post-closure reclamation paradigms. Collectively, these investigations underscore the pervasive degradation of post-mining soils and unequivocally establish the indispensable role of targeted soil amendments in fostering successful ecological recovery and sustained land productivity [8].

This study is driven by the urgent requirement for sustainable and cost-effective ecological restoration approaches for land severely impacted by quarrying. Specifically, it investigates the potential of locally sourced organic waste amendments-including domestic sludge, municipal solid waste, livestock manure, and agricultural residues-for the ecological rehabilitation of quarry-affected areas in the Hoa Vang district. The methodology involves a phased approach: first, a comprehensive and scientifically sound characterization of the key physicochemical properties of quarry waste material and the selected local organic waste streams will be performed. Second, the relative suitability of these amendments for restoring quarry soil will be evaluated by integrating the practical experience of local farmers with the Analytical Hierarchy Process (AHP). This methodology will quantitatively assess the effects of these amendments on key soil quality indicators, including soil structure, nutrient availability, water retention capacity, cation exchange capacity, and microbial activity. The findings of this research are anticipated to provide evidence-based insights into the most effective organic waste materials and their optimal application strategies for achieving successful and sustainable quarry land reclamation in the study area.

2. Methodology

2.1. Study area

Da Nang (Vietnamese: Đà Nẵng), the fifth most populous city in Vietnam, encompassed a population of 1,046,876 within its 1,285.4 km² area in 2022. Administratively, the city is structured into six urban districts (Hai Chau, Thanh Khe, Cam Le, Lien Chieu, Son Tra, and Ngu Hanh Son) and two rural units (Hoa Vang and Hoang Sa), which are further subdivided into 45 wards and 14 villages. The city has experienced a notable average annual urban population growth rate of 3.5% (as of 2022), with urban residents constituting 87% of the total population [9].

