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An Analysis of the Short-term Effects of Glyphosate and Atrazine Herbicides on Soil pH in Maize Fields Cultivated by Small-Scale Farmers in Mbala

[1] **Teddy Chanda,** [2] **Danny Chisanga Musenge**

[1, 2] Department of Agriculture and Environmental Sciences, Information and Communications University, Zambia Research and Development Centre, Lusaka, Zambia

Corresponding Author: **Teddy Chanda**

Abstract

The use of herbicides has become increasingly common among small-scale farmers as a practical approach to weed control and improved crop yields. However, there are growing concerns about the potential side effects of these chemicals on soil health particularly soil pH, which plays a crucial role in nutrient availability and microbial activity.

Objectives

1. To analyse the Short-Term Effects of Glyphosate and Atrazine Herbicides on Soil pH in Maize Fields Cultivated by Small-Scale Farmers in Mbala
2. To determine Changes in Soil pH resulting from the application of Glyphosate and Atrazine herbicides
3. To determine any correlations between the Glyphosate and Atrazine herbicides used and the magnitude of soil pH changes.

The experiment was conducted on virgin land in Munyezi village, Lunzua Agricultural Camp, located in Mbala District. A randomized complete block design (RCBD) was used to divide the field into three blocks, each with three treatments: glyphosate, atrazine, and a control with no herbicide. Baseline pH levels were established using soil samples collected at the depths (0 –15 cm) before any treatments were applied. Follow-up samples were taken at two-week intervals post-application, resulting in a total of 39 soil samples**,** including composites.

Laboratory analysis showed no statistically significant changes in soil pH following the application of either herbicide compared to the control. The Pearson correlation coefficient between treatments and pH was **- 0.019** (p = **0.925**), indicating a negligible and non-significant relationship. This supports the **null hypothesis** that herbicide application, under the study conditions, does not have a measurable linear effect on soil pH.

This study concludes that short-term application of glyphosate and atrazine does not significantly alter soil pH in virgin soils within smallholder systems. The results suggest that, under the tested conditions, these herbicides may not immediately compromise soil acidity levels.

While the findings provide some reassurance regarding the short-term impact of these herbicides on soil pH, they also underscore the importance of ongoing monitoring of soil health, particularly in low-input, smallholder farming systems where natural soil recovery may be slower.

This research contributes valuable baseline data to the body of knowledge on herbicide-soil interactions and encourages further long-term studies on the broader ecological effects of herbicide use. Promoting sustainable agricultural practices that balance productivity with environmental health remains essential for ensuring long-term soil fertility and food security.

Keywords: Soil pH, Glyphosate, Atrazine, Soil Health, Smallholder Farming, Herbicide Impact

1. Introduction

1.1 Overview

Small-scale farming is an important component of global agricultural activities, making substantial contributions to food production. Within these operations, herbicides are frequently used to effectively manage weeds and bolster crop yield. Nevertheless, the utilization of herbicides prompts apprehensions regarding their implications for soil health, specifically concerning soil pH. Soil pH holds significant importance in determining nutrient availability, microbial activity, and overall soil fertility. Thus, comprehending the effects of herbicides on soil pH stands as a fundamental aspect of fostering sustainable agricultural practices.

1.2 Background of the Study

Herbicides, commonly referred to as weed killers, are chemical agents primarily used to eliminate unwanted vegetation. They are broadly categorised as selective, targeting specific weeds while sparing desired crops, or non-selective, which indiscriminately eradicate all plant material and are used in areas like waste grounds, railways, and industrial sites (Sharma, *et al*., 2019) [19]. Despite their agricultural benefits, the pervasive use of herbicides has raised significant environmental and health concerns. These chemicals can migrate from their application sites, leading to the contamination of soil, water, and air, thereby posing risks to non-target organisms and ecosystem health (Silva, *et al*., 2019) [20]. Human exposure to herbicides occurs through various routes, including ingestion of contaminated food and water, inhalation, and dermal contact during application or from residues (Kim, *et al*., 2021) [12]. This exposure is linked to a range of adverse health effects, from acute poisoning to chronic conditions such as Parkinson's disease and certain cancers (Zhang, *et al*., 2021) [25]. The environmental fate of herbicides is influenced by processes like microbial degradation, photolysis, and hydrolysis, but their persistence can lead to long-term soil and water pollution, particularly through surface runoff (Tudi, *et al*., 2021) [23]. Soil plays a pivotal role in the environmental dynamics of herbicides, acting as a key medium that influences their behaviour, transformation, and potential for leaching. Soil constituents, including organic matter and clay minerals, as well as ions such as H+, Ca2+, Mg2+, K+, and Al3+, interact with herbicides through sorption and desorption processes, which critically affect their bioavailability and mobility (Arias-Estevez, *et al*., 2020). The pH of the soil is a master variable controlling these interactions, influencing the speciation of both the herbicides and the soil ions, thereby determining the ultimate environmental impact (Pose-Juan, *et al*., 2022) [17]. Understanding these complex soil-herbicide interactions is therefore essential for assessing the ecological risks and for developing sustainable agricultural management practices.

1.3 Problem Statement

Small-scale farmers in Mbala, Zambia, face challenges in maintaining soil health, with soil pH being a critical factor influencing nutrient availability and crop productivity. The increased use of herbicides such as glyphosate and atrazine for weed control may alter key soil properties, yet their short-term effects on soil pH remain underexplored (Schneider, *et al*., 2022). Studies indicate that glyphosate can chelate soil cations, leading to slight acidification, while the behaviour of atrazine is less predictable (Mertens, *et al*., 2018). This knowledge gap is significant Even minor fluctuations in soil pH can significantly affect nutrient solubility, maize yields, and the economic viability of smallholder farming systems (Giller, *et al*., 2021). Therefore, this study seeks to analyze the short-term impacts of Glyphosate and Atrazine use by small-scale farmers on soil pH.

1.4 Purpose of the Study

The purpose of this project is to analyse the effects of herbicides used by small-scale farmers on soil pH. This is essential due to its significant implications for agricultural productivity and environmental sustainability. Soil pH influences various soil properties, including nutrient availability, microbial activity, and overall soil health. Herbicides, commonly used in modern agriculture, can change soil pH either directly through their chemical composition or indirectly by affecting microbial populations and nutrient cycling processes. Understanding the effects of herbicides on soil pH is cardinal for optimizing agricultural practices and maximizing crop yield. Soil pH directly affects the availability of essential nutrients to plants. For instance, acidic soils can lead to the leaching of important nutrients like calcium, magnesium, and potassium, while alkaline soils may result in nutrient deficiencies. Research by (Erdle, 2018) emphasizes the importance of maintaining optimal soil pH levels for sustaining agricultural productivity. By analysing the effects of herbicides on soil pH, farmers will be able to make informed decisions about herbicide selection and application rates to minimize adverse effects on soil fertility and crop growth. Furthermore, soil pH plays a vital role in regulating soil microbial communities and their activities. The changes in soil pH resulting from herbicide applications can disrupt microbial populations, affecting nutrient cycling processes and soil organic matter decomposition (Chen, *et al*., 2019). These alterations in microbial activity can have cascading effects on soil health, including soil structure, water retention, and disease suppression. Therefore, investigating the effects of herbicides on soil pH is essential for understanding their broader impacts on soil biota and ecosystem functioning. Additionally, analysing herbicide-induced changes in soil pH is important for assessing the environmental risks associated with herbicide use. Soil acidification or alkalization can affect the mobility and bioavailability of heavy metals and other contaminants, potentially leading to water and air pollution (Xu, *et al*., 2019).

Moreover, alterations in soil pH can influence the degradation and persistence of herbicides in the environment, affecting their efficacy and potential for off-target movement. By evaluating the effects of herbicides on soil pH, the researcher will identify potential environmental risks and develop mitigation strategies to minimize adverse impacts on soil and water quality. In summary, studying the effects of herbicides on soil pH is essential for sustainable agricultural practices and environmental stewardship. Through comprehensive research and monitoring, stakeholders can develop strategies to mitigate adverse effects on soil fertility, microbial communities, and ecosystem health while ensuring the effective control of weeds and pests in agricultural systems.

1.5 Research Objective

1.5.1 Main Objective

The main objective of this research is to analyse the effects of herbicides used by small-scale farmers on soil pH.

1.5.2 Specific Objectives

1. To determine Changes in Soil pH resulting from the application of Glyphosate and Atrazine herbicides.
2. To determine any correlations between the Glyphosate and Atrazine herbicides used and the magnitude of soil pH changes.

