EFFECT OF MIXING RATIOS OF SUPERABSORBENT POLYMER AND PUMICE ON CLAY SOIL PROPERTIES AND CROP PRODUCTIVITY

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not wholly or in part, been presented for the award of degree in Egerton University or any other institution.

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Recommendation

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DEDICATION

This thesis is dedicated to my family: Maribelle, Anslem, and Elizabeth, for their patience and support throughout my studies.

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ABSTRACT

Water scarcity and poor soil conditions pose substantial challenges to agricultural productivity in arid and semi-arid lands (ASALs), such as Mogotio Sub-County in Kenya. Specifically, the complex problems exhibited in the clay soils that are the most common in such areas. These soils hold water firmly in fine particles, reducing the water availability to plants. They waterlog during rainy seasons, and are compacted after a rainfall event. This makes the conditions unfavourable to crop growth more so the crops that are highly sensitive to water like the bell pepper (*Capsicum annuum*). In this regard, superabsorbent materials show potential in enhancing soil hydraulic properties and moisture availability. However, the best application of such amendments in clay soils is not well documented. The study was conducted to determine the effect of various mixing ratios of a superabsorbent polymer (SAP) and pumice on soil moisture dynamics using the growth of bell pepper, and to identify the optimum mixing ratio to promote agricultural water management in clay soils. The research utilized a completely randomized design that included treatment combinations of SAP at levels of 0, 5, 10, and 15 kg/ha and pumice at levels of 0, 6250, 12500, and 18750 kg/ha. All treatment combinations were replicated. The data was collected for one cropping season and analysed using analysis of variance in John's Macintosh Program Pro 17. It consisted soil physical properties (porosity, bulk density, hydraulic conductivity, moisture retention, and available water) and plant performance (growth parameters, number and weight of fruits). The amendment mixing ratios were found to have a significant effect on soil hydraulic properties. The 15 kg/ha SAP and 6250 kg/ha pumice treatment had the highest porosity (60.18%), the lowest bulk density (1.03 g/cm^3), reduced available water, and a 53% increase in yield over the control. However, high concentrations of amendments lowered hydraulic conductivity which could be attributed to pore clogging. The optimal soil conditions were characterized by a balanced enhancement of both water retention and aeration. Physical optimization identified the best amendment rate as 15 kg/ha SAP and 6250 kg/ha pumice. The combinations of various mixing ratios of SAP and pumice have the potential to enhance soil water retention, reduce compaction, and boost bell pepper yield in clay soils in some ASALs. However, disproportionate amendment levels may restrict water movement or root respiration.

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LIST OF ABBREVIATIONS AND ACRONYMS

CSP	Control (Treatment with no additives)
DD	SAP Double: Pumice Double
DF	SAP Double: Pumice Full
DH	SAP Double: Pumice Half
FAO	Food and Agriculture Organization
FD	SAP Full: Pumice Double
FF	SAP Full: Pumice Full
FH	SAP Full: Pumice Half
HD	SAP Half: Pumice Double
HF	SAP Half: Pumice Full
HH	SAP Half: Pumice Half
IPCC	Intergovernmental Panel on Climate Change
NGSS	Next Generation Science Standards
UNEP	United Nations Environment Programme
WWF	World Wildlife Fund

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Availability of freshwater maintains ecosystems, promotes agriculture, and supports human well-being worldwide. Freshwater accounts for only 2.5% of the Earth's total water (World Wildlife Fund [WWF], 2022). Of the total freshwater, an even smaller portion is easily accessible for human use, as much is trapped in glaciers, ice, or deep underground. The distribution of freshwater resources, whether in rivers, lakes, reservoirs, or underground aquifers, is very uneven in the world. This results in vast disparities in water availability and access where some areas enjoy plenty and others are water-stressed (Gleeson et al., 2015). Some regions receive high rainfall and have large rivers, while arid and semi-arid zones often suffer from recurring water deficits. Water scarcity is aggravated by increasing demand for water globally. In addition, climate change exacerbates the water crisis by altering the distribution of rainfall across the world and affecting the temperatures (Intergovernmental Panel on Climate Change [IPCC], 2021). These climatic changes can alter the time, intensity, and distribution of water supply, making it unreliable. Consequently, it makes effective management of freshwater more challenging and poses a great direct risk to sustainable development and food security in the world (Alotaibi et al., 2023; Clarke et al., 2022). The uncertainty can make the process of water supply and agricultural production hard to plan.

Agriculture abstracts the most freshwater on earth. It uses approximately 70% of the total amount of water used (World Wide Fund for Nature, 2022). This huge consumption is largely explained by the necessity to produce enough food to feed a growing population, inefficient irrigation methods and the increasing cultivation of water-intensive crops in unfavourable climates. Most of the farming activities in Africa, especially in the Arid and Semi-Arid Lands (ASALs), largely depend on rainfed systems, whereby crops fully rely on rainfall. Smallholder farmers in the regions face poor and usually insufficient irrigation systems; as they cannot afford the funds, land, and technological requirements for large-scale irrigation systems (Mekonnen & Hokestra, 2016; Rosa et al., 2020; United Nations Environment Programme [UNEP], 2008). This reliance on rainfed agriculture predisposes the output of farms to erratic and uneven rainfall patterns characteristic of ASALs. Climate change worsens these variable rainfall patterns further. Weather variability causes differences in the duration of wet and dry seasons. Sudden extended dry seasons increase the magnitude and geographical distribution of agricultural droughts which have substantial impacts on food production (Gobarah et al., 2015; Karuku, 2018). However, the quantity and timing of crop water demands do not usually coincide with the quantity and timing of rainwater availability, especially during critical stages of crop growth (Gobarah et al., 2015; Karuku, 2018). Healthy root development is necessary to the overall plant health, which can be described as a plant's ability to carry out its physiological functions efficiently at its maximum genetic potential. To be considered healthy, a plant needs to have a dense and developed root network, thus, facilitating efficient movement of water and nutrients from the soil and anchoring the plant securely to the ground (Linn et al., 2018).

Physical characteristics of a soil are very important in determining the availability of water, its accessibility, and the growth of plants. Clay soils, specifically Ferric Luvisols, pose special but complex issues in water management in agriculture. Though these soils naturally hold a lot of water because their constituent particles are very fine and have a large surface area, their main problem is their low water-yielding capacity. This implies that a large proportion of the water they hold is retained too tightly by the tiny clay particles (due to strong forces between water and soil – adhesive and cohesive forces) and cannot easily be made available to plants. This is often characterised to as "unavailable water," and it causes plants to experience stress although the soil may appear moist (Williams et al., 1983). In addition, they drain slowly and thus likely to get saturated and be waterlogged during heavy rains. Clay soils have small pores that are tightly packed together thereby preventing the water from moving downwards, leading to puddles on the surface. This waterlogging also deprives the plant roots of adequate oxygen and accumulates carbon dioxide, which inhibits respiration, thus stifling growth, and even causing the roots to die, as most crops require oxygen for healthy metabolism (Zheng et al., 2010). Conversely, during dry seasons, these clay soils shrink a lot, resulting in deep cracks and making them extremely hard. Additionally, after a rainfall event, a hard crust is formed on the surface of the soil as the water dries due to a thin compact layer of dispersed fine particles. This hardening and the formation of dense crusts on the surface considerably hinders water infiltration in later rainfall or irrigation events where the water does not soak in effectively. It also physically impedes the emergence of germinating seeds and further restricts the supply of oxygen to the root zone, thus decreasing crop growth and overall land productivity (Szejba, 2020; Zheng et al., 2010). These problems also worsen due to the higher intensity but shorter duration rainstorms (that facilitate soil compaction) that are more often experienced due to climate change and as a characteristic of tropical rainfall (Szejba, 2020). The potential swelling and shrinking of clay particles after several cycles of wetting and drying cycles greatly affect how they interact with water, depending on both the rainfall intensity and duration (Szejba, 2020).

On the contrary, sandy soils have a weak and unstable structure, characterized by large particles that create large pore spaces. This ensures that water infiltrates and drains very fast, resulting in poor water retention (Gogo et al., 2020). As a result, sandy soils are more susceptible to high extent of losing nutrients through leaching, where soluble nutrients are washed away from the root zone. They are also usually low in microbial activity. When a rainfall event takes place, these soils saturate rapidly and lose water just as fast through deep percolation. During dry seasons, the quantity of water the soil can retain is minimal and moisture is easily lost to the atmosphere through evaporation causing water stress to the crops. Low fertility and poor water retention substantially reduces the productivity of the plants (Gogo et al., 2020). As a result, both conditions - waterlogging and low available water in clay soils, and high drainage and nutrients loss rates in sandy soils - pose considerable constraints in crop growth, development, and overall production. Hence, effective strategies of soil management should be developed and utilized to enhance these natural constraints and promote sustainability in farming.

Irrigation is presently used by majority of the farmers in an effort to optimize crop water productivity by providing water directly to plants (Sezen et al., 2010). However, it depends on the soil type and weather conditions at the locality. Poor soils and very high temperatures, especially in ASALs may severely reduce the positive impacts of irrigation by leading to the occurrence of water stress, which has an effect on crop development. When crops are grown in soils with low water yielding ability and are subjected to extreme temperatures, they always face water stress which results in wilting and early drying before maturity or harvest time. Early plant growth especially in the critical periods of germination and seedling establishment heavily depends on soil moisture. Crops have high water demands that require numerous and frequent irrigation to serve the crop throughout the growing period. This may be expensive, laborious and unsustainable in areas where water is scarce. Thus, effective implementation of soil amendments on the root zone of the plant may enhance the ability of the plant in retaining water and releasing it to the dry seasons in ASALs. This enhancement causes the irrigation systems to be more efficient (with less water wasting and the intensity of irrigation decreasing), or the rainfed systems to be more effective (with more water available to be utilized during dry seasons), to guarantee that each drop of water is utilized more efficiently (Brouwer et al., 2001; Sharma et al., 2012). Figure 1 illustrates this concept by depicting a soil profile which highlights the root zone.

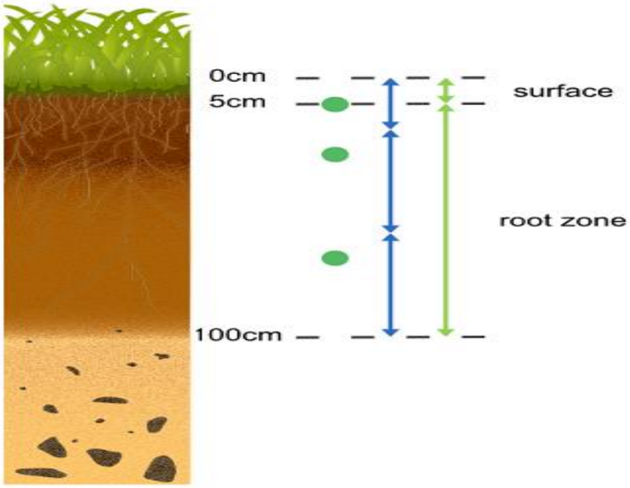

Figure 1: Soil profile illustrating the root zone

Source: Shrestha, R., and Boyer, A. G., (2019)

Soil amendment is becoming increasingly important in increasing food security, especially in ASALs. Boosting food production is an urgent need that is heightened by increased population growth and the intensification of the effects of climate change. Crop growth and yield can be further enhanced by improving soil moisture availability through increased water storage capacity and water-yielding capacity (Mueller et al., 2012). Additionally, soil amendments also help to enhance surface soil drainage making it resistant to waterlogging, reduce soil erosion and enhance overall land productivity and climate shock resistance (Mueller et al., 2012). Superabsorbent materials are an attracting category of soil amendment which is characterised by the outstanding qualities of water absorption and retention (Behera & Mahanwar, 2019). This renders them especially appropriate in enhancing the poor water retention of various soils, more so those in water stressed environments that either hold too little water or retain it too tightly for plants to utilize.

Superabsorbent polymers (SAPs) are innovative, three-dimensional, insoluble, hydrophilic polymer networks. Their distinct structure enables them to have a high capacity to absorb and retain large quantities of water and aqueous solutions (sometimes several hundred or even thousand times of their own weight). They behave like little sponges that can be used again and again (Ekebafe et al., 2011). Their high absorption capacity and extraordinary durability (some types are known to be useful for as much as four years in the soil before getting decomposed) make them highly sought after for amelioration of agricultural soil physical properties (Abobatta, 2018). SAPs are usually biocompatible (safe for living organisms), non-toxic, and, mostly, in increasing order, biodegradable. They are composed of a wide variety of industrially available raw materials and for this reason, they are a preferred solution for many sectors, including agriculture (Abobatta, 2018). These polymers are either sodium or potassium based. Potassium-based superabsorbent polymers (P-SAPs) are considered to be particularly suitable for agricultural use due to their potential soil salinization prevention. SAPs are able to take in when it is present (e.g., during rain or irrigation) and then slowly release the water back to the plants as the soil dries and the plant roots become drier. The controlled release can increase soil water holding capacity by 50% to 70% in the root zone and release water for long periods (Abd El-Rehirn et al., 2004; Bai et al., 2010; Dabhi et al., 2013). As well as storing water, SAPs also have positive impacts on a number of other key soil properties. They can decrease compaction (by creating voids as they expand), enhance texture (although sand/silt/clay ratios are unchanged, they can increase aggregation which creates better pore space), increase permeability (water and air can move through easily), promote beneficial microbial activity (by creating stable moisture), and enhance infiltration and aeration and improve soil structure. This combined effect will reduce irrigation water requirements and the duration of available water to crops, ensuring more efficient use of water (Barros et al., 2017). The SAP products most common in the Kenyan market that expose these principles are Belsap, Zeba, Stockosorb, and Alsta. The reason that Belsap was chosen is that, as it was locally available in the study area, its potential recommendations more feasible and practical for the application in the region.