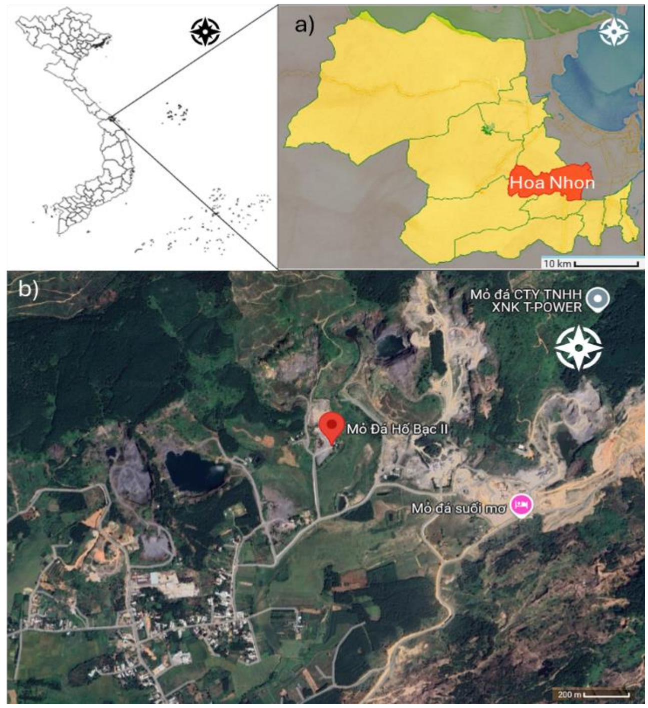

Figure 1. *a) Hoa Nhon village; b) Study areas: Ho Bac II quarry*

The Hoa Nhon village, situated within Da Nang City's Hoa Vang Commune, is characterized by a high density of quarry sites, directly attributable to its extensive reserves of construction-grade stone. According to data from the local Department of Natural Resources and Environment (DONRE), Da Nang City hosts 59 quarrying sites in total, with 13 currently operational and 46 either abandoned or inactive. Notably, Hoa Nhon village alone accounts for 8 of these sites; 3 remain active, while 5 are permanently disused but lack significant ecological restoration [10]. Given this prevalence of degraded quarry land, Hoa Vang commune was selected as the primary study area for this research. Within Hoa Nhon village, specifically at the Ho Bac II quarry sites and adjacent agricultural areas, samples of soil and potential amendment materials were procured for controlled laboratory experimentation (Figure 1). The Ho Bac II quarry, designated as the study site, encompasses a total area of 7.0 hectares, measuring approximately 520 meters in length and 138 meters in width. With an annual production capacity of 80,000 m³ of stone, this facility serves as a key supplier of aggregates, including dimension stone, crushed stone, and gravel, for construction within Da Nang city. Its estimated total reserves of approximately 2,227,082 m³ project an operational lifespan of 22 years, spanning from 2016 to 2037. The extraction methodology at this site involves a systematic, layered approach, progressing downwards from the mountain's summit. The primary stages of the quarrying process are: 1) initial overburden removal; 2) blasting the rock face for material detachment; 3) transportation of the dislodged material for further processing; and 4) mechanical processing of raw materials via crushing and screening technologies.

To acquire localized expertise concerning suitable soil amendments for quarry land reclamation, in-depth, semi-structured interviews were conducted with 20 experienced farmers residing in Hoa Nhon village, nearby the Ho Bac II quarry. This approach, consistent with qualitative research methodologies often employed in environmental management studies, allowed for the collection of rich, contextualized knowledge on traditional and practical land management strategies. Participants were purposively selected based on two primary criteria: a minimum of 10 years of agricultural experience within the commune and demonstrated experiential knowledge of edaphic conditions in degraded or marginal lands, particularly those impacted by quarrying activities. Furthermore, efforts were made to ensure geographical representation across various hamlets within Hoa Nhon, thereby capturing a diverse range of perspectives and localized insights into soil challenges and potential remediation approaches, as highlighted in similar community-based research efforts.

2.2. Laboratory analysis

The elemental profiles of both the chosen organic amendments and the initial quarry soil were thoroughly determined in this study using stringent laboratory procedures. Representative *quarry soil samples (A0)* were collected from the designated site before any amendments were applied. The selection of organic amendments for this study, comprising Domestic sludge (A1), Organic waste (A2), Livestock manure (A3), Crop residues (A4), and Rice husk ash (A5), was primarily guided by the recommendations from A. D. Bradshaw's seminal work on ecological engineering principles in degraded land restoration [6]. Beyond this foundational guidance, these five amendment alternatives (A1–A5) were meticulously chosen based on three crucial criteria: (i) their local availability within the Da Nang region, ensuring practical applicability; (ii) their cost-effectiveness and the ease with which they could be collected or produced, addressing economic viability; and (iii) their historical familiarity or traditional use by local farmers in agricultural practices, leveraging existing knowledge and practices. These criteria were specifically aligned with the practical constraints and opportunities inherent in the quarry site reclamation context of Hoa Nhon village. To ensure consistency, all soil and amendment samples were subjected to air-drying and homogenization. Subsequently, the samples underwent microwave-assisted acid digestion with a mixture of nitric acid (HNO_3) and hydrochloric acid (HCl) to effectively dissolve the elemental components, strictly following the sample preparation guidelines specified in the Vietnamese National Standard. The quantification of key macronutrients involved distinct analytical techniques: total carbon (TC) and total nitrogen (TN) were determined via the Dumas combustion method utilizing a Vario EL III elemental analyzer and a Total Kjeldahl Nitrogen analyzer; available phosphorus (P) was extracted following the Olsen method and quantified spectrophotometrically; and exchangeable potassium (K), calcium (Ca), and magnesium (Mg) were extracted with an ammonium acetate (NH_4OAc) solution and their concentrations measured using inductively coupled plasma optical emission spectrometry. The number of sample and the number of replicates for each analyzed parameter are shown in Table 1. The analytical process incorporated calibration standards derived from certified reference materials, and rigorous quality control measures, including the analysis of procedural blanks and sample replicates, were implemented to guarantee the accuracy and precision of the generated data.