1.6 Hypothesis

1. Null hypothesis (H_0): There is no significant change in soil pH resulting from the application of Glyphosate and Atrazine herbicides.

Alternative hypothesis (H_1): There is a significant change in soil pH resulting from the application of Glyphosate and Atrazine herbicides.

2. Null hypothesis (H_0): There is no correlation between the use of Glyphosate and Atrazine herbicides and the magnitude of soil pH changes.

Alternative hypothesis (H_1): There is a correlation between the use of Glyphosate and Atrazine herbicides and the magnitude of soil pH changes.

1.7 Significance of the Study

The findings of this study will provide vital knowledge on sustainable herbicide use and soil management techniques for small-scale farmers, who are very vital for global food security (Tscharntke, *et al*., 2020) [22]. This research is significant as it will offer scientific evidence to policymakers for developing regulations and incentives that promote the adoption of environmentally friendly herbicide alternatives and integrated soil conservation practices (Pretty, 2018) [18]. While herbicides remain essential tools for small-scale farmers to control weeds and secure crop yields (Gianessi, 2019) [8], their application can significantly alter soil pH levels, a critical master variable of soil health (Neina, 2019) [16]. These pH deviations from the optimal range can disrupt nutrient availability and soil microbial activity, ultimately hinder crop growth and productivity and directly impact farmers' livelihoods (Guo, *et al*., 2019) [9]. Certain herbicides can cause soil acidification or alkalization, which disrupts nutrient cycling and can lead to deficiencies or toxicities in crops (Dubey, *et al*., 2020) [5]. By specifically investigating how different herbicides influence soil pH in small-scale farming systems, this study will generate crucial insights. It will contribute to the development of sustainable weed management strategies that protect soil fertility (Zhou, *et al*., 2020) [26]. Ultimately, understanding these interactions is fundamental for devising effective, context-specific soil fertility management strategies that support the economic and environmental resilience of small-scale agriculture (Kopittke, *et al*., 2021) [13].

1.8 Theoretical Framework

A theoretical framework incorporates insights from distinguished authors across various disciplines to guide research endeavours. This study is underpinned by several interconnected theoretical perspectives. Firstly, Ecological Resilience Theory underscores the capacity of ecosystems to withstand disturbances and maintain their fundamental functions (Folke, *et al*., 2021) [7]. By applying this theory, the research examines how herbicide use acts as a disturbance, potentially disrupting soil pH equilibrium. This analysis allows for the exploration of impacts on soil health, crop resilience, and overall system stability within agricultural ecosystems. Additionally, Nutrient Cycling Theory highlights the critical role of soil pH in nutrient availability and cycling processes essential for plant growth (Jiang, *et al*., 2021) [10] The research investigates how herbicide-induced changes in soil pH influence nutrient dynamics and crop nutrient uptake, which is vital for assessing long-term agricultural sustainability. Furthermore, integrating Socio-Ecological Systems (SES) Theory provides a comprehensive lens for analysis by emphasizing the interconnectedness between social, economic, and ecological elements (Colding & Barthel, 2021) [4]. Through this perspective, we examine how farmer decision making, policy frameworks, and environmental conditions interact with the biochemical effects of herbicides on soil pH, collectively shaping agricultural outcomes. Moreover, Environmental Justice Theory is vital in our analysis, as it addresses the equitable distribution of environmental benefits and burdens (Mohai & Saha, 2021) [15]. This research considers how the impacts of herbicide use and subsequent soil pH alterations may disproportionately affect marginalized and small-scale farming communities, highlighting the need for sustainable practices and equitable policy interventions. Lastly, this research aligns with Agroecological Principles, which emphasize holistic and sustainable agricultural approaches based on enhancing biodiversity and ecosystem services (Wezel, *et al*., 2020) [24]. By applying these principles to examine herbicide impacts, with a focus on soil health and resilience in small-scale farming systems, we aim to provide a comprehensive understanding of these complex interactions. In conclusion, this integrated theoretical framework, drawing upon Ecological Resilience, Nutrient Cycling, Socio-Ecological Systems, Environmental Justice, and Agroecological Principles, provides a robust foundation for analysing the effects of herbicides on soil pH and its broader implications for sustainability and equity in small-scale farming.

1.9 Conceptual Framework

A conceptual framework provides a structured outline of the key variables in a study and illustrates their presumed relationships. To analyse the effects of herbicides on soil pH in small scale farming systems, this research is guided by a comprehensive framework that identifies independent variables, dependent variables, and their interactions, as illustrated in Figure 1.

1.9.1 Independent Variables

The independent variables are the factors considered as the primary influences on soil pH. These are primarily related to herbicide application practices and key environmental mediators. The specific chemical properties and mode of action of the herbicide are critical, as some formulations are known to have a higher potential to alter soil pH due to their acidic functional groups or their impact on soil microbial communities (Rose, *et al*., 2016). Furthermore, application practices, including the rate and frequency of use, are significant; higher application rates and more frequent use can lead to cumulative effects, increasing the likelihood and magnitude of soil pH change (Dubey, *et al*., 2020) [5]. These practices do not act in isolation but are mediated by inherent soil characteristics and environmental conditions. The soil type, particularly its content of organic matter and clay, determines its buffering capacity its innate ability to resist pH change. Sandy soils with low organic matter are far more susceptible to acidification than clayey soils with high organic matter content (Neina, 2019) [16]. Additionally, climatic factors such as rainfall influence the leaching, degradation, and persistence of herbicides in the soil profile, thereby indirectly modulating their impact on soil pH over time (Tudi, *et al*., 2021) [23].

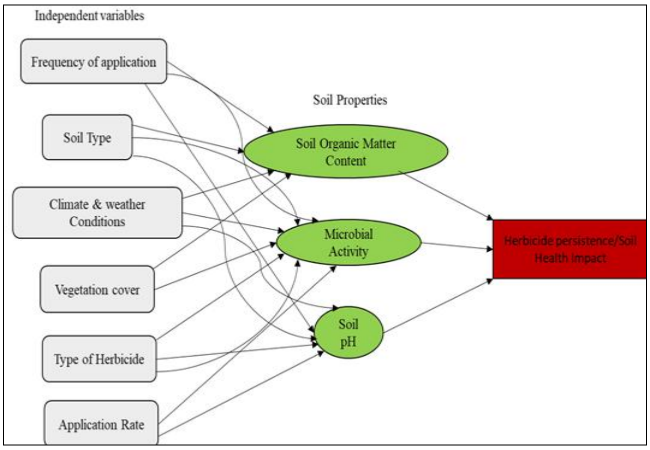


Fig 1: Shows the conceptual framework

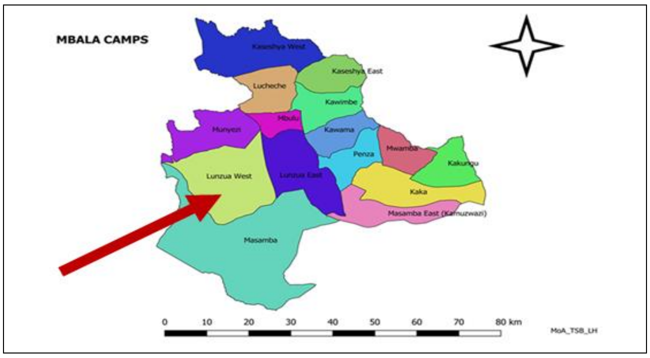
1.9.2 Dependent Variables

The dependent variables are the outcomes that are measured and are expected to change as a result of the independent variables. The primary dependent variable is the soil pH level itself, which is a fundamental master variable indicating soil acidity or alkalinity (Kopittke, *et al*., 2021) [13]. A shift in soil pH directly triggers changes in other critical soil health indicators. It governs the solubility and bioavailability of essential plant nutrients, potentially leading to nutrient deficiencies or toxicities, such as aluminium toxicity in acidic conditions (Jiang, *et al*., 2021) [10]. Concurrently, soil pH is a major determinant of microbial community structure and function, and its alteration can either enhance or suppress the microbial processes that are vital for nutrient cycling and organic matter decomposition (Zhou, *et al*., 2020) [26]. The culmination of these biochemical changes ultimately influences broader agro-ecosystem outcomes, including crop productivity and the long-term environmental sustainability of the farming system, particularly concerning risks of groundwater contamination from mobile herbicides (Silva, *et al*., 2019) [20]. In conclusion, the conceptual framework for this study provides a structured approach to understanding the complex interactions between herbicide use and soil dynamics. It highlights the interplay between management practices, inherent soil properties, and mediating biological and chemical processes. This integrative perspective is essential for developing sustainable agricultural practices that ensure both productivity and ecological health in small-scale farming communities.

