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Coffee Response to Liming in the Acid Soils of Tanzania: Pilot Study in Three Agro-ecological Zones

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Abstract A pilot study was undertaken to establish the response of Arabica and Robusta coffee to liming in the acid coffee soils of Tanzania, and its applicability to smallholder coffee farmers. It involved three field trials at Lyamungu (Hai) and Mbimba (Mbozi) for Arabica coffee, and Maruku (Bukoba) for Robusta. In each site, two side-by-side trials were laid out under Randomized Complete Block Design (RCBD), six treatments replicated three times. Random soil samples were taken and pH-water measured at 1:2.5 soil-water ratio. Lime requirement was determined using the barium chloride-triethanolamine titration method and regressed against the pH values. The ensuing linear trendline equations were used to calculate the standard lime requirements (LR), and treatments were assigned in the order 0.0LR, 0.25LR, 0.5LR, 0.75LR, 1.0LR and 1.5LR. Methods were top-dressing and incorporation to at least 10cm depth. Change in soil pH, growth characteristics and 3-year yield data were collected, rearranged to fit a split-plot design where methods were considered as sub-factors, and exposed to ANOVA and mean separation by Tukey's HSD method using CoStat software. The change in pH reflected the dosage of lime used. Dosages were highly significant in Mbimba, and very highly significant in Lyamungu and Maruku, showing an added advantage of liming. Mean yields increased in the order Robusta new (313-426 kg ha^{-1}) < Arabica new (988-1347 kg ha^{-1}) < Arabica superimposed (1252-1815 kg ha^{-1}). This study has unveiled the hitherto unrealized hurdles of lime application among smallholders; including complexities in lime requirement determination, availability and quality of liming materials, methods and uniformity of application. While research is underway to determine a simple but accurate LR determination method and explore the interaction between lime and phosphorus, mulch and manure/compost, smallholder coffee farmers should adopt a CAN/MRP regime rather than direct liming.

Keywords: *acid soils, coffee response, ecological zones, lime requirement, Tanzania*

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1. Introduction

The pH scale, ranging from 0 to 14, is used to indicate acidity and alkalinity. pH is a measure of the concentration of hydrogen ions in a solution. It is the negative logarithm of hydrogen ion concentration - negative because it is the reciprocal of the hydrogen concentration [H^+], and logarithmic because it varies by the *i*-th power of 10. Soil pH affects crops through its influence on chemical factors and biological processes [1]. It is an excellent chemical indicator of soil quality. Low pH induces P fixation and deficiency of major cationic nutrients, Fe and Al toxicity and a conducive environment for fusarium bark disease. Conversely, high pH induces micronutrient deficiency, salinity and/or sodicity. Most of the humid tropical soils, including the Acrisols, Alisols, Nitisols, Ferralsols, and even some Andosols have a tendency towards acidity [2]. Goulding [3] gave an account of soil acidification process, its cause and effect on soil health and crop production. Cordingley [4], in his work on smallholder coffee farms in four coffee zones of Tanzania, noted that 80% of the surveyed districts had minimum pH less than 5.5, and 40% less than 5.0. He noted a total of 18 districts which showed at least one location with pH <5.2. This observation was corroborated by the TaCRI Soil Database Project which showed low pH in 12 of the 23 districts surveyed.

Although planting crops tolerant of soil acidity is a reasonable option for dealing with acid soils, liming is traditionally used to correct soil acidity and to improve soil productivity [1,3]. Common liming materials are the oxides, hydroxides, carbonates, and silicates of Ca or Ca-Mg mixtures. The rates of lime application are usually based on lime requirement (LR), which is defined as the amount of liming material that must be applied to a soil to raise its pH from an initial acid condition to a level selected for near-optimum plant growth. Procedures for LR determination vary with location and soil conditions (particularly clay content, organic matter content and CEC). In the US alone, different methods are used in different states [1,5], whereby the mostly used method is the Shoemaker-McLean-Pratt (SMP) buffer technique [6,7]. Of about 7 different techniques, TaCRI has adopted the Barium Chloride – Triethanolamine direct titration method [8] for lime requirement determination due mainly to its simplicity. And because this is a laboratory method, the next step would be to verify it through field experimentation.