Table 1. *Analyzed parameter and standard*

Parameter	Standard	Samples	Replicates
TOC	TCVN 8941:2011	6	3
T-N	TCVN 6643:2000	6	3
T-P	TCVN 8940:2011	6	3
K	TCVN 8662: 2011	6	3
Ca	TCVN 9284:2018	6	3
Mg	TCVN 9284:2018	6	3

2.3. Controlled experiment

In a controlled experimental design, five replicate experimental units were established to evaluate the impact of distinct organic amendments on the hydrophysical and chemical properties of quarry soil. The methodology for assessing soil water retention characteristics adhered to protocols outlined in studies comparing laboratory methods across the full moisture range, such as that by Mielenz Henrike et al. [13]. Individual pilot units, each measuring 40 cm (width) x 60 cm (length) x 60 cm (height), were prepared. Each unit contained a homogenized substrate comprising quarry soil combined with one of five distinct amendments at a consistent volumetric ratio of 2:1. The specific amendments evaluated were domestic sludge, household organic waste, livestock manure, rice hulls, and rice husk ash. A control group, consisting solely of homogenized quarry soil, was maintained concurrently to establish a baseline for comparison. All experimental units were positioned within a uniform environmental condition and subjected to daily irrigation with a standardized volume of deionized water (7 liters per square meter). The experimental protocol encompassed a two-week assessment of water retention capacity, quantified by the daily application of the specified irrigation volume followed by the precise measurement of leachate volume.

2.4. Analytical Hierarchy Process

Rooted in mathematical and psychological principles, the Analytical Hierarchy Process (AHP) stands as a structured multi-criteria decision analysis (MCDA) technique within decision-making theory, offering a framework for organizing and analyzing intricate decisions. Developed by Thomas L. Saaty in the 1970s and later facilitated by software implementation through Expert Choice in 1983 in collaboration with Ernest Forman, AHP has been the subject of considerable academic scrutiny and methodological advancement [11-12]. This approach presents a rigorous method for quantifying the relative significance of decision criteria by systematically obtaining expert evaluations through paired comparisons. Specifically, individual specialists utilize their field-specific expertise to assess the relative weight of factors by evaluating them in dyadic sets using a tailored questionnaire.

The implementation of this methodology involves the assignment of salience weights to the criteria that underpin the overall objective. This weighting process is achieved through a systematic pairwise comparison of the criteria. Consider two criteria, denoted as C_j and C_k. The Decision Maker (DM) is tasked with articulating a graded comparative judgment regarding the pair, specifically assessing the relative importance of C_j over C_k with respect to the defined goal. This comparative judgment is elicited using a semantic scale (*e.g., equally important, moderately more important, strongly more important*) and subsequently transformed into a numerical integer value, a_{jk}. The reciprocal relationship, representing the relative importance of C_k over C_j, is defined as $a_{kj} = 1/a_{jk}$. Consequently, a reciprocal pairwise comparison matrix A is constructed, where each element ajk represents the aforementioned numerical judgment for all pairs of criteria j and k. It is noteworthy that the diagonal elements of this matrix, a_{jj}, are equal to unity. It has been generally agreed that the weights of criteria can be estimated by finding the principal eigenvector w of the matrix A:

$$AW = \lambda_{max} w \quad (1)$$

Upon normalization, the eigenvector w represents the vector of priority weights of the criteria with respect to the defined goal, where λ_{max} denotes the largest eigenvalue of the pairwise comparison matrix A, and its corresponding eigenvector w comprises exclusively positive entries. Furthermore, the methodology incorporates established procedures for assessing the consistency of the DM's judgments. Employing analogous procedures, the priority weights of the alternatives are determined with respect to each criterion. Subsequently, the overall composite priority weights of the alternatives are computed through a weighted summation of their criterion-specific weights.

To normalize the pairwise comparison matrix, each element within a column is divided by the sum of that respective column. Subsequently, the priority weight for each criterion (W_i) is calculated by determining the arithmetic mean of the normalized pairwise comparison values of that criterion relative to all other criteria. To ascertain the reliability of the derived weights (W_i), the Consistency Ratio (CR) is computed. A CR value below the threshold of 0.1 indicates an acceptable level of consistency in the pairwise judgments. The CR is calculated as follows:

$$CR = \frac{CI}{RI} \quad (2)$$

Where:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (3)$$

$$\lambda_{max} = \frac{1}{n} \times \left(\frac{\sum_1^n w_{1n}}{w_{11}} + \frac{\sum_1^n w_{2n}}{w_{22}} + \cdots + \frac{\sum_1^n w_{nn}}{w_{nn}} \right) \quad (4)$$

where, n: number of criteria; RI: Random index.