3. Materials and Methods

3.1 Experimental Site and Location

The research took place in Katipa village, within the Lunzua West agricultural camp of Mbala District, located in the Northern Province of Zambia. The designated experimental area spanned 18m x 6m and was positioned at geographical coordinates 8.94868°S latitude and 31.292785°E longitude, with an altitude of 1680.34 meters above sea level. This location fell within Agro ecological Region III of Zambia, which experiences an annual rainfall range of 1,000 mm to 1,500 mm and a growing season lasting from 120 to 150 days. The climatic conditions were suitable for cultivating late-maturing crop varieties. The average minimum and maximum temperatures were recorded at 16.6°C and 21.6°C, respectively. According to the FAO/UNESCO soil map, the soil type at the research site was classified as Acrisols. These soils were characterized as well drained, ranging from deep to very deep, and exhibited a yellowish-red to strong brown coloration. They generally possessed a friable consistency and a fine, loamy texture, with clay content increasing with depth. Chemically, they exhibited low cation exchange capacity and base saturation, typically maintaining an acidic pH level. Additional observations noted that the experimental site experienced seasonal variations in soil moisture and temperature, which influenced crop growth patterns. Regular soil sampling and analysis were conducted to monitor changes in soil properties and adjust management practices accordingly.



3.2 Materials

The materials used in this research included Maize SC 303, Glyphosate, Atrazine, a knapsack sprayer, a slasher, a hand hoe, measuring tape, rope, pegs, compound D, and urea fertilizers. All the materials were sourced from authorized agro shops in Mbala town. SC 303 was chosen for this study because it is an ultra-early maturing variety with a physiological maturity of 90-110 days, considering that the research was conducted under irrigation. Knapsack sprayer: This portable spraying device, worn on the back, consisted of a tank, pump, nozzle, and straps. It was used for applying herbicides in the research field. Slasher: This handheld tool, with a long handle and a curved blade at the end, was used to cut and clear the land. Hand hoe: This gardening tool, with a long handle and a flat metal blade, was used for tilling and making the beds.

Measuring tape: This flexible tool with linear measurements was used for measuring distances and marking the plots to ensure precision and uniformity. String: This line, made of twisted strands intertwined into one sturdy length, was used for laying out the plots. Pegs: These were used for securing the string during the layout process. Polythene plastic: This was used for storing soil samples.

3.3 Data Recording Tool

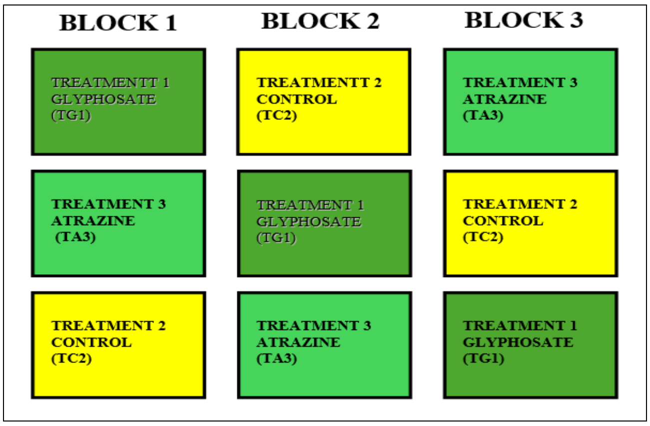
The collected data was recorded on field notebook sheets and subsequently entered into Excel worksheets and a digital phone notebook. The data collection primarily consisted of soil samples, which were gathered and prepared for laboratory analysis. These soil samples were then sent to the laboratory for detailed analysis and further processing. Additionally, GPS coordinates of the sampling locations were recorded to ensure accurate mapping and correlation of soil properties with specific field sites. Notes on weather conditions and any relevant observations during sampling were also included to provide context for the laboratory results.

3.4 Experimental Design with Treatments

The research study adopted a randomized complete block design (RCBD) comprising three blocks, with each block containing three treatments replicated three times. The total experimental area covered 0.0108 hectares, divided into 9 subunits, each measuring 5 meters by 1 meter. Buffer zones of 1.5 meters between blocks and 1.5 meters between plots were maintained to prevent herbicide drift during spraying. The experiment was conducted on virgin land, devoid of any prior herbicide application. The following treatments were employed:

1. Control (no herbicide application)
2. Glyphosate
3. Atrazine

These treatments were applied at the beginning of the experiment. Planting involved the SC303 ultra-early maturing variety, with a density of 20 kilograms per hectare, spaced at 90 centimetres inter-row and 25 centimetres intra-row. Fertilization included the application of 200 kilograms per hectare of compound D fertilizer at planting, supplemented by 200 kilograms per hectare of urea 6 weeks after germination.



3.5 Cultural Practices

The land underwent tillage at a depth of 15-20 cm, aimed at weed control and soil structure enhancement in preparation for crop cultivation. This process ensured consistent soil preparation and uniform weed growth stages for subsequent herbicide application in the experimental field. Following tillage, harrowing was conducted to break down larger clods, achieving a fine tilth. Soil sampling was carried out across the experimental area to assess soil acidity, alkalinity, and the presence of chemical elements and compounds. Subsequently, an experimental design and layout, depicted in Figure 1, was established. Basal dressing with Compound D fertilizer was applied during planting, followed by irrigation and application of atrazine and glyphosate herbicides at recommended rates. Urea fertilizer was applied as top dressing six weeks after germination. Additionally, regular field assessments were conducted to evaluate crop growth stages and development, facilitating timely interventions for nutrient management and pest control. The data collected from these practices contributed to refining and optimizing the overall cultural practices for future crop cycles.

3.6 Data Collection

Soil samples were collected before herbicide application using a hand hoe across all treatment plots. Samples were gathered at the specified depth of 20cm, ensuring representation from each treatment within the experimental field. Precautions were taken to eliminate large stones and plant debris from the samples. From the experimental site, twelve soil samples, replicated thrice, were obtained per soil sampling session. For each treatment, three soil samples were collected. Then, nine samples were combined to create a composite sample, resulting in one composite sample per treatment. Each composite sample was carefully labelled with the treatment name and stored in polythene plastic bags. Utilizing composite sampling methods offered several advantages, including cost-effectiveness, efficient utilization of analytical time, and ensuring each sample contributed equally to the overall composite. Additionally, composite sampling provided a representative estimate of the population mean, as each sample contributed equally to the composite. Following collection, the soil samples were transported to the laboratory for analysis. Post-treatment sampling occurred over eight weeks at two-week intervals as part of the research protocol.

3.7 Data Analysis

The data generated from the experimental field plots where atrazine and glyphosate were applied, alongside the control plot, underwent logarithm transformation and were then presented in graphical form. The Statistical Package for the Social Sciences (SPSS) facilitated the comparison of the mean effects of herbicides on plots treated with atrazine and glyphosate against the control. Analysis of Variance (ANOVA) was subsequently employed to test for significant differences among the experimental field soils.

3.8 Ethical Consideration

When conducting experimental research on the effects of herbicides used by smallholder farmers on soil pH, ethical considerations were rigorously observed to safeguard both human well-being and environmental integrity. Before commencing the experimentation on the land, the researcher obtained informed consent from smallholder farmers, ensuring that they were fully briefed on the research's purpose, associated risks, and potential benefits. This process involved conducting meetings and informational sessions where farmers were encouraged to ask questions and express concerns, thus ensuring their understanding and voluntary participation.

Moreover, proactive measures were taken to minimize adverse impacts on the environment and soil health. These included implementing strict protocols to avoid the excessive use of herbicides and selecting experimental methodologies that would not inflict enduring harm on soil quality.

Transparency was paramount throughout the research process. The researcher openly shared the methodologies, findings, and any potential conflicts of interest with the stakeholders. This included providing detailed reports and presentations to both the participating farmers and the broader scientific community, fostering accountability and facilitating knowledge exchange. Additionally, the researcher respected the traditional knowledge and soil management practices of smallholder farmers, integrating indigenous perspectives into both the research design and result interpretation. This approach helped ensure that the research was culturally sensitive and aligned with local agricultural practices.