Many large coffee farmers and estate agronomists in acidic soils are familiar with liming, though they differ in the methods of lime estimation and mode of application. These two are key factors of lime effectiveness [9]. Liming is not common with smallholder coffee growers in Tanzania, and it appears as if [4] wanted to influence the adoption of the practice among the smallholders. It is therefore imperative to provide farmers with enough information on liming to ensure effective use of resources and environmental sustainability. The overall objective of this undertaking was to establish the response of Arabica and Robusta coffee to liming in the acid coffee soils of Tanzania, and explore factors governing its effectiveness, particularly among smallholders.

2. Materials and Methods

2.1. Study Areas

Field trials were established onstation at Lyamungu (Hai) and Mbimba (Mbozi) for Arabica coffee, and Maruku (Bukoba) for Robusta. Lyamungu lies approximately at Latitude 3°14'158" south and Longitude 37°14'463" east, with altitude 1305 metres above sea level (masl). It experiences a bimodal rainfall pattern with short rains extending from October to December, and the main rains from March to May. Total annual precipitation is 1679 mm. Soil is classified as Haplic Nitisol (Humic, Dystric) according to WRB [10]. Mbimba lies approximately at Latitude 9°05'245" south and Longitude 32°57'184" east, with altitude 1400 masl. It experiences a unimodal rainfall pattern with rains extending from November to May. Total annual precipitation is 1250 mm. The soil is classified as Haplic Alisol (Hyperdystric, Profondic). Maruku lies approximately at Latitude 1°24'527" south and Longitude 31°46'407" east, with altitude 1620 masl. It experiences a unimodal rainfall pattern with rains (>100mm) extending from October to May, and lesser rain from June to September. There is no defined dry spell with rainfall less than 50 mm. Total annual precipitation is 2040 mm. Soil is classified as Ferralic Cambisol (Humic, Vitric).

2.2. Experimental Design

In each of the three sites, two side-by-side trials were laid out, each one under Randomized Complete Block Design (RCBD), six treatments replicated three times. Random soil samples were taken from the trial fields and pH-water measured at 1:2.5 soil-water ratio. Lime requirement was determined using the barium chloride-triethanolamine method developed by [8] and suggested by [1]; and regressed against the pH values. Each location had its own trendline equation as shown below:

Lyamungu: LR = -147.75pH + 1422.6; $R^2 = 0.89$

Average pH was 4.8, so the standard LR became 713.4 ≈ 710 kg ha^{-1}

Mbimba: LR = -92.92pH + 1293; $R^2 = 0.77$

Average pH was 5.15, so the standard LR became 813.93 ≈ 814 kg ha^{-1}

Maruku: LR = -173pH + 1518.6; $R^2 = 0.89$

Average pH was 4.8, so the standard LR became 688.2 ≈ 690 kg ha^{-1}

The treatments were then 0LR, 0.25LR, 0.5LR, 0.75LR, 1.0LR and 1.5LR as shown in Table 1. In one of the two blocks, the material was topdressed (Method 1) while in the other it was incorporated into the soil to at least 10cm depth (Method 2). Plot size was 50 m^2 (12.5m x 4m), involving a total of 18 trees (6 x 3) uniformly treated, whereby the 4 middle trees were tagged as observational trees. At Lyamungu and Maruku, fresh trials were established while at Mbimba it was superimposed into existing coffee field of about 4 years' age. An old, pre-TaCRI stock of calcitic lime was used because lime is not a popular product in the retail farm input markets in the Northern Zone of Tanzania. With the exception of the lime, all other management routines were followed, including a blanket application of 150g $tree^{-1}$ of NPK 20:10:10.

2.3. Data Collection

Change in soil pH was monitored for Lyamungu only, and was recorded weekly for 8 weeks after treatment. It was not possible to monitor change in available P due to defects in the colour grating spectrophotometer. Data for growth characteristics (canopy size, tree height and stem girth) were also taken for Lyamungu only, to represent the rest of the trials. Cherry yield data per tree and per plot were collected from all the three sites and converted to cherry per ha and then to clean coffee per ha.