This study established five criteria for evaluating the suitability of potential locally avaiable soil amendments:

Soil Structure (C1): Amendment application is a recognized strategy for the amelioration of soil structure. The propensity of soils to undergo compaction over time negatively impacts root proliferation, thereby diminishing the efficiency of plant nutrient and water acquisition. Soil conditioners function to enhance soil porosity and refine textural characteristics, maintaining a friable matrix conducive to root development [3, 4, 13].

Soil Nutrients (C2): The practice of amending soils exhibiting nutrient deficiencies to enhance their capacity to support robust phytogenesis has been a long-established agronomic technique. Materials such as compost, clay minerals, and peat remain prevalent for their contribution to soil fertility and nutrient provision. Furthermore, the incorporation of organic soil amendments introduces essential macronutrients, including carbon and nitrogen, alongside beneficial pedospheric microbial communities. The bioavailability of secondary macronutrients *(e.g., calcium, magnesium*) and micronutrients (*e.g., phosphorus*) can also be augmented through amendment application, thereby enriching the soil environment and promoting optimal plant growth [5, 14, 16].

Soil Microbial Activity (C3): Pedospheric microorganisms are critical mediators of biogeochemical nutrient cycling and serve as fundamental drivers of terrestrial ecosystem functionality. While diverse anthropogenic disturbances, encompassing urbanization, agricultural intensification, pesticide application, and pollution emanating from extractive industries, possess the potential to perturb soil microbial diversity, the precise ecological consequences of altered microbial community structure and function on belowground and aboveground ecosystem processes remain an active area of scientific investigation [5, 7, 17].

Water Retention (C4): The application of soil conditioners represents a viable intervention for improving the hydrophysical properties of coarse-textured soils characterized by limited inherent water-holding capacity and increased susceptibility to water deficit. The incorporation of organic matter, for instance, can significantly enhance the soil's capacity to retain moisture. Furthermore, amendments can be employed to modulate soil pH, aligning it with the specific physiological requirements of target plant taxa or rendering excessively acidic or alkaline soils more amenable to cultivation. Early 20th-century scientific inquiries explored the potential of alternative materials to emulate the soil-conditioning functions of traditional amendments such as compost and clay minerals, leading to the conceptual framework of "soil conditioning." The principal evaluation metrics for these materials typically encompass their cost-effectiveness, capacity to extend the duration of plant-available soil moisture, stimulation of pedospheric microbial activity, enhancement of plant-available nutrient pools, and augmentation of plant survival rates [3, 4, 13-17].

Cation Exchange Capacity (CEC) (C5): Soil amendments can substantially augment the cation exchange capacity (CEC), a critical edaphic property reflecting the soil's capacity to retain and exchange positively charged plant nutrients (cations). The predominant exchangeable cations in soils include calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), ammonium (NH_4^{+}), hydrogen (H^{+}), and sodium (Na^{+}). The CEC, representing the total net negative charge of the soil colloidal fraction, dictates the quantity of cations that can be adsorbed and subsequently exchanged with plant root systems, thereby ensuring adequate nutrient provision for plant uptake. Elevated CEC values indicate a greater density of negatively charged exchange sites and a correspondingly enhanced capacity for cation retention and exchange, ultimately supporting optimal plant nutrition and soil fertility [4, 5, 15, 16].