Pumice is also a common and naturally occurring soil additive. It is a cinder cone that is formed when lava that is highly gas-rich is ejected from a volcano. The fast cooling and solidifying of the lava results in gas bubbles that are trapped, which form a frothy, very porous, and extremely light rock (Nugraha et al., 2022). As a pH-neutral, inorganic and non-degradable material, pumice fragments are extremely stable in the soil and do not disintegrate over time and thus deliver long-lasting structural advantages when used for soil. Their natural irregular shapes and high porosity make it easier for gaseous exchange to occur between the soil and the plants, with the oxygen getting to the roots and the carbon dioxide being released, which is essential to root respiration. They do this by producing stable macropores (large pores) and inhibiting compaction, especially useful in clay soils (Boivin et al., 2004; Nugraha et al., 2022). Pumice fragments further enhance the amount of available soil water and drainage by eliminating waterlogging. While pumice does not swell like SAPs (it does not absorb water), its internal porosity means that pumice can retain some amount of available water within its structure. By loosening and aerating the soil, pumice can improve root environment, which will help in improving plant growth and productivity. This causes an increase in plant cover and therefore less soil erosion by physically binding soil particles and increasing infiltration of water (Maksoud et al., 2020; Nugraha et al., 2022).

The research was carried out in Baringo County, which is typical of semi-arid area in Kenya. This is a region with harsh climatic conditions with high mean annual temperatures of 32.8°C and low annual rainfall of 512 mm (Ezenwa et al., 2018). Such high temperatures are one of the major causes of drought stress in the soils and intermittent rainfall is pivotal in enhancing the land productivity (Ezenwa et al., 2018). In particular, the clay soils (soils with over 40% clay particle) are dominant in Mogotio sub-county within Baringo County and clay soils are known to reduce agricultural water productivity in the region. The soil has particles less than 0.002 mm, high-water holding capacity with low permeability, tendency to compact and thereby restrict the transfer of air and water movement, and shrink-swell potential.

During long periods of dry seasons, these clay soils shrink significantly. This shrinkage has the drastic effect of reducing soil porosity, hence reducing the availability of both moisture and air to plant roots. As a result, reduced aeration and infiltration tends to cause more serious plant wilting, growth retardation, or even death of plant, and substantially reduced yields. On the other hand, in wet seasons, the clay soils become saturated and waterlogged in a short amount of time, again restricting aeration and the general percolation and infiltration of water into the soil. In these anaerobic conditions, the germinating seedlings are unable to develop well-structured root systems because of an oxygen shortage and this adversely affects their overall growth and survival.

The growing global and local demand for water for agricultural use together with the increasing challenges of weather unpredictability and acute water stress in ASALs identify an urgent need for effective and sustainable water management. This research was specifically designed to ascertain the effectiveness of superabsorbent materials (SAP and pumice), in the form of soil amendments to improve agricultural water management. The main purpose was to determine the best mixing ratio of these additives to enhance crop water productivity for bell peppers (an important but water-sensitive crop), under the harsh local conditions of Mogotio Sub-County. This research was designed to provide evidence-based recommendations to make the agricultural system more resilient in similar vulnerable regions.

1.2 Problem Statement

The arid and semi-arid lands (ASALs) largely rely on rainfed agriculture making it very susceptible to the vagaries and variability of the rainfall intensity and distribution during the entire growing period (Benites & Castellanos-Navarrete, 2003; Liao et al., 2016). This presents a massive and chronic challenge to millions of farmers who rely entirely on rainfall as their only source of water supply to their crops thus causing food insecurity and constant yield crunch along with extreme economic susceptibility. Ferric Luvisols are rich in clay content which possesses a high capacity to hold water but their major constraint is their low water yielding ability. This implies that the clay particles tightly hold much of the retained water, thus, it is not readily available for uptake by plants, resulting in plant stress even when the soil appears and feels moist (Gidigasu & Gawu, 2013; Yang et al., 2020). Besides, rainfall intensity and time is responsible for the distinctive characteristics of shrink-swell of clay particles, which generate a cycle of complex conditions. During heavy rains, these soils become saturated rapidly and waterlogged due to poor drainage which leads to a lack of oxygen for the roots. As the water recedes, fine clay particles at the surface often filter and form a tough crust, which then impedes the emergence of germinating seeds and severely restricts further flow of water, root water uptake, and vital oxygen flow (Boivin et al., 2004; Williams et al., 1983). Conversely, these soils become hard like bricks when dry and make the water that is there considerably inaccessible to the crops. Such extreme responses - from waterlogged to extreme hardening – have a direct detrimental effect on the crop growth and the overall land productivity affecting the persistent challenge of managing water in such soil types.

Superabsorbent materials (SAMs) in the form of superabsorbent polymer (SAP) and pumice have proven to be promising and innovative materials for improvement of soil hydraulic properties that can help increase water conservation. Individually, these amendments have been shown to have a proven ability to absorb and hold water (SAPs) or enhance drainage and aeration with some water holding properties (pumice), gradually releasing the water to the plant roots. This helps extend water availability and reduce water stress in plants and also potentially lower irrigation costs and the frequency of plant water stress (Malekian et al., 2012; Nnadi & Brave, 2011). However, the effectiveness of these materials can vary significantly depending on the specific type of soil, the prevailing environmental conditions (e.g. rainfall patterns, temperature, evaporation rates), and the water requirements of the target crop. A dosage or application method that works well in one type of soil or climate may be suboptimal or even ineffective in another. Previous work has been mainly done on the single application of these amendments or has been done in settings that are different from those caused by the complex clay soils. Consequently, there is a distinct knowledge gap on the synergistic effects and optimal application strategies when these materials are used in combination.

This study investigated the interactive effects of superabsorbent polymers and pumice when used in combination to alleviate the effects of unpredictable rainfall pattern thus reducing dependence on erratic rain-fed systems, lessening the inherent limitations of clay soils by combating waterlogging and crusting, and optimizing soil amendment strategies by establishing the best mixing ratio of SAP and pumice for maximum water conservation and crop yield. This study, therefore, aimed to contribute indirectly to improved food security and farmer resilience.

1.3 Objectives

1.3.1 Broad Objective

The broad objective of this research was to determine the effect of different mixing ratios of superabsorbent polymer and pumice as soil amendment materials in clay soil for agricultural water management.

1.3.2 Specific Objectives

The specific objectives of the study were to:

i. Determine the effect of the various mixing ratios of superabsorbent polymer and pumice on clay soil hydraulic properties.
ii. Determine the effect of the various mixing ratios of superabsorbent polymer and pumice on crop growth and yield in clay soil.
iii. Determine the optimum mixing ratio of superabsorbent polymer and pumice for soil water yielding capacity and crop productivity in the clay soil.

1.3.3 Research Questions

i. How do the various mixing ratios of superabsorbent polymer and pumice influence soil hydraulic properties?
ii. How do the various mixing ratios of superabsorbent polymer and pumice influence the growth and yield parameters in clay soil?
iii. What is the optimum mixing ratio of superabsorbent polymer and pumice for soil water yielding capacity and crop productivity in clay soil?

1.4 Justification

Healthy and productive plants are inextricably linked to good soil conditions, i.e. by adequate nutrients and water. Ideal soils have a strong structure that allows for the best root development and continuous exchange and transportation of water and gases between plant roots and the soil surface (Karuku, 2018; Singh et al., 2015). This has an equal pore space where water is retained and aeration is made possible. In most agricultural contexts, especially where cultivation is on a large scale or in areas such as the ASALs, however these model conditions are rarely met naturally. This necessitates the strategic usage of soil amendments in an effort to enhance soil health and productivity.

The study area in Mogotio Sub-County exhibits unreliable and erratic weather conditions typical of semi-arid regions. The resulting soil degradation causes several serious problems such as low storage and retention of soil moisture, and poor yielding of stored moisture to plants (despite having water, it is not accessible). Superabsorbent polymers (SAPs) provide a promising solution by providing their unique ability to absorb and store large amounts of moisture during wet periods and then slowly return this available moisture back to the soil. This ensures that plants apply limited water throughout the growing season. Eventually this "smart" water management leads to more yields by buffering plants from drought stress (Benites & Castellanos-Navarrete, 2003; Liao et al., 2016; Malekian et al., 2012). Pumice, on the other hand, improves soil's physical properties by providing improved soil structure, aeration, and drainage. These developments indirectly lead to better nutrient retention and an improved overall water-holding capacity through the stabilization of pore networks within the soil (Nugraha et al., 2022; Sahin et al., 2005).

Also, whilst the separate advantages of SAP and pumice are well established, the interaction between SAPs (expanding and contracting) and pumice (hard porous rock) within the complex matrix of various soil types (especially clays), is not simple. Their combined effects on pore size distribution and water flow can be highly non-linear and complex to predict without empirical testing. For example, excess SAP in clay may cause excessive swelling and blockage of pores, which can reduce the aeration, whereas excess much pumice may cause the soil to be too coarse, which can reduce the water-holding capacity of the soil. The right balance can only be determined by some empirical data. Most studies of these amendments were performed on individual amendments under controlled greenhouse conditions or on sandy soils. Clays are unique soils that pose challenges to work with, as wet conditions cause waterlogging and dry conditions cause excessive cracking and hard tillage. There would also be substantial difficulties in extrapolating research from sands in which the problem is typically with excessive drainage to clays in which the problem is with poor drainage and water availability. There is also the additional problem of the influence of the normal local weather conditions, such as erratic precipitation and high temperatures unique to ASALs. The combination of climatic conditions and soil amendments are complex with as yet unknown interactions that cannot be extrapolated from other location. For example, the potential of SAPs to release water is controlled as a function of temperature and humidity, both of which are extreme and variable in ASALs. Lastly, different target crops have different site-specific water requirements and physiological requirements, making it impossible to apply the amendments in a one-size-fits-all fashion, especially for target crops that are susceptible to both drought and waterlogging, such as bell pepper. Accordingly, the implementation of the optimal mixing ratio is of great importance for an optimum utilisation and for avoiding undesired side effects such as the formation of surplus amounts of water.

The study offers useful information for advocating for adoption of effective soil water conservation and management practises among the farmers of the study area so as to promote the water productivity of crops and climate-resilient agriculture.

1.5 Scope and Limitations

The research was conducted in the form of a field experiment on a local farmer's farm in Ngubreti, Mogotio Sub-County in Baringo County, Kenya. The experimental period was chosen to be from November 2021 to February 2022, purposefully to align with the dry season (less likelihood of rainfall being out of control) thereby reducing possible confounding effects from rain-rich growing conditions. Two superabsorbent materials were used; a superabsorbent polymer (SAP) and pumice. The study investigated the various ratios of the two amendments. To determine their effect, the study focused on two key aspects: soil hydraulic properties (measurements of porosity, bulk density, hydraulic conductivity, water retention and available water) and crop performance (growth and yield parameters of bell pepper [*Capsicum annuum*]) which were monitored throughout the experiment. Planting was standardised so that all seeds/seedlings were placed at the same depth to eliminate the effect of planting depth on soil additives.

The experimental design was Completely Randomised Design (CRD) with 10 pre-defined treatment combinations of superabsorbent polymer (SAP) and pumice. All ten distinct combinations of treatments were randomised to the sub-plots, so all combinations are equally distributed across the experimental area. A control group (without application of any soil amendments) was also included in these combinations for baseline comparison, so a precise comparison could be made of the impact of the SAP and pumice combinations. Each of the 10 treatment combinations was repeated three times for a total of 30 experimental sub-plots. Each sub-plot was 1 m by 0.8 m, which was big enough to allow for plant production and data collection. Within each subplot, four plants of bell pepper were grown to provide enough samples for accurate measurements of plant growth and yield. The in-row spacing of plants was 45 cm, while row to row spacing was 60 cm following local agronomic guidelines.