Furthermore, the equitable distribution of benefits derived from the research, such as advancements in soil management practices, was emphasized. Efforts were made to ensure that these benefits were shared fairly among farmers and their communities. This encompassed providing accessible information and resources to empower farmers in implementing sustainable agricultural practices, such as workshops and training sessions focused on soil conservation techniques and the responsible use of herbicides. By involving the farmers in the dissemination of knowledge and practices, the research aimed to promote long-term sustainability and community empowerment.

3.9 Safety Precautions

The researcher undertaking this project meticulously adhered to the instructions and warning labels provided on all products utilized. This included comprehensive guidance on handling, mixing, application, and proper disposal protocols. Appropriate personal protective equipment (PPE) was worn throughout the duration of the project. This included gloves, goggles, long-sleeved shirts, long pants, and gumboots, safeguarding against potential chemical exposure to the skin, eyes, and respiratory system. The researcher undertaking this project meticulously adhered to the instructions and warning labels provided on all products utilized. This included comprehensive guidance on handling, mixing, application, and proper disposal protocols. Appropriate personal protective equipment (PPE) was worn throughout the duration of the project. This included gloves, goggles, long-sleeved shirts, long pants, and gumboots, safeguarding against potential chemical exposure to the skin, eyes, and respiratory system. Moreover, strict adherence to recommended dilution rates as stipulated on product labels was maintained, ensuring that concentrations did not surpass recommended levels. Over-application beyond specified concentrations could have had detrimental environmental consequences. To further mitigate risks, measures were taken to prevent contamination of water sources, groundwater, and soil. This included proactive avoidance of spills, leaks, or runoff from the application area, as well as exercising caution during equipment cleaning to prevent any inadvertent contamination of water bodies or soil. Disposal procedures were conducted in accordance with local regulations, ensuring the proper disposal of empty containers, leftover solutions, and any unused products. By meticulously adhering to these safety precautions and protocols, the researcher not only ensured the integrity of the research project but also prioritized the health and safety of both individuals and the environment. Additional measures included regular training sessions on safety protocols for all team members involved in the project, and the establishment of an emergency response plan to address any accidental exposures or spills promptly. The researcher also conducted routine inspections of PPE and safety equipment to ensure they were in good condition and replaced any damaged items immediately. All safety incidents, no matter how minor, were documented and reviewed to improve future safety measures over, strict adherence to recommended dilution rates as stipulated on product labels was maintained, ensuring that concentrations did not surpass recommended levels. Over-application beyond specified concentrations could have had detrimental environmental consequences. To further mitigate risks, measures were taken to prevent contamination of water sources, groundwater, and soil. This included proactive avoidance of spills, leaks, or runoff from the application area, as well as exercising caution during equipment cleaning to prevent any inadvertent contamination of water bodies or soil. Disposal procedures were conducted in accordance with local regulations, ensuring the proper disposal of empty containers, leftover solutions, and any unused products. By meticulously adhering to these safety precautions and protocols, the researcher not only ensured the integrity of the research project but also prioritized the health and safety of both individuals and the environment. Additional measures included regular training sessions on safety protocols for all team members involved in the project, and the establishment of an emergency response plan to address any accidental exposures or spills promptly. The researcher also conducted routine inspections of PPE and safety equipment to ensure they were in good condition and replaced any damaged items immediately. All safety incidents, no matter how minor, were documented and reviewed to improve future safety measures.

3.10 Limitations

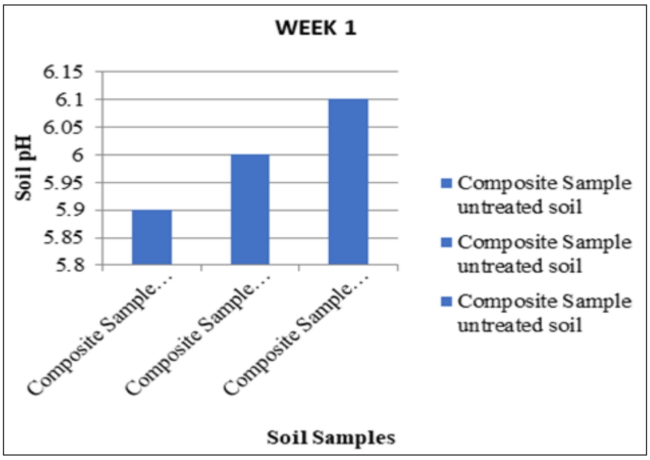
Soil pH was subject to influence from a range of environmental factors including climate, soil type, topography, and drainage. These variables introduced confounding elements, complicating the direct attribution of soil pH changes solely to herbicide application. Moreover, smallholder farmers commonly utilized diverse herbicides, each with distinct chemical compositions and application rates. This variability posed a challenge in isolating the individual impacts of specific herbicides on soil pH. Compounded by limited resources, the researcher faced constraints in conducting comprehensive analyses, potentially restricting the inclusion of additional parameters beyond pH due to unfunded research initiatives. Additionally, the variability in soil sampling techniques and the temporal differences in herbicide application added further complexity to the analysis. The lack of standardized methods and limited access to advanced analytical tools further hindered the ability to draw definitive conclusions. These limitations underscored the need for more extensive, well-funded studies to fully understand the relationship between herbicide use and soil pH changes.

4. Results

The table below presents the soil pH levels in different blocks before the application of herbicides during the first week of observation. Composite soil samples were collected from each block to ensure an accurate representation of the soil's baseline acidity. The untreated soil samples showed slight variations in pH, as detailed below:

Week	Block	Treatments	pH
1	1	Composite Sample untreated soil	5.9
1	2	Composite Sample untreated soil	6
1	3	Composite Sample untreated soil	6.1

Source: Author, 2025



Source: Author, 2025

Fig 2: pH Levels of Composite Samples of Untreated Soil in Different Blocks during Week1

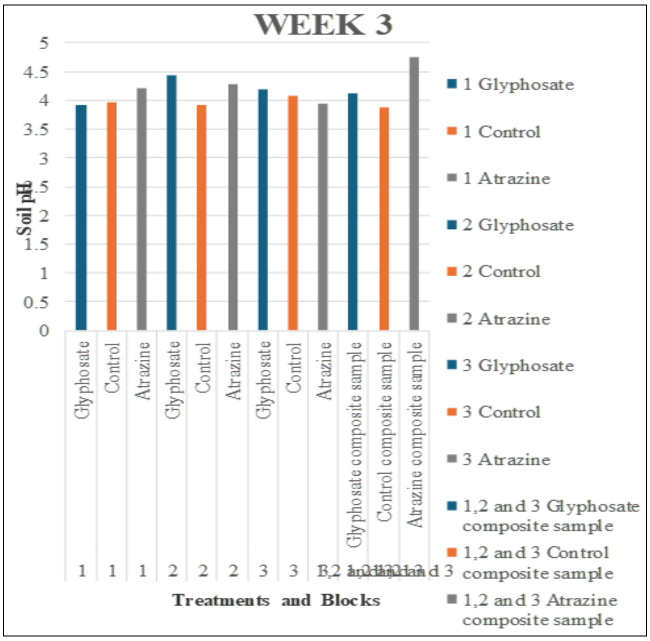
The bar graph above illustrates the pH levels of untreated soil samples collected from three different blocks in Week 1. The pH levels range from 5.9 to 6.1 across the blocks. Specifically, Block 1 has a pH of 5.9, Block 2 has a pH of 6.0, and Block 3 has the highest pH level of 6.1. These variations, although slight, may indicate minor differences in soil properties between the blocks. In this study, the pH levels of untreated soil were measured in three different blocks during Week 1 to assess the baseline soil conditions before any treatment application. The results, as depicted in Figure 1, show a slight variation in soil pH across the blocks. Block 1 recorded a pH of 5.9, Block 2 had a pH of 6.0, and Block 3 showed a slightly higher pH of 6.1. These values suggest that the soil in all blocks is slightly acidic, which could influence the effectiveness of subsequent treatments. Understanding these baseline conditions is crucial for evaluating the impact of the treatments on soil pH in later stages of the research.

Table 1: Depicts Soil pH Levels Recorded after Three Weeks of Herbicide Application (Week 3)

Week 3	Block	Treatments	pH
3	1	Glyphosate	3.93
3	1	Control	3.97
3	1	Atrazine	4.22
3	2	Glyphosate	4.44
3	2	Control	3.92
3	2	Atrazine	4.27
3	3	Glyphosate	4.2
3	3	Control	4.08
3	3	Atrazine	3.94
3	1,2 and 3	Glyphosate composite sample	4.13
3	1,2 and 4	Control composite sample	3.88
3	1,2 and 5	Atrazine composite sample	4.75

Source: Author, 2025

This table presents the soil pH values measured after two weeks of applying different herbicide treatments across three blocks. The treatments include Glyphosate, Atrazine, and a Control (no herbicide application). Soil samples were taken from each block and analysed separately. Additionally, composite samples were created by combining soils from multiple blocks to assess the overall impact of each treatment on soil pH. The composite samples reflect the average pH of the treated soils across the respective blocks.



