Agronomic Performance of Enhanced Rock Weathering in a Tropical Smallholder System: A Maize Trial in Kenya

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Abstract

Enhanced Rock Weathering (ERW) is a promising negative emission technology that can simultaneously sequester atmospheric CO_2 and improve agricultural productivity. While its efficacy has been demonstrated in temperate climates, a critical knowledge gap exists regarding its application within the complex, low-input smallholder farming systems of sub-Saharan Africa. This study investigates the agronomic impacts of applying a locally sourced volcanic rock powder (nephelinite) on smallholder farms in Kisumu County, Kenya. The trial was conducted with 56 women smallholder maize farmers, with each farm divided into a control plot and a treatment plot. A single application of the rock powder (20 t/ha) was applied at the start of the trial. This resulted in an average maize yield increase of 71.17% in the first year compared to control plots (2159 kg/ha control, 3184 kg/ha treatment). This significant yield benefit was sustained and amplified in the second year, with the average increase growing to 79.24% without any further rock dust application (2540.5 kg/ha control, 4366.5 kg/ha treatment).

Post-harvest soil analysis provided strong indication for weathering; while the net change in soil pH between treatment and control plots was not statistically significant, treated plots showed a positive trend toward pH improvement. A similar positive trend was also observed for the soil's cation exchange capacity. The impacts on micronutrients were complex and site-specific: the amendment acted as a direct source of iron in one cluster, increasing its availability by 14.8% ($p < 0.05$), while dynamics of manganese, zinc, and copper were primarily driven by environmental factors like seasonal flooding and crop uptake. While the soil data presented here is inconclusive regarding possible modes of action, the yield results clearly demonstrate ERW's ability to deliver substantial agronomic benefits in smallholder farming. Further research will be required to test its effects in a wider range of cropping systems and pedoclimatic conditions.

Introduction

Limiting global warming to below the 2°C target stipulated by the Paris Agreement requires the large-scale deployment of negative emission technologies capable of removing historical atmospheric carbon dioxide (CO_2) (Masson-Delmotte et al., 2021). There is no single solution for all emissions sources, Pacala and Socolow (2004) proposed the concept of "stabilization wedges." In this model, a "wedge" represents an individual mitigation strategy sized to achieve an emissions reduction of 3.67 Gt of CO_2 equivalent per year by 2054. While many original wedges focused on preventing future emissions, achieving climate goals now also requires a portfolio of negative emission technologies capable of removing historical atmospheric CO_2 (Haque et al., 2019; Masson-Delmotte et al., 2021). Enhanced Rock Weathering (ERW) has emerged as a particularly promising Carbon Dioxide Removal (CDR) approach that could constitute its own powerful stabilization wedge.

The strategy involves accelerating the natural geochemical weathering process by mining, crushing, and applying fine-grained silicate rocks, such as basalt, to managed ecosystems like agricultural soils. The core chemical process begins when atmospheric carbon dioxide (CO_2) dissolves in soil water, forming a weak carbonic acid. This natural acid then reacts with the applied silicate rock powder, accelerating the rock's natural weathering. This reaction has two crucial and simultaneous outcomes. First, it breaks down the mineral structure of the rock, releasing essential plant nutrient cations—such as calcium, magnesium, and potassium—into the soil where they become available for crop uptake. Second, the carbon from the original CO_2 molecule is transformed into a stable, water-soluble form known as bicarbonate (Hangx and Spiers, 2009; Washbourne et al., 2015). These bicarbonate ions are transported to the ocean, where they are stored for geological timescales (>10,000 years) (Beerling, 2017).

Beyond its climate mitigation potential, ERW can deliver significant agronomic co-benefits, creating a rare win-win scenario for climate action and food security. The dissolution of silicate rocks releases a suite of essential plant macronutrients (e.g., calcium, magnesium, potassium, phosphorus) and micronutrients (e.g., iron, manganese, zinc) in a slow-release manner, functioning as a multi-nutrient rock fertilizer (Manning and Theodoro, 2020). Furthermore, the consumption of acidity during weathering provides a liming effect, raising soil pH. This can be crucial for improving overall soil health, as it enhances the availability of pH-sensitive nutrients like phosphorus and can alleviate the toxicity of elements like aluminum and manganese in acidic soils (Swoboda et al., 2022). These benefits are particularly relevant for the world's smallholder farmers, who constitute over 80% of all farmers and are central to global food production. These farmers often cultivate on marginal, nutrient-poor lands where access to conventional synthetic fertilizers and liming agents is severely limited by competitive costs and fragmented supply chains (Lowder et al., 2016; Samberg et al., 2016).

Sub-Saharan Africa (SSA) represents a critical and high-potential region for ERW deployment. The region's predominantly warm and humid climate provides ideal kinetic conditions for accelerated weathering reactions, while abundant resources of suitable rocks across the continent offer vast potential for carbon sequestration at scale (Boudinot et al., 2023). This potential aligns with a pressing need. Many of the region's agricultural soils are highly weathered, acidic, and severely depleted of nutrients after decades of intensive cultivation without adequate replenishment, leading to a cycle of low productivity, land degradation, and widespread food insecurity (Giller et al., 2021). While a growing body of literature has demonstrated the efficacy of ERW in controlled laboratory settings and temperate field trials in the Global North (Haque et al., 2020; Skov et al., 2024), or in well-managed tropical plantation systems (Larkin et al., 2022), these findings are not directly transferable. There remains a notable lack of research on ERW's efficacy within the complex, low-input, and diverse biophysical and socio-economic conditions of smallholder farming systems in Africa.

This study aims to address this critical knowledge gap. The novelty of our research lies in its specific context and approach: it is one of the first trials to evaluate ERW within the real-world operational environment of women-led smallholder maize farms in Western Kenya, using a locally sourced volcanic rock powder. This participatory approach, conducted in partnership with farmers, ensuring the rock powder intervention was integrated into existing practices to assess its practical feasibility and potential for adoption. Lastly, unlike most initial trials, we report on two consecutive growing seasons, providing crucial insights into not only the immediate impacts but also the persistence of the agronomic benefits.

We hypothesized that a single application of silicate rock powder would increase maize yields and improve key soil health indicators within a single growing season. The primary objectives of this study were to a) quantify the effect of the rock powder application on maize grain yield compared to control plots over two consecutive seasons; b) assess the impact on key soil chemical properties- soil pH, cation exchange capacity, phosphorus, total nitrogen, total organic carbon, and micronutrients (manganese, iron, zinc, and copper); c) provide a preliminary field-based evaluation of ERW as a viable soil amendment for enhancing crop productivity in a representative African smallholder farming system. This paper reports on the preliminary yield results from the first growing season and the subsequent post-harvest soil analysis, providing foundational data for the potential of ERW in this priority region, as well as the second growing season.

2. Methodology

2.1. Study Site and Participant Onboarding

The study was conducted in two community clusters, Ombeyi and Wawidhi wards, in Kisumu County, Kenya (0.0934° S, 34.7623° E), a region characterized by a tropical climate and geology associated with the East African Rift System (Figure 1). Positioned along the equator, the region experiences warm daytime temperatures (~28°C on average) and substantial precipitation (~1900 mm) year-round, with most rainfall occurring during the two wet seasons from March-May (~230 mm/month) and October-December (~210 mm/month). The tropical climate conditions support robust agricultural activity at the commercial and smallholder scales, with Kisumu County serving as a major producer of sugarcane, cassava, and rice in the region.

A community-based participatory approach was used for farmer engagement, beginning with stakeholder meetings at the county level, followed by engagement with local community leaders to ensure community buy-in and trust. During the community meetings, over 100 farmers volunteered to be part of the trial. 56 farmers were selected, using a minimum field size of 0.05 ha as the main criterion to guarantee sufficient space for the experiment.

Each farm was divided into two adjacent plots with a shared land-use history: a control plot and a treatment plot (termed the 'Application' plot). To ensure accuracy, the "Fields Area Mapper" app (Figure S2) was used to map each plot's boundaries.

A unique identification system was created for each plot. The ID begins with a prefix for the cluster (KO for Ombeyi, KW for Wawidhi), followed by the farm's number, and ends with a letter for the plot type (C for Control, A for Application). For example, the ID KW21A refers to the application plot on farm number 21 in the Wawidhi cluster.

Throughout the course of the single growing season, a number of participants withdrew or were lost from the study due to a variety of factors, including logistical challenges, unforeseen environmental events, and participant-led decisions. Consequently, the complete dataset for harvest and soil analysis was collected from a final sample of 31 farms. A detailed breakdown of participant attrition and the specific reasons for the loss of farms at each stage of the trial are provided in the Results section (Section 3.1).

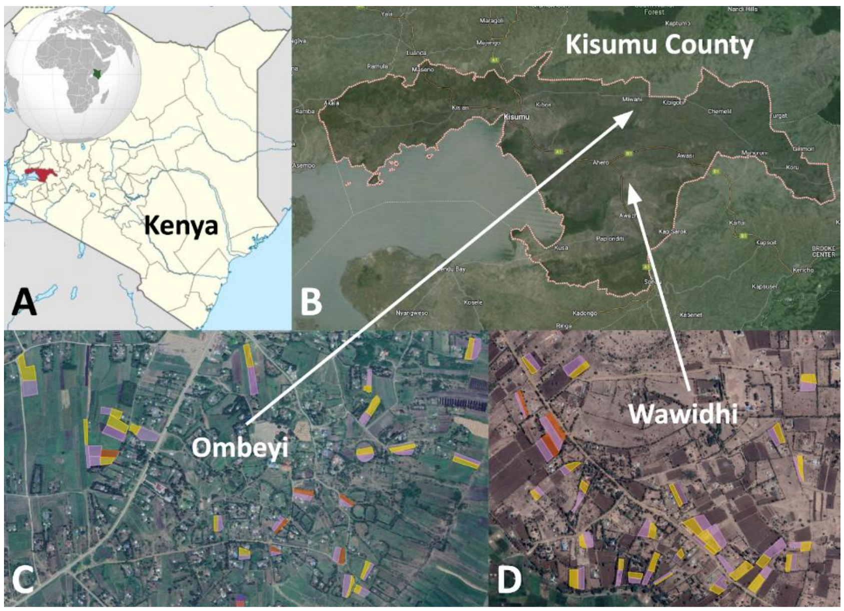


Figure 1. Study area. A) Map of Kenya in eastern Africa. Red shows the location of Kisumu County in western Kenya. B) Kisumu County outlined by the red dotted line. C) Ombeyi cluster with control and application plots shown by the coloured polygons. D) Same as C but for the Wawidhi cluster. Refer to Figure S1 (Supplementary material) for detailed deployment map for Wawidhi and Ombeyi cluster.

2.2. Field Trial Procedures

The trial was conducted from January to August 2024. On each participating farm, the selected field was divided into two adjacent sub-plots of at least 0.05 ha each: a control plot and a treatment plot (Figure 1 C and D). The control plot was managed according to the farmer's standard practices. In addition to standard management, the treatment plot received a one-time application of volcanic rock powder at a rate of 20 tonnes per hectare. The material used had a particle size of 0-4 mm, which was selected for its logistical feasibility and ready availability from the quarry.

Throughout the trial, personal health and safety were paramount. To mitigate risks associated with heavy machinery, strict safety protocols were implemented. Only trained operators, equipped with high-visibility gear and protective equipment, were allowed to operate the tractor and spreader. Regular maintenance ensured the machinery's safe operation. Dust inhalation was a potential concern. Exposure was minimized by restricting access to deployment areas during windy conditions, providing dust masks to all personnel, and conducting regular safety briefings.

The rock powder was applied between the first and second ploughing to ensure it was incorporated into the top ~30 cm of soil. Application was performed using a combination of mechanical and manual methods: a local contractor used a twin-disc spreader for mechanical application, while teams of farmers used buckets for manual spreading. No other inputs, such as synthetic fertilizers, were provided or directed by the study. However, it was noted that approximately 50% of farmers applied unquantified amounts of local livestock manure to both their control and treatment plots as part of their routine.

2.3. Feedstock Characterization

Sourcing and Geological Context

The feedstock was a nephelinite rock powder sourced as a quarry by-product from Homa Bay County, Kenya, approximately 110 km from the field sites. This location is within the East African Rift System, a region characterized by silica-undersaturated mafic volcanism. This geology yields rock types rich in fast-weathering silicate minerals containing calcium, magnesium, and sodium, making them theoretically well-suited for ERW.

Chemical Properties

The mineralogical and geochemical composition was determined using X-ray diffraction (XRD) and X-ray fluorescence (XRF), respectively (Table 1). The powder was predominantly composed of augite (47.8%) and nepheline (17.2%), with minor phases including magnetite and monticellite. Geochemically, the rock was rich in key base cations, with a composition of 16.96% CaO and 8.26% MgO. Based on this composition, the feedstock has a theoretical gross CO_2 sequestration potential of 0.50 tonnes of CO_2 per tonne of rock (Table 2). The silicate rock powder was analysed for heavy metal content using both ICP-MS for comparison with regulatory standards for soil and fertiliser. To date, Kenya has not established national standards for potentially toxic elements in agricultural soils or inorganic soil improvers. We therefore deferred to maximum permissible soil limits set by the World Health Organization (WHO) and Food and Agriculture Organization (FAO), and to the European Union (EU) for inorganic fertilisers. Data from this exercise are displayed in Table 3. Heavy metal concentrations for the feedstock used in this study are less than the WHO/FAO permissible limits for soils with the exception of Co, Cr, Cu, and Ni. However, metal content is below the maximum limits for As, Cd, Cu, Ni, Pb, Zn as established by the EU for inorganic fertilisers. We estimate based on the Cr and Ni content of this feedstock that several hundred applications at a rate of 20 tonnes per hectare would be required to attain soil concentrations that exceed the WHO/FAO permissible limits, which suggests that this feedstock is safe for use in ERW field trials.

Table 1. Main phases of feedstock mineralogy as determined by XRD.