The results are mainly valid for clay soils, and their transferability to other soil types (e.g., sandy) requires further studies. The research was done on bell pepper only. While it serves as a representative crop sensitive to water stress, the effects of the amendments may differ for other crops having different water demands or root architectures. The experiment was run during a dry season, and the results of the experiment provide information on conservation of water under a limited supply. The effectiveness of these amendments at the time of heavy rainfall or continuously wet conditions was out of the scope of this study. The economic analysis of the costs and benefits of the application of the superabsorbent materials was not performed in this research. The study was confined to one cropping season (about four months) and hence the long-term impacts of the amendments on soil quality, their degradation rates, microbial activity, and their combined impact across several cropping cycles was not adequately evaluated.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Agricultural production is the basis of most economies of the world, and in Kenya it is of critical importance. It makes a direct contribution of about 21% to the total economic output of the country (Gross Domestic Product, or GDP) and an indirect contribution of 27% through its linkages to other industries. Apart from its direct economic role, agriculture is also an important source of employment, providing more than 40% of the total population and more than 70% of the rural population with employment. This is an important contribution to highlight the potential of sustainable agriculture to improve the life and livelihoods of farmers (Food and Agriculture Organization, 2017).

However, agriculture is suffering from a fundamental paradox: as the biggest consumer of water but also the industry most dependent on its availability and access. Land and water management is therefore key to reducing the amount of total water used by this sector at critical yield stages. Food security is a key global issue with continuing population increase and mounting effects of global warming. These demand that current farming practices are organised into a critical mass, so as much as possible can be gained from the current available water supplies without exacerbating their abstraction. Due to population pressure, societies tend to be pushed to semi-arid and arid-lands (ASALs) in search of space and livelihood provision (Gobarah et al., 2015).

Most of these ASALs are water stressed and some have clay soils that are extremely challenging to agriculture. The clay soils often react in an extreme manner. During dry seasons, they can become very hard and brick-like, preventing water from penetrating and plant roots growing. Conversely, following heavy rainfall these same soils can be waterlogged because of poor internal drainage, thus suffocating plant roots. Another common problem is severe soil crusting in which a hard, impervious layer develops on the surface of the soil, particularly after short periods of intense rainstorms. This crust prevents water from soaking into the ground and makes it very difficult for young plants to emerge (Zheng et al., 2010). All these issues together lead to the overall unproductivity and unreliability of these lands. To enable the inhabitants implement more sustainable farming practices, this research investigates ways to apply affordable and readily available soil additives: namely, superabsorbent polymer (SAP) and pumice.

The impact of these materials is immediately obvious from the results of this study. Developing a knowledge of their contribution will give proper advisories to the farmers of

ASALs that in turn will help them improve their food production and enhance their income, particularly on high value crops such as bell pepper which is most vulnerable to water stress and difficult soil conditions.

2.2 Soil Conditioning

Soil conditioning is a long-term solution aimed at increasing the soil's water-holding and infiltration capabilities. Its main function is to mitigate the drying of the soil so that it does not dry out quickly through evaporation or deep percolation. The improvements in soil water management can be attained by a series of means. These include direct use of valuable soil amendment materials and use of certain conservation tillage practices. Other practices used for this purpose include but are not limited to mulching (applying organic or inorganic materials to the soil surface) or cover cropping (growing plants to protect and enrich the soil) (Linn et al., 2018).

In Kenya, rainfall is the main source of water for crop production in the country's agricultural sector. However, the country suffers from extreme difficulties related to the uncertainty of rain patterns and widespread areas of aridity and semi-aridity. Thus, with the low and erratic precipitation, it becomes difficult to achieve steady crop yields resulting in food shortages. In turn, adopting effective management practices of the soil and water resources is becoming increasingly necessary to guarantee an increase in the water content of soil, improve the water holding capacity, and increase available water to plants. These measures are not only necessary to optimize agricultural productivity but also for minimizing the adverse effects of water scarcity. Some of the methods considered effective in this regard include terracing (level steps on hillsides) and building furrows (small ditches). These structures provide protection against surface runoff, enabling water to infiltrate into the soil more effectively, and in the end, increasing the soil water content (Duveskog et al., 2003; Singh et al., 2015).

The water holding capacity of a soil is extremely important to maximize crop production. High soil moisture-holding capacity will reduce evaporation and deep drainage losses. This, in turn, results in more water for the plants which improves crop production allowing farmers to earn more and hence fulfil the basic demand of the people for better living standards. Several of the natural soil properties play an important role in its moisture holding capacity. These are those regarding soil grain size distribution (texture), arrangement of the soil grains (soil structure), the overall depth of the soil, the activity of the biota of the soil, and the content of the organic matter in it (Benites & Castellanos-Navarrete, 2003). For example, water molecules adhere to small more than they do to coarse soil particles such as sand, compared to fine particles such as clay. Additionally, soils with a greater amount of pore spaces (porous soils) tend to hold a greater amount of water than soils that are densely packed. The percentage of these pore space, and the exact percentage composition of silt, sand, and clay particles go a long way in determining how much moisture a soil can hold and how readily available it is for the plants to acquire it from. In this case, the clayey soil with very high moisture retention capability, known as Ferric Luvisol, is understood to be the best type of soil. The small clay particles stick tightly to water molecules and so hold a lot of water in the soil. Also, there are Luvisols which are marked by the presence of iron oxides which give them a reddish colour and which cement the constituent of the soil into stable aggregates. These soils are highly susceptible to compaction, mostly due to frequent tillage, destroying the soil structure. Compaction decreases water infiltration rate and root growth, and in the areas where it occurs, waterlogged conditions are likely, while the areas where it is excessive, water stress will likely lead to reduced crop productivity.

As the moisture dynamics in the soil are of paramount importance, lots of additives as well as methods can be used to improve the moisture-holding capacity of the soil. These include the use of organic amendments, the use of mulches, and the use of efficient irrigation systems. In addition, special soil additives such as superabsorbent polymers and crop rotation application may also increase soil moisture storage. In the case of the clay soils, including those of Mogotio Sub-County, despite the presence of high-water storage capacity, the soils possess a poor yield capacity. This is an indication that much of the water is held so tightly between soil particles that plants cannot draw it out. Again, the soils are also subject to excessive compaction, internal drainage, and surface crusting, which reduces infiltration of water and root respiration. This is where superabsorbent polymers (SAPS) and pumice can show promise as they can address these problems directly by improving the structure, aerating (allowing more air into) the soil, and making more water available to crops such as bell pepper that are sensitive to drought and waterlogging.

2.3 Superabsorbent Materials (SAMs)

Superabsorbent polymers form a class of materials with an extraordinary capacity to absorb and hold large amounts of liquids, especially water, upon contact. The exact amount of water they can retain or absorb varies depending on the specific properties of each superabsorbent material. This study particularly focuses on superabsorbent polymer (SAP) and pumice due to their different and complementary characteristics. Whereas pumice is valued for its porosity that provides good drainage and aeration, SAP is valued for its ability to hold and slowly release large amounts of water. These materials individually have the potential of acting in a synergistic manner, and hence the overall effect of the mixture is possibly greater than the individual effect of each to enhance the soil texture and water supply in the study region. The ingenuity of the study is in determining the collective effects of these two materials, particularly their mixing proportions, as an attempt to solve complicated water management issues created by clay soils found in arid and semi-arid regions.

2.4 Superabsorbent Polymer (SAP) and Properties

Superabsorbent polymers (SAPs) are hydrophilic polymers which are able to absorb and hold much water compared to their own mass or volume. The absorption of water is a result of the highly cross-linked nature of the polymer chains, with formation of three-dimensional network structures. Numerous authors have discoursed SAPs in detail, detailing their characteristics and potential uses. Bai et al. (2010) conducted substantial work on SAPs and established that they are capable of holding large amount of water and are therefore very useful for water management and condensation control. Their water-holding capacity helps retain moisture in soil, reduce irrigation water requirements, and optimize water availability for plant use. It is shown that the range of uptake is type-dependent. This in-built potential ability makes their use and performance in agriculture especially concerning water availability, and water stress regimes. There was no study that delved into the interactions of the SAPs and pumice in clay soils.

Scientists like Feng et al. (2020) studied the behaviour of SAPs with soil parameters via a laboratory soil column. They noted that application of SAPs would increase the water-holding capacity of soil, raise soil air penetration, and decrease soil bulk density. The mechanism is that SAPs soak up water, swell, and consequently retain water in their body and location. When dissipation of water is achieved, they leave temporary voids in the soil fabric that are created through displacing denser soil materials with less dense water materials, consequently lessening the cumulative bulk density of soil. These effects together tend to enhance soil structure and overall soil health and in theory lead to better nutrient uptake by the plants and optimum root development. While promising directions for broad amelioration, the degree to which these benefits will be realized in addressing the specific challenges posed by clay soils requires further study.

Milani et al. (2017) examined the environmental effects of SAPs, in terms of inertness. They based their research on the finding that there are no adverse effects from SAPs on human beings, plants, soil, and the general environment. It is therefore safe and sustainable for agricultural activity to deploy SAPs as a reliable measure of water management and soil improvement from an ecological perspective. It is sustainable in the long term for using SAPs in agricultural systems, particularly in ecologically fragile ASAL zones.

Wilske et al. (2014) researched the biodegradability of SAPs. They noted that SAPs generally decompose in a slow biodegradation process, usually taking five to twelve years. Biodegradation may occur through microbial activity or exposure to sunlight, ultimately leading to the breakdown of SAPs into water, carbon dioxide, and ammonia. This means that SAPs leave very minimal long-term environmental effects and are environmentally friendly. However, the multi-year time taken for breakdown also means that the effects of the amendments are not flash-in-the-pan ones, providing long-term gains over multiple cropping cycles. This is an important consideration for ASAL farmers as they determine investment in SAPs.

2.4.1 Effects of Superabsorbent Polymers (SAP) on Soil Properties

Superabsorbent polymers (SAPs) are used for water absorption and storage, mainly to optimise water productivity, improve fertiliser use efficiency, and alleviate stress due to moisture variations in crop plantations (Krasnopeeva et al., 2022). SAPs have invariably been beneficial in several major soil attributes: they improve the water-holding capacity of the soil, enhance soil porosity and aeration, decrease bulk density, improve overall soil properties, increase nutrient use efficiency (NUE), and conserve water (Sayyari & Ghanbari, 2012). Through the formation of an available water store near the plant root zone, SAPs are capable of slowly releasing both water and dissolved nutrients to the plant as required, providing a steadier supply (Nezhad-raeini et al., 2021).

The incorporation of SAPs in soil management practices is an efficient tool in controlling soil erosion, because it reduces the amount of water that flows over the surface. They also improve the water absorption and size of soil aggregates, lower soil bulk density, and improve water-holding capacity. They also increase the capacity of plants to regain nutrients from fertilizers allowing plants growing in unfavourable soils to absorb more nutrients, and minimise nutrient losses due to leaching. They also reduce the frequency of irrigation requirements (Feng et al., 2020). In addition, the use of SAPs in soils is seen to augment the proportions of solid, liquid, and gas phases in soils. This maximizes the water-holding capacity and makes valuable nutrients, such as potassium available (Havrilyuk et al., 2021). The SAP application also has positive effects on the mineralization and release of nutrients from soil organic matter, increasing the total organic matter content in soil, as adequate moisture facilitates growth and activation of decomposer microbes (Nezhad-raeini et al., 2021).

However, it is imperative to state that research on the actual effect of SAPs on the physical characteristics of soil is somewhat inconclusive. These differences are mostly based on the type of soil and the amount of SAP used. For example, although there is a prediction that SAPs will increase water infiltration by increasing the void size, some studies show mixed effects. Abrisham et al. (2018) found that use of SAPs at a concentration of 1 gram/Liter (g/l) in clay soil increased available water by 68.5% and reduced the soil bulk density by 25.5%. It also lowered the infiltration rate by 21.5%. This drop in infiltration could be attributed to the nature of the SAP used, how it swells in clay, or that the swollen polymers actually clogged some existing pores at a particular concentration. While SAPs are known to lower bulk density, the magnitude and consistency of this effect can vary. Cao et al. (2017) found that SAPs raised soil bulk density by 4.8% to 8.9% in loess plateau terraces over a period of nine years. This is counter to the general expectation that the swelling of SAPs will lower bulk density.

Furthermore, most studies focused on the effects of SAPs as a stand alone or in combination with organic materials (compost or biochar). There is little to no research on their synergistic effects - specifically, how they are combined to achieve a greater effect when used with inorganic porous materials such as pumice in clay soils. Many current studies were carried out in controlled greenhouse conditions or in sandy soils which behaved differently from clay soils in regard to water dynamics (how water moves) and compaction issues. For example, in sandy soils, the main role of SAPs is to enhance water retention, while in clay soils, they improve compaction and poor drainage. The long-term effects of SAPs and the exact optimal application rates for particular crops like bell pepper in ASAL clay environments are yet to be thoroughly explored.

For example, the application of poly-glutamic acid superabsorbent polymer (PGA SAP) at a concentration of 0.20% (weight by weight) in clay soil lowered the cumulative water infiltration rate by 32.4% to 52.0% than the control group (Guo et al., 2019). Despite this reduction in infiltration, the application of PGA SAP also resulted in an increase in the field capacity (amount of water the soil holds after drainage), varying between 18.7% to 58.3% compared to the control. The observed increase in cumulative evaporation (17% to 25% than the control group) can be explained by the increase in plant growth and rate of transpiration, which were enabled by the increase in water availability close the soil surface due to SAPs. It further increased the number of water-stable aggregates (<0.25 mm) with increasing concentrations of γ-PGA SAP (γ-PGA SAP concentrations rose higher than 0.10%) (Guo et al., 2019).