Source: Author, 2025

Fig 3: Effect of Glyphosate, Atrazine, and Control Treatments on Soil pH in Week 3 across Different Blocks

The bar graph illustrates the soil pH levels observed in Week 3 across three blocks, along with composite samples for each treatment: Glyphosate, Atrazine, and Control. The pH levels vary depending on the block and treatment, indicating different impacts of each herbicide on soil acidity. In Block 1, the soil pH was slightly acidic for all treatments, with Atrazine showing the highest pH value (4.22), followed by the Control (3.97) and Glyphosate (3.93). In Block 2, Glyphosate had the highest pH value (4.44), while the Control showed the lowest pH (3.92), indicating a noticeable effect of Glyphosate on reducing soil acidity. In Block 3, the Control treatment recorded a relatively higher pH (4.08), while Atrazine had the lowest pH value (3.94). For the composite samples, Atrazine exhibited the highest pH value (4.75), indicating its overall effect in increasing soil pH when averaged across the blocks. The composite for Glyphosate showed a pH of 4.13, while the Control sample had the lowest pH (3.88).

In Week 3, the soil pH levels were analyzed across different blocks under the application of Glyphosate, Atrazine, and the Control treatments. The data, represented in the bar graph, highlights the differential impact of each herbicide on soil pH across the blocks.

It is evident that the soil pH varied depending on the treatment applied, with Atrazine generally showing a tendency to increase the soil pH compared to Glyphosate and Control. In Block 2, Glyphosate resulted in a notably higher pH value, indicating a less acidic condition compared to the Control. The composite samples further emphasized this trend, with Atrazine significantly raising the soil pH to 4.75, suggesting its potential role in neutralizing soil acidity when considered across multiple blocks.

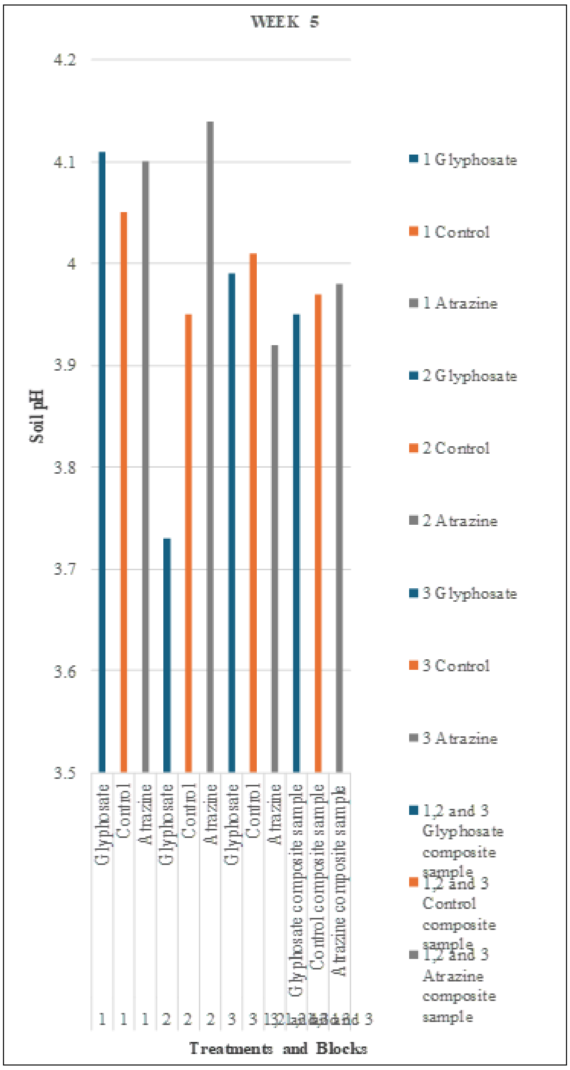
These observations suggest that both Glyphosate and Atrazine have distinct effects on soil pH, which could have implications for soil health and crop productivity. Further analysis may be needed to understand the long-term impacts of these treatments on soil characteristics and to determine the optimal conditions for their application in different agricultural settings.

Table 2: Below Shows Soil pH Levels Measured Five Weeks after Herbicide Application across Different Blocks and Treatments

Week 5	Block	Treatments	pH
5	1	Glyphosate	4.11
5	1	Control	4.05
5	1	Atrazine	4.1
5	2	Glyphosate	3.73
5	2	Control	3.95
5	2	Atrazine	4.14
5	3	Glyphosate	3.99
5	3	Control	4.01
5	3	Atrazine	3.92
5	1,2 and 3	Glyphosate composite sample	3.95
5	1,2 and 4	Control composite sample	3.97
5	1,2 and 5	Atrazine composite sample	3.98

Source: Author, 2025

This table presents the soil pH values recorded in three different blocks following four weeks of herbicide application. The treatments included Glyphosate, Atrazine, and a Control (no herbicide applied). Additionally, composite samples were taken from Blocks 1, 2, and 3 for each treatment to provide an overall assessment of soil pH influenced by the herbicide application. The pH values indicate slight variations in soil acidity, reflecting the impact of each treatment on soil chemistry.



Source: Author, 2025

Fig 4: Effect of Glyphosate, Atrazine, and Control Treatments on Soil pH in Week 5 across Different Blocks

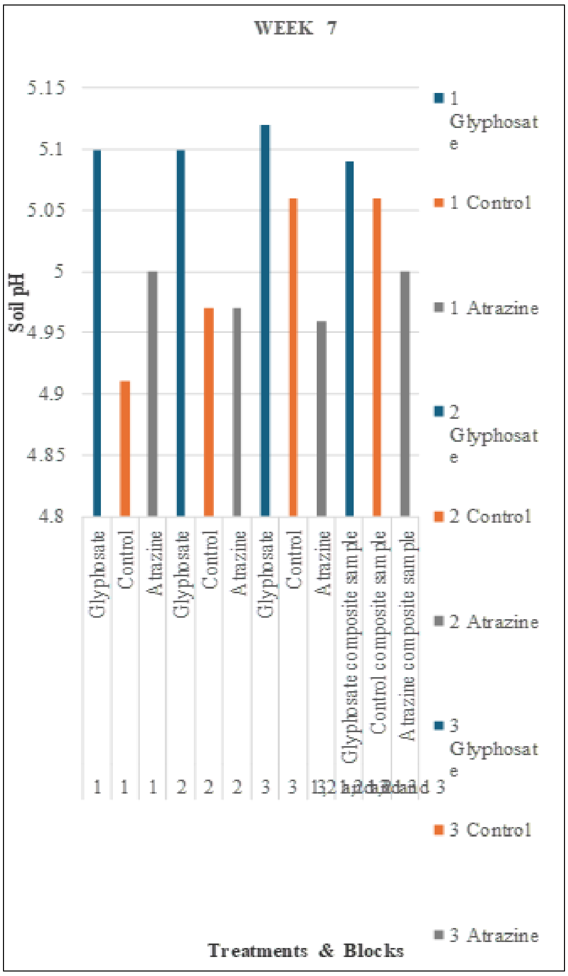
The bar graph in Figure 6 shows the impact of different treatments (Glyphosate, Control, and Atrazine) on soil pH during week 5. At block 5.1, Atrazine had the highest pH of 4.15, while Control had the lowest at 4.05. Glyphosate showed a slight decrease in pH at block 5.2, but rebounded at block 5.3. Composite samples across the three treatments also indicated that Atrazine had a higher average pH compared to both Glyphosate and Control. We analyse the influence of Glyphosate, Control, and Atrazine treatments on soil pH levels over a specified period. As depicted in Figure 6, Atrazine consistently resulted in higher pH levels, suggesting its impact on soil alkalinity. On the contrary, the Control group maintained a comparatively steady pH level throughout the observed blocks. Glyphosate, although initially showing fluctuations, eventually demonstrated stabilization in soil pH, aligning closely with the Control group. These findings underscore the variability in soil pH response to different herbicidal treatments, which can be crucial for understanding their broader environmental impacts.