Mineralogy	Chemical composition	Composition %
Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	47.8
Nepheline	$(Na,K)AlSiO_4$	17.2
Magnetite	Fe_3O_4	12.8
Monticellite	CaMgSiO4	6.4
Akermanite - Alumoakermanite	$Ca_2Mg[Si_2O_7]$-$(Ca,Na)_2(Al,Mg,Fe^{2+})[Si_2O_7]$	3.2
Montmorillonite	$(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$	3.1
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	2
Tobermorite	$Ca_5Si_6O_{16}(OH)_2 \cdot 4H_2O$ or $Ca_5Si_6O_{17} \cdot 5H_2O$	1.9
Perovskite	$CaTiO_3$	1.4
Sodalite	$Na_8(Al_6Si_6O_{24})Cl_2$	1.4
Illite-Smectite (mixed layer)	(K, H_3O) $(Al, Mg, Fe)_2$ $(Si, Al)_4O_{10}[(OH)_2, (H_2O)]$	1.2
Natrolite	$Na_2Al_2Si_3O_{10} \bullet 2(H_2O)$	1
Talc	$Mg_3Si_4O_{10}(OH)_2$	0.5
Kaolinite	$Al_2Si_2O_5(OH)_4$	0.2

Table 2. Major element composition of the feedstock material as determined via XRF, as well as LOI, Total C, and Total S.

Oxide	Composition %
SiO_2	39.14
CaO	16.96
Fe_2O_3	16.38
MgO	8.26
Al_2O_3	8.21
Na_2O	3.4
TiO_2	3.25
K_2O	1.7
P_2O_5	0.86

MnO	0.21
Sr	0.126
SO_3	0.081
Ba	0.06
Cr_2O_3	0.01
TOT/C	0.1
TOT/S	0.05
LOI	1.3
Total	100.1

Table 3. Trace element concentrations in feedstock determined by ICP-MS.

Element	**EU limits for fertiliser** (EU, 2019) **(mg/kg)**	**Feedstock content (this study) (mg/kg)**
As	40	<1
Cd	1.5	<0.1
Co	—	53.5
Cr	—	65
Cu	300	127.4
Mn	—	1554
Ni	100	67.1
Pb	120	11.9
Se	—	<1
Zn	800	115

2.4. Soil Sampling and Analysis

Soil Sampling Protocol

Soil sampling was conducted at two points: a baseline collection prior to rock application and planting (January 2024) and a second-round post-harvest (January 2025), with one mixed sample taken per control and per treatment plot. For each plot (both control and treatment), a composite sample was created from 10-15 soil cores. As part of the study's participatory approach, these samples were collected by community members using a jembe (a common hand hoe). The cores were taken at 5-meter intervals in a 'W' pattern across the plots to ensure a random and representative sample from a depth of 0-30 cm. This process resulted in a total of 112 initial soil samples.

Soil Analysis

Samples were sent to the Kenya Agriculture and Livestock Research Organisation (KALRO) for the determination of texture classification, soil pH, organic carbon and nitrogen content, and major and trace elemental composition. The specific standard analytical protocols used are detailed in Table 4.

Baseline Soil Characteristics

According to available soil maps (RCMRD, 2023), the study region is dominated by haplic xerosols and pellic vertisols. More specifically, the Ombeyi cluster contains haplic, partially sodic, and calcaro-cambic xerosols, while the Wawidhi cluster is dominated by pellic and vertic vertisols and gleysols.

The baseline analysis of the collected samples confirmed a predominantly clay soil texture across the majority of farms. In the Wawidhi cluster, 90% of farms have a clay texture, 7% are silt clay, and 3% are silt clay loam. In the Ombeyi cluster, 90.5% of farms have a clay texture, with the remainder classified as silt clay. The low exchangeable sodium percentages in the topsoil (~0.51% in Wawidhi and ~0.46% in Ombeyi) indicate that the particular plots used in the study are not affected by sodification. A full summary of the baseline soil properties is presented in Table 4.

Table 4. Characterization of soil. Error represents 1 SE.

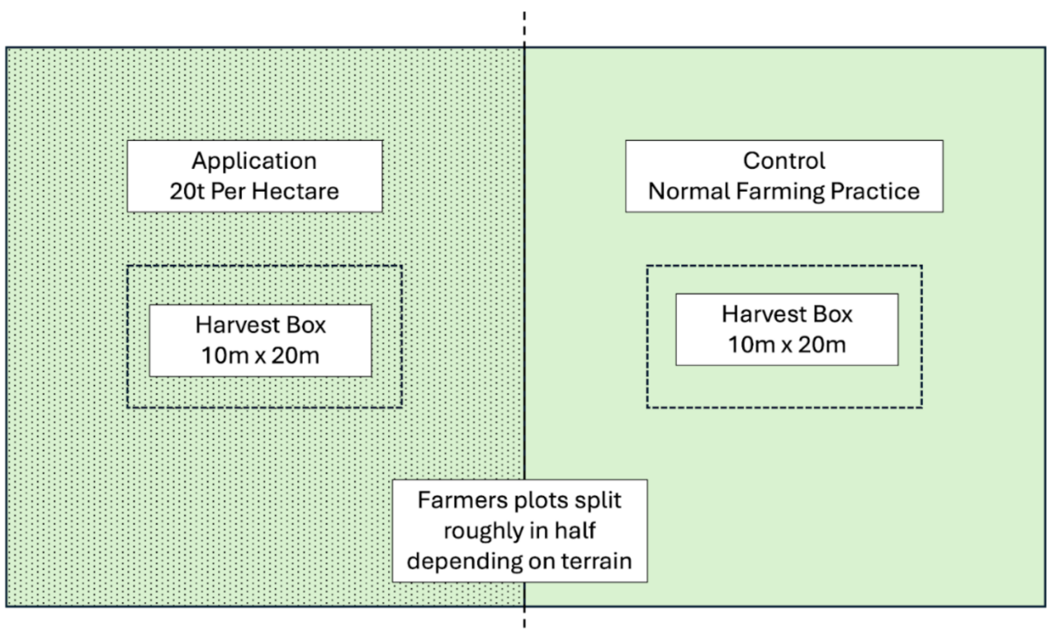
Parameter	Method	Wawidhi Cluster	Ombeyi Cluster
Soil Texture	Hydrometer method	Clay	Clay
Sand (%)		20.7 ± 1.5	37.0 ± 1.4
Silt (%)		28.3 ± 1.8	13.9 ± 1.0
Clay (%)		51.0 ± 1.1	49.1 ± 2.1
Soil pH	pH meter on 1:1 water:soil slurry	6.51 ± 0.07	6.81 ± 0.09
Total Nitrogen (%)	Kjeldahl method	0.15 ± 0.1	0.25 ± 0.01
Total Organic Carbon (%)	Walkley-Black method	1.53 ± 0.06	2.55 ± 0.12
Phosphorus (ppm)	Mehlich I extraction	28.20 ± 0.71	31.97 ± 7.23
Copper (ppm)	0.1M HCl extraction	1.24 ± 0.1	1.05 ± 0.14
Iron (ppm)		98.92 ± 4.06	37.03 ± 4.65
Zinc (ppm)		5.14 ± 0.34	3.60 ± 0.37
Potassium (meq/100g)	1N Ammonium Acetate at pH 7, Ethanol, 1N KCl at pH 7	1.36 ± 0.06	1.05 ± 0.07
Calcium (meq/100g)		13.91 ± 0.83	35.09 ± 3.94
Magnesium (meq/100g)		3.41 ± 0.04	3.75 ± 0.06
Manganese (meq/100g)		0.60 ± 0.03	0.30 ± 0.03

Sodium (meq/100g)		0.51 ± 0.04	0.46 ± 0.04
Cation Exchange Capacity (meq/100g)		32.2 ± 1.12	50.34 ± 2.84

2.5. Maize Analysis

Harvest and yield data were collected in July-August 2024 (first season, referred to as Year 1) and in July-August 2025 (second season, referred to as Year 2). To ensure a representative and comparable measurement of crop yield, a standardized sampling area, hereafter referred to as the 'Harvest Box,' was delineated within each plot (Figure 4). Each Harvest Box measured 10 m x 20 m (0.02 ha) and was strategically positioned to encompass the observed variability within the plot while avoiding field edges prone to disturbances from footpaths or livestock. At maturity, all maize plants inside this box were manually harvested. The cobs from each Harvest Box were then collected and weighed, and this total weight was recorded as the final plot yield, expressed in kilograms per 0.02 hectares (kg/0.02 ha).

In addition, cob length (cm) and the number of kernels per cob were determined on a subsample of 20 cobs per field. The number of kernels was estimated for each cob by counting the number of rows and multiplying by the number of kernels in a representative row. The total weight from the Harvest Box served as the primary yield metric for this study, while the cob length and kernel estimations provided supporting data on agronomic performance from a representative subsample.



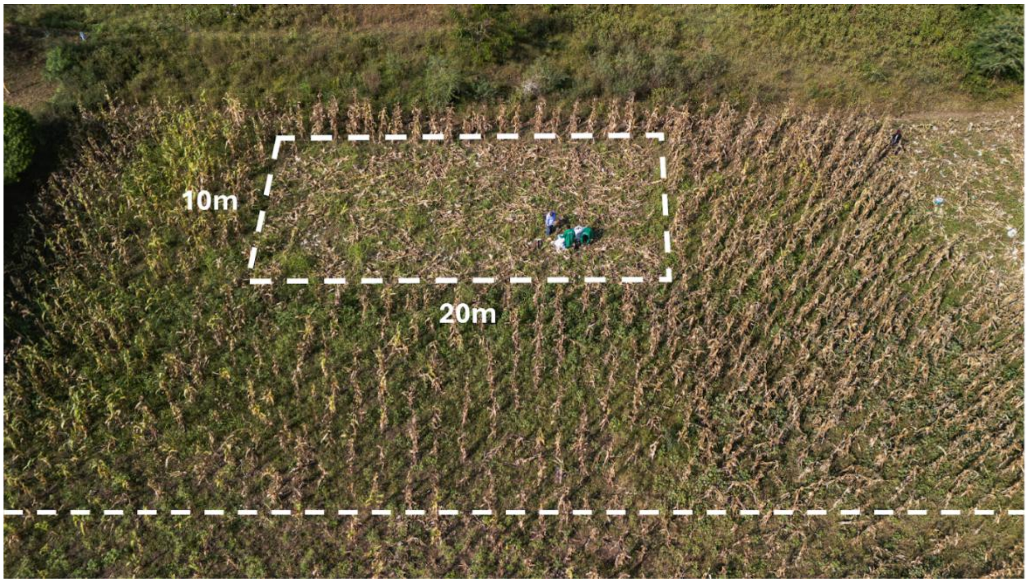


Figure 2. Diagram of harvest analysis collection protocol (Top). An overhead photo of a harvest box being implemented in the field (Bottom).

2.6. Statistical Analysis

Yield changes were calculated for each farm and reported as both an Average Yield Change (the mean of individual farm percentage changes, reflecting field-specific variability) and an Aggregate Yield Change (the percentage change between the average yield of all treatment plots and all control plots, reflecting the overall intervention effect). Soil data were analyzed by comparing initial and final measurements within plots. Statistical significance of changes was determined using paired t-tests, with a significance level of $p < 0.05$.

3. Results and Discussion

3.1. Participant Attrition

Of the 56 farms initially enrolled in the trial, a total of 25 were lost at various stages of the study. Consequently, the final analysis was conducted on a complete dataset from 31 farms located in the Wawidhi and Ombeyi clusters. The specific reasons for this attrition are summarized in Table 5 and detailed below:

Social and Participatory Constraints

Seven farmers withdrew their farms from the study due to what was reported as pressure from their spouses. The study's engagement was intentionally focused on women smallholder farmers; however, this approach reportedly left some male spouses feeling under-informed or excluded, which ultimately led to the withdrawal of their family's participation.

Environmental Factors: Flooding

The single largest cause of data loss was environmental. The study area in Kisumu County received unseasonably high and prolonged rainfall, which resulted in severe flooding on 10 farms. The flooding destroyed either the entire crop or a significant portion of the plots. Although some farmers subsequently replanted, the resulting growth conditions and timelines meant the yield data would not have been comparable or applicable for this study's analysis and were therefore excluded.

Logistical and Coordination Challenges

Other data losses resulted from logistical challenges in coordinating research activities with individual farming practices. For example, some farmers planted their fields before the research team was able to apply the rock powder treatment. In another case, a farmer harvested the crop inside the harvest box before the team arrived to conduct the formal yield analysis, resulting in the loss of that data point.

Table 5**.** Number and reason for losses of participants throughout the trial. Detailed explanations can be found in Table S1.