Table 1. Calculated lime dosages from the trendline equations

Lime	Lyamungu		Mbimba		Maruku	
Dosages	Kg per ha	Kg per plot	Kg per ha	Kg per plot	Kg per ha	Kg per plot
0LR	0	0	0	0	0	0
0.25LR	177.5	1.42	203.5	1.02	172.5	0.81
0.5LR	355	2.84	407	2.04	345	1.62
0.75LR	532.5	4.26	610.5	3.06	517.5	2.71
1.0LR	710	5.68	814	4.08	690	3.23
1.5LR	1065	8.52	1221	6.12	1035	4.85

2.4. Data Handling and Analysis

Data for plant characteristics (Lyamungu only) and yield (all three sites) were compiled on Excel Spreadsheet, rearranged to fit a split-plot design where method (topdressing and incorporation) could be considered as sub-treatments. They were later exposed to Analysis of Variability (ANOVA) according to the split plot model suggested by [11]; and means were separated by Tukey's HSD method using CoStat software Version 6.4.

3. Results and Discussion

3.1. Change in Soil pH

Change in average soil pH after treatment is shown in Figure 1. Whereas the untreated control steadied around 4.8-4.9, the treated areas experienced a slight drop during the first week, followed by a steady increase up to the third week, the attained pH level maintained thereafter. The change in pH reflected the dosage of lime used, with the highest level of 5.54 attained with the application of 1.065 tons of lime per ha (1.5LR). This observation is in line with [12] who did a meta-analysis of data accrued globally and concluded that the most important driver of change in pH is the liming dosages – higher dosages induce a greater change in pH.

3.2. Plant Characteristics

A summary of the ANOVA for plant characteristics is given in Table 2. None of the analyzed sources of variability showed any significant effect on the number of berry clusters, internode length or number of bearing branches. While dosages had no significant variation throughout ($p > 0.05$), blocks were surprisingly significant in tree height and stem girth, and highly significant in canopy width. Methods differed significantly in terms of canopy width ($p < 0.05$), highly significantly in terms of tree height ($p < 0.01$) and very highly significantly ($p < 0.001$) in terms of stem girth. Interactions were only significant ($p < 0.05$) in terms of tree height.

3.3. Average Yield of Clean Coffee in Three Years

A summary of the ANOVA for average yields is given in Table 3. Blocks were not significant in the freshly laid out trials of Lyamungu and Maruku, and was significant in the superimposed trial at Mbimba. Dosages were highly significant ($p < 0.01$) in Mbimba, and very highly significant ($p < 0.001$) in Lyamungu and Maruku. This shows an added advantage of liming in the study areas. Methods (whether topdressed or incorporated) were not significant in Lyamungu, but significant ($p < 0.05$) in Mbimba and Maruku. The interaction of dosage and methods did not show significance in any of the three sites. The split-plot model [11] was significant in Mbimba ($R^2 = 0.64$ and CV = 16.27%), highly significant in Maruku ($R^2 = 0.7$ and CV = 9.08%) and very highly significant in Lyamungu ($R^2 = 0.76$ and CV = 7.29%).

Mean yields did not follow any particular trend except that the untreated control was the last throughout. The highest dosages of 1221 kg ha^{-1} (Mbimba) and 1035 kg ha^{-1} (Maruku) had the first mean yield rankings of 1815 and 425 kg clean coffee respectively, whereas the highest dosage of 1065 kg at Lyamungu ranked third (1142 kg ha^{-1}). The first ranking went to the dosage of 532.5 kg of lime. The trend in Lyamungu and Mbimba (for Arabica) and Maruku (for Robusta) is shown in Table 4. This variation in trend indicates that different soils differ markedly in their response to liming. As for methods of application, incorporation performed better than topdressing in Mbimba and Maruku, while the reverse was true in Lyamungu. As regards interactions, the first three entries were 0.5LR incorporated > 1.5LR incorporated > 1.5LR topdressed (Maruku), 1.5LR incorporated > 1.5LR topdressed > 0.75LR incorporated (Mbimba) and 0.75LR incorporated > 0.75LR topdressed > 1.0LR topdressed (Lyamungu).