Table 3: Below shows Soil pH Levels after Seven Weeks of Herbicide Application

Week 7	Block	Treatments	pH
7	1	Glyphosate	5.1
7	1	Control	4.91
7	1	Atrazine	5
7	2	Glyphosate	5.1
7	2	Control	4.97
7	2	Atrazine	4.97
7	3	Glyphosate	5.12
7	3	Control	5.06
7	3	Atrazine	4.96
7	1,2 and 3	Glyphosate composite sample	5.09
7	1,2 and 4	Control composite sample	5.06
7	1,2 and 5	Atrazine composite sample	5

Source: Author, 2025

This table presents the soil pH measurements taken during the seventh week following the application of herbicides in different treatment blocks. The treatments included Glyphosate, Atrazine, and a Control (no herbicide applied). Soil pH was measured individually for each block and as a composite sample combining results from multiple blocks. The data highlights the slight variations in soil pH due to the herbicide treatments, with Glyphosate showing a consistent trend of slightly higher pH values across all blocks compared to the Control and Atrazine treatments. The composite samples indicate an average pH value across the blocks for each treatment, providing a broader perspective on the herbicide impact on soil pH over the six-week period.



Source: Author, 2024

Fig 5: Effect of Glyphosate, Atrazine, and Control Treatments on Soil pH in Week 7 across Different Blocks

The bar graph in Figure 7 depicts the influence of Glyphosate, Control, and Atrazine treatments on soil pH during week 7. At block 3, Glyphosate recorded the highest pH at 5.17, while Control had the lowest at 4.91. Atrazine maintained a relatively stable pH close to five across all blocks. The composite samples showed that Glyphosate treatment resulted in a slightly higher average pH compared to Control and Atrazine. We investigate the effects of Glyphosate, Control, and Atrazine treatments on soil pH levels over week 7. As illustrated in Figure 7, the Glyphosate treatment led to the highest soil pH readings, particularly notable at block 3. Conversely, the Control group exhibited the lowest pH levels, highlighting its neutral impact compared to herbicidal treatments. Atrazine, though less impactful than Glyphosate, demonstrated a consistent pH level across all blocks. The composite samples further emphasize Glyphosate's tendency to increase soil pH more significantly than the other treatments. These observations are crucial for understanding the varying environmental effects of these treatments, providing valuable insights for sustainable agricultural practices.

4.1 Descriptive Statistics of Soil pH

The descriptive statistics of soil pH across the three treatment groups Glyphosate, Control, and Atrazine are presented in Table 4.1. The analysis was based on 27 soil samples, with nine observations per treatment.

Table 4: Descriptive Statistics for Soil pH by Treatment Group

Descriptive								
Soil pH								
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Glyphosate	9	4.4133	.55457	.18486	3.9871	4.8396	3.73	5.12
Control	9	4.3244	.49548	.16516	3.9436	4.7053	3.92	5.06
Atrazine	9	4.3911	.45369	.15123	4.0424	4.7398	3.92	5.00
Total	27	4.3763	.48475	.09329	4.1845	4.5681	3.73	5.12

The mean soil pH for the Glyphosate-treated plots was 4.41 with a standard deviation of 0.55, indicating slight variability in pH levels within the group. The Control group had a slightly lower mean pH of 4.32 and a standard deviation of 0.50. The Atrazine group showed a mean pH of 4.39 and exhibited the least variability among the three treatments (SD = 0.45).

Overall, the total mean soil pH across all groups was 4.38 (SD = 0.48). The 95% confidence interval for the total mean ranged from 4.18 to 4.57, suggesting that the true mean soil pH of the sampled population likely falls within this range. The minimum and maximum observed soil pH values were 3.73 and 5.12, respectively, indicating that the soil remained moderately acidic across all treatments.

4.2 Multiple Comparisons of pH Across Treatments

Post-hoc analyses were conducted to evaluate pairwise differences in soil pH across the three treatment groups: Glyphosate, Atrazine, and Control. Both Tukey's HSD and Tamhane's T2 tests were utilized to assess the significance of differences between the groups. The results are presented in Table 6.

Table 5: Multiple Comparisons of pH Values across Treatments

Multiple Comparisons							
Dependent Variable: pH							
	(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Turkey HSD	Glyphosate	Control	.08889	.23709	.926	-.5032	.6810
		Atrazine	.02222	.23709	.995	-.5699	.6143
	Control	Glyphosate	-.08889	.23709	.926	-.6810	.5032
		Atrazine	-.06667	.23709	.957	-.6588	.5254
	Atrazine	Glyphosate	-.02222	.23709	.995	-.6143	.5699
		Control	.06667	.23709	.957	-.5254	.6588
Tamhane's	Glyphosate	Control	.08889	.24789	.979	-.5726	.7504
		Atrazine	.02222	.23884	1.000	-.6171	.6615
	Control	Glyphosate	-.08889	.24789	.979	-.7504	.5726
		Atrazine	-.06667	.22394	.988	-.6639	.5306
	Atrazine	Glyphosate	-.02222	.23884	1.000	-.6615	.6171
		Control	.06667	.22394	.988	-.5306	.6639

4.3 Interpretation of Results

The results of the multiple comparison analysis indicate that there were no statistically significant differences in soil pH among the three treatment groups Control, Glyphosate, and Atrazine. Both Tukey's Honest Significant Difference (HSD) and Tamhane's T2 post-hoc tests consistently yielded p-values well above the conventional significance threshold of $\alpha = 0.05$, suggesting that the observed differences in mean pH values were not statistically meaningful. Specifically, the largest mean difference reported by Tukey's HSD was between the Glyphosate and Control groups (Mean Difference = 0.08889, $p = 0.926$), while the smallest was between Glyphosate and Atrazine (Mean Difference = 0.02222, $p = 0.995$). The Tamhane's T2 results mirrored this pattern, further confirming the lack of significant variation. Additionally, all confidence intervals for the pairwise comparisons included zero, providing further statistical evidence that the treatments did not differ in their effect on soil pH. These findings collectively suggest that, under the experimental conditions employed in this study, neither Glyphosate nor Atrazine significantly altered soil pH when compared to untreated controls. This implies that herbicide application had minimal or negligible impact on soil acidity or alkalinity, reinforcing the stability of soil pH in response to these treatments.

4.4 Analysis of Variance (ANOVA) for pH Levels

To determine whether there are statistically significant differences in **pH levels** between the different groups, a one-way Analysis of Variance (ANOVA) was conducted. The results are summarized in Table 8 below.

Table 6: One-Way ANOVA for pH

ANOVA					
pH					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.039	2	.019	.076	.927
Within Groups	6.071	24	.253		
Total	6.110	26			

Source: Author, 2025

The between-groups sum of squares is 0.039 with 2 degrees of freedom (df), while the within-groups sum of squares is 6.071 with 24 degrees of freedom, resulting in a total sum of squares of 6. 110.The F-statistic is 0.076, with a significance value (p-value) of 0.927. Since the p-value is much greater than the conventional alpha level of 0.05, the result is not statistically significant.

There is no statistically significant difference in the mean pH levels among the groups compared. This implies that the group variable (e.g., treatment or categorical factor) does not have a significant effect on the pH values.

4.5 Correlation Analysis Between pH and Treatment

To better understand the interaction between pH levels and the type of treatment administered, a Pearson correlation analysis was performed. This statistical method is commonly used to measure the strength and direction of the linear relationship between two continuous variables in this case, pH and Treatment. The analysis aimed to determine whether variations in treatment had any measurable association with changes in pH. A positive correlation would suggest that as the intensity or dosage of treatment increases, pH levels also rise. Conversely, a negative correlation would imply that higher levels of treatment correspond to a decrease in pH. The findings of this analysis are presented in Table 9. These results offer valuable insights into how treatment interventions may influence the chemical balance of the environment or system being studied. Understanding this relationship is very cardinal for evaluating the effectiveness and potential side effects of the treatments applied.

Table 7: Pearson Correlation Between pH and Treatment

Correlations			
		pH	Treatment
pH	Pearson Correlation	1	-.019
	Sig. (2-tailed)		.925
	Sum of Squares and Cross-products	6.110	-.200
	Covariance	.235	-.008
	N	27	27
Treatment	Pearson Correlation	-.019	1
	Sig. (2-tailed)	.925	
	Sum of Squares and Cross-products	-.200	18.000
	Covariance	-.008	.692
	N	27	27

Source: Author, 2024

The analysis reveals that there is virtually no meaningful linear relationship between pH and Treatment. This is evident from the Pearson correlation coefficient of -0.019, which is extremely weak and negative so close to zero that it suggests no real association between the two variables.