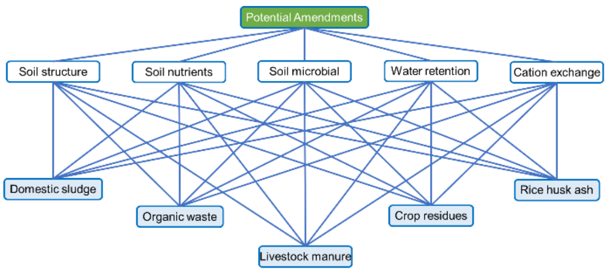

Figure 2. *AHP herrarchy for choosing potential amendments*

3. Results and discussions

3.1. Elemental composition analsis

The elemental composition analysis, presented in Table 2, indicated a deficiency of essential nutrients within the quarry soil matrix, thereby underscoring the necessity for targeted soil amelioration strategies. Furthermore, Table 1 delineates the elemental profiles of the investigated organic amendments, categorized into two distinct groups based on their carbon-to-nitrogen (C/N) ratios: those exhibiting a low C/N ratio (< 20) and those characterized by a high C/N ratio (> 20). The scientific literature extensively documents the critical influence of organic amendment biochemical composition on decomposition kinetics and subsequent nutrient release dynamics [4, 6, 18]. For example, the incorporation of organic materials with a low C/N ratio typically promotes net nitrogen mineralization, whereas amendments with a high C/N ratio frequently induce net nitrogen immobilization processes. The interactive effects of the simultaneous incorporation of plant residues exhibiting heterogeneous biochemical compositions have also been the subject of considerable scholarly attention. In such residue mixtures, predictive models of nutrient availability can be parameterized based on the established nutrient release kinetics of individual residue components and their relative proportions within the composite amendment. Moreover, the sequential incorporation of plant residues with contrasting biochemical characteristics, a common practice in intercropping agricultural systems, has been investigated. Prior empirical studies have demonstrated that nutrient availability following the subsequent incorporation of a second residue is significantly modulated by the C/N ratios of both the initial and subsequent amendments, a phenomenon commonly referred to as the legacy effect [5, 14, 16]. For instance, enhanced nitrogen availability has been observed following the application of a high C/N residue when it succeeded a low C/N residue amendment, in contrast to its application to a previously unamended soil matrix. Notably, the magnitude of this legacy effect exhibits an inverse temporal relationship with the interval separating successive residue incorporations. The chemical analysis of the incorporated residues, characterized by differing C/N ratios, is a critical factor influencing subsequent soil biogeochemical processes. While existing literature extensively documents the effects of single additions of residue mixtures on decomposition kinetics and immediate nutrient availability, the temporal dynamics of soil respiration, microbial biomass, and nutrient fluxes under varying amendment frequencies of such mixtures remain poorly understood, particularly in comparison to sequential residue incorporation regimes [3, 4, 13, 14].

Table 2. *The element component analyze results*

Subtrates	C	N	P	K	Ca	Mg	C/N
	% of dry weight						
Quarry soil	0.1	0.0	0.2	8.1	7.1	3.5	2.5
Domestic sludge	34.0	5.1	0.1	0.1	1.6	0.1	6.7
Organic waste	39.4	4.2	2.8	1.4	0.5	0.1	17.3
Manure	27.2	1.5	0.5	0.6	1.0	0.3	18.0
Rice husk	51.0	0.6	0.1	0.7	0.4	0.1	85.0
Rice husk ash	56.8	1.5	1.1	3.7	0.3	0.0	39.2

3.2. Water holding capacity

Soil water holding capacity (WHC) is a critical determinant of plant survival, growth, and overall ecosystem productivity, especially in water-limited environments [13]. Adequate WHC ensures consistent moisture availability for plant uptake and concurrently enhances nutrient retention by minimizing leaching losses [14]. The observed high evaporative water loss (18%) from the unamended quarry soil (Figure 3) underscores its inherent limitations in moisture retention, thereby necessitating the application of amendments to improve its hydrophysical properties and mitigate potential desiccation stress on establishing vegetation. Experimental findings indicate the potential of rice husks to enhance the WHC of quarry soil, a result corroborating the traditional knowledge of local farmers in Da Nang who utilize rice husks to improve soil structure. The porous architecture of rice husks likely increases the specific surface area and inter-aggregate pore space within the soil matrix, thereby facilitating both water infiltration and subsequent retention. Enhancing WHC through organic amendments such as rice husks contributes to the development of a more resilient soil environment, crucial for successful vegetation establishment and sustained growth in the challenging conditions of reclaimed quarry lands, complementing the broader requirements of holistic ecological restoration strategies that address soil nutrient content. Furthermore, the experimental results also reveal the potential of domestic sludge to enhance water retention when incorporated into the quarry soil, suggesting its potential as an additional amendment for improving the hydrophysical characteristics of the degraded substrate.