	Registered interest in Trial	**Initially Onboarded**	**Rock Spread**	**Harvest Data Collected**	**Data Utilised in Study**
Participants	100	56	46	34	31
Losses	—	44	10	12	3
Reasons for losses		Farm size too small Spouses not engaged Requested payment	7 due to spouses 3 Planted before spreading	10 destroyed by floods 1 harvested before analysis 1 farm eaten by donkeys	3 contaminated yield results

3.2. Maize Yield

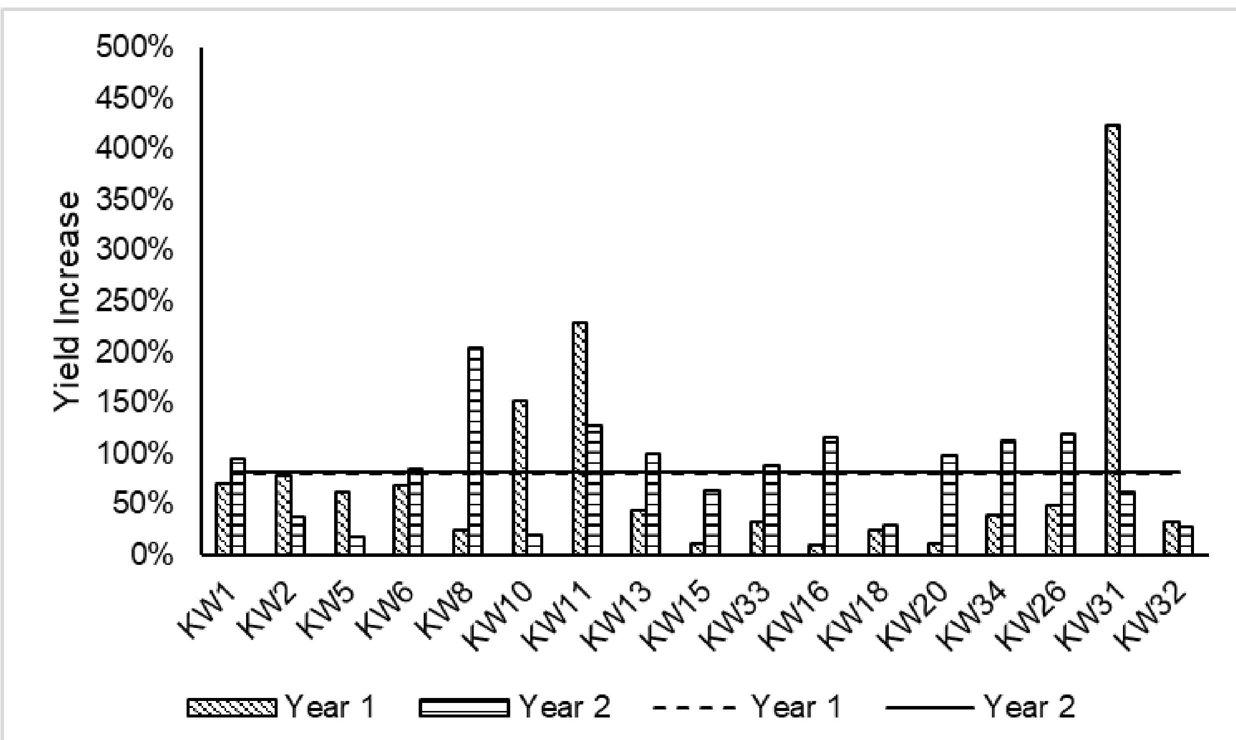
The application of silicate feedstock resulted in statistically significant ($p < 0.05$) increases in maize yield across both growing seasons. Figure 3 presents the yield increases for each individual farm in the Ombeyi (KO) and Wawidhi (KW) clusters for Year 1 and Year 2, respectively.

Season 1: Initial impact

After roughly four months of growing, farmers began to harvest their maize crops as they became ready. The harvest came earlier by two weeks in the Wawidhi cluster compared to Ombeyi. Statistically significant ($p<<0.05$) increases in crop yield for the Ombeyi cluster (60.4±15.7%) and the Wawidhi cluster (80±25.4%) are attributed to the application of silicate feedstock (Figure 3). To report yield changes comprehensively, we present both the Average Yield Changes and the Aggregate Yield Change. The Average Yield Changes, calculated by averaging the yield change across all fields, shows a yield change of 71.17 ± 15.5%. This measure reflects the variability in yield across individual fields, offering insights into field-specific performance and highlighting any variability or potential outliers in the data. In contrast, the Aggregate Yield Change of 47.47

± 5.73%, which is derived by averaging the control and treatment data separately and calculating the yield difference between them, provides a broader assessment of the treatment's overall effectiveness across the entire study area. This finding is notably higher than the more modest yield gains (10-24%) typically reported in ERW trials on temperate soils (Haque et al., 2020; Guo et al., 2023; Skov et al., 2024) but is consistent with the high potential predicted for weathered tropical systems (Edwards et al., 2017; Beerling et al., 2020) and initial increased yield results reported for maize and beans (Conceição et al., 2022). The accelerated weathering kinetics in the warm, humid climate of Western Kenya likely drove this strong response. This effect was likely compounded by the baseline nutrient-poor status of the soils; the application of the silicate feedstock served to correct key nutrient deficiencies, a factor further detailed in the soil chemistry analysis (Section 3.3).

To analyze the impact of the treatment relative to initial farm productivity, the farms were stratified into three groups based on their control plot yield. The results show a strong inverse relationship between the baseline yield and the relative yield increase from the rock powder application (Table 6). The lowest-productivity farms (control yield < 1600 kg/ha, n=10) experienced the most dramatic effect, with an average yield increase of 143.5%. For the medium-productivity farms (control yield 1600 - 2600 kg/ha, n=11), the treatment resulted in a more moderate average increase of 44.2%. The highest-productivity farms (control yield > 2600 kg/ha, n=10), which already exceeded the Kenyan national average yield of 1900 kg/ha, saw the smallest relative gain, with an average increase of 28.5%. This stratification clearly indicates that the agronomic benefit of the treatment was most pronounced on the least fertile plots.



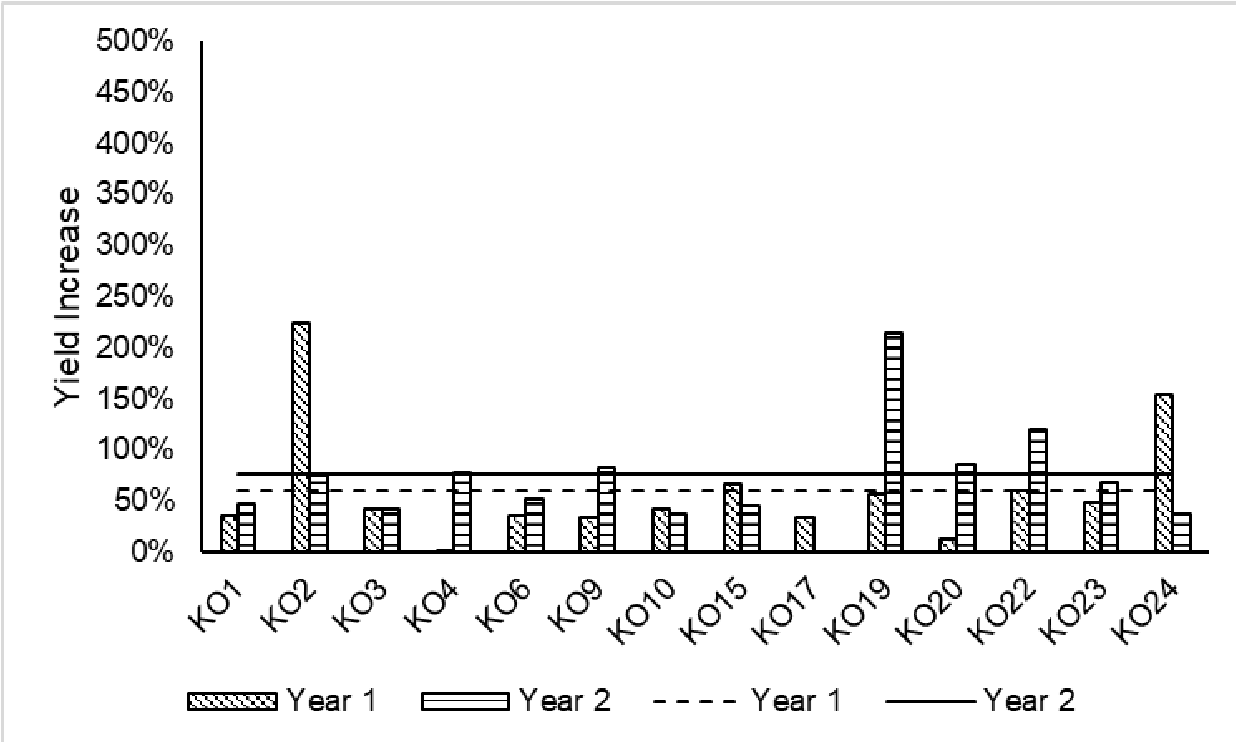


Figure 3. Farm-specific yield increases for maize for Year 1 and Year 2**.** Top: bar plots showing increase in harvest yield at each farm plot with the Wawidhi cluster. Bottom: same but for the Ombeyi cluster. Dotted lines and solid lines denote the average yield increase for each cluster for Year 1 and Year 2, respectively.

Table 6. Summary of average yield increases by control yield. It is apparent that low-productivity plots saw the highest relative yield impact of rock powder application. For comparison, the average corn yield in Kenya was 1900 kg/ha in 2023/2024 (USDA, 2024).

Control yield [kg/ha]	**n**	**Average yield increase [%]**
< 1600	10	143.5
1600 - 2600	11	44.2
> 2600	10	28.5

Season 2: Amplification of effect

A key finding of this study is the amplification of the treatment effect in the second year, despite no new rock dust being added. The aggregate yield increase across all fields grew from 47.47% in Year 1 to 71.89% in Year 2. This trend was not merely an artifact of the average but was observed at the individual farm level. In the Ombeyi cluster, 9 out of 13 fields (69%) showed a greater yield increase in Year 2 than in Year 1, a pattern mirrored in the Wawidhi cluster where 11 out of 17 fields (65%) improved upon their first-year results. This individual farm improvement is reflected in the cluster averages, where the average yield increase in Ombeyi grew from 60.44 ± 15.68% to

75.56 ± 13.28%, which is higher compared to Wawidhi, where the yield increased slightly from 80.01 ± 25.42% to 82.06 ± 11.75% (Figure 3). This demonstrates a lasting, cumulative benefit of the single silicate application.

This year-on-year amplification is visualized in Figure 4. The trend was not only observed in the primary metric of harvest yield but was also supported by dramatic improvements in underlying agronomic factors. The “kernels per cob” increased from 26.07% to 62.6%, and “cob length” increased from 17.63% to 40.5%. The enhanced crop performance is consistent with the known mechanisms of enhanced rock weathering. The amplification of the effect in the second year is particularly significant. As the silicate material had more time to interact with the soil microbiome and physicochemical environment, the rate of nutrient release as a result of weathering likely increased. This concept is similar to the gradual, slow-release liming effect observed with silicate amendments (Van Der Bauwhede et al., 2024). This would lead to greater nutrient availability during the critical growth stages of the Year 2 crop, explaining the substantial improvements in both yield and its underlying components like kernel count and cob size (Ruiz et al., 2022). The determination of potential kernel number in maize is a critical process that occurs early in the plant's vegetative development stages. During this period, the plant establishes the number of kernel rows and ovules based on an assessment of available soil nutrients. In the treated plots, the sustained, slow release of essential nutrients from the silicate amendment likely mitigated early-season nutrient stress. A more consistent supply of key cations and phosphorus would enable the plants to develop more robustly, thereby initiating and retaining a higher number of viable kernel sites per cob (Ritchie and Hanway, 1982). On the other hand, plants in the nutrient-deficient control plots likely experienced greater stress during this foundational development phase. In response to these limitations, such plants typically conserve resources by initiating fewer kernel rows or, more commonly, by aborting potential kernels before pollination. This physiological response results in a lower final kernel count, not because the kernels failed to fill post-pollination, but because the foundational nodes for their development were not fully established (Sangoi et al., 2002). Therefore, the dramatic increase in kernel count observed in the second year serves as a direct indicator that the silicate amendment created a more fertile and stable nutritional environment during the most crucial, early stages of maize development.

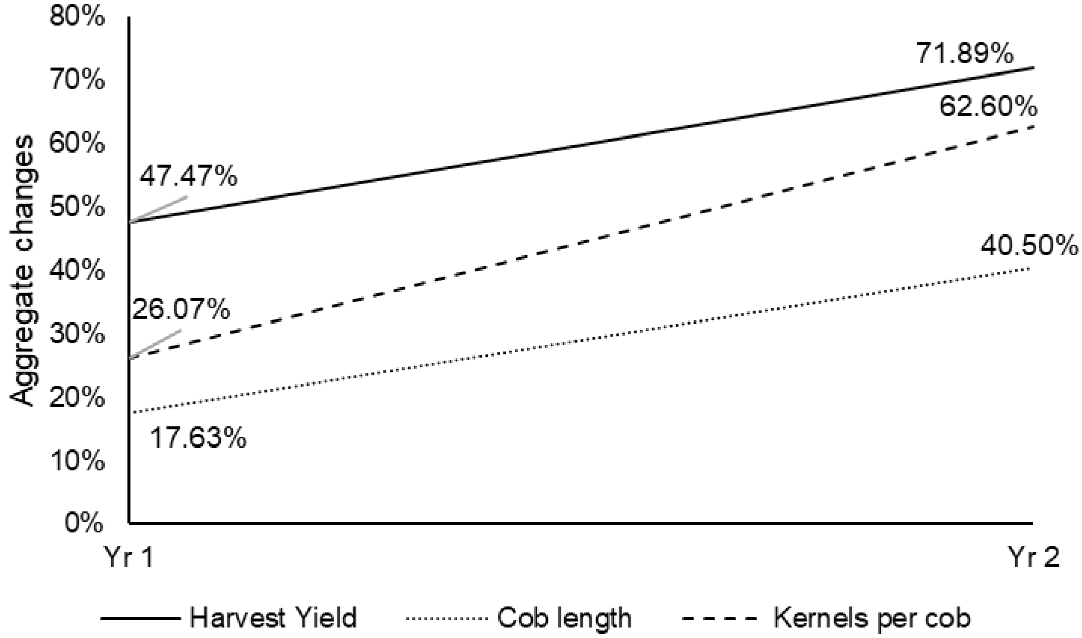


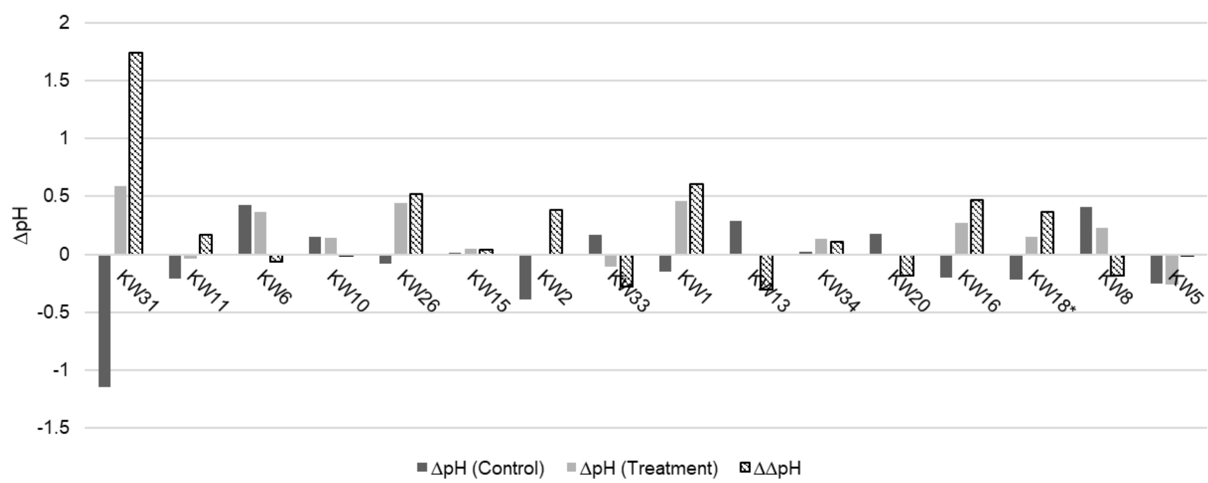
Figure 4. Year-over-year comparison of the aggregate percentage increase in maize yield and its components. The data illustrates the lasting and amplifying effect of a single silicate rock powder application from Year 1 to Year 2.