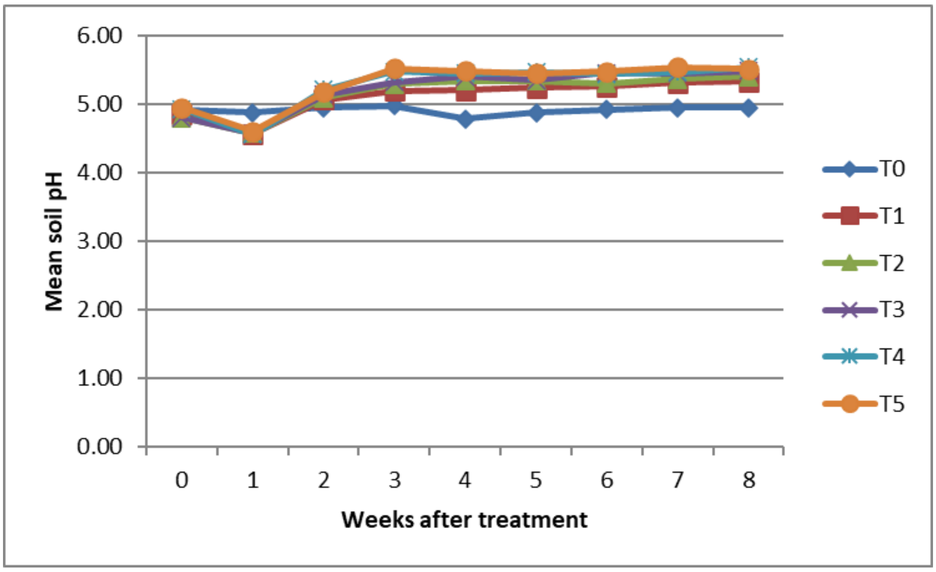

Figure 1. Change in soil pH attributed to liming, Lyamungu

Table 2. ANOVA summary for plant characteristics, Lyamungu

SV	p values					
	Berry cluster	Internode length	Bearing branches	Canopy width	Tree height	Stem girth
Replication	0.5537	0.7739	0.1434	0.0029**	0.0283*	0.0211*
Dosages	0.8855	0.8633	0.9618	0.8248	0.3873	0.7335
Methods	0.8088	0.1598	0.9598	0.0101*	0.0011**	0.0004***
Dos x Meth	0.3189	0.3925	0.5404	0.2868	0.0202*	0.4426

Table 3. ANOVA summary for 3-year mean yields

SV	p values		
	Lyamungu	Mbimba	Maruku
Block	0.0629 ns	0.0173*	0.9871 ns
Dosage	0.0000***	0.0075**	0.0002***
Method	0.6516 ns	0.0266*	0.0153*
Dosage x Method	0.6872 ns	0.6754 ns	0.7311 ns
Model	0.0003***	0.0100*	0.0023**
R^2	0.76	0.64	0.70
CV%	7.29	16.27	9.08

Table 4. Mean rankings for different treatments in the three sites

Site	Ranking	Mean name	Mean value	Significance
Lyamungu	1	0.75LR	1347	a
	2	1.0LR	1217	b
	3	1.5LR	1142	bc
	4	0.25LR	1090	c
	5	0.5LR	1072	c
	6	0.0LR	988	d
Mbimba	1	1.5LR	1815	a
	2	0.75LR	1577	ab
	3	0.5LR	1515	ab
	4	0.75LR	1392	bc
	5	1.0LR	1329	bc
	6	0.0LR	1252	c
Maruku	1	1.5LR	426	a
	2	0.5LR	416	a
	3	1.0LR	387	ab
	4	0.75LR	380	ab
	5	0.25LR	360	b
	6	0.0LR	313	c

Comparing the three trial sites in terms of their mean yields (Table 4), we note that the means ranged from 313-426 kg ha^{-1} (Robusta, new establishment), 988-1347 kg ha^{-1} (Arabica, new establishment) and 1252-1815 kg ha^{-1} (Arabica, superimposed). The variation between new establishments of Arabica and Robusta has no concrete explanation, and we are still probing as to whether the two species differ in time lag for attaining optimum yield. Other possible factors such as soil properties (depth, drainage, texture etc.) will also be assessed. At least the variation between newly established and superimposed sites can be explained in the sense that the Mbimba site took advantage of fully established coffee trees and optimal yield was realized since the first year.