2.4.2 Effects of SAP on Plant Growth and Yields of Crops

Superabsorbent polymers (SAPs) have been increasingly exhibiting favourable responses in plant development and crop growth, primarily through facilitating quicker and even seed germination and increasing plant availability of soil moisture. They hold water in soil in a highly efficient capacity, generating an immediate localized supply of available moisture for germinating seeds and expanding roots. With optimal moisture availability around seeds, SAPs enhance rates of seedling emergence and stand establishment (Malik et al., 2023). When such polymers are brought into and hold water, they create a root-zone microenvironment that is kept adequately moist for an increased time duration. It increases water supply availability for plant roots even after water supply is scarce and water stress is apparent, and it aids plant growth and development over time (Feng et al., 2020; Nezhad-raeini et al., 2021).

In addition to augmenting water supply, SAPs substantially save water and decrease irrigation frequency. Absorbing and retaining enormous quantities of water, the polymers decrease the evaporation of water from the soil surface and restrict water losses from runoff and deep percolation (Sayyari & Ghanbari, 2012). Decreasing water losses and improving water application efficiency makes it feasible to cut irrigation frequency, achieving significant water savings and lesser cost of irrigation (Feng et al., 2020). Energy-saving potential of SAPs is equally linked with water-saving potential as less frequent irrigation saves energy needed for pumping and conveyance of water for irrigations, accomplishing sustainable and less costly farming systems (Feng et al., 2020).

While overall positive impacts of SAPs on plant growth and water application efficiency are general knowledge, very limited research is available regarding their solo application on bell pepper grown with clay. The cumulative effect of SAPs with other amendments, particularly on bell pepper yield in ASAL conditions, is an important area of research to understand their full potential in synergy. Previous research has primarily focused on mixing SAP with organic materials; there is a clear need to further study on the effect of two superabsorbent materials in combination, on water yielding capacity and crop productivity. There are no unified application rates for different soil types, locations, and crops hence need for further study (Behera & Mahanwar, 2019).

Table 1: Summary of previous superabsorbent polymer studies

No.	Researcher	SAP Type	Dosage	Recommendation	Gaps
1	Islam, et al., 2011	Synthetic polyacrylamide with a potassium salt base	30 kg/ha	For levels of severe water stress and improved yield	Effect of SAP on bell pepper
2	Fallahi, et al., 2015	Potassium polyacrylate and polyacrylamide copolymers	60 kg/ha	To moderate the bad effects of drought stress on crops	No mixing done
3	Taheri, et al., 2017	A 200	6 g/kg of soil	To improve yield	Stand-alone treatment: no mixing done
4	Yang, et al., 2020	Model BJ2101XM	90 kg/ha	For improved yield	Stand-alone treatment: no mixing done
5	Sayyari & Ghanbari, 2012	A 200	0.5% of weight; 5 days irrigation interval	To increase irrigation periods and improve crop growth and yield	No mixing done

2.5 Pumice and its Composition

Pumice is a volcanic rock that is naturally occurring. It is very lightweight, and highly porous. It is formed when lava that is very rich in gas is violently ejected from a volcano and cools quickly, trapping gas bubbles in its structure (Nugraha et al., 2022). Its high porous nature makes it a superabsorbent in terms of its ability to hold water within its pore spaces, though through a dissimilar mechanism than SAPs. It holds water physically and not through chemical absorption and swelling. As an inorganic material, pumice is chemically inert, non-degradable, and pH neutral, meaning it does not break down over time nor does it change the pH of the soil, thus providing long-term stability in the soil. The exact mineral composition of pumice can vary based on its geological origin (Mang'uriu et al., 2012). Scholarly investigations by researchers such as Jativa et al. (2021) and Kong et al. (2022) provide important insights into the common minerals that can be found within pumice, which typically include feldspar, pyroxene, and hornblende. These mineralogical findings bring into perspective the dynamic nature of pumice and its potential utility in agriculture. The interplay of these minerals can affect the availability of soil nutrients and pH levels, which adds an interesting dimension to its use as a soil amendment. Pumice is considered pH-neutral meaning it can be used without altering the acidity or alkalinity of the soil. This adjusts physical properties without disturbing the chemical balance necessary for uptake of nutrients.

The inherent porosity of pumice is an asset beyond measure in the field of agriculture. The vast structure of voids and holes allow quick drainage and air penetration throughout the ground, precluding waterlogging and at the same time providing a favourable atmosphere for root respiration (Ciriminna et al., 2022; Gbollie et al., 2022; Hassanpour et al., 2023). This property alleviates poor aeration and drainage in clay soils, which limits crop growth as pumice establishes lasting macropores which facilitate the flow of water as well as air. Researchers such as Nugraha et al. (2022) focused on enhancing the soil structure, increasing water-holding capacity, and increasing the availability of key nutrients for plant absorption. These researches shed light on the potential of pumice in many agronomic practices and provide basis for further study on its multifaceted potential.

Pumice is also well known for being intrinsically lightweight. It is a great choice among smallholder farmers with minimal means to acquire labour and equipment as it does not require a lot strength and effort to apply into the field. Scientists such as Balkic et al. (2021) and Zakharikhina et al. (2022) found that pumice improves the physical quality of soil. It alleviates soil compaction which is a common challenge for farmers in areas with heavy clay soils. It also aids in improving water infiltration through the formation of stable networks that cause water to flow with ease into and throughout the soil. These studies show the versatile use of pumice in agriculture and its significance as a material that requires further study and wider application. Pumice increasing farming vigour, by blending with hydroponics or soilless growth of plants, container farming, and greenhouse farming, where its superb virtues work as a changing agent. In soilless systems, pumice provides plants with stable physical support, encourages growth inside cramped spaces, and conditions that favour growth of the crop.

Senior researchers, such as Rosa et al. (2023) and Kontaxakis et al. (2023), have established pumice as an incredibly effective horticultural instrument. In the role of growth medium, pumice ensures efficient water flow, preventing oversaturation and preventing suffocation of the plant. In addition, it retains nutrients crucial to plant growth, while promoting root aeration. Research on the use of pumice in agriculture emphasizes its potential in horticulture and agronomy encouraging further investigation.

2.5.1 Effects of Pumice on Soil Properties

Notable researches by Balkic et al. (2021) and Rosa et al. (2023) have been on the physical characteristics of soil, aiming to find out ways in which the use of pumice can induce positive changes. Their research revealed that pumice improved the tillage and reduced soil compaction, thus enhancing plant growth. This is valuable in clay soils, where pumice is a useful permanent aggregate. Its porous nature improved infiltration and drainage of water, consequently improving the soil moisture management by creating macropores (for draining) and micropores (for water retention). Moreover, it was found to lower the soil bulk density thus improving root growth and uptake of valuable nutrients. Pumice also demonstrated positive effects on the soil chemistry, as highlighted by Kong et al. (2022). Pumice was found to modify soil chemistry by raising the pH of the soil in acidic conditions closer to neutral or slightly alkaline conditions. This pH modification increases the availability of nutrients (since numerous nutrients are best taken up in neutral to slightly alkaline conditions) and provides a favourable environment for microbial activity in the soil. Additionally, the pumice cation exchange is very high and helps retain and release nutrients in the soil to improve uptake by plants.

In view of its biological effect on the soil, the research by Ciriminna et al. (2022) determined its use on enhancing plant growth and microbial presence. It was observed that with application of pumice increased beneficial microorganisms in the soil. Its sponge-like nature provides ideal conditions for microorganisms to establish and thrive. These micro-habitats provide shelter from the fluctuations of extreme temperatures, drought conditions, and predation by larger soil organisms; provide adequate moisture and aeration, and sufficient surface area for bacteria, fungi like mycorrhizae, and other beneficial microbes to attach, form biofilms, and establish colonies. The increased microbial activity enhances nutrient cycling and the breakdown of organic matter, which are vital for soil fertility and nutrient availability.

While previous studies have highlighted these benefits, one of the main limitations is that many were carried out in soilless media or sandy soils (Gizas & Savvas, 2007; Prisa & Caro, 2023; Segura-Castruita et al., 2012). The soil issues in such conditions vary from those of clay soils. For example, pumice improves drainage and aeration promoting root health in artificial substrates. In clay soils, pumice reduces excessive compaction, improves internal drainage, and the reduces the close binding of water. There are little to no studies on effects of pumice in clay soils, let alone in ASALs. Little is known about the synergistic interaction between pumice and SAP in such conditions. This research determines the effect of pumice and SAP addition on the physical characteristics of clay soils in a semi-arid environment.

2.5.2 Effects of Pumice on Growth and Yield of Plants

Numerous studies delved into the effects of pumice on the growth and yield of crop, which showed its potential as a beneficial soil amendment in farming. In a study by Ramirez-Gomez et al. (2015), its effect on growth and productivity of tomato was examined. When pumice was added to the soil, it enhanced several growth factors, such as plant height, stem diameter, and leaf area, compared to the control (soil without pumice). This is perhaps due to the porous structure of pumice improving soil aeration and drainage, providing a healthier root environment and increasing water availability, which are important for vegetative growth. Furthermore, the study showed a significant increase in the yield of tomato, suggesting that pumice increases crop productivity. Malekian et al. (2012) also examined the effect of pumice on maize crop growth and yield. It was found that applying pumice improved various growth characteristics, including improved plant height, leaf area, and biomass accumulation (total plant material). The enhanced soil structure and water flow is likely to have enabled maize roots to better explore the soil and have increased access to nutrients and water.

Table 2: Summary of previous pumice studies

No.	Researcher	Dosage	Recommendation	Gaps
1.	Tangolar, et al., 2020	50 t/ha/yr	To improve yield and quality	Effects on plant growth were not monitored
2.	Sahin, et al., 2005	45% by volume	To improve water retention capacity and yield	Use of the superabsorbent polymer and pumice in mixing ratios
3.	Malekian, et al., 2012	3.6 g/kg of soil	To reduce irrigation costs	Use of the superabsorbent polymer and pumice in mixing ratios
4.	Gizas & Savvas, 2007	33% by volume	To improve growth and yield	Use of the superabsorbent polymer and pumice in mixing ratios

In another study, Hassanpour et al. (2023) studied the growth and productivity response of olive tree to pumice as a soil amendment. It was found that there were significant improvements in tree growth (i.e. trunk diameter and canopy volume) and yield in the pumice-amended plots when compared to the control treatment. These improvements suggest that pumice created a favourable long-term condition for the perennial olive trees to develop sturdy structural capacity. While these studies show the numerous benefits of pumice on various crops in diverse situations, there is very little information on its specific effects on bell peppers in clay soils in ASAL areas when used in combination with SAPs. Most of the published works on the influence of pumice on plant growth were performed in soilless medium or sandy soils, where the physical constraints of clay are not present. For example, in soilless culture, pumice improved drainage and aeration preventing root rot in confined systems. However, in clay soils, pumice would also be important in treating severe compaction, improving internal drainage, and increasing the availability of water which is often tightly held by clay particles. This research therefore hopes to bridge this information gap by offering accurate information on the response of bell peppers to the combination of SAP and pumice amendments under the challenging conditions of Mogotio Sub-County.

2.6 Soil Analysis and Assessments

Soil quality analysis is a combined and planned assessment of the physical, chemical, and biological properties of a soil. In this way, through comprehensive assessment, the overall situation of the soil, fertility and the extent to which it is suitable for different purposes from agriculture to construction, is provided. The whole exercise begins with careful levelling out of samples of the soil with respect to different geographies with the view of having a good reflection of the study location. This is followed by strict standardized laboratory techniques for determining specific properties and thereafter the interpretation of the collected data. With such systematic analysis, valuable information is obtained and clarity is given on soil composition, nutrient levels, activity of microorganisms in the soil, and soil capacity and ability to promote good and sustainable plant growth.

Soil analysis is a very important part of agriculture and it is not just about curiosity. It provides a link between the theoretical scientific knowledge and the practical application in agricultural management. Soil analysis is an accurate tool which assesses the total quality of soils before and after their exposure to conditioning. It assists farmers, land managers, and agriculture specialists derive information for making informed decisions. These are relative to choosing and using of certain crop and soil management methods that are best for their lands.

Some of the most important parameters analysed in soils are:

2.6.1 Soil pH

Soil pH is an important indicator of soil acidity or alkalinity. Aside from measuring pH, it gives a complete picture of how the soil can regulate availability of essential nutrients and the toxicity potential of certain elements for plants, which are of utmost importance for growth and health of the plant. A pH reading of less than 7.0 is an indication of acidic soil and may also indicate a magnesium deficiency. When the pH level falls below 5.5, the crops have an increased risk of nutrient deficiencies and toxic metal interactions (some metals will be more soluble and toxic). Conversely, when the pH of the soil goes above the neutral line and beyond 7.0, it is classified as an alkaline soil, this could indicate possible future iron deficiency which alters the plants nutritional environment. Consequently, to maintain an optimal soil pH range, usually between 5.8 and 6.5 for most crops, is one of the recommendations on agricultural practices. This range guarantees the maximum availability of nutrients and that the risks of metal toxicity are reduced to a good level ideal for crop growth.