While the average effect was robust, considerable farm-to-farm variability was observed in both seasons (Figure S3), which is expected in real-world agricultural settings due to differences in weather, soil micro-variations, and farming practices. The consistency of the positive average result, despite this "noise," underscores the resilience and effectiveness of the treatment. Future studies could aim to better constrain this variability by implementing stricter protocols for harvest data collection to minimize data loss, employing a stratified random sampling strategy for cob measurements to ensure subsamples are fully representative, deploying local weather sensors, and maintaining detailed records of individual farming practices.

3.3. Post harvest Soil Chemistry

Soil fertility and macronutrient dynamics

In the Wawidhi cluster, ERW treatment plots showed an average pH increase of 0.15 units (from 6.47 to 6.62), which was statistically significant ($p = 0.02$). Control plots did not show a significant change in pH (mean ΔpH = -0.06, $p = 0.52$). However, when comparing the difference in pH change between treatment and control plots for each field ($\Delta\Delta$pH=0.21), the effect was not statistically significant ($p = 0.11$). Nevertheless, the observed increase in the treatment group suggests a potential positive effect of ERW that may warrant further investigation with a larger sample size. In the Ombeyi cluster, the net difference in pH change between treatment and control plots ($\Delta\Delta$pH) was 0.14, indicating a slight trend toward pH maintenance in ERW plots compared to controls, but this difference was not statistically significant ($p=0.37$). This indicates that ERW did not have a measurable effect on soil pH in Ombeyi over the trial period. Figure 5 illustrates the effect of ERW on soil pH across both clusters. Although the absolute change was small, these results are consistent with those from a basalt trial on spring oats in a temperate climate, which reported a comparable pH increase of 0.2 units (Skov et al., 2024). While other studies in tropical climates have reported higher pH changes, such as a 0.5-unit increase in Malaysian cacao plantations (Anda et al., 2013), these differences are readily explained by key variations in experimental conditions. The aforementioned study utilized a much finer feedstock (<250 µm) on soils with a lower initial pH (4.7), both of which are known to accelerate weathering rates. In contrast, the modest pH change observed in our trial is a significant finding, given the substantially larger particle size (0-4 mm) of the feedstock used. The reactivity of the 0-4mm material is constrained by its coarse particle size, with only a small fraction expected to be active within the trial's duration. This supports the established principle that silicate weathering is a complex process governed by numerous factors, including initial soil pH, feedstock size, and local environmental conditions (Haque et al., 2019, Haque et al., 2023).



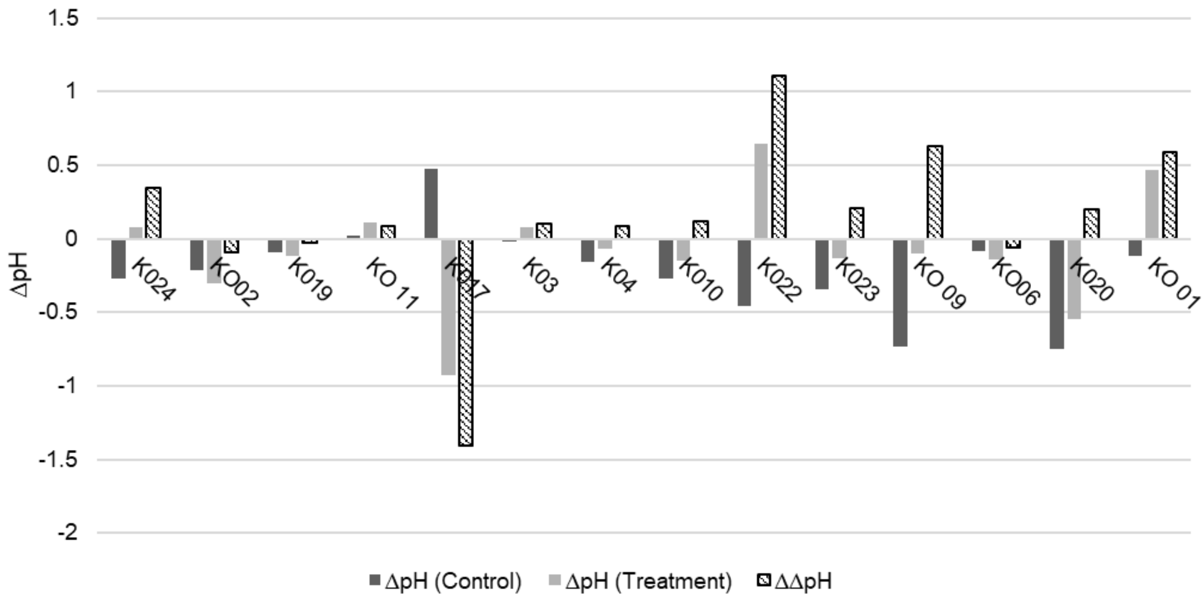
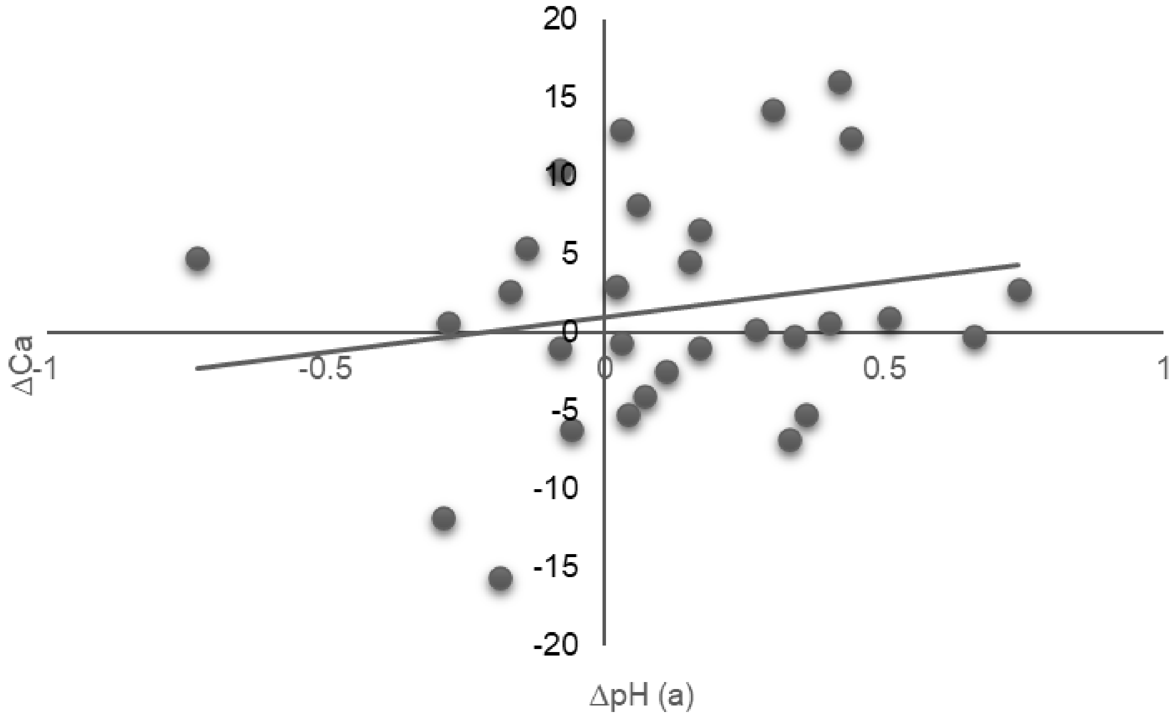


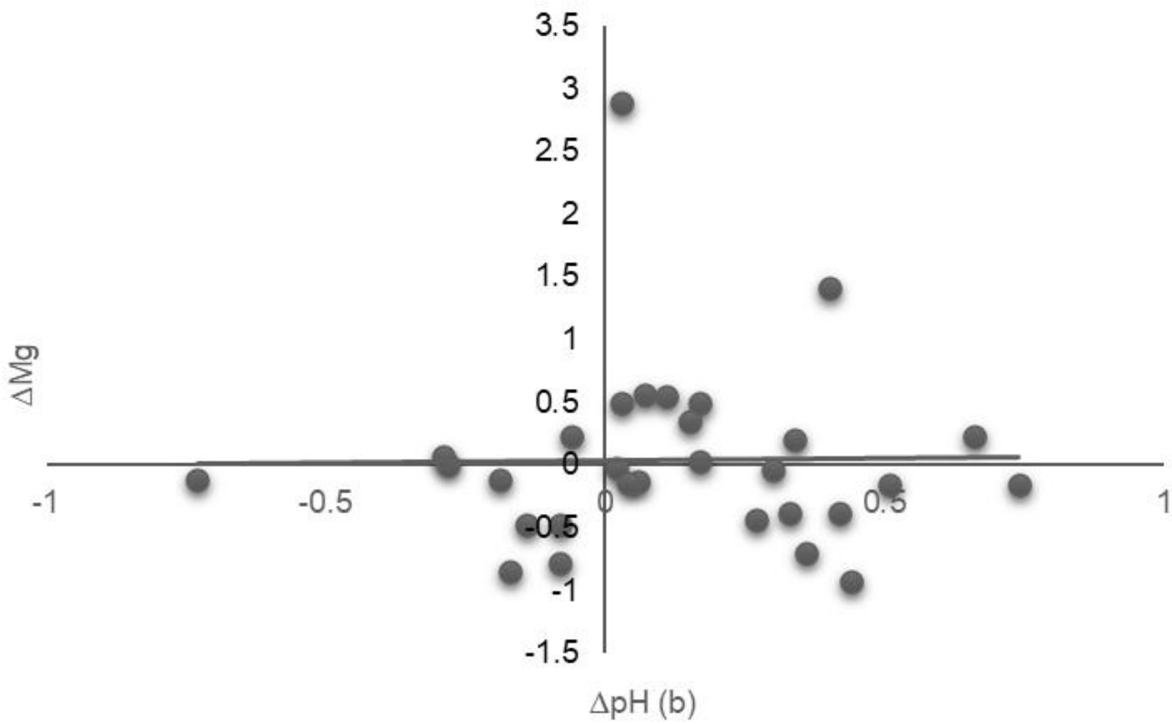
Figure 5. Changes in soil pH for Wawidhi cluster (Top), and Ombeyi cluster (Bottom).

In theory, if ERW is functioning as intended, one would expect the silicate weathering process to release basic cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) into the soil. These cations help neutralize soil acidity by replacing hydrogen ions (H^{+}), which should in turn lead to an increase in soil pH (Beerling et al, 2020). Accordingly, a positive correlation between changes in soil pH and changes in exchangeable Ca or Mg would be anticipated if ERW is effectively altering soil chemistry. To investigate this, we examined the relationship between the difference in Ca and Mg concentrations and the corresponding difference in soil pH, combining data from both the Wawidhi and Ombeyi clusters.

The resulting ΔCa versus ΔpH graph displayed a positive trend (Figure 6a), indicating that plots with greater increases in Ca tended to also exhibit greater increases in soil pH. In contrast, the ΔMg versus ΔpH graph showed only a very slight positive trend (Figure 6b), suggesting a much weaker association between Mg increase and pH change. This difference in trend likely reflects the chemical composition of the basalt feedstock used in the study. Specifically, the feedstock contained a higher proportion of CaO (16.96%) compared to MgO (8.26%). As a result, more calcium was available for release into the soil following weathering, which is consistent with the more pronounced effect of Ca on soil pH observed in the data. The positive trend between Ca and Mg changes with pH is further supported by the positive relationship observed between CEC and pH (Figure 6c). This suggests that as silicate weathering releases basic cations and raises soil pH, it also enhances the soil's cation exchange capacity. Such an increase in CEC is agronomically beneficial, as it improves the soil's ability to retain and supply essential nutrients to plants, thereby contributing to overall soil fertility and crop productivity (Santos et al., 2023).