3.4. Discussion

3.4.1. Variation in Al and Ca Saturation with Soil pH

According to [4], variation in aluminium and calcium saturation with soil pH is given in Figure 2. Looking at the top figure (Al saturation), it is clear that the points are more scattered in space at pH 5 and below, implying that, at those low levels, different soils vary in Al saturation, a situation that may be attributed to the soil properties known to affect LR determination, such as clay content, organic matter content and CEC. If blanket recommendations were to work, we would have expected a clear trend like the one shown in the bottom figure (Ca saturation). Cordingley [4] gave blanket recommendations of 200-300 g $tree^{-1}$ $year^{-1}$ of calcitic lime, alternated with 100-200 g $tree^{-1}$ $year^{-1}$ of dolomitic lime in Iringa, Mufindi, Njombe, Ludewa, Mbinga, Songea, Mbozi, Mbeya, Rungwe and Ileje (Southern zone), Muheza (Northern zone), Kibondo, Kasulu and Kigoma (Western zone). These blanket recommendations may be misleading due to the heterogeneity in soil properties as shown in Figure 2 top, thus calling for LR determination on individual farm basis.

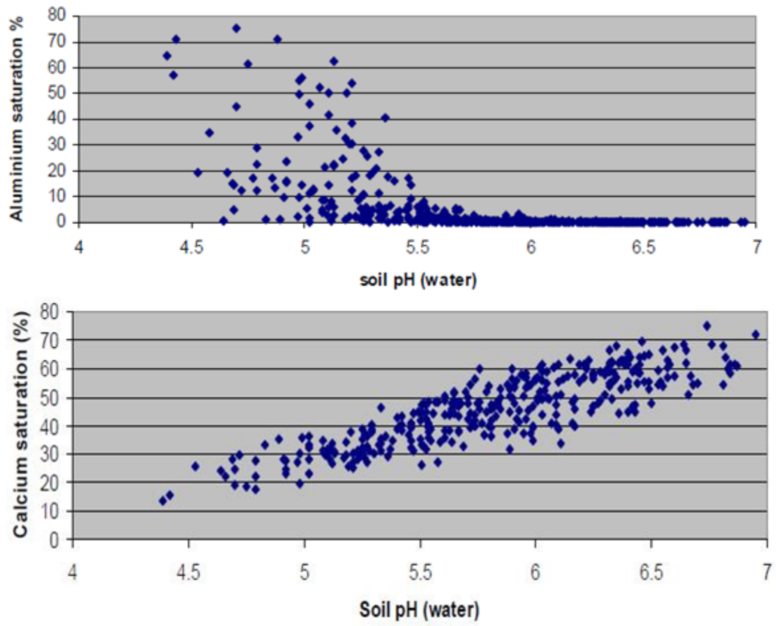

Figure 2. Variation of Al (top) and Ca (bottom) saturation with soil pH

3.4.2. Sensitivity of LR determination Techniques

It was noted by [5] that the determination of LR has no unique method applicable to all soils, and that clay content, CEC and organic matter content of the soil are the determinant factors [13]. According to [14], higher CEC implies higher LR for achieving a unit change in pH, and that the SMP buffer technique was designed to estimate the LR for soils of variable CEC. Studies that used SMP buffer technique like [15] and [16] came up with higher rates than those used in this work (a minimum of 2 tons of lime per ha). As the yields were still increasing at the maximum dosages in two of the three sites, we might assume that the dosages could be increased substantially in those areas without risking overliming. Espinosa [17] recommended SMP buffer method for temperate, 2:1 clay soils and explained why it is inappropriate for tropical red soils (Nitisols, Alisols, Lixisols and Ferralsols) and those from ash deposits (Andosols). He recommended methods that either use the exchangeable Al present in the topsoil, or the percent base saturation. Even though the Barium chloride-triethanolamine titration method [8], which appears to be a blend of the two, had been tested in four contrasting zones growing coffee in Tanzania, not much attention was given to other properties like CEC, OC and texture. So, it could be by chance that the selected areas happened to be alike in some of these properties during the calibration of methods and somehow differed in actual use. Other methods in use include the Adams-Evans buffer method [18], Mehlich buffer method [19], Woodruff buffer method [20], $CaCO_3$ incubation method [1,21], $Ca(OH)_2$ titration method [22] and indirect method from soil properties [23]. We therefore need to re-calibrate the LR determination methods for the soils of Tanzania by screening all these methods for applicability and reliability, like in [24].