Precise pH measurements of soils are normally done using a pH meter. While some soil amendments can greatly change soil pH, inert or pH-neutral additives, such as many superabsorbent polymers and pumice, are generally expected to have little to no effect on soil pH.

2.6.2 Soil Texture

The physical properties of soil, namely the composition and arrangement of its particles, are the key to determining soil texture. Soil texture is determined by analysing the relative amounts of sand, silt, and clay particles in a given sample of soil. This textural composition impacts the ability of soil to regulate water infiltration and hold important nutrients. Soil scientists have standardised names to indicate the wide variety of soil textural categories, such as "silty clay," "sandy loam," and "sandy clay." This can be done using the textural triangle Figure 2, whereby the measured percentages of sand, silt, and clay are traced to find their intersection point in the triangle. Specifically, the sand percentage is located along the bottom axis and followed diagonally upward its corresponding line to the left. Then, the clay percentage is located on the left axis and followed horizontally to the right. Finally, the silt percentage is located on the right axis, and traced diagonally downward to the left. The textural class of the soil is where all three lines meet.

It is important to understand that soil behaviour is not only a function of the textural composition of soil; the structural organization of soil particles into bigger clumps called soil aggregates, also plays a great part. This arrangement is referred to as soil structure. Soil structure influences permeability (ability of water and air can to travel through), aeration (amount of air in soil), and ease of plant roots to penetrate the soil matrix.

Figure 2: U.S Department of Agriculture soil texture triangle

Source: Groenendyk et al. (2015)

Soil texture is often assessed using sieving and hydrometer techniques in which the aggregates are separated by size, or by visual evaluation of aggregate stability, which is the evaluation of how well the soil clumps hold together when wet. While soil additives, especially those that alter particle arrangement can affect the soil structure by either creating or stabilising aggregates, their impact on textural classification is generally considered to be subtle or negligible. However, some understanding of how these amendments may interact with soil texture is essential.

2.6.3 Porosity

Porosity defines the amount of empty space (pore space) in the soil matrix, which is occupied by either air or water. This parameter is of great importance to the quality and functioning of soils as it determines the ability of soil to allow movement and retention of dissolved nutrients and water. In an ideal and healthy soil ecosystem, this spatial allocation (the volume of pore space) is around 50% of the whole soil volume. The balance is naturally favourable to the harmonious coexistence of the water and air phases. The equilibrium is important because it promotes easy movement of water through the soil matrix and effective storage of vital soluble nutrients as well as their availability to plants. Such an equilibrium helps avail important nutrients and improves the water storage capacity of soil to maintain suitable moisture levels within the soil.

Porosity is expressed as a percentage with respect to the total volume of soil (Castellini et al., 2021). The current study aimed to compare the baseline and the post-intervention measurements (before and after introduction of soil amendments) so to understand how the porosity reacts to external stimuli, including the introduction of soil additives such as pumice and SAP. These amendments are materials that can physically alter the soil matrix through increasing pores spaces, improving the arrangement of the existing ones, and reducing compaction. The comparison of pre and post intervention measurements ascertains the effectiveness of the intervention in inducing quantifiable changes in the porosity of soils.

2.6.4 Bulk Density

Bulk density is a measure of the mass of the dry soil in a unit volume and is expressed in grams per cubic centimetre (g/cm3). It gives a direct indication of the degree of compaction of the soil as it is without moisture. For an accurate measurement, undisturbed soil samples are collected from different parts and layers in order to obtain trustworthy and representative estimates of the natural compaction of the soil. In contrast, particle density only considers the level of density of the actual soil particles without any reference to the voids and spaces or pores distributed within the soil mass. As such, a higher bulk density indicates a tightly packed soil with little available space for pores, whereas a lower bulk density indicates a loosely packed soil with more pore space.

Values of bulk density reflect certain soil conditions, including high sand content (high bulk density with larger, less aggregated particles) or soil compaction. Soil compaction is typically caused by intensive farming methods, repeated passes with heavy machinery and even heavy foot traffic that forces soil particles to pack together, increasing bulk density. Higher bulk density leads to modifications of soil characteristics affecting porosity (decreasing the space for air and water), permeability (slowing water and air flow), and water storage (affecting the amount of water that a soil is able to hold and release). These modifications may hinder root penetration and nutrient availability.

According to recent studies, accurate measurement and interpretation of bulk density gives valuable indications of soil behaviour and nature (Bandyopadhyay, et al. 2012). Studying the variations in bulk density as well as the causes of fluctuations provides important information on valuable soil dynamics in agricultural planning, land management, and decision-making related to environmental issues. Inclusion of superabsorbent polymers and pumice is particularly anticipated to lower bulk density through an increase in pore spaces and enhancement of soil aggregation, improve overall structure of soil and enhance better movement of water leading to sustainable and durable use of lands.

2.6.5 Infiltration

Infiltration is the downflow of water into lower parts of the soil profile from the ground surface. It is established on the basis of water flow (hydraulic conductivity) through soil, soil composition (percentage of sand, silt, and clay) as it comes in contact with, soil compaction or porosity (volume of spaces), and soil structure (distribution of soil materials). These are all factors which influence the flow of water in soil and determine the depth and rate of penetration.

Hydraulic conductivity directly controls the capacity of soil to permit transmission of water and is basically the medium along which infiltration happens. Soil texture determines the level of ease in which water infiltrates; sand-containing soils, for example, typically have higher infiltration rates than clay-containing soils. Soil denseness either hinders or helps in water infiltration; soils with more denseness are subjected to low water infiltration rates. Porosity directly adjusts the total amount of water that is absorbed. In tandem, soil structure influences the course along which water infiltration takes place and as such plays a crucial role in the process. Soil with stable aggregates and proper balance often has higher infiltration rates because of the presence of substantial macropores.

Infiltration aids in determining the rate at which the root zone can be recharged with water and is an important factor in producing good crops. Understanding infiltration rates in the ground is central in ensuring optimal irrigation, efficient water delivery (at a rate the soil can absorb) and sustainable land use so as to control runoff and erosion. These rates can be measured using the double ring infiltrometer which gives both initial and steady-state readings of infiltration in controlled settings (Castellini et al., 2021).

2.6.6 Soil Moisture Content

Soil moisture content is the amount of water that is held in the soil matrix. It is descriptive when it comes to the hydration status of the soil, and directly controls the growth of plants and crop management practices as well as the health of the entire ecosystem. Soil moisture promotes the physiological functions of plants, nutrient movement, and microbial activity. Measurement is done through the gravimetric method where a site representative soil sample is collected and its original wet weight is recorded. Then, the same soil sample is dried in an oven at 105°C until the weight remains constant as an indication that all the moisture has been eliminated. The sample final weight is then calculated. The difference of the original wet weight and the final weight after drying is calculated as a percentage weight of the dry weight, to give an accurate reading of the moisture content of the soil (Bandyopadhyay, et al. 2012). The technique gives a reading of water content by weight.

The obtained information thus provides an indication of what it can do in sustaining plant life and is also useful in refining irrigation methods so that water is used more efficiently avoiding over-watering and under-watering. In hydrological and climatological studies, measurement of the moisture content of the soil provides valuable information on an area's water balance, helps understand hydrological cycles, and improve forecasting potential concerning development and extent of droughts or probability of floods. Soil moisture content in practical application in the field therefore supports sustainable resources management.

2.7 Experimental Designs

Experimental designs are useful tool of science research which offer an explicit, systematic way of organising experimental units and obtaining data during the course of an investigation. These conscious designs predetermine data collection methods and affect the statistical methods of data interpretation. Careful adherence to a chosen design allows the researcher to safeguard internal validity and external generalizability of study findings, so that inferences are firm and trustworthy.

Randomization is one of the inviolable rules of experimental work. It encourages the fairness and integrity of experimentation the application of treatments or conditions to experimental units in a random manner. This assigns any uncontrolled variable, known or unknown, equally across all groups of treatments. In turn, this eliminates systematic bias in the allocation of treatments and not some confounding variables. This increase in statistical reliability leads to an ultimate improvement in the generalizability of the results to a broader population or other situations with similar conditions.

There are numerous experimental designs, each of which is precisely selected and adjusted to research goals and means of coping with/controlling a variety of sources of variability present in an environment of a study or experimental units.

2.7.1 Factorial Experimental Design

Factorial experiments are useful in investigating the effects of two or more independent variables (factors) simultaneously at different predetermined levels. The main goal is usually to first know the individual effect of each factor on a dependent variable and then, to discover how these factors jointly act on the dependent variable. This combination of influences is called an "interaction." Usually in such experiments, treatments or unique combinations of factor levels (e.g., a particular SAP level combined with a particular level of pumice), are randomly determined and used on experimental units. The factors or variables in the experiment could interact or not. There is an interaction when the impact that one variable has on a dependent variable varies according to the level of another variable. To a large extent, this type of design examines complicated relationships and further enables the researcher to not only determine the primary effects but also determine synergistic or antagonistic effects of various treatments.

2.7.2 Completely Randomised Experimental Design

Completely randomised experiments are used when experimental units (plants, pots, or small plots in a controlled environment) are deemed to be inherently homogeneous in their characteristics prior to the application of the treatment. The design mainly aims to reduce errors in the experiment and maximize comparisons of the treatments by making sure that the observed differences in the dependent variable are attributed to the treatments and not some of the pre-existing, uncontrolled differences that are not under the study. Under this design, all experimental units are completely assigned any treatment at random and each has an equal opportunity of receiving any treatment. This design can be used to compare any number of treatments. It is, however, best adapted in scenarios where the number of treatments is relatively fewer and a high level of homogeneity among experimental units can be assured with high confidence. This is especially necessary since it may be difficult to statistically detect genuine differences in treatments due to an inflated experimental error when there is a large number of treatments or an occurrence of severe variations across units that have not been identified.

2.7.3 Randomised Block Experimental Design

A randomised block experiment is a more sophisticated version of the completely randomised experimental design, designed particularly to address any instances where experimental units are known or presumed to be not altogether homogenous. Within this design, experimental units are selected in strategic clusters known as blocks based on a factor that may result in differences in the outcome (e.g., different soil fertility gradients, unequal exposure to sunlight exposure, or irregular drainage patterns on a field). The units within a block should be as homogeneous as possible, but different between blocks. In each defined block, all treatments appear only once, and the treatments of one block are then randomly assigned. The main advantage of this is that the difference between the various blocks, due to a blocking factor stands between effects of the treatment and random error. This allows researchers to distinguish and empirically measure accepted sources of variability significantly minimising sources of total experimental error. To prevent inflating the error term, the design avoids masking actual effects of treatments which may result in less true and precise conclusions about the treatments. This is mostly helpful in experiments where there are known environmental gradients or plot differences which increase the accuracy and statistical influence of the study.

This study was conducted in the field on a farm located in Mogotio Sub-County. It used a completely randomized design (CRD) with 10 different treatment combinations of superabsorbent polymer (SAP) and pumice. Full randomisation was done on all the 30 experimental sub-plots. The CRD made the assumption that any pre-existing differences within the field could be sufficiently diffused and accommodated through full randomization and whatever systematic bias it produced was allayed. Internal validation and generalizability are achieved through full randomisation.

2.8 Plant Growth and Characteristics Measurements

Plant growth is greatly affected by the local ecological factors. Each crop has different rates of growth with diverse traits based on the environmental conditions it is subjected to. Such conditions include water availability, light intensity, soil nutrient content, air circulation, available space and temperature. Any changes in these conditions have the potential to affect the internal growth hormones of a plant resulting in stress which may either be beneficial, inhibit or alter the growth patterns and overall development of a plant. Biologically, growth involves the physical growth and reproduction. It entails an increase in the mass and volume of a plant, which may come with the creation of new cells, tissues, cellular components (organelles), and organs.

Table 3: Summary of plant growth and yield measurement techniques

No.	Parameter	Equipment	Method	Standards
1.	Plant height	Metric ruler	A ruler is placed at ground level near the plant and measured to the highest stem	NGSS LS1A NGSS LS1B (Hilty et al., 2017)
2.	Stem diameter	Ruler	The diameter of the plant is measured using a calliper at ground level	NGSS LS1A NGSS LS1B (Beadle, 1985)
3.	Number of leaves	-	All visible leaves including the tip of newly emerging leaves are counted	Science Buddies (Hilty et al., 2017)
4.	Number of branches	-	All branching stems along the main stem are tallied	Science Buddies (Beadle, 1985)
5.	Number of fruits	-	All fruits are counted	Science Buddies (Beadle, 1985)
6.	Weight of fruits	Weighing scale	All fruits per plant are weighed on a weighing scale	NGSS LS1A NGSS LS1B (Hilty et al., 2017)

Data collection involves the careful observation and measurement of these changes over time. Some of the commonly assessed aspects of growth are stem diameter (vitality level of structural strength and biomass concentration), plant height (reflectance of vertical development and vegetative vitality), and root-shoot ratio (vitality of nutrient and water uptake). When estimating the economic yield of a crop, measurable characteristics that directly provide the overall productivity of the plant and its marketable output are assessed. The current study focussed on the total number of fruits and fresh weight of fruits. The methods and instruments chosen to measure growth of plants might change depending on the type and size of a plant. Non-contact and non-destructive contact methods are ideal in small plants or fragile seedlings to avoid plant injury and disturbance in plant growth (Hilty et al., 2017). Non-contact methods ensure minimal disturbance and optimality in terms of the reflection of growth as the measurements are taken without coming into contact with the plant. This work involved non-contact methods, Table 3, to determine the effect of superabsorbent amendments on bell pepper in clay soils.