20
15
10
5
0
-5
-10
-15
-20
-1
-0.5
0
0.5
1
ΔCa
ΔpH (a)



3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
ΔMg
ΔpH (b)

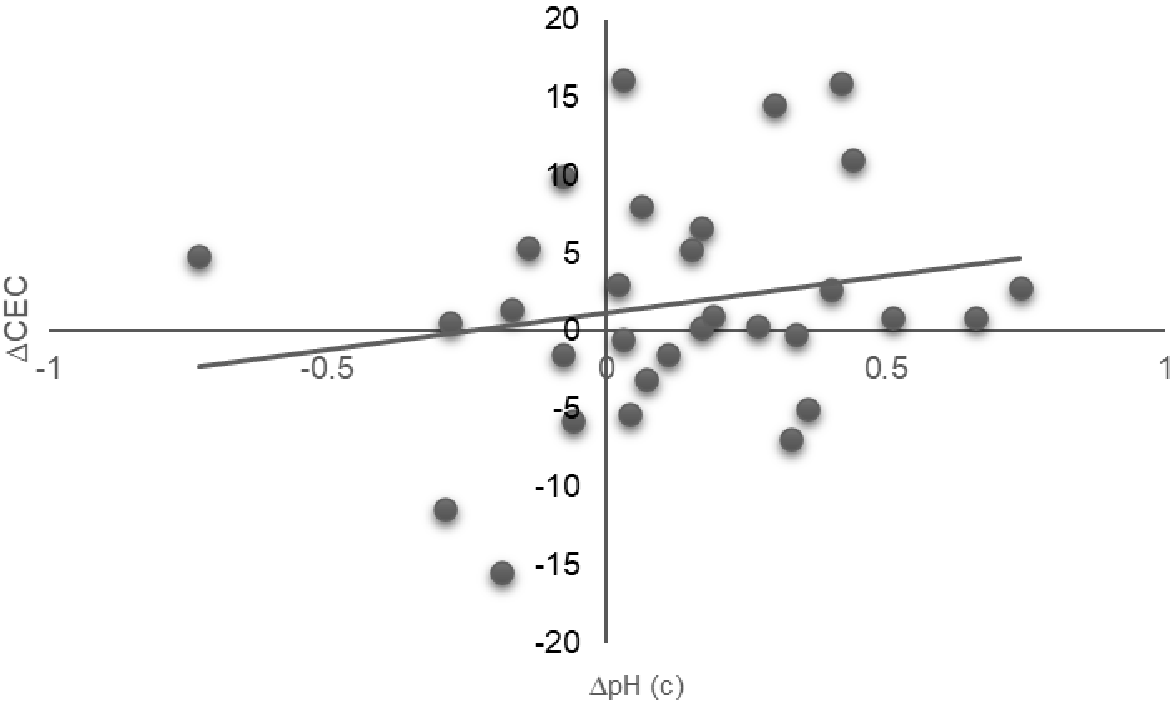


Figure 6. Relationship between the change in soil pH (ΔpH) and the change in a) calcium (ΔCa); b) magnesium (ΔMg); and c) cation exchange capacity (ΔCEC). Each point represents an individual field plot from the Ombeyi and Wawidhi clusters.

While these findings are in line with the expected mechanism of ERW, the overall correlations were still relatively weak. This could be due to several factors, including the relatively small application rate of basalt, the high buffering capacity of the soils, or the possibility that released cations were taken up by crops or lost through leaching before significantly affecting soil pH. Given a higher maize yield is obtained, the primary reason could be the increased uptake of Mg by the plants. Magnesium is essential for photosynthesis (it's a central component of the chlorophyll molecule) (Cakmak and Kirkby, 2008), so this substantial increase in its availability is another key factor contributing to the improved crop health and yield in this study. The silicate rock powder didn't just add Mg; it corrected the soil pH and released other essential nutrients (like phosphorus and calcium). Because of the improved soil conditions, the maize plants in the treatment plots grew significantly larger, and healthier, than the plants in the control plots. These bigger productive plants would need more nutrients and thus increase nutrients uptake from the soil to build their stalks, leaves, and roots, thus storing Mg it in their own biomass. This explains the lower levels of Mg in the soil at the end of the growing season (Figure S4). A secondary mechanism influencing the final magnesium concentration is the principle of cation exchange competition on soil colloids. CEC of a soil dictates the number of available exchange sites for cations (Mengel DB, 1993), primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}) for this study. The silicate feedstock used in this study has a significantly higher calcium-to-magnesium ratio. Consequently, the dissolution of the amendment introduced a large influx of Ca^{2+} ions, which likely outcompeted and competitively displaced Mg^{2+} ions from the exchange sites into the soil solution. This increase in soluble Mg^{2+} would render it more available for plant uptake—supporting the primary hypothesis of increased crop assimilation—or make it more susceptible to leaching from the soil profile during periods of heavy rainfall.

Post-harvest soils from the treated plots exhibited an increase in P concentration compared to both the initial baseline and the final control plots (Figure 7). The increase in P in post harvest soil samples is 26.5% compared to the control for the Wawidhi cluster, and 59% for the Ombeyi cluster. Although these strong positive trends did not reach the threshold for statistical significance ($p = 0.39$ and $p = 0.24$, respectively), likely due to high plot-to-plot variability, the observed mobilization of P is consistent with the established agronomic co-benefits of ERW. The observed increase in soil P may be attributed to two potential mechanisms, first, the direct, slow release of P from the apatite mineral within the feedstock (which contained 0.71% P_2O_5) provided a nutrient source. Second, and likely more impactful, was an indirect mechanism where the formation of silicic acid (H_4SiO_4) during weathering competitively displaced phosphate ions from aluminum and iron oxide surfaces (Luchese et al., 2021, Scherwietes et al., 2024). This enhancement of P availability is a key indicator of improved soil fertility and a likely contributor to the observed increases in crop yield. These results, increase in soil P as a result of silicate application, are consistent with the findings of Rodrigues et al. (2024) in their study to investigate the role of basalt on soil P.

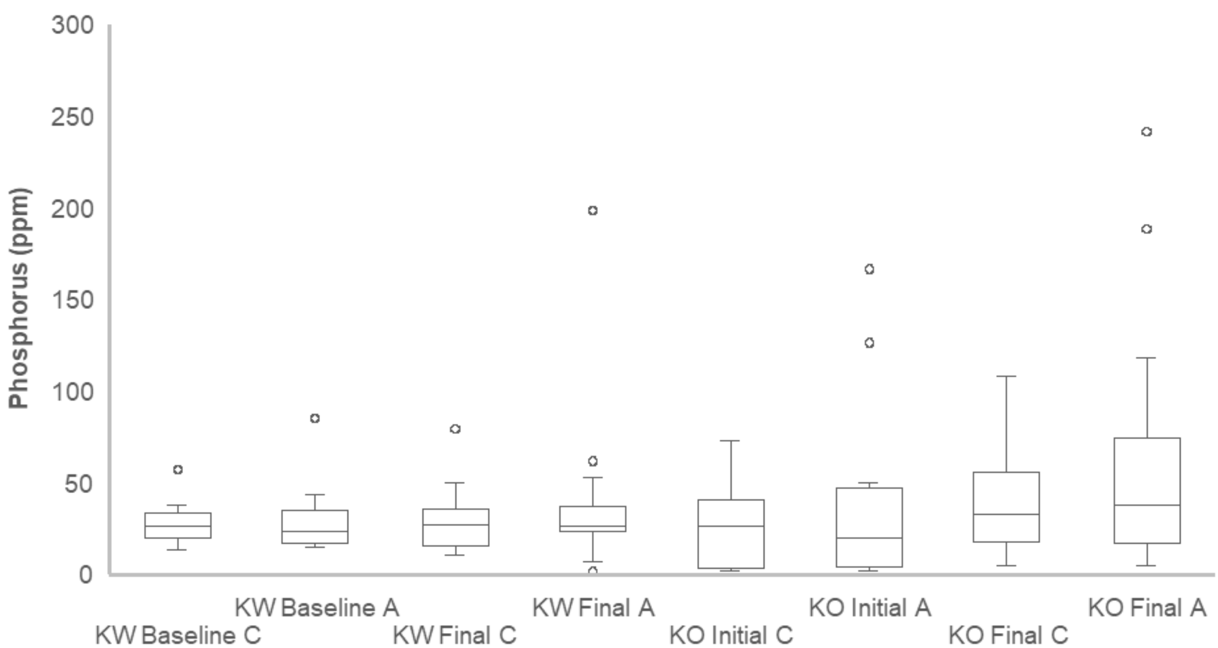


Figure 7. Box plot for phosphorus concentration in the soil in control (C) and treated (A) plots for initial soil samples (baseline) and post harvest soil samples (Final). KW=Wawidhi cluster, KO=Ombeyi cluster.

The silicate amendment significantly influenced the cycling of Total Nitrogen (TN) and Total Organic Carbon (TOC), with treated plots in the Ombeyi cluster showing a greater net depletion of both elements compared to controls (Figure S5). In Ombeyi, the post-harvest soils of the treated plots showed a significantly greater decrease in TN (-18.23%) and TOC (-19.14%) compared to the control plots (-13.02% and -12.82%, respectively; $p < 0.05$). This high background loss in TOC is not common; however, this could be explained by the interaction between the site's high initial carbon stock (baseline TOC of 2.57% for control, and 2.53% for treatment plot) and the heavy rainfall event that was common during the trial. The study area experienced unseasonably high and prolonged rainfall which resulted in severe flooding. These conditions likely triggered significant carbon loss through two primary mechanisms: the physical erosion of topsoil and the accelerated mineralization of organic matter during subsequent soil drying cycles (Nachimuthu and Hulugalle, 2016; Franzluebbers et al., 2000). The soil's vulnerability to this loss was likely exacerbated by the standard agricultural practice of ploughing, which was used on the trial plots (Sharma et al., 2022; Freitas et al., 2024). The application of rock dust increases soil pH and releases nutrients, stimulating both microbial activity and more robust plant growth. The larger, healthier plants then have a higher nitrogen demand. To meet this demand, the plants stimulate the microbial community, likely through root exudates, to mineralize soil organic matter. This process releases the nitrogen the plant needs, but it concurrently results in organic matter decomposition (Kuzyakov et al., 2000). Therefore, while the pH increase is an initial trigger, the stimulated plant growth acts as the primary driver for the increased demand that leads to the significant TOC drawdown. The decrease in soil TN reflects a successful transfer of nitrogen into the crop, while the concurrent loss of TOC might also be attributed to the increased microbial mineralization of organic matter required to make that nitrogen available. To better understand and confirm these mechanisms in future studies, additional parameters such as in-situ gas flux could be monitored. Deploying automated soil gas chambers to continuously measure CO_2 emissions from the soil surface would provide real-time data on microbial respiration. This would capture the pulses of carbon loss after rainfall and drying events, allowing for a more precise correlation between environmental triggers and TOC decline (Pumpanen et al., 2004).

In the Wawidhi cluster, the trends were less pronounced and not statistically significant. The treated plots showed a slightly larger decrease in TN (-4.32%) than the control plots (-2.89%; $p = 0.51$). Conversely, the decrease in TOC was slightly less in the treated plots (-2.90%) compared to the control (-3.71%), suggesting a more neutral effect in that location. These results are in consensus with the findings of Jariwala et al. (2022), Khalidy et al. (2025), te Pas et al. (2023), and Sokol et al. (2024), where TN and TOC in the soil were either statistically similar or decreased slightly post silicate application.

Micronutrient dynamics and availability

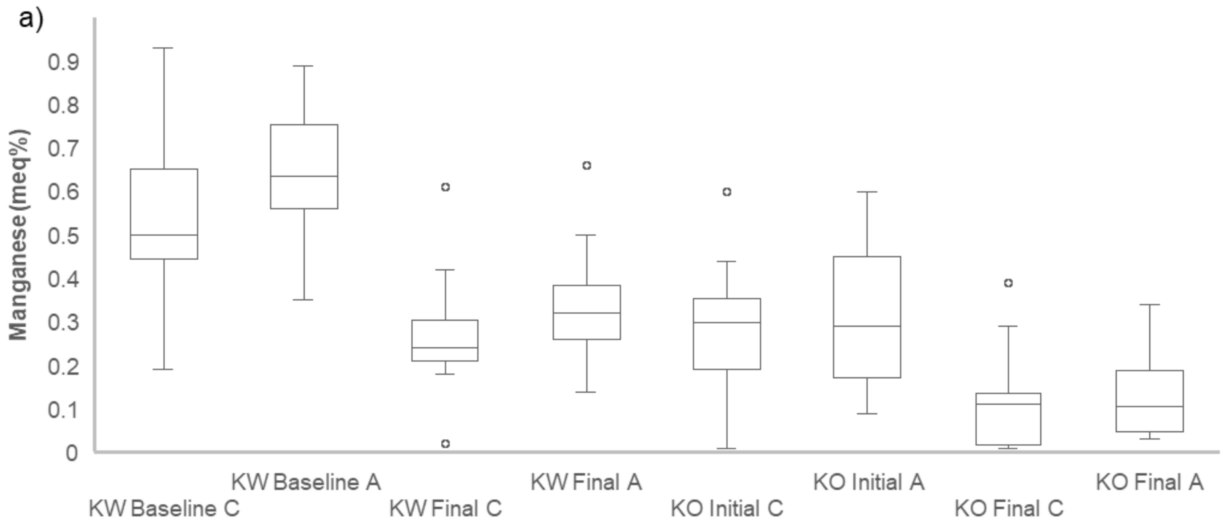
The silicate amendment influenced the availability of key soil micronutrients. Initial soils in both the Wawidhi (KW) and Ombeyi (KO) clusters had high and variable manganese (Mn) concentrations (Figure 8a). Post-harvest, a significant and consistent decrease of approximately 50% from the baseline was observed across all experimental groups. Specifically, the decrease in the Wawidhi cluster was 47.8% for treated and 50.5% for control plots, while the Ombeyi cluster saw decreases of 56.3% and 57.9%, respectively ($p < 0.05$ for all comparisons). Since this effect was observed equally in plots that did not receive the amendment, it cannot be attributed to the rock powder application. The likely mechanism is a seasonal shift in soil redox conditions, driven by the extreme precipitation events leading to flooding during the trials. The baseline soil sampling may have captured the soil in a more reduced (anaerobic) state, where insoluble Mn(IV) is reduced to the more soluble and mobile Mn(II), elevating its measured availability (Narteh and Sahrawat, 1999). The post-harvest sampling, likely conducted under drier, more oxidized (aerobic) conditions, would have captured the subsequent oxidation of Mn(II) back into less available forms (McBride, 1994). This environment event appears to have completely masked any potential influence of the amendment on Mn availability.