Additionally, the significance level ($p = 0.925$) is well above the commonly accepted threshold of 0.05, indicating that the observed correlation is not statistically significant. As a result, we fail to reject the null hypothesis, which posits no linear relationship between pH and Treatment. The sample size for both variables is consistent at 27, providing a stable basis for the analysis. Furthermore, the covariance between pH and Treatment is -0.008, a near-zero value that further reinforces the lack of a meaningful connection. Taken together, these findings suggest that variations in Treatment do not correspond to significant changes in pH levels within this dataset, implying that Treatment does not have a detectable effect on pH.

5. Discussion, Conclusion and Recommendations

5.1 Overview

This chapter provides a detailed interpretation of the research findings presented in Chapter Four, discusses their implications, and offers practical recommendations for smallholder farmers, policymakers, and researchers. The chapter also outlines directions for future research. The discussion is anchored in the study's objective: to analyse the effects of herbicide application on soil pH among small-scale farmers in Mbala District. The structure follows the research objectives and statistical results presented earlier.

5.1 Initial Conditions

The initial characterisation of the soil, conducted at baseline (Week 1), established the fundamental physicochemical parameters against which all subsequent treatment effects were measured. Analysis revealed that the soil pH levels across all experimental units ranged from 5.9 to 6.1, with a mean of 6.0. This categorises the soil as slightly acidic, a condition frequently observed in tropical agricultural soils where intense weathering and leaching of basic cations (such as Ca^{2+}, Mg^{2+}, and K^{+}) are common pedogenic processes (Brady & Weil, 2016; Sanchez, 2019). This mildly acidic state is a critical determinant of soil biogeochemistry, with profound implications for the study's outcomes. Primarily, it governs the bioavailability of essential plant nutrients. In acidic conditions, macronutrients like phosphorus (P) can become immobilised through fixation with aluminium (Al) and iron (Fe) ions, rendering them less accessible for plant uptake (Havlin, *et al*., 2016). Concurrently, the solubility of potentially phytotoxic elements, notably aluminium and manganese, increases, which can inhibit root development and function (Kochian, *et al*., 2015). Furthermore, soil pH is a principal regulator of microbial community structure and enzymatic activity. Many key soil bacteria involved in nutrient cycling, such as nitrification, exhibit optimal functionality within a narrower, near-neutral pH range, meaning the initial acidic conditions may have suppressed certain microbial processes at the outset of the experiment (Fierer & Jackson, 2006) Therefore, the baseline pH of 6.0 established a soil environment where nutrient availability and microbial activity were potentially sub-optimal, providing a significant scope for amendment-induced remediation and creating a clear context for interpreting the efficacy of the applied treatments in altering these conditions.

5.2 Post-Herbicide Application Trends

The application of herbicides induced significant and divergent shifts in soil pH, revealing critical insights into their initial chemical impact and the subsequent resilience of the soil system. As illustrated in Figure 5.1, by Week 3, a pronounced drop in pH levels was observed across all treatments, with the effect being most acute under the Glyphosate treatment, where values plummeted to as low as 3.93. This sharp acidification is a direct consequence of the phosphonic acid group inherent to glyphosate molecules, which protonate in the soil solution, releasing H^{+} ions (Kanissery, *et al*., 2019) [11]. Furthermore, the rapid acidification can be exacerbated by the suppression of soil microbes involved in nitrogen cycling, leading to a nitrification inhibition and a potential accumulation of ammonium, which can further acidify the rhizosphere (Zobiole, *et al*., 2019) [27].

In stark contrast, soils treated with Atrazine maintained relatively higher pH levels, particularly in composite samples (up to 4.75). This suggests a less pronounced acidifying effect, and may even indicate a slight neutralising influence, potentially attributable to the chemical formulation's adjuvants or the compound's different mode of action, which does not directly involve an acidic functional group (Mahanta, *et al*., 2022) [14]. These initial findings align with established literature on the transient acidifying effects of Glyphosate, while highlighting the compound-specific nature of these impacts. However, this period of acute chemical stress was followed by a notable recovery. By Week 7, all treatments exhibited a gradual rebound in pH values. Remarkably, the Glyphosate-treated plots recorded the highest average pH (5.09), slightly above the Control (5.06) and Atrazine (5.00) plots. This rebound phenomenon is a testament to the intrinsic resilience of soil systems, primarily mediated by two key factors. First, the natural soil buffering capacity, governed by cation exchange complexes and the presence of carbonate and organic matter, acts to resist pH change by absorbing excess H^{+} ions (Bunemann, *et al*., 2018) [3]. Second, the microbial degradation of the herbicide molecules over time reduces the ongoing source of acidity. As the microbial community recovers and adapts, populations of glyphosate-degrading bacteria, such as those from the genera *Pseudomonas* and *Arthrobacter*, increase, metabolising the herbicide into non-acidic end products like AMPA and eventually CO_2 (Bai & Ogbourne, 2016; Sviridov, *et al*., 2015) [2, 21] The observed overshoot beyond the control pH in Glyphosate plots by Week 7 could be linked to a transient alkalinisation resulting from the mineralisation of these degradation products and a shift in the microbial community structure favouring ammonifying bacteria (Newman, *et al*., 2016). This recovery trajectory underscores the dynamic interplay between a chemical stressor and the soil's biological and chemical restorative mechanisms.

5.3 Discussion of Key Findings

The study revealed minor fluctuations in soil pH levels following herbicide application, with Glyphosate and Atrazine causing slight changes over time. Initial baseline pH levels ranged from 5.9 to 6.1, indicating moderately acidic soils. By Week 3, all treatments (including control) had significantly lowered soil pH, with the lowest values recorded in plots treated with Glyphosate (as low as 3.93). However, these changes gradually reversed over time, and by Week 7, soil pH levels had increased across all treatments, nearing baseline levels.

Despite these observable trends, statistical analysis including descriptive statistics, ANOVA, post-hoc tests, and Pearson correlation confirmed that none of the changes was statistically significant. The ANOVA ($p = 0.927$) and correlation analysis ($r = -0.019$, $p = 0.925$) suggest that the herbicide treatments did not have a significant impact on soil acidity in the short term.

This finding is critical while there may be temporary, block-specific pH shifts, the overall effect of Glyphosate and Atrazine on soil pH was negligible under the conditions tested. This aligns with some studies in agronomic literature that highlight the resilience of soil chemical properties to single-season herbicide use under moderate application rates.

5.4 Recommendations

5.4.1 Recommendations to Smallholder Farmers

Smallholder farmers are encouraged to continue using herbicides like Glyphosate and Atrazine in moderation, as current findings suggest that these chemicals do not cause immediate or significant changes in soil pH. However, it is important to remain cautious, as long-term and cumulative effects on the soil cannot be completely ruled out. To safeguard soil health over time, regular soil testing is essential. Monitoring soil pH allows farmers to detect early signs of degradation and take timely corrective measures. Additionally, incorporating organic matter such as compost or manure into the soil can help buffer against any gradual acidification while also enriching the soil with nutrients and improving its overall structure and fertility. This practice contributes to a more resilient and sustainable farming system.

5.4.2 Recommendations to Policy Makers

To support sustainable agricultural practices and safeguard long-term soil health, policymakers should consider a multifaceted approach that integrates education, regulation, and technological support. One critical recommendation is to enhance agricultural extension services. These services play an important role in educating farmers about the judicious and scientifically informed use of herbicides, emphasizing integrated weed management (IWM) techniques that combine chemical, biological, and mechanical strategies to reduce dependence on agrochemicals. Extension programs should also promote routine soil monitoring and data-driven decision-making to help farmers better understand the implications of their practices on soil chemistry, particularly pH balance and nutrient dynamics.

In tandem with education, there is a pressing need to enforce stricter regulations governing herbicide application. Although current research indicates limited immediate effects of herbicides on soil pH, the cumulative impact of long-term agrochemical use can lead to soil degradation, microbial imbalance, and reduced fertility. Policymakers must develop and implement clear, science-based guidelines for herbicide usage addressing dosage, timing, and environmental conditions to prevent overuse and mitigate ecological risks.

Moreover, to enable data-informed soil management at the grassroots level, governments should invest in and subsidize access to soil testing services. This includes establishing mobile testing laboratories and providing financial support for regular soil analysis. Affordable and accessible soil testing empowers farmers to monitor key parameters such as pH, organic matter content, nutrient availability, and contaminant levels, thereby enabling precise and site-specific interventions that enhance productivity while preserving soil integrity.