2.9 Bell Pepper Plant Farming

Bell peppers (Capsicum annuum) is a high-value vegetable in the local and global market, due to its nutritional and economic benefit. They are vulnerable to drought stress just like other vegetable crops due to their high sensitivity to water shortages. This sensitivity may be explained by its physiological factors such as high level of stomatal conductance, shallow roots, and wide leaf cover. Exposure to water scarcity could reduce the productivity of bell peppers drastically affecting the capital yield of farmers (Islam et al., 2011; Sayyari & Ghanbari, 2012). Bell pepper sensitivity renders it an ideal indicator crop in the determination of how water management techniques in a drought-prone environment should work.

Capsicum or bell pepper is a dicot plant that contains Vitamin C-rich. A single green bell peppers contain about 120mg of Vitamin C in it whereas a single red bell pepper has approximately 190mg of Vitamin C in it. They are highly nutritious sources of the non-essential Vitamin C which helps the body develop grow and repair body tissues (Leap et al., 2017). Similar to any other plant, peppers are highly sensitive to variations in the supply of resources. Peppers grow well at temperatures between 20°C and 25°C but do not grow at low temperatures below 15°C. Planting to the late of harvest normally takes not more than 110 days in which germination and plant establishment takes 25–30 days, flowering 35 days and maturation 40 days. Water stress during flowering and fruit development may result in small, unhealthy fruits and even crop failure. Temperature and soil moisture are very important factors that determine bell pepper productivity. Flowering takes place in optimum day and night temperatures of between 25℃ and 21℃ to prevent delays in flower bud initiation and ensure robust yields (Plant Production Directorate, 2013).

Plant spacing directly influences the productivity of plants. It is determined based on the growth pattern of the plant. Since the roots of bell pepper can extend from 20 to 30 cm wide, and stems to a height of 30 to 90 cm, the plants can be spread out 20 to 90 cm apart. In addition, it is important to consider where the sun is positioned to prevent the plants from experiencing sun scalds. Sufficient spacing guarantees the peppers adequate nutrients, air circulation, and space to develop. Also, it is easy to detect and remove weeds on time and harvest the mature fruits easily (Islam et al., 2011). In Kenya, the agronomic recommendation for the spacing of bell pepper plant is 60 cm by 40 cm, a spacing that was adopted for this research to ensure conditions favouring optimal growth and production.

Figure 3: Bell pepper growth stages from seed to fruit production

Source: Eldeweni et al. (2023)

Bell peppers can grow in deep, fertile, and well-drained soils with a pH close to neutral, preferably on the alkaline side. Peppers cannot thrive in clay soils that tend to compact, as their roots typically grow to a maximum depth of 1 meter, with the majority located in the top 60 cm. This is the characteristic that makes them especially vulnerable to the challenges that Mogotio's clay soils present-predominantly compacted soils with poor drainage. Bell peppers need to be watered regularly during dry seasons to ensure they have optimum growth. The total water requirement for bell peppers is 600 - 900 mm in short growing seasons, and up to 1250 mm in a prolonged period with extended harvesting (Ashilenje, 2013; University of Georgia Cooperative Extension, 2009). Soil moisture stress directly influences the quality and quantity of pepper fruits hence the need to incorporate amendment materials to stabilise moisture availability. This coupled with its soil requirements to grow in uncompacted, well drained soils makes them appropriate test crops to offer relevant and contextual information on the use of amendments in alleviating moisture stress and enhancing yield.

2.10 Conceptual Framework

Figure 4 shows the conceptual framework model for this study. It visually describes the relationships among the variables used in the study. At the top of the diagram are the inputs, otherwise known as the independent variables. This is the beginning starting point of the study, where the inputs were systematically manipulated or varied. In this study, the inputs are the superabsorbent polymer (SAP) and pumice in different mixing ratios based on their weight. Below that are the intermediate variables, which include dependent variables, mediating variables, and moderating variables. The outcomes are listed at the bottom to outline the final desired results of the study, which are optimised soil moisture retention, improved plant growth, increased crop yield, and enhanced soil water storage capacity. Table 4 shows an overview of the variables used in the study.

Independent variables are controlled by the researcher to observe their impact on the dependent variables. Mediating variables explain how or why such an effect is produced (e.g., changes in soil physical properties mediate the effect of amendments on plant growth). Moderating variables affect the strength or direction of the relationship between independent and dependent variables (e.g., temperature may moderate the effect of water retention on plant growth). This framework ensures a systematic approach towards investigations of the complex interaction in the soil-plant system.

Table 4: Conceptual framework summary

Variable Type	Variables
Independent Variables	- Super absorbent polymer (SAP) quantities
	- Pumice dose
Dependent Variables	- Soil moisture retention
	- Plant growth parameters (height, leaf count, stem diameter)
	- Crop yield parameters (fruit weight, fruit count)
Mediating Variables	- Soil physical properties (bulk density, porosity, HC, AW)
Moderating Variables	- Irrigation practices (frequency, amount)

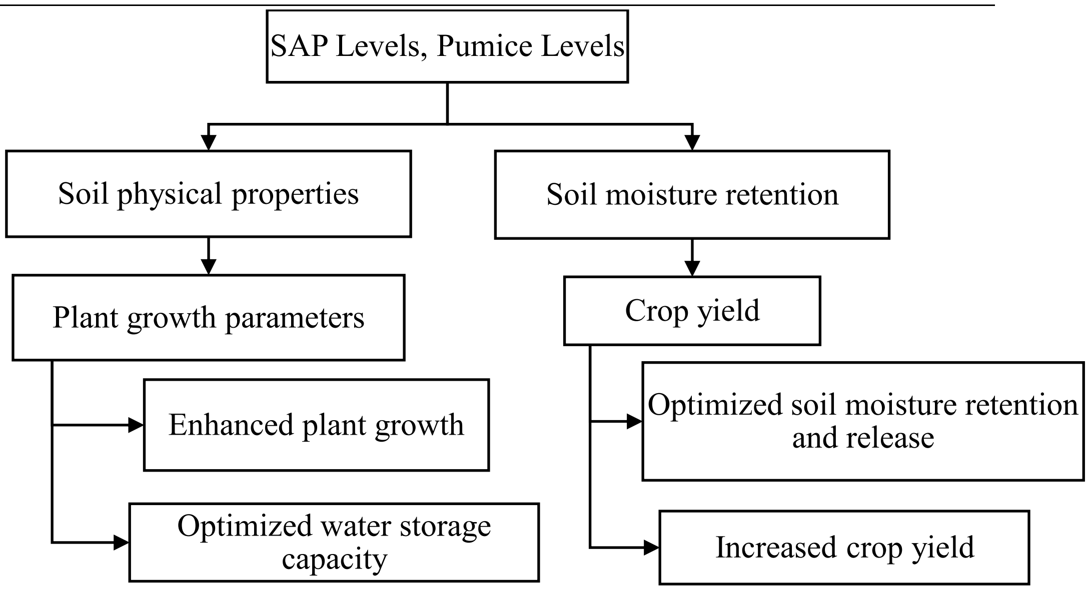

Figure 4: Summary of the conceptual framework

CHAPTER THREE
MATERIALS AND METHODS

3.1 Study Area

This research was carried out on a selected farm located in Ngubreti Centre, Mogotio Sub-County, Baringo County, Kenya. Mogotio Sub-County covers an area of about 1315 km^2. The site of the particular experimental farm is at the latitude 0° 34′ 59″ N and longitude 35° 55′ 3″ E, with an average altitude of 1590 m above sea level. The farm was deliberately chosen because it is was a representative in terms of clay, had on-farm resources such as a good water supply for experimental irrigation and sufficient space for plot installation. Another reason was the owner was willing to cooperate on the farm.

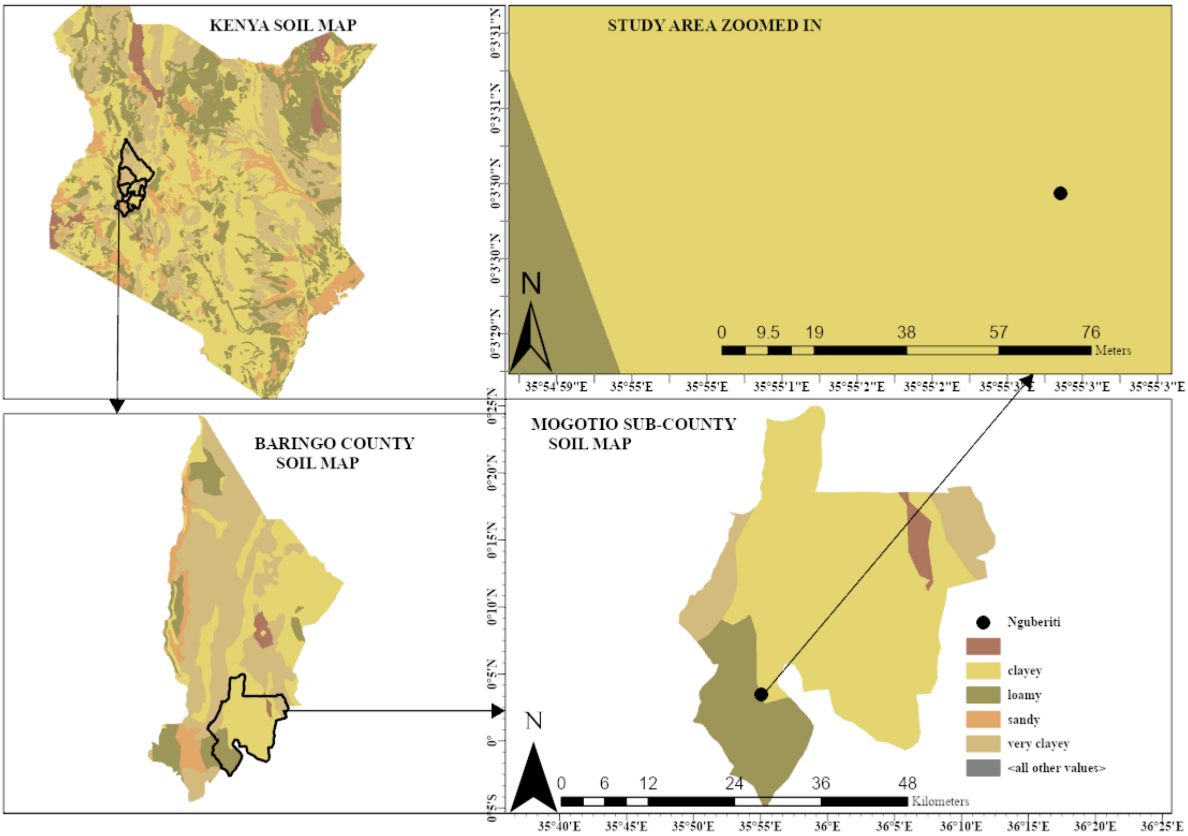

Figure 5: Geographical location of experimental site

The climate of the area is described as warm and temperate, which indicates an arid and semi-arid land (ASAL) region. It is characterised by a mean annual precipitation of about 531 mm, which occurs mainly in two seasons. The annual average temperature of the region is particularly high with 27°C, favouring high rates of evapotranspiration and thus higher water demand by plants. The soils of Mogotio sub-county have different drainage classes, ranging from well-drained to moderately deep and very deep. However, clay soil is the predominant soil texture on the experimental farm. The experimental site is a relatively flat land with a gentle slope.

Mogotio is a representative area whose findings are directly applicable and relevant to improving agricultural water management in similar water-scarce regions. The Ferric Luvisols of the area are rich in clay content which despite having a high-water retention capacity, poses substantial challenges to crop growth and yield. These include poor drainage, slow infiltration rates and the susceptibility to waterlogging and compaction. Clay also exhibits contradictory properties whereby after heavy rainfall, the plants may experience water stress.

3.2 Experimental Design

3.2.1 Treatments

This study was conducted under the Completely Randomised Design (CRD) whereby 10 pre-defined treatments (superabsorbent polymer (SAP) and pumice in mixing ratios) were randomly allocated to experimental plots to determine their effect on soil hydraulic properties and bell pepper growth and yield. The SAP treatment levels applied were 0 kg/ha (control level), 5 kg/ha ('Half' (H)), 10 kg/ha ('Full' (F)), and 15 kg/ha ('Double' (D)). The SAP used was Belsap® polymer which was sourced from Bell Industries Kenya. The choice of the doses was mainly based on the label recommendation by the manufacturer for Belsap® (about 8-10 kg/ha) and information from the literature regarding the efficacy of SAP (e.g., Feng et al., 2020; Sayyari & Ghanbari, 2012). The 10 kg/ha is taken as a reference for large scale application, 5 kg/ha was selected to determine whether significant benefits could be achieved with reduced input in terms of materials and 15 kg/ha explored the upper limit beyond which diminishing returns or negative effects were likely to be seen.