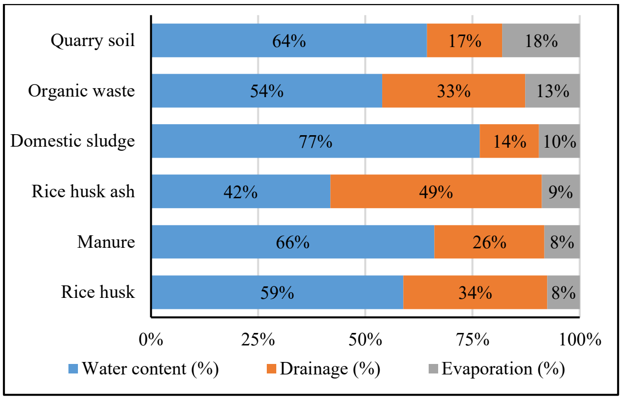

Figure 3. *Water holding capacity results*

3.3. AHP analysis

The pairwise comparison of criteria for selecting potential amendments, as illustrated in Figure 4, reveals the relative importance assigned by local farmers. The results indicate that soil nutrient content (C2), in conjunction with soil structure (C1), were identified as the key determinants for successful soil reclamation, followed by water retention capacity (C4). Notably, the cation exchange capacity (C5) and soil microbial activity (C3) were considered to be of lesser importance by the local farmers.

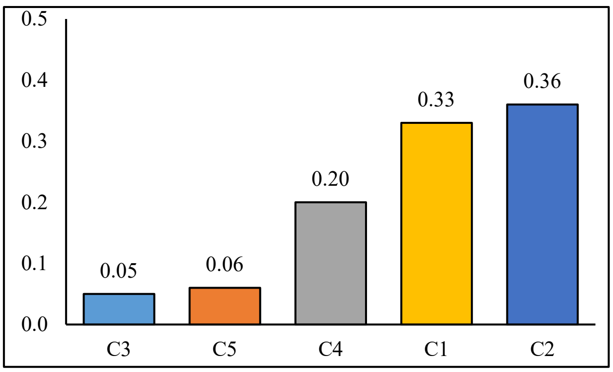

Figure 4. *Pairwise comparisons on criterias*

This reduced emphasis is attributed to their perceived dependence on inorganic fertilizer application in conventional cultivation practices within the region. This reliance on inorganic fertilizers highlights a potential issue in local agricultural awareness, as the long-term and excessive use of such fertilizers is a recognized driver of land degradation, a significant environmental concern impacting agricultural sustainability. The AHP analysis thus underscores the immediate practical concerns of local farmers regarding fundamental soil properties directly influencing crop yield under current management practices, while potentially underestimating the long-term ecological significance of cation exchange capacity and soil microbial activity for sustainable soil health and resilience. This discrepancy warrants further investigation and potential educational outreach to promote a more holistic understanding of soil quality parameters in the context of long-term agricultural sustainability and ecological restoration.

The pairwise comparison of criteria for selecting potential soil amendments, as presented in Figure 5, revealed the relative importance of each amendment for improving soil structure. Rice husk ash (A5) exhibited the highest comparative score, indicating its superior perceived potential for enhancing soil structural properties compared to the other evaluated amendments. This finding is further supported by the results presented in Figure 8, which demonstrate the significant role of rice husk ash in improving water retention capacity, a soil physical property closely linked to structural integrity.