The effects on iron (Fe), zinc (Zn), and copper (Cu) were more varied and highlighted the amendment's primary role as a complex soil conditioner, influencing nutrient dynamics in a site-specific manner rather than acting as a simple fertilizer. The most complex response was observed for iron (Fe), which showed opposing trends in the two clusters (Figure S6a). The Wawidhi (KW) cluster showed a statistically significant increase in available Fe, with post-harvest soils in the treated plots containing 14.8% more available Fe than in the control plots ($p < 0.05$). In this case, the direct addition of iron from the feedstock (containing 17.03% Fe_2O_3) was the prevailing effect. These results are in consensus with the increased Fe concentrations reported in the mesocosm study by Amann et al. (2022) using olivine under cropped conditions. In contrast, the amendment had no statistically significant effect on available Fe in the Ombeyi cluster ($p > 0.05$), which started with higher initial Fe levels. This highlights that the amendment's impact on iron availability was highly site-specific.

In the Wawidhi (KW) cluster, available zinc (Zn) significantly decreased from the baseline in both the control (-32.6%) and treated (-31.4%) plots (Figure S6b). This uniform drawdown of approximately 30% ($p<0.05$) across both groups indicates that crop uptake was the dominant factor influencing Zn concentration. The lack of a significant difference between post harvest control and treated plots (4.6%, $p>0.05$) indicates that the Zn added by the amendment was not substantial enough to offset the amount consumed by the crop. In the Ombeyi (KO) cluster, Zn levels remained stable across all groups, suggesting that Zn was not a limiting factor in that soil.

Post-harvest, a significant two-fold increase in available copper (Cu) was observed across all experimental groups relative to the baseline ($p < 0.05$; Figure 8b). Despite this general increase, the final treated plots contained 10% less Cu than the final control plots, a consistent trend observed in both clusters. The dynamics of copper (Cu) were primarily influenced by biological cycling and crop uptake. The twofold increase in available Cu observed in all post-harvest plots, including the controls, is attributed to the biological pump effect. This process involves the uptake of Cu from the soil profile during the growing season and its subsequent concentration in the topsoil as post-harvest crop residues decompose (Marschner H, 2012). The final soil sampling was done 150-180 days after harvest.

Against this background increase, the post harvest treated plots exhibited a net decrease of 10% in available Cu relative to the controls (i.e., difference between Final A and Final C for both KW and KO, Figure 8b). This suggests that the plant uptake of Cu was significantly enhanced in the amended plots. The amendment's primary role was not to supply Cu, but rather to improve overall soil health, primarily net increase in pH and P availability for this study, so effectively that it stimulated more vigorous crop growth. This resulted in a greater nutrient demand that outpaced the amount of Cu being supplied by the amendment and recycled from crop residues, leading to a net drawdown from the soil.



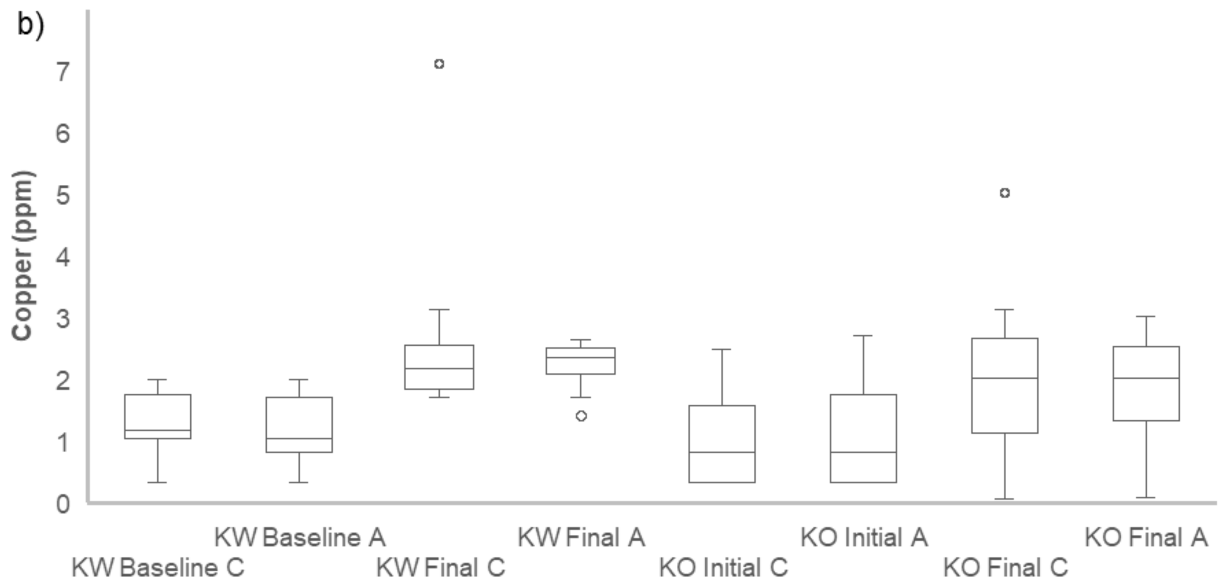


Figure 8. Box plot for a) manganese, and b) copper concentration in the soil in control (C) and treated (A) plots for initial soil samples (baseline) and post harvest soil samples (Final). KW=Wawidhi cluster, KO=Ombeyi cluster.

It is important to contextualize the statistical significance of the soil chemistry results. As noted by Khalidy et al. (2025), achieving a p-value below 0.05 in field-based studies is challenging due to the high natural variability of cropland soils. The p-value does not solely measure the magnitude of an effect but is also highly sensitive to sample size and data variance. For this reason, while not all changes were statistically significant, the consistent direction and magnitude of the average changes are presented here as the most relevant indicators of the amendment's agronomic impact.

4. Conclusion

The results of this study provide strong evidence that enhanced rock weathering can deliver significant agronomic benefits in a real-world smallholder farming context in sub-Saharan Africa. The average yield increase of 71.17% ± 15.5% and the aggregate yield increase of 47.47% ± 5.73% collectively in the first year demonstrate that the application of silicate rock powder significantly enhances soil health and boosts crop productivity. The primary finding was a statistically significant increase in maize yield that not only persisted but grew from the first to the second growing season, demonstrating a lasting, cumulative effect of enhanced rock weathering. This remarkable improvement may be partly due to the initially low baseline yield on these marginal lands, where soil conditions were suboptimal for high productivity. The addition of silicate minerals likely enriched the soil with essential nutrients, while also raising soil pH, which can improve nutrient availability. The observed maize yield increase is a substantial improvement that has direct implications for local food security and farmer income. At local 2024 maize prices, this yield increase equated to an additional revenue of $326 per hectare, a meaningful economic gain in a region where average farmhand wages are $60-$80 per month.

The underlying mechanisms for this yield enhancement are well-supported by the soil chemistry data. The positive trend between Ca and Mg changes with pH is further supported by the positive trend observed between CEC and pH. This suggests that as silicate weathering releases basic cations and raises soil pH, it also enhances the soil's cation exchange capacity. This study has several limitations, inherent to its real-world, community-based design. The loss of 25 farms due to flooding and social factors reduced the final sample size and could introduce a survivorship bias. The use of unquantified manure by some farmers introduces a potential confounding variable, though the control/treatment design on each farm helps mitigate this. The absence of historical yield data also prevents ruling out selection bias completely. Future research should incorporate more detailed tracking of all farm inputs, establish multiple harvest boxes to account for intra-plot variability, and extend monitoring over multiple seasons to quantify long-term impacts on soil health and carbon sequestration.

This study demonstrates that ERW is not merely a theoretical carbon removal strategy but a practical agricultural intervention with the potential to significantly improve livelihoods in some of the world's most vulnerable regions. By using a local resource to simultaneously enhance yields, improve soil health, and sequester carbon, ERW could help reduce smallholder reliance on expensive and often inaccessible imported synthetic fertilizers. If scalable, this approach could contribute to the Nationally Determined Contributions (NDCs) of countries like Kenya by offering a pathway that aligns agricultural development with climate mitigation goals.

Acknowledgement

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No Conflict of Interest

Data availability

Data is available through the Cascade Climate ERW Data Quarry (https://data.cascadeclimate.org/) . Access to the data can be obtained via Cascade Climate's official platform.

References

Amann T, Hartmann J, Struyf E, de Oliveira Garcia W, Fischer EK, Janssens I, Meire P, Schoelynck J. Enhanced Weathering and related element fluxes–a cropland mesocosm approach. Biogeosciences. 2020 Jan 8;17(1):103-19.

Anda M, Shamshuddin J, Fauziah CI. Increasing negative charge and nutrient contents of a highly weathered soil using basalt and rice husk to promote cocoa growth under field conditions. Soil and Tillage Research. 2013 Aug 1;132:1-1.

Beerling DJ, Epihov DZ, Kantola IB, Masters MD, Reershemius T, Planavsky NJ, Reinhard CT, Jordan JS, Thorne SJ, Weber J, Val Martin M. Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits. Proceedings of the National Academy of Sciences. 2024 Feb 27;121(9):e2319436121.

Beerling DJ, Kantzas EP, Lomas MR, Wade P, Eufrasio RM, Renforth P, Sarkar B, Andrews MG, James RH, Pearce CR, Mercure JF. Potential for large-scale CO2 removal via enhanced rock weathering with croplands. Nature. 2020 Jul 9;583(7815):242-8.

Beerling DJ. Enhanced rock weathering: biological climate change mitigation with co-benefits for food security?. Biology letters. 2017 Apr 30;13(4):20170149.

Boudinot FG, Dreyfus G, Frederick C, Powers Y. Enhanced Rock Weathering in the Global South: Exploring Potential for Enhanced Agricultural Productivity and Carbon dioxide Drawdown.

Cakmak I, Kirkby EA. Role of magnesium in carbon partitioning and alleviating photooxidative damage. Physiologia plantarum. 2008 Aug;133(4):692-704.

Conceição LT, Silva GN, Holsback HM, de Figueiredo Oliveira C, Marcante NC, de Souza Martins É, de Souza Santos FL, Santos EF. Potential of basalt dust to improve soil fertility and crop nutrition. Journal of Agriculture and Food Research. 2022 Dec 1;10:100443.

Edwards DP, Lim F, James RH, Pearce CR, Scholes J, Freckleton RP, Beerling DJ. Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. Biology letters. 2017 Apr 30;13(4):20160715.

EU Regulation 1009/2019. Annex 1, Part 2, PFC 3(B): Inorganic soil improver. 129 pp

Franzluebbers AJ, Haney RL, Honeycutt CW, Schomberg HH, Hons FM. Flush of carbon dioxide following rewetting of dried soil relates to active organic pools. Soil Science Society of America Journal. 2000 Mar;64(2):613-23.

Freitas VS, Babos DV, Guedes WN, Silva FP, de Lima Tozo ML, Andrade CA, Villas-Boas PR, Milori DM, Martin-Neto L. Soil organic matter dynamics and soil carbon stocks from tropical and sub-tropical areas under no-till: An on-farm research. Catena. 2024 Dec 1;247:108491.

Giller KE, Delaune T, Silva JV, van Wijk M, Hammond J, Descheemaeker K, van de Ven G, Schut AG, Taulya G, Chikowo R, Andersson JA. Small farms and development in sub-Saharan Africa: Farming for food, for income or for lack of better options?. Food Security. 2021 Dec;13(6):1431-54.

Guo F, Sun H, Yang J, Zhang L, Mu Y, Wang Y, Wu F. Improving food security and farmland carbon sequestration in China through enhanced rock weathering: Field evidence and potential assessment in different humid regions. Science of the Total Environment. 2023 Dec 10;903:166118.

Hangx SJ, Spiers CJ. Coastal spreading of olivine to control atmospheric CO2 concentrations: A critical analysis of viability. International Journal of Greenhouse Gas Control. 2009 Dec 1;3(6):757-67.

Haque F, Chiang YW, Santos RM. Alkaline mineral soil amendment: a climate change ‘stabilization wedge’?. Energies. 2019 Jun 16;12(12):2299.

Haque F, Chiang YW, Santos RM. Alkaline mineral soil amendment: a climate change ‘stabilization wedge’?. Energies. 2019 Jun 16;12(12):2299.

Haque F, Khalidy R, Chiang YW, Santos RM. Constraining the capacity of global croplands to CO2 drawdown via mineral weathering. ACS Earth and Space Chemistry. 2023 Jun 9;7(7):1294-305.

Haque F, Santos RM, Chiang YW. CO2 sequestration by wollastonite-amended agricultural soils–An Ontario field study. International Journal of Greenhouse Gas Control. 2020 Jun 1;97:103017.

Jariwala H, Haque F, Vanderburgt S, Santos RM, Chiang YW. Mineral–soil–plant–nutrient synergisms of enhanced weathering for agriculture: short-term investigations using fast-weathering wollastonite skarn. Frontiers in Plant Science. 2022 Jul 22;13:929457.

Khalidy R, Haque F, Chiang YW, Santos RM. Tracking pedogenic carbonate formation and alkalinity migration in agricultural soils amended with crushed wollastonite ore–Evidence from field trials in Southwestern Ontario. Geoderma Regional. 2025 Mar 1;40:e00918.

Kuzyakov Y, Friedel JK, Stahr K. Review of mechanisms and quantification of priming effects. Soil Biology and Biochemistry. 2000 Oct 1;32(11-12):1485-98.

Larkin CS, Andrews MG, Pearce CR, Yeong KL, Beerling DJ, Bellamy J, Benedick S, Freckleton RP, Goring-Harford H, Sadekar S, James RH. Quantification of CO2 removal in a large-scale enhanced weathering field trial on an oil palm plantation in Sabah, Malaysia. Frontiers in Climate. 2022 Aug 30;4:959229.