Pumice treatment levels applied included 0 kg/ha (control level), 6250 kg/ha ('Half' (H)), 12500 kg/ha ('Full' (F)), and 18750 kg/ha ('Double' (D)). Pumice used was obtained and shipped from Naivasha, Kenya. The chosen doses are significantly lower to avoid altering the overall soil texture as excessive amounts could over-dilute the clay percentage and result in high drainage which could lower the water retention capacity. At the selected levels, pumice was hypothesised to slowly increase the soil aeration, decrease initial compaction, and improve the infiltration. However, the 18750 kg/ha level was used as an upper limit beyond which any point of diminishing returns or potential negative effects were likely to be observed.

A control group (0 kg/ha SAP, 0 kg/ha Pumice) was included among the 10 unique combinations. This group was given the same cultivation practises, irrigation, and plant care as all of the other treatment plots but no soil amendments. Its main purpose was to act as an extreme baseline for comparison purposes so that it could be unambiguously determined whether the amendments led to statistically significant improvements and to what extent and in this way verifying the impact of the proposed soil management solutions.

Table 5: The different treatments used in the research

Treatment Abbrev	SAP Level (kg/ha)	Pumice Level (kg/ha)	Description
CSP	0	0	Control (No amendments)
HH	5	6250	SAP Half: Pumice Half
HF	5	12500	SAP Half: Pumice Full
HD	5	18750	SAP Half: Pumice Double
FH	10	6250	SAP Full: Pumice Half
FF	10	12500	SAP Full: Pumice Full
FD	10	18750	SAP Full: Pumice Double
DH	15	6250	SAP Double: Pumice Half
DF	15	12500	SAP Double: Pumice Full
DD	15	18750	SAP Double: Pumice Double

3.2.2 Experimental Layout

There were three replicates for each combination, consisting of four plants within each. A total of 30 sub-plots were created for this study, representing the 10 unique factorial treatment combinations, each replicated thrice. The experimental design was completely randomised design. The exact location of each treatment in the experimental area was established through randomisation to reduce bias. Each sub-plot was designed to accommodate four bell pepper plants, with a spacing of 60 cm between rows and 45 cm between plants within a row, as recommended locally for bell pepper production (Ashilenje, 2013). This spacing provides a sufficient plant spread, nutrient uptake, and optimal sunlight exposure while facilitating uniform cultural practices.

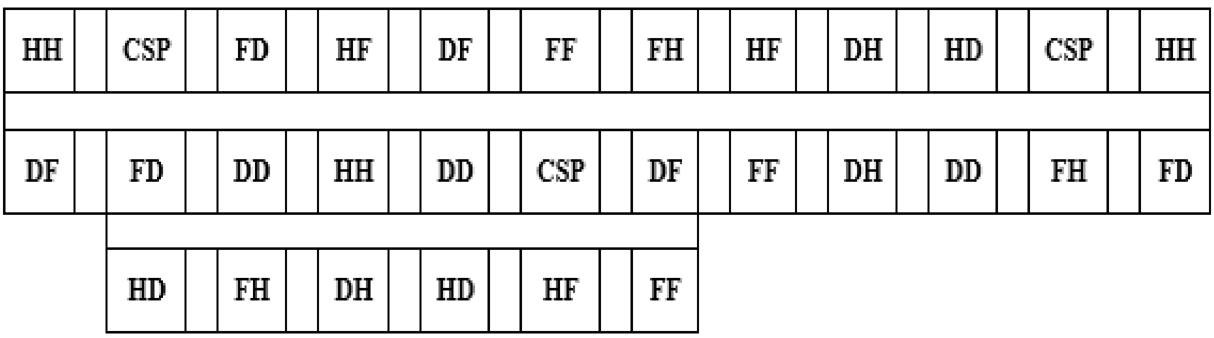

Figure 6: Experimental layout

3.3 Field Setup

3.3.1 Land Preparation and Cultivation of Crops

Initially, the experimental field was deep ploughed to break up any hardpans which may have been present. Afterwards, a uniform layer of organic manure was spread out evenly over the entire field to give all the experimental units an identical baseline level of nutrients and enhance overall soil health. The field was then divided into 30 equal sized sub-plots. Each sub-plot was then randomly assigned a treatment combination of CSP, HH, HF, HD, FF, FH, FD, DD, DH, and DF. In order to promote accurate water management and avoid lateral water migration between neighbouring sub-plots, each was isolated by two equal bunds (small earthen ridges) of length 1m constructed around its perimeter. For each sub-plot, four planting holes were prepared for the bell pepper seedlings.

For treatment application, the exact, pre-weighed quantities of the superabsorbent materials (SAP and pumice) for each assigned sub-plot were evenly mixed with the top 20 cm of soil excavated from the planting hole (cross-sectional area = $0.0883125m^2$) and returned to the hole. This particular mixing depth was selected in order to have the amendments were placed optimally within the active root zone of the bell pepper seedlings. After thorough mixing, a small amount of water was added to each hole in order to trigger the absorption of SAP and to compact the soil-amendment mixture to provide good initial contact. The treatments were added specifically to plant holes and not broadcasted. Healthy seedlings of the cultivar 'Super bell' of bell pepper were transplanted carefully into each prepared planting hole. The remaining soil was then carefully used to cover the transplanted seedlings tightly around the root ball to reduce transplant shock.

During the whole experimental period, all cultural management practises were carried out identically in all sub-plots, strictly following the best management practices for bell pepper cultivation in the region. Weeding was performed regularly and consistently on all plots to avoid competition for water and nutrients, ensuring that the soil amendments and irrigation primarily influenced plant growth. Pruning (removal of diseased leaves) was also done on all plots, pest and disease control to avoid severe crop loss, chemical fertilizers (standard NPK (Nitrogen, Phosphorus, Potassium)) were applied uniformly at standard rates based on initial soil tests, and uniform irrigation.

3.3.2 Irrigation

Irrigation water was obtained from a nearby unlined pond located on the farm. A drip irrigation system was set up to ensure that each plant received an accurate, efficient, uniform amount of water with minimised water loss due to evaporation and runoff that occurs with other irrigation systems. The system consisted of drip emitter lines with an emitter spacing of 45 cm where each emitter applied water at a constant application rate of 1.2 litres per hour (lph).

The start and end times of irrigation events were then set manually based on intensive monitoring of soil moisture content. The total irrigation time of each treatment was estimated from measurements taken by a handheld volumetric soil moisture meter each day along with the calculations based on the soil-water balance method. This method recharged the soil water to field capacity after a predetermined depletion by the plants, in this case for the 100% irrigated plots, which was considered the reference for water requirement. The laboratory-derived field capacity, permanent wilting point, and other constants for investigating soil moisture were used to calculate readily available water (RAW) for bell peppers as outlined in Soil Analysis below). Irrigation was applied when the soil moisture content in the 100% irrigated plots was depleted to the maximum allowable depletion (MAD). For bell peppers, this is usually set at 50% of the total available water. Once this depletion threshold was reached, irrigation was done to replenish the soil water deficit to field capacity. Volume of irrigation water needed for achieving 100% water requirement for a given plot was determined using the following formulas:

$$\theta_{V_{FC}} = \frac{\theta_{G_{FC}} \times \rho_b}{\rho_w} \qquad \text{eqn 3.1}$$

Where $\theta_{V_{FC}}$ is the percentage volumetric moisture content at field capacity, $\theta_{G_{FC}}$ is the percentage gravimetric moisture content at field capacity, $\theta_{V_{PWP}}$ is the percentage gravimetric moisture content at permanent wilting point, ρ_b is the bulk density of soil in gcm-3 and ρ_w is the density of water in gcm-3.

$$d_n = (\theta_{V_{FC}} - \theta_{V_{PWP}}) \times d_{rz} \qquad \text{eqn 3.2}$$

Where d_n is the net depth of irrigation in cm, $\theta_{V_{FC}}$ is the percentage volumetric moisture content at field capacity, $\theta_{V_{PWP}}$ is the percentage gravimetric moisture content at permanent wilting point and d_{rz} is the root zone depth in cm.

$$V = d_n \times A \qquad \text{eqn 3.3}$$

Where A: is the wetted area in cm^2, d_n is the net depth of irrigation in cm and V: is the volume of water in cm^3.

$$Runtime_{in\ mins} = \frac{Volume\ of\ water \times 60}{Application\ rate} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eqn\ 3.4$$

The gravimetric moisture content is then converted to a volume basis (volumetric soil moisture content, $\theta_{V_{FC}}$) which is more applicable for irrigation scheduling.

3.4 Data Collection

A major emphasis of this research was the collection of data in the form of continuous measurements and periodic measurements to describe the interactions of soil amendments, soil properties and plant responses. Volumetric soil moisture content was measured with a handheld digital volumetric soil moisture meter every morning (6:30 AM) before irrigation. The probe was inserted vertically into the soil about 5-10cm from the stem and the value displayed was noted down. This daily monitoring was sufficient to give details of soil water content under the various treatments, and allowed precise irrigation management to be applied. Weekly, plant growth parameters (height, number of leaves, stem diameter) and plant yield parameters (number and weight of fruits) were collected from all 30 sub-plots. Data collection lasted about 90 days from transplantation to the end of harvesting. All raw data was noted into field and laboratory sheets and then keyed into Microsoft Excel 2016 for organisation and preliminary analyses and preparation for advanced statistical analyses.

3.4.1 Measurement of the Soil Hydraulic Properties

Initial soil properties were measured in the laboratory before the amendment were applied. These acted as the baseline characteristics against which the effects of the treatments could be measured. These analyses were based on standard manuals on soil hydraulic properties (Castellini et al., 2021) and other standard soil science methods (Bandyopadhyay, et al., 2012). The initial soil properties that were measured were field capacity, hydraulic conductivity, available water, permanent wilting point, texture, bulk density, and soil salinity.

Subsequently, key soil hydraulic properties (water retention, hydraulic conductivity, porosity, bulk density, and available water capacity) were measured again 12 weeks after transplanting (WAT). These post-application analyses were performed on undisturbed samples of soil which were collected carefully using standard stainless steel core rings in order to reflect in-situ conditions. The results were systematically presented in tabular format for direct comparison and allow trend determination.

The specific methodologies for soil characteristics and quality analysis were as follows:

1. **Soil Texture (Particle Size Distribution)**

Here, mechanical sieving was done for coarser sand fractions and the hydrometer method for the finer soils. The percentage of sand, silt, and clay was determined according to

Stokes' Law, and the soil textural class was determined with the help of the USDA soil textural triangle.

2. Bulk Density

This was measured in the laboratory by oven-drying undisturbed soil samples obtained using standardized core rings. A soil core ring is carefully hammered into the soil, ensuring minimal compaction or disturbance to the sample in the ring. The soil core is then slowly dug up and excess soil at both ends is carefully cut flush using a sharp, flat knife, ensuring the soil sample fills the exact volume of the ring. The sample is then weighed to ascertain its moist mass. The soil sample is carefully removed from the ring, placed in a pre-weighed aluminium tin, and oven-dried at 105°C for 24 hours in order to calculate the mass of oven-dry soil. The bulk density is calculated as:

$$\boldsymbol{\rho_b = M_s/V} \text{ ; } \quad \ldots\ldots\ldots\ldots \text{eqn 3.5}$$

$$\boldsymbol{V = \pi r^2 h} \quad \ldots\ldots\ldots\ldots \text{eqn 3.6}$$

Where ρb is the bulk density in gcm^{-3}, Ms is the mass of dry soil in g, V is the Volume of soil, cm3, π =3.14, h is the thickness of soil on ring in cm, and r^2 is the radius squared in cm^2.

3. Soil Moisture Content

Here, the gravimetric method was used whereby fresh soil samples were weighed, oven-dried at 105°C for 24 hours, and re-weighed. Gravimetric soil water content was calculated as:

$$\boldsymbol{\theta_g = \frac{M_{wet} - M_{dry}}{M_{dry}}} \quad \ldots\ldots\ldots\ldots \text{eqn 3.7}$$

Where: θ_g is the gravimetric soil water content, M_{wet} is the mass of moist soil sample, g, and M_{dry} is the mass of dry soil, g.

4. Field Capacity and Permanent Wilting Point

The method utilised a pressure plate apparatus; whereby undisturbed soil core samples were collected using core rings, saturated for at least 24 hours by placing them in a tray with a shallow water level.

For field capacity, the saturated samples were placed on a ceramic plate in a pressure plate extractor, sealed and an air pressure (e.g., 33 kPa or 0.33 bar) applied. Water drained from the samples until equilibrium is attained (no more water drips from the outflow tube), usually in 24 - 48 hours. The soil cores were then weighed, oven-dried, and re-weighed to obtain the gravimetric water content at 33 kPa, which represents field capacity.