3.4.3. Availability and Quality of Lime

Another area of interest is the availability and quality of lime. Liming is not common with smallholders in Tanzania because, as [3] put it, rates and timing of lime application depends on the economies of the farmer. It was one objective of [4], to inspire smallholder coffee farmers to use lime in their farms. Even then, lime materials are not common with retail farm input stockists. That’s why we had to use an old, pre-TaCRI stock of calcitic lime, whose purity had not been checked beforehand. Factors affecting the quality of lime and, impliedly, its effectiveness, have been itemized by [9]. The first one is solubility. Since agricultural lime is in its primary mineral form (usually calcite or dolomite or some mixture of the two), calcium or magnesium solubility is relatively low. This means that some time lag after spreading will be required for dissolution of enough calcium and/or magnesium to materially change soil pH. This phenomenon may explain the slight drop in soil pH during the first week of application (Figure 1) as also noted by [25]. It implies that planning ahead is an important consideration in the timing of lime application. Other factors are fineness (the finer the lime, the faster it dissolves) and purity (measured as % calcium carbonate equivalent – CCE).

3.4.4. Effects of the Application Modes

In this work we included the application methods (topdressing versus incorporation) as one of the factors because many literatures including [26,27,28] prefer incorporation, while most estates in Tanzania prefer topdressing. It is noted by [9] that, as lime dissolves in soil, the soluble calcium and/or magnesium does not move very far from its point of dissolution until it reacts with other soluble components or with the cation exchange complex of the soil. The net result is that it doesn't move downward through the soil very fast. Thus, if pH of the plough layer needs adjusting, a surface application of lime will not change the pH of the plough layer below the soil surface very rapidly. They recommended incorporation to a depth of 15 cm with tillage equipment, as also observed by [16]. Even though mean yields were higher with incorporation in two of the three sites, the difference was not significant, and this could be attributed to uniformity, both horizontal and vertical. As topdressing was done by hand, and finally incorporation in due plots was done manually with a hand-hoe, lack of uniformity may have affected the results.

3.4.5. Contrasting Schools of thought about Liming

Rothwell *et al* [29] applied recommended liming rates to a sandy loam soil (increasing soil pH from 5.5 to 6.2) and observed a decreased pod yield of field bean (*Vicia faba* L. cv. Fuego) by ~30%. Subsequent pot trials, with liming that raised soil pH to 6.3–6.7, reduced stomatal conductance by 63, 26, and 59% in *V. faba*, bean (*Phaseolus vulgaris*), and pea (*Pisum sativum*), respectively. Furthermore, liming reduced shoot dry biomass by 16–24% in these species. Ionomic analysis of root xylem sap and leaf tissue revealed a decrease in phosphorus concentration that was correlated with decreased stomatal conductance: both reductions were partially reversed by adding superphosphate fertilizer. Further analysis of pea suggests that leaf gas exchange was reduced by a systemic increase (roots, xylem sap, and leaves) in the phytohormone abscisic acid (ABA) in response to lime-induced suboptimal plant phosphorus concentrations. This research describes physiologically how lime application can limit crop yields, and questions the suitability of current liming recommendations.