Lowder SK, Skoet J, Raney T. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World development. 2016 Nov 1;87:16-29.

Luchese AV, Pivetta LA, Batista MA, Steiner F, Giaretta AD, Curtis JC. Agronomic feasibility of using basalt powder as soil nutrient remineralizer. Afr. J. Agric. Res. 2021 Mar 31;17(3):487-97.

Manning DA, Theodoro SH. Enabling food security through use of local rocks and minerals. The Extractive Industries and Society. 2020 Apr 1;7(2):480-7.

Marschner H. Marschner's mineral nutrition of higher plants. Academic press; 2012.

Masson-Delmotte et al. Climate change 2021: The physical science basis. *Cambridge University Press*. 2391 pp.

McBride MB. Environmental chemistry of soils.

Mengel DB. Fundamentals of soil cation exchange capacity (CEC). Purdue University Cooperative Extension Service West Lafayette, Indiana, USA. 1993.

Nachimuthu G, Hulugalle N. On-farm gains and losses of soil organic carbon in terrestrial hydrological pathways: a review of empirical research. International Soil and Water Conservation Research. 2016 Dec 1;4(4):245-59.

Narteh LT, Sahrawat KL. Influence of flooding on electrochemical and chemical properties of West African soils. Geoderma. 1999 Jan 1;87(3-4):179-207.

Pacala S, Socolow R. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. science. 2004 Aug 13;305(5686):968-72.

Pumpanen J, Kolari P, Ilvesniemi H, Minkkinen K, Vesala T, Niinistö S, Lohila A, Larmola T, Morero M, Pihlatie M, Janssens I. Comparison of different chamber techniques for measuring soil CO2 efflux. Agricultural and Forest Meteorology. 2004 Jun 20;123(3-4):159-76.

RCMRD (2023). Kenya Soils Map (https://opendata.rcmrd.org/maps/rcmrd::kenya-soils-map/about)

Ritchie, S.W. and Hanway, J.J. (1982) How a Corn Plant Develops. Special Report No. 48, Iowa State University of Science and Technology, Cooperative Extension Service.

Rodrigues M, Bortolini PC, Neto CK, de Andrade EA, dos Passos AI, Pacheco FP, Nanni MR, de Melo Teixeira L. Unlocking higher yields in Urochloa brizantha: the role of basalt powder in enhancing soil nutrient availability. Discover Soil. 2024 Sep 19;1(1):4.

Ruiz A, Archontoulis SV, Borrás L. Kernel weight relevance in maize grain yield response to nitrogen fertilization. Field Crops Research. 2022 Oct 1;286:108631.

Samberg LH, Gerber JS, Ramankutty N, Herrero M, West PC. Subnational distribution of average farm size and smallholder contributions to global food production. Environmental Research Letters. 2016 Nov 30;11(12):124010.

Sangoi L, Gracietti MA, Rampazzo C, Bianchetti P. Response of Brazilian maize hybrids from different eras to changes in plant density. Field Crops Research. 2002 Dec 6;79(1):39-51.

Santos RM, Araujo F, Jariwala H, Khalidy R, Haque F, Chiang YW. Pathways, roundabouts, roadblocks, and shortcuts to safe and sustainable deployment of enhanced rock weathering in agriculture. Frontiers in Earth Science. 2023 Aug 1;11:1215930.

Scherwietes E, Stein M, Six J, Bawen TK, Schaller J. Local sediment amendment can potentially increase barley yield and reduce the need for phosphorus fertilizer on acidic soils in Kenya. Frontiers in Environmental Science. 2024 Oct 1;12:1458360.

Sharma S, Singh P, Angmo P, Satpute S. Total and labile pools of organic carbon in relation to soil biological properties under contrasting land-use systems in a dry mountainous region. Carbon Management. 2022 Jan 2;13(1):352-71.

Skov K, Wardman J, Healey M, McBride A, Bierowiec T, Cooper J, Edeh I, George D, Kelland ME, Mann J, Manning D. Initial agronomic benefits of enhanced weathering using basalt: A study of spring oat in a temperate climate. PLoS One. 2024 Mar 27;19(3):e0295031.

Sokol NW, Sohng J, Moreland K, Slessarev E, Goertzen H, Schmidt R, Samaddar S, Holzer I, Almaraz M, Geoghegan E, Houlton B. Reduced accrual of mineral-associated organic matter after two years of enhanced rock weathering in cropland soils, though no net losses of soil organic carbon. Biogeochemistry. 2024 Aug;167(8):989-1005.

Swoboda P, Döring TF, Hamer M. Remineralizing soils? The agricultural usage of silicate rock powders: A review. Science of The Total Environment. 2022 Feb 10;807:150976.

te Pas EE, Hagens M, Comans RN. Assessment of the enhanced weathering potential of different silicate minerals to improve soil quality and sequester CO2. Frontiers in Climate. 2023 Jan 10;4:954064.

USDA (2024): Country Summary Kenya (https://ipad.fas.usda.gov/countrysummary/?id=KE)

Van Der Bauwhede R, Muys B, Vancampenhout K, Smolders E. Accelerated weathering of silicate rock dusts predicts the slow-release liming in soils depending on rock mineralogy, soil acidity, and test methodology. Geoderma. 2024 Jan 1;441:116734.

Washbourne CL, Lopez-Capel E, Renforth P, Ascough PL, Manning DA. Rapid removal of atmospheric CO2 by urban soils. Environmental science & technology. 2015 May 5;49(9):5434-40.

Supplementary Materials

Figure S1. Deployment map for Wawidhi cluster (top) and Ombeyi cluster (bottom).

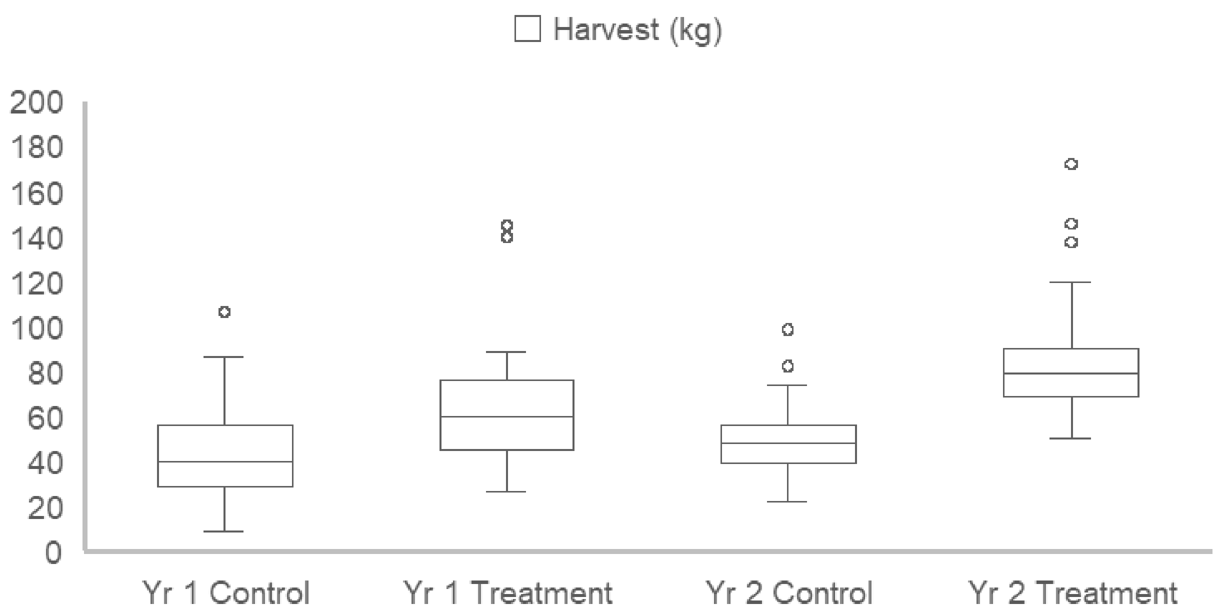
Figure S2. Field Area Mapper to collect data for each farm for accurate mapping.

Table S1. List of farms removed from study

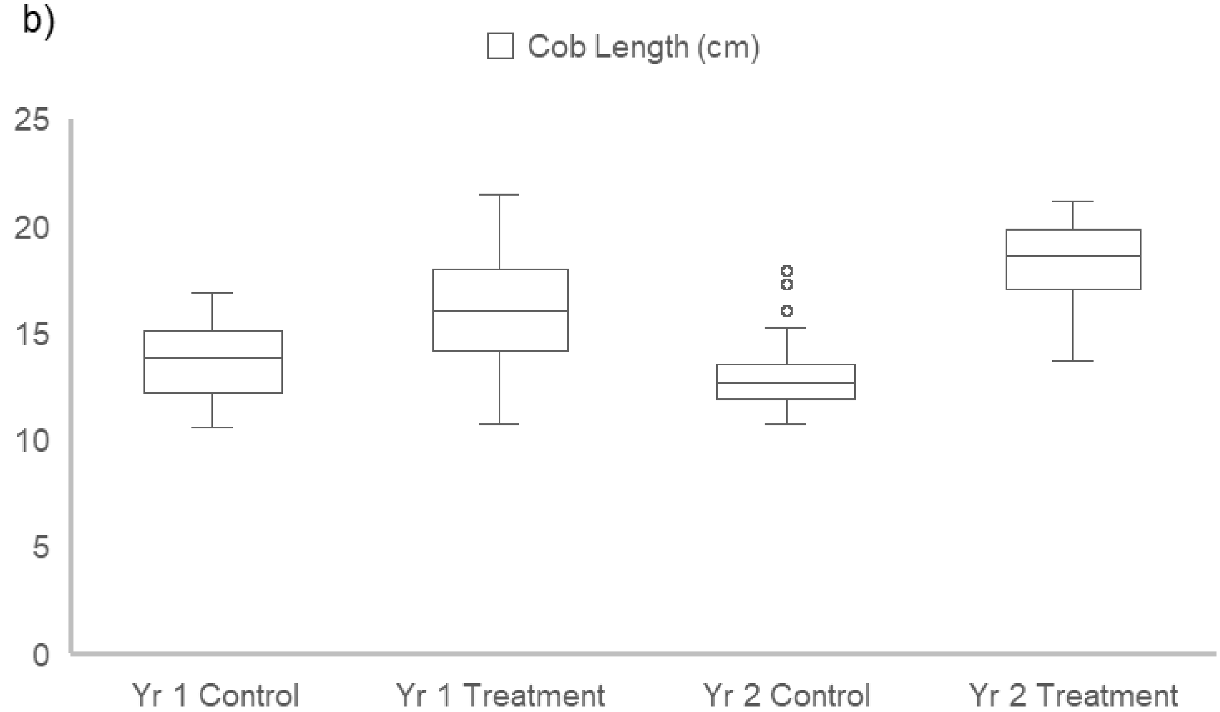
	Farmer ID	**Reason for Removal from Study**
1	KO5	Rock not spread - Spouse declined
2	KO13	Rock not spread - Spouse declined
3	KW17	Rock not spread - Spouse declined
4	KO26	Rock not spread - Spouse declined
5	KW23	Rock not spread - Spouse declined
6	KW25	Rock not spread - Spouse declined
7	KW28	Rock not spread - Spouse declined
8	KO16	Rock not spread – Planted before Flux team arrived to spread rock
9	KO29	Rock not spread -Planted before Flux team arrived to spread rock
10	KW21	Did not plant on the control side
11	KO12	Affected by flooding – Rains overwhelmed the control and application areas.
12	KO14	Affected by flooding - Rains overwhelmed the control and application areas.
13	KO25	Affected by flooding - Rains overwhelmed the control and application areas
14	KW3	Affected by flooding - Rains overwhelmed the control and application areas.
15	KW7	Affected by flooding - Rains overwhelmed the control and application areas
16	KW9	Affected by flooding - Rains overwhelmed the control and application areas
17	KW12	Affected by flooding - Rains overwhelmed the control and application areas

18	KW19	Affected by flooding - Rains overwhelmed the control and application areas
19	KW22	Affected by flooding - Rains overwhelmed the control and application areas
20	KW29	Affected by flooding -Rains overwhelmed the control and application areas
21	KO18	Control side destroyed by flooding
22	KO21	Harvested before Flux team arrived to do analysis
23	KW21	Harvest Errors
24	KO21	Harvest Errors
25	KO18	Harvest Errors

a)



b)



c)

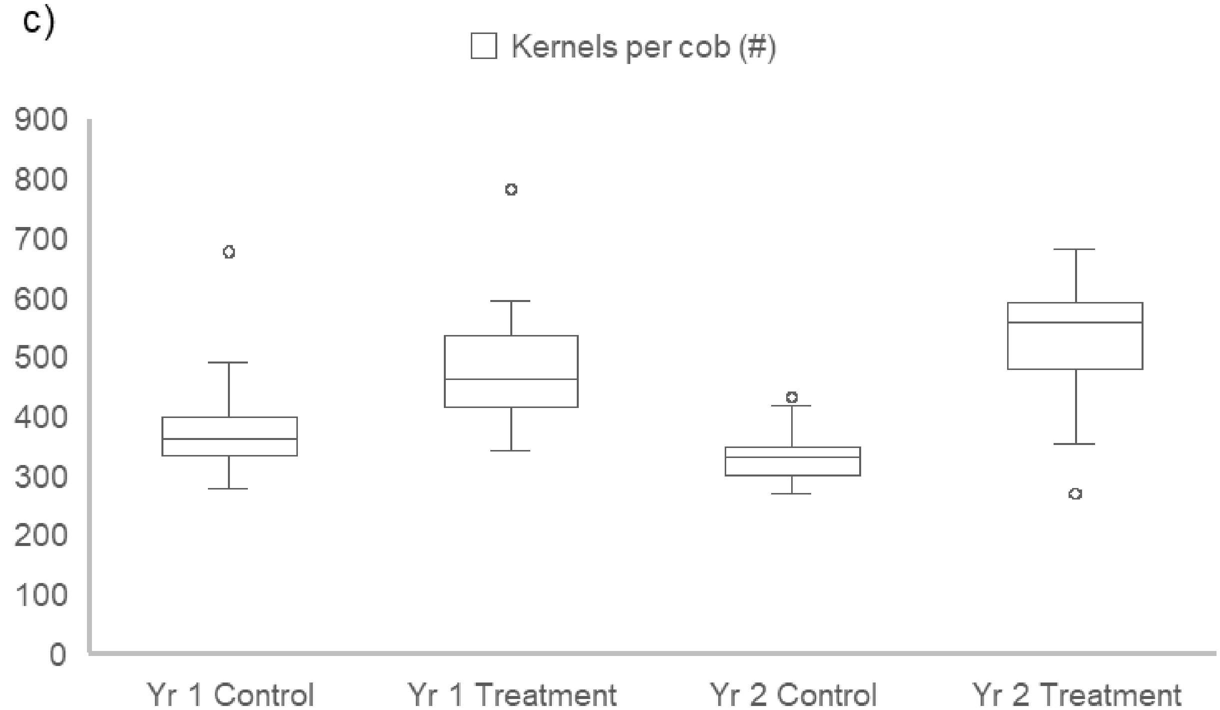


Figure S3. Box plots for a)harvest yield; b) cob length; and c) kernels per cob for Year 1 and Year 2.