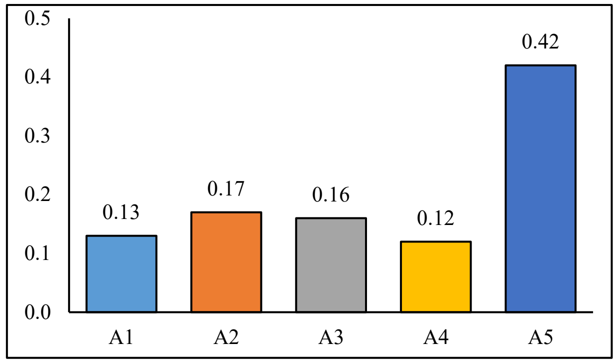

Figure 5. *Pairwise comparisons on soil structure (C1)*

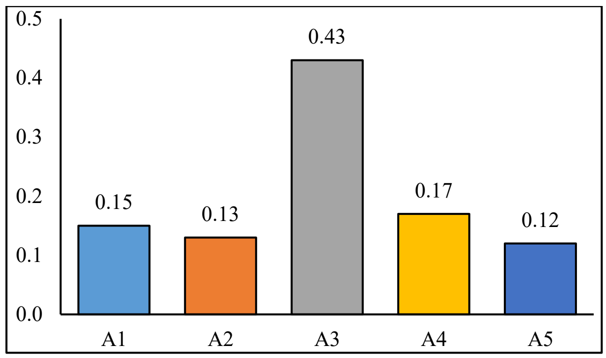

Figure 6. *Pairwise comparisons on soil nutrient (C2)*

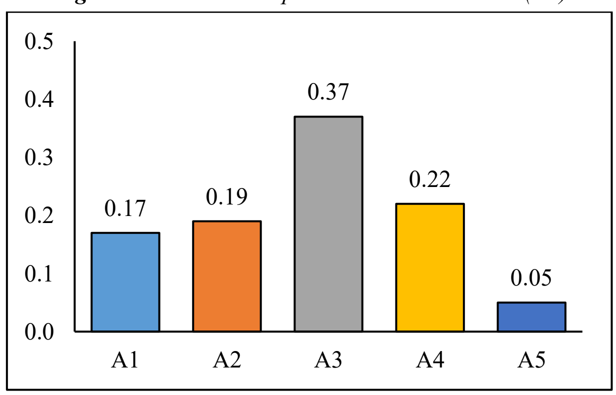

Figure 7. *Pairwise comparisons on microbial activity (C3)*

Conversely, livestock manure (A3) attained the highest scores in the pairwise comparisons for both soil nutrient content and soil microbial activity, as depicted in Figures 6 and 7, respectively. This suggests that local farmers recognize livestock manure as the most effective amendment for enriching soil nutrient status and fostering a beneficial soil microbial community, likely due to its inherent organic matter content and diverse microbial populations.

Regarding cation exchange capacity (CEC), the results of the pairwise comparisons revealed a notable lack of clear distinction among the amendments by the local farmers. This suggests that CEC is not a primary criterion considered in their assessment of amendment potential, possibly due to a less direct or immediately observable impact on crop yield compared to factors like soil structure and nutrient availability under their current management practices, as previously discussed. This lack of differentiation highlights a potential area where further education on the long-term benefits of enhanced CEC for nutrient retention and overall soil fertility could be beneficial for promoting sustainable soil management strategies. The limited discrimination among amendments for CEC underscores the prevailing focus on more immediate and tangible soil properties in local agricultural decision-making processes.