The relationship of liming and phosphorus application was also noted by [15] who tested various dosages of lime with and without application of P fertilizers and concluded that lime application at a low rate, combined with moderate amounts of P is appropriate for maize production in acid soils. Another important combination is between liming and organic matter application. It was argued by [30] that lime application with compost and/or manure improves is positive effect on crop yields. With special reference to Arabica coffee in Rwanda, [31] evaluated lime effect on nutrient availability and cherry yield of Arabica coffee grown on acid soils using two lime treatments (0 and 1.25 t ha^{-1} $Ca(OH)_2$) applied under eragrostis mulched and non-mulched conditions. Lime increased soil pH and decreased aluminium saturation and enhanced nutrient availability. Moreover, interaction lime-mulch led to higher N content in the soil (0.19%) and higher cherry yield (8.5t ha^{-1}) compared to the control (3.8 t ha^{-1}). They recommended application of lime in mulched coffee to improve nutrient availability and coffee yield on acid soils.

3.4.6. Other Options Available to Smallholders

It is well established [32,33,34,35] that the wide pH range for Robusta is 4.5-7.0 while the narrow range for Arabica is 5.2-6.5. Maro and Mbwambo [36], considering the information given by [4], refrained from giving direct recommendation on liming, especially with smallholders. They recommended, where a substantial number of sites (4 or more) have pH between 4.5 and 5.5, routine application of CAN. Fertilizer grade CAN contains roughly 11-15% CaO and 26% nitrogen. It is preferred for use on acid soils, as it has an alkalinizing effect. Dissolved in water, CAN dissociates into its respective cations Ca^{2+} and NH_4^+ and anion NO_3^-. NH_4^+ and NO_3^- are taken up by plant roots leaving behind the Ca^{2+} which reacts with the OH of water to form $Ca(OH)_2$ which is alkaline and therefore raises the pH of soil solution [37]. Another option is the use of Minjingu Rock Phosphate (MRP), which has 38-40% CaO. In addition to several positive attributes cited by [38,39,40,41], it was recommended by [42] as a liming material in acid soils, and appears to have gained a substantial market in Western Kenya.

4. Conclusion

This pilot undertaking aimed to establish the response of Arabica and Robusta coffee to liming in the acid coffee soils of Tanzania and explore its usability among smallholder coffee growers. An added advantage of liming was noted, of varying significance levels, in the study areas. Several hitherto unrealized research gaps were unveiled in devising liming programmes with smallholders. While there is no generic procedure for estimating lime requirement for all acid soils of coffee in the country, many such procedures require background knowledge of a number of soil parameters like CEC, OC, available P and texture, which will be taken on board during future researches. Another concern is the availability of standard liming materials of required purity and fineness – currently liming is done by estates which can outsource lime from their countries of origin for their use only, so liming materials are not common items in retail shops. We therefore need to collaborate with other stakeholders with the aim to establish a reliable source in East Africa, where a certain amount for research purposes can be procured. As follow-up activities, we envisage a re-run of the trials using up-to-date, certified liming material with and without added P, mulch and manure/compost. Before a more thorough information about small-scale liming is available, we do not recommend it for smallholders. Instead, they should monitor their pH regularly and apply CAN routinely at fruit setting if it is between 5.0 and 5.5; and an additional dose of 50g $tree^{-1}$ of MRP at onset of season if pH <5.0 or if there is an imminent threat of fusarium bark disease.

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Statement of Competing Interests

The authors wish to declare no competing interests in this work.

Abbreviations

Acronym	Long form
ABA	Abscisic acid

ANOVA	Analysis of variance
CAN	Calcium ammonium nitrate fertilizer
CCE	Calcium carbonate equivalent
CEC	Cation exchange capacity of a soil
CV	Coefficient of variability
HSD	Honestly significant difference (a method of mean separation)
IUSS	International Union of Soil Sciences
LR	Lime requirement
MRP	Minjingu rock phosphate
NPK	Nitrogen, phosphorus and potassium compound fertilizer
OC	Organic carbon (a measure of soil organic matter)
pH	Measure of acidity or alkalinity in a solution
RCBD	Randomized complete block design (of an experiment)
SMP	“Shoemaker-McLean-Pratt” method of LR determination
TaCRI	Tanzania Coffee Research Institute
WRB	World reference base for soil resources

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