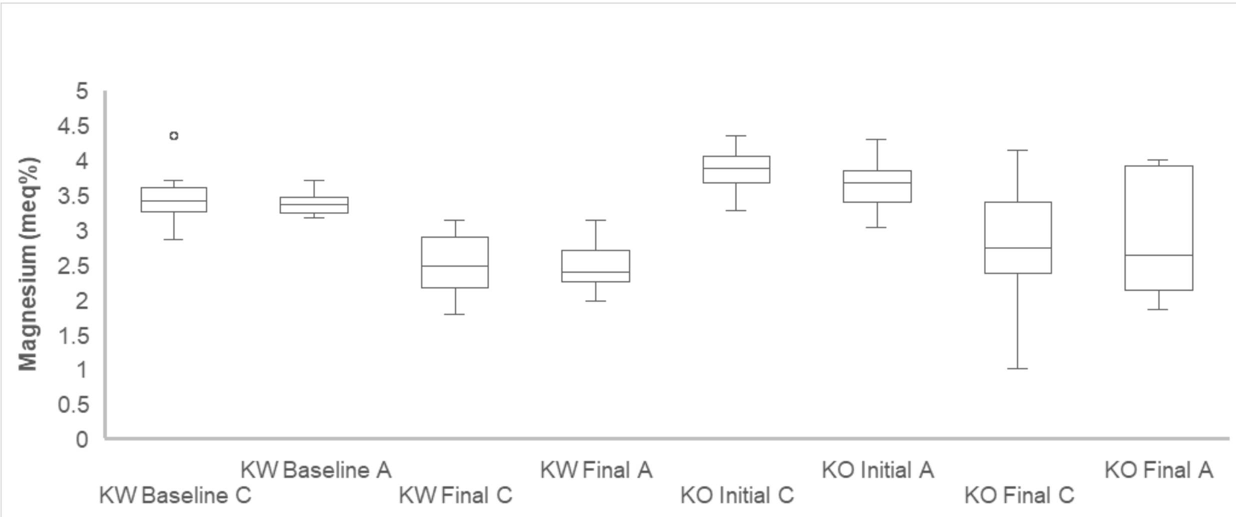
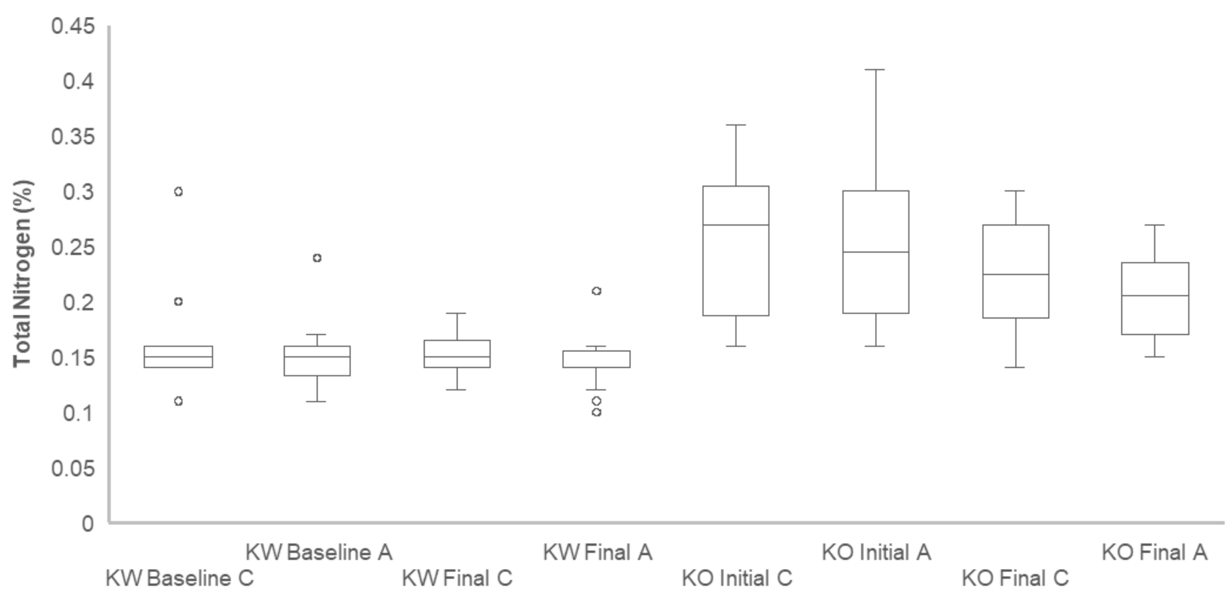


Figure S4. Box plot for magnesium concentration in the soil in control (C) and treated (A) plots for initial soil samples (baseline) and post harvest soil samples (Final). KW=Wawidhi cluster, KO=Ombeyi cluster.



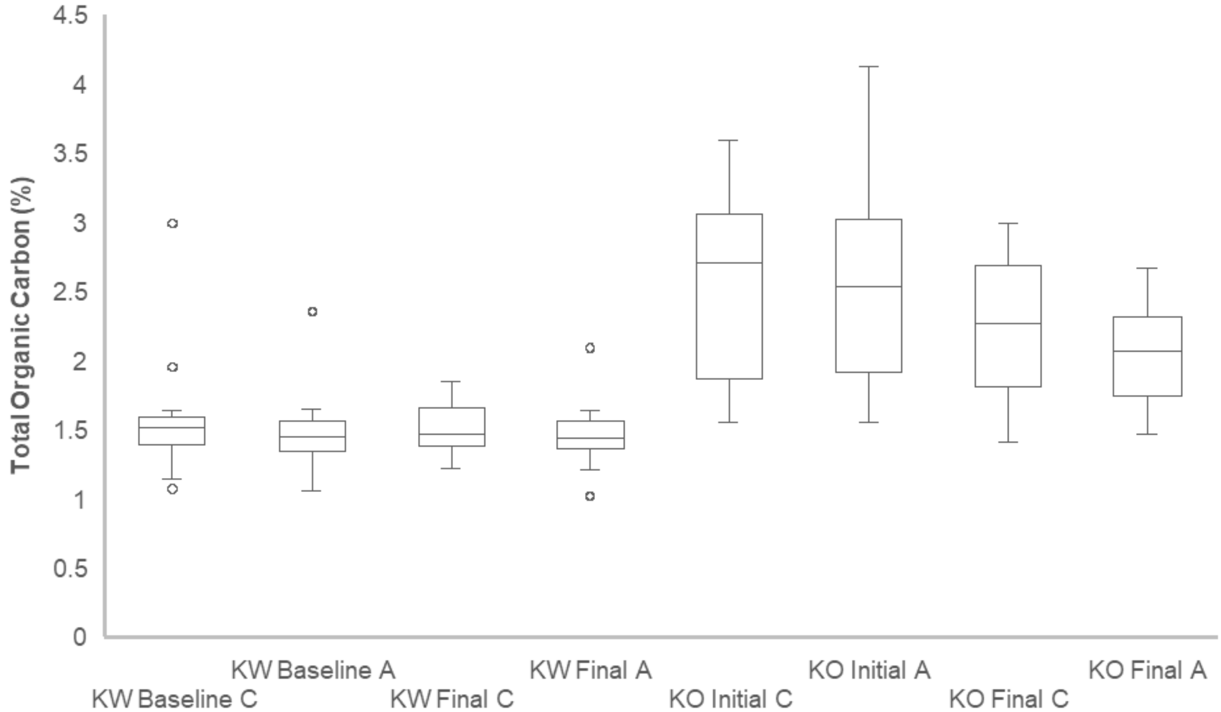
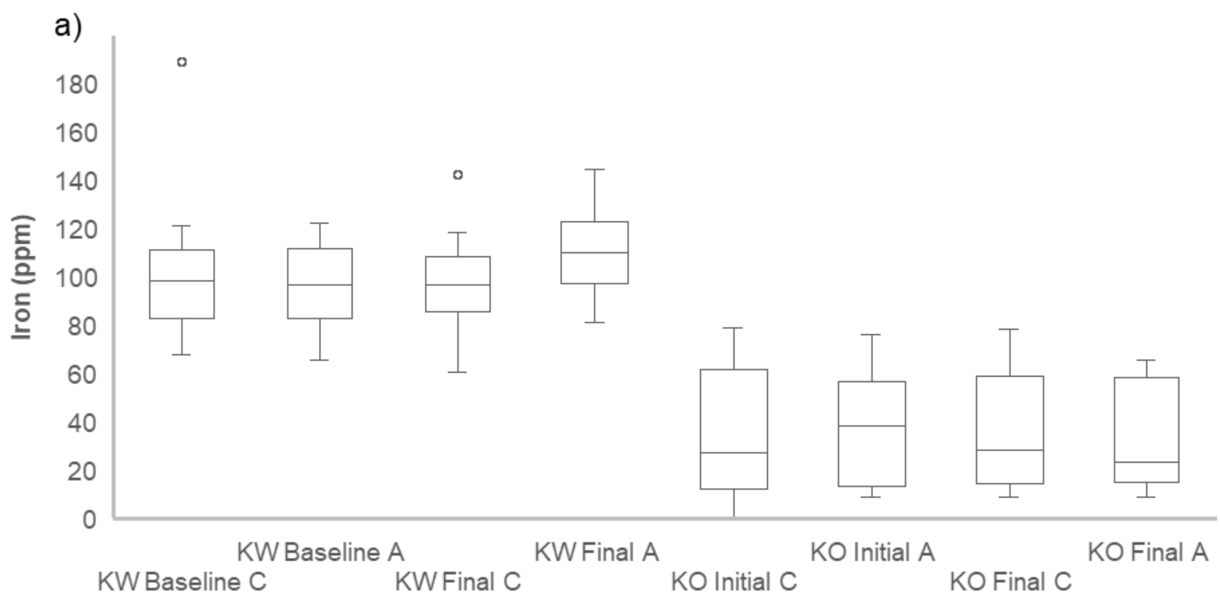


Figure S5. Box plot for a)Total nitrogen, and b)Total Organic Carbon concentration in the soil in control (C) and treated (A) plots for initial soil samples (baseline) and post harvest soil samples (Final). KW=Wawidhi cluster, KO=Ombeyi cluster.



b)

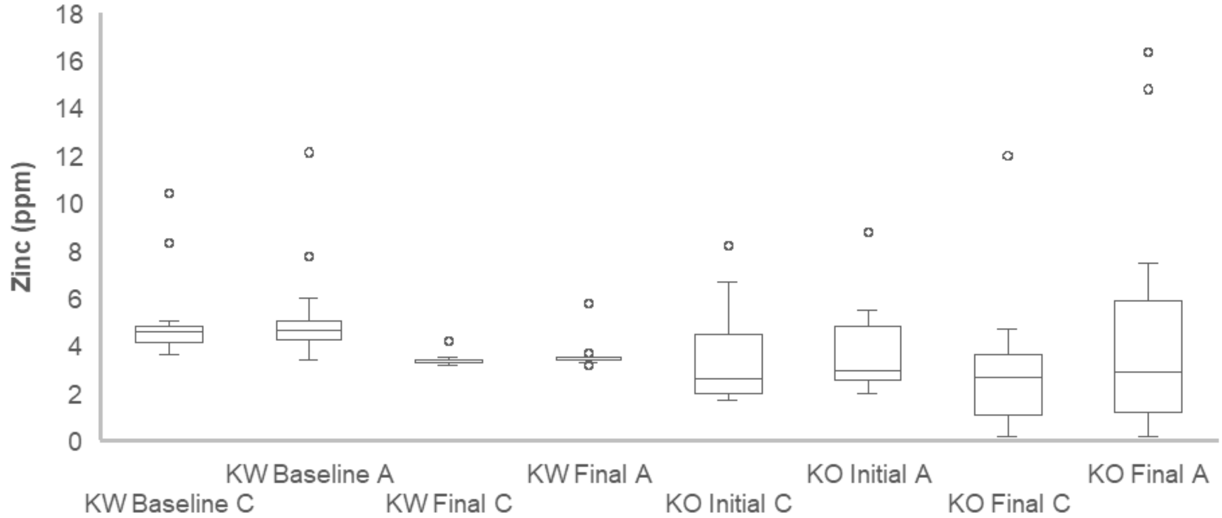


Figure S6. Box plot for a) iron, and b) zinc concentration in the soil in control (C) and treated (A) plots for initial soil samples (baseline) and post harvest soil samples (Final). KW=Wawidhi cluster, KO=Ombeyi cluster.