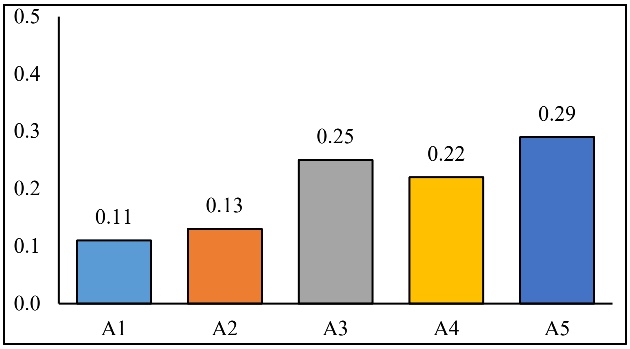

Figure 8. *Pairwise comparisons on water retention (C4)*

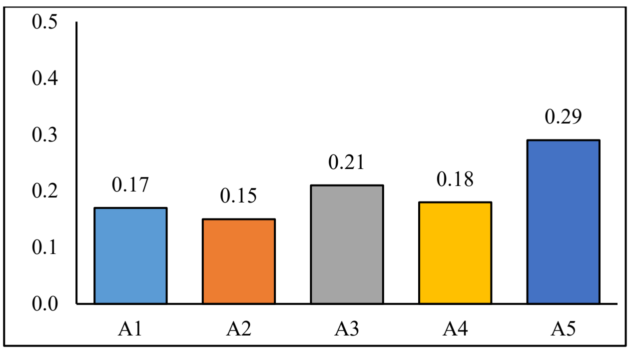

Figure 9. *Pairwise comparisons on cation exchange (C5)*

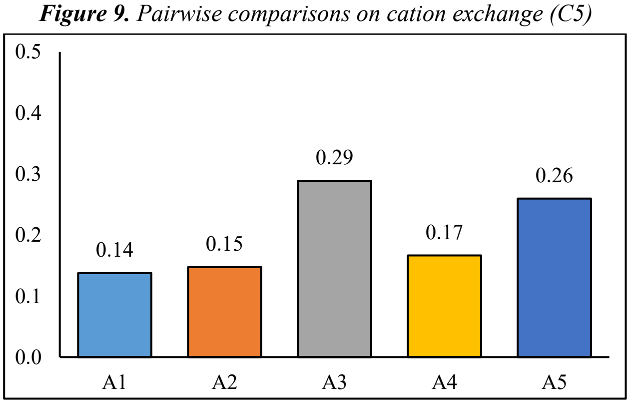

Figure 10. *Alternative's total score*

The Analytical Hierarchy Process analysis, the aggregated results of which are presented as total scores for each alternative amendment in Figure 10, reveals that livestock manure achieved the highest overall score (0.29), indicating its superior suitability for quarry land reclamation based on the weighted preferences of local farmers across all considered criteria. Rice husk ash followed as the second most preferred amendment with a total score of 0.26. The remaining amendments, namely rice husk (0.17), organic waste (0.15), and domestic sludge (0.14), exhibited similar and comparatively lower total scores. This ranking of amendments strongly aligns with the traditional knowledge and practical experience of local farmers in the Da Nang region. Their long-standing familiarity with the beneficial effects of livestock manure in enhancing soil fertility, structure, and water retention, often observed through generations of agricultural practice, likely contributed significantly to its high weighting in the AHP analysis. Similarly, the relatively high score for rice husk ash reflects the local farmers' experience with utilizing burnt crop residues, including rice husks, for improving soil structure and, as previously discussed, water holding capacity. The lower scores assigned to organic waste and domestic sludge may stem from less direct or less understood benefits within the context of their traditional cultivation practices, or potentially concerns regarding handling, availability, or perceived risks associated with these materials. The consistency between the AHP results and the local farmers' experiential knowledge underscores the significant influence of traditional agricultural practices and accumulated wisdom in their assessment of suitable soil amendments for land reclamation. This highlights the importance of incorporating local knowledge into scientific evaluations for context-specific and practically relevant solutions. While modern scientific analysis provides quantitative data on amendment properties, the AHP framework effectively captures the nuanced understanding and prioritized needs of the end-users, in this case, the local farming community, whose long-term success is intrinsically linked to effective land reclamation strategies. This synergy between scientific assessment and local expertise enhances the potential for the adoption and sustainability of the recommended reclamation practices.

4. Conclusion

This study demonstrates the significant potential of locally sourced organic waste amendments for the ecological restoration of quarry lands in Hoa Nhon village, Da Nang. Integrating local farmer knowledge through the Analytical Hierarchy Process (AHP) with laboratory experiments provided a multi-faceted approach. Baseline soil analysis revealed critical nutrient deficiencies and structural limitations, highlighting the urgent need for remediation. AHP modeling identified soil nutrient content as the paramount restoration criterion, with livestock manure perceived by farmers as the most promising single amendment. Experimental results corroborated these perceptions, showing rice husk ash effectively enhanced water retention, while livestock manure synergistically improved overall nutrient availability. These findings strongly advocate for the use of readily available organic wastes as a sustainable and cost-effective solution for quarry land reclamation. While AHP effectively incorporated local experiential knowledge, its inherent subjectivity and potential for inconsistencies with increased criteria/alternatives necessitate careful interpretation. Future research should prioritize long-term field trials and comprehensive economic feasibility analyses to facilitate practical, region-specific implementation of these promising reclamation strategies.

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