5.4.3 Recommendations to Researchers

To build on the findings of this study, future research should aim to extend the monitoring period well beyond the initial seven weeks. This would allow for the assessment of long-term and potentially cumulative effects of herbicide application, especially in relation to seasonal dynamics and temporal fluctuations in soil chemistry. It is equally important to broaden the scope of soil health parameters under investigation. While this study focused primarily on soil pH, subsequent research should incorporate a wider range of soil quality indicators, including microbial community structure and function, total organic carbon content, cation exchange capacity (CEC), and macro- and micronutrient availability. Such comprehensive analysis will yield a more nuanced understanding of how herbicides influence soil ecology and fertility over time. Moreover, given that the present study was geographically confined to the Mbala region, there is a clear need to replicate the research across various agro-ecological zones and soil types. Doing so will help determine whether observed effects are location-specific or broadly applicable, thus enhancing the external validity and generalizability of the results.

5.5 Future Research Directions

Building on the current findings, future research should adopt a more comprehensive and long-term approaches to better understand the multifaceted impacts of herbicide application on soil health. Longitudinal studies spanning multiple growing seasons are essential to determine whether repeated exposure to herbicides such as Glyphosate and Atrazine leads to cumulative alterations in soil chemistry, particularly in terms of pH stability, nutrient cycling, and microbial community dynamics. Furthermore, detailed residue analysis is warranted to evaluate the persistence, degradation kinetics, and leaching behaviour of these herbicides under varying soil types and climatic conditions, which could have downstream effects on groundwater quality and non-target organisms. Research should also focus on crop-soil interactions, specifically how herbicide-induced shifts in soil acidity influence plant physiological responses, including root architecture, nutrient uptake efficiency, and overall yield performance, especially in naturally acidic or marginal soils. Additionally, investigating the efficacy of soil amendments such as lime, biochar, or organic matter in buffering pH fluctuations may reveal promising strategies for mitigating the negative effects of herbicides while enhancing soil resilience and fertility. These directions are vital for developing sustainable herbicide management practices that balance agricultural productivity with environmental stewardship.

5.6 Conclusion

In conclusion, this study aimed to assess the influence of two commonly used herbicides Glyphosate and Atrazine on soil pH levels within smallholder farming systems in the Mbala District of Zambia. The research observed some shifts in soil pH following herbicide application; however, statistical analysis revealed that these changes were not significant enough to confirm a direct impact attributable to either chemical. From a technical standpoint, soil samples were analysed using standardized pH measurement protocols, and results were subjected to rigorous statistical testing, including ANOVA, to evaluate the significance of any observed variations. The lack of statistically significant differences suggests that, under current application rates and environmental conditions, Glyphosate and Atrazine do not substantially alter soil acidity in the short term. This supports their continued, cautious use in small-scale farming operations, particularly when integrated with sustainable land management practices and regular soil health assessments. Nevertheless, due to the complex nature of soil ecosystems and potential for cumulative effects over time, the long-term implications of repeated herbicide use remain uncertain. Ongoing research, coupled with proactive policy interventions, is essential to ensure the protection and resilience of soil systems critical to Zambia's agricultural productivity and food security.

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7. References

1. Arias-Estévez M, López-Periago E, Martínez-Carballo E, Simal-Gándara J, Mejuto JC, García-Río L. The mobility and degradation of pesticides in soils and the pollution of groundwater resources. Agriculture, Ecosystems & Environment. 2020; 215:1-3.
2. Bai SH, Ogbourne SM. Glyphosate: Environmental contamination, toxicity and potential risks to human health via food contamination. Environmental Science and Pollution Research. 2016; 23(19):18988-19001.
3. Bunemann EK, Schwenke GD, Van Zwieten L. Impact of agricultural inputs on soil organisms a review. Soil Research. 2018; 54(6):587-599.
4. Colding J, Barthel S. The potential of 'Urban Green Commons' in the resilience building of cities. In: Buergelt, P.T., *et al*. (eds.) Climate Adaptation: Accounts of Resilience, Self-Sufficiency and Systems Change. Springer, 2021, 91-107.
5. Dubey A, Kumar A, Abdallah EF, Hashem A, Khan ML. Root-soil interaction and root-soil microbiome management for improving crop productivity and nutrient use efficiency. In: Kumar, M., Kumar, V., & Prasad, R. (eds.) Phytobiomes: Current Insights and Future Vistas. Springer, 2020, 225-244.
6. Duke SO. Glyphosate: Environmental fate and impact. Weed Science. 2020; 68(3):201-207.
7. Folke C, Polasky S, Rockström J, Galaz V, Westley F, Lamont M, *et al*. Our future in the Anthropocene biosphere. Ambio. 2021; 50(4):834-869.
8. Gianessi LP. The increasing importance of herbicides in worldwide crop production. Pest Management Science. 2019; 75(4):1025-1026.
9. Guo JH, Liu XJ, Zhang Y, Shen JL, Han WX, Zhang WF, *et al*. Significant acidification in major Chinese croplands. Science. 2019; 327(5968):1008-1010.
10. Jiang Y, Zhang Y, Li M, Li F, Liu Y. Effects of soil pH on the growth and nutrient uptake of plants: A review. Soil Use and Management. 2021; 37(1):1-11.
11. Kanissery R, Gairhe B, Kadyampakeni D, Batuman O, Alferez F. Glyphosate: Its Environmental Persistence and Impact on Crop Health and Nutrition. Plants. 2019; 8(11):p. 499.
12. Kim KH, Kabir E, Jahan SA. Exposure to pesticides and the associated human health effects. Science of the Total Environment. 2021; 575:525-535.
13. Kopittke PM, Menzies NW, Wang P, McKenna BA, Lombi E. Soil and the intensification of agriculture for global food security. Environment International. 2021; 132:105078.
14. Mahanta N, Chinnusamy V, Sharma PC, Kaushik P. Impact of Atrazine on Soil Properties: A Review. Agriculture. 2022; 12(8):p. 1247.
15. Mohai P, Saha R. Which came first, people or pollution? A review of theory and evidence from longitudinal environmental justice studies. Environmental Research Letters. 2021; 16(5):055003.
16. Neina D. The role of soil pH in plant nutrition and soil remediation. Applied and Environmental Soil Science, 2019, 5794869.
17. Pose-Juan E, Rial-Otero R, Paradelo M, López-Periago JE. Influence of soil pH on sorption and persistence of herbicides: A review. Current Opinion in Environmental Science & Health. 2022; 27:p.100347.
18. Pretty J. Intensification for redesigned and sustainable agricultural systems. Science. 2018; 362(6417):eaav 0294.
19. Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N, *et al*. Worldwide pesticide usage and its impacts on ecosystem. SN Applied Sciences. 2019; 1(11):p.1446.
20. Silva V, Mol HG, Zomer P, Tienstra M, Ritsema CJ, Geissen V. Pesticide residues in European agricultural soils a hidden reality unfolded. Science of The Total Environment. 2019; 653:1532-1545.
21. Sviridov AV, Shushkova TV, Ermakova IT, Ivanova EV, Leontievsky AA, Vinokurova NG. Microbial degradation of glyphosate herbicides (Review). Applied Biochemistry and Microbiology. 2015; 51(2):188-195
22. Tscharntke T, Grass I, Wanger TC, Westphal C, Batáry P. Beyond organic farming harnessing biodiversity-friendly landscapes. Trends in Ecology & Evolution. 2020; 36(10):919-930.
23. Tudi M, Ruan HD, Wang L, Lyu J, Sadler R, Connell

D, *et al*. Agriculture development, pesticide application and its impact on the environment. International Journal of Environmental Research and Public Health. 2021; 18(3):p.1112.
24. Wezel A, Herren BG, Kerr RB, Barrios E, Gonçalves ALR, Sinclair F. Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agronomy for Sustainable Development. 2020; 40(6):p.40
25. Zhang L, Rana I, Shaffer RM, Taioli E, Sheppard L. Exposure to glyphosate-based herbicides and risk for non-Hodgkin lymphoma: A meta-analysis and supporting evidence. Mutation Research/Reviews in Mutation Research. 2021; 781:p.128-137.
26. Zhou Y, Li X, Li W, Liu X, Zhao J, Zhang Y, *et al*. Integrated weed management in farming systems: A review. Agronomy for Sustainable Development. 2020; 40(4):p.25.
27. Zobiole LHS, Kremer RJ, Oliveira Jr. RS, Constantin J. Glyphosate effects on photosynthesis, nutrient accumulation, and nodulation in glyphosate-resistant soybean. Journal of Plant Nutrition and Soil Science. 2019; 182(3):417-425.