For the permanent wilting point, a similar process is followed, but a much higher air pressure (e.g., 1500 kPa or 15 bar) is used. This pressure mimics the tension at which plants cannot extract water from the soil, causing permanent wilting. The gravimetric water content when the air pressure is 1500 kPa represents the permanent wilting point.

5. Hydraulic Conductivity

The method employed was the constant head method, in which an undisturbed soil core sample is placed in a permeameter cell, ensuring a snug fit to prevent bypass flow. The soil sample is saturated from the bottom to remove air bubbles. A constant head of water is maintained at the top of the soil sample. The volume of water flowing through the sample over a definite time interval is collected and measured. The hydraulic conductivity (*K*) is calculated using Darcy's Law:

$$K_{sat} = AhtQL \quad \text{……………………………………………………………………} \quad eqn\ 3.8$$

Where Q is the volume of water (cm^3), L is the sample length (cm), A is the cross-sectional area of the soil sample (cm^2), h is the hydraulic head difference (cm), and t is the time duration of collection.

6. Porosity

Here, porosity was calculated from the values of bulk density and particle density. The values are used in the formula:

$$\emptyset = 1 - \frac{\rho s}{\rho b} \quad \text{……………………………………………………………………} \quad eqn\ 3.9$$

Where *ps* is the particle density in gcm^3 while pb is the bulk density in gcm^3

7. Daily Volumetric Moisture Levels:

A portable, calibrated digital volumetric soil moisture meter was used. The probe of the meter was vertically inserted into the soil to the desired depth (0-30 cm) in representative locations in each sub-plot. The readings were made on a daily basis, usually early in the morning before significant evapotranspiration has occurred. Multiple readings were taken per plot and averaged to ensure representativeness. Soil moisture depletion rates were calculated from the daily volumetric moisture content and averaged for early and late growing seasons.

3.4.2 Measurement of the Bell Pepper Growth and Yield Parameters

Plant growth parameters were measured and recorded every two weeks from the day of transplanting up to the end of the harvest period.

1. **Plant Height:** Measured from the ground level to the highest growing point of the plant using a standard ruler, in cm.
2. **Stem Diameter:** At the ground level (or at a standard point above ground level) using a calliper, in mm.
3. **Number of Leaves:** Count of the total number of fully expanded healthy leaves per plant.
4. **Total Number of Fruits:** Tally of the total number of marketable fruits collected from each plant, over the entire harvesting period.
5. **Total Weight of Fruits:** Fruits from each plant were weighed separately using a digital weighing scale to obtain their fresh weight in kilograms. This was done in the field as soon as they were picked to reduce moisture loss.
6. **Relative growth rate (RGR):** This takes account of the initial size of the plant, allowing for a more meaningful comparison of inherent growth efficiency than absolute growth rate (AGR). It is the increment of a growth parameter of the plant compared to its current value. the increase in a plant growth parameter relative to the current value of the parameter. RGR was calculated as:

$$RGR = \frac{ln(Parameter2) - ln(Parameter1)}{(Time2 - Time1)} \quad \text{.........} \quad eqn\ 3.10$$

Where *ln* is the natural logarithm, *Parameter 2* represents the growth parameters at Time 2 (e.g., height), *Parameter1* represents the growth parameters at Time 1.

3.4.3 Determination of Optimal Mixing Ratio

The final objective of this research was to identify the best mixing ratio of superabsorbent polymer (SAP) and pumice that improved both the water retention capacity of soil and bell pepper crop productivity in the clay soils of Mogotio. For both, the optimal application rate and amendment ratio were found by investigating those which consistently produced the most positive and statistically significant changes. Physical optimisation was done.

3.5 Statistical Analysis

Data collected in the field and laboratory was quantitative. It was organised and systematically subjected to statistical analysis. Initial data organisation and preliminary calculations were carried out in Microsoft Excel 2016. These calculations include, but are not limited to: data means, growth rate, and volumetric moisture content differences. Statistical Analysis Software (SAS) JMP Pro 17.0.0. was used to perform all advanced statistical modelling and analyses. A one-way Analysis of Variance (ANOVA) was conducted for soil hydraulic properties (porosity, bulk density, saturation, field capacity, permanent wilting point, available water, soil moisture depletion rates both early and late growing seasons and hydraulic conductivity), plant growth parameters (plant height elongation, stem diameter enlargement, and change in number of leaves) and yield characteristics (number of fruits and weight). This analysis tested the treatment's effect on each dependent variable.

Tests of hypotheses concerning each factor and interaction were conducted at a 95% confidence level (significance level, $\alpha=0.05$). The null hypothesis for each test assumed there was no statistically significant difference between the means of the treatments, or no significant interaction with time. The F-statistic for each factor and interaction was derived by dividing the mean square by the error mean square from the table of the results of ANOVA. If the associated p-value from the F-statistic was less than 0.05, then the null hypothesis was rejected, indicating that there was a statistically significant difference between the treatment means or a significant interaction effect. Where the null hypothesis was rejected, a post hoc test analysis was done using the Fisher's Least Significant Difference (LSD) to determine which treatments differed significantly from each other.

Furthermore, to study the continuous effects of varying superabsorbent polymer (SAP) and pumice application rates on some of the key performance indicators, namely available water and yield (measured as weight), physical optimization was done. In the results, the curves of plant growth were plotted for each treatment to graphically represent the growth trends and relative performance over time. The statistical analyses, mean comparisons, and growth trends were clearly and concisely presented using tables and figures.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

In this chapter, the results obtained through the quantitative data analysis performed in the Microsoft Excel 2016 and SAS JMP Pro 17 software were presented and discussed. This is done in direct correspondence to the research objectives stated. The chapter is arranged in three main sections, whereby the first describes the effects on the soil hydraulic properties, the second on the growth and yield of bell pepper; and the third identifies the optimal mixing ratio.

4.1 Effect of the Superabsorbent Materials on Soil Hydraulic Properties

This research objective was focused on determining the effect of superabsorbent materials (SAP and pumice) on various variables that determine soil moisture retention and yield capacity. Prior to the application of treatments, baseline soil properties of the experimental site were analysed to give a background for the characterization of the inherent soil quality before planting and to give a relative framework for the assessment of the land management treatment effectiveness. The variables measured were field capacity, hydraulic conductivity, available water, permanent wilting point, texture, and bulk density. Post-treatment, the physical properties that were measured were water retention, hydraulic conductivity, daily volumetric moisture content, porosity, bulk density, and available water capacity. The findings of these sections are presented and discussed in relation to the available literature.

4.1.1 Initial Soil Properties

The results for the initial soil properties of the experimental site, before the application of any treatments are summarised in Table 6. The properties under consideration, had been specially chosen because of their direct relationship to the water retention properties of the soil and its overall water dynamics.

The soil texture analysis revealed that the dominant soil type at the experimental site was clay soil, in which the particles of clay were more than 40%. This finding is very substantial as the clay soil presents both opportunities and challenges in agriculture. While they have a high total water holding capacity as a result of the large surface area of the fine particles, their water yielding capacity is usually low, and that is to say a large proportion of the held water is bound tightly and not easily available for uptake by the plants. Furthermore, clay soils are susceptible to compaction, limited internal drainage and crusting of the soil surface, which can greatly reduce water infiltration and gas exchange, especially in semi-arid areas of the world where heavy rainfall periods can cause sudden runoff (Szejba, 2020). The initial pH analysis of the soil found medium acidic soil pH of 5.09 which measurements fell into a range broadly deemed as sustainable for most crop plants including bell pepper (Plant Production Directorate, 2013). This pH baseline suggested that although not necessarily ideal, the acidity of the soil was not likely to represent a major limiting condition for nutritional availability and plant growth upon the beginning of the investigation. This gave the research the ability to centre primarily on physical and hydraulic changes provoked in the soil through amendments. The quantitative reading of the other initial soil properties, including bulk density and porosity, constituted important references to compare and evaluate the impact of the superabsorbent material addition to the ground throughout the research to draw an exact indicator of the effect of amendments.

Table 6: Results of initial soil properties

	Property	Units	Result
1	Texture	-	Clay soil (Sand 24% Clay 50% Silt 26%)
2	Moisture content	%	4.73
3	Bulk density	gcm^{-3}	1.05
4	Field capacity	%	34.80
5	Permanent wilting point	%	20.90
6	Saturation Moisture Content	%	46.60
7	Available water	%	13.90
8	Hydraulic conductivity	cm/hr	0.17
9	pH	-	5.09

4.1.2 Bulk Density

As an indication of soil compaction, the bulk density has a direct effect on the soil porosity and therefore on the movement of air and water through the soil. It is ordinarily desirable to reduce the bulk density, which is an indication of less dense and more porous soil, which is conducive to root growth, water infiltration, and gaseous exchange. High bulk density, on the other hand, indicates compacted soil which can severely hinder root growth and decrease water and air movement.

The lowest bulk density was recorded in treatment DH, which was statistically similar to DF (1.20 g/cm^3), HD (1.19 g/cm^3), HF (1.15 g/cm^3), CSP (1.05 g/cm^3), HH (1.10 g/cm^3), and FD (1.10 g/cm^3) but significantly lower than DD and FH. This decrease in bulk density in the DH treatment is extremely desirable, as it is a direct indication of better soil structure, less soil compaction and a more favourable environment for plant roots. The results of the analysis of variance showed that the factors (applied treatments) had a significant effect on the bulk density ($F (9, 20) = 3.8510$, $p = 0.0058$). Specifically, post-hoc analysis based on Fisher's tests with a threshold of 0.057 indicated that the treatments DD (1.25 g/cm^3) and FH (1.26 g/cm^3) resulted in significantly higher bulk density compared to DH (1.03 g/cm^3) ($p = 0.0009$ for DD vs DH; $p = 0.0006$ for FH vs DH) and HH (1.10 g/cm^3) ($p = 0.0021$ for DD vs HH; $p = 0.0017$ for FH vs HH). Furthermore, DD and FH also showed significantly higher bulk densities than FD (1.10 g/cm^3) ($p = 0.0021$ for DD vs. FD; $p = 0.0017$ for FH vs. FD).

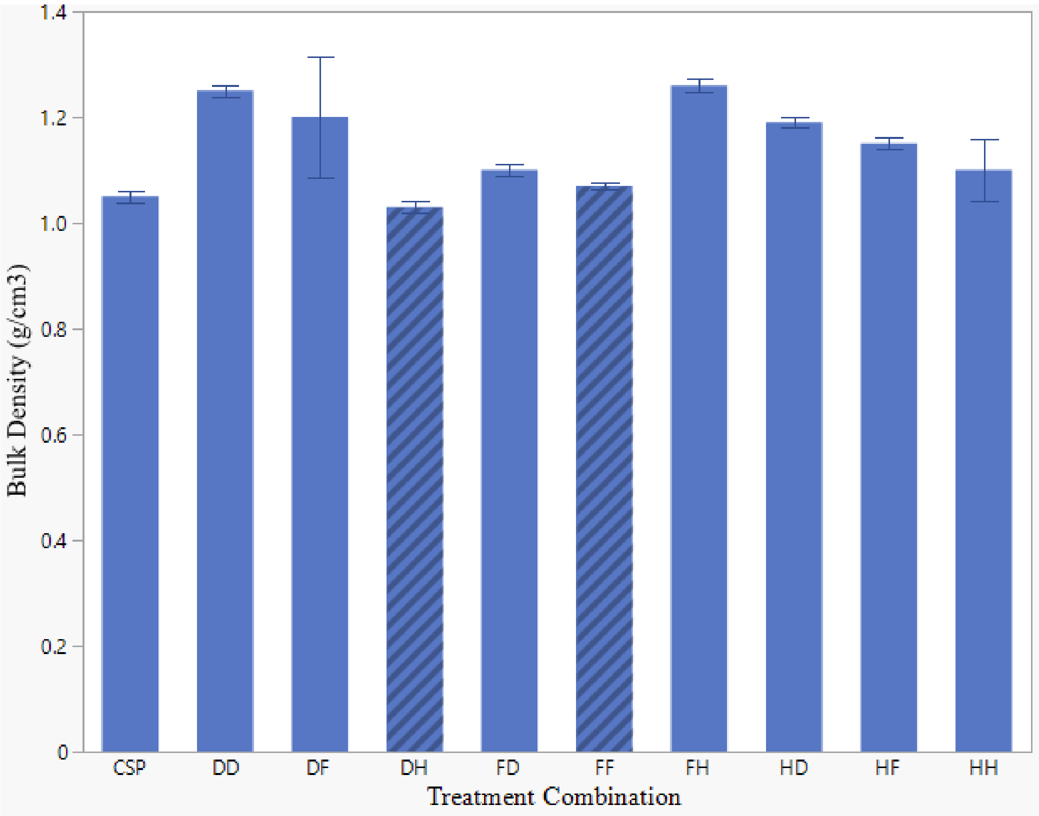

Figure 7: Effect of superabsorbent materials on soil bulk density

Note: *The shaded treatments had lower values of bulk density than the control.*

The observation that bulk density increased in many treated plots, particularly in FH, DD, DF, HD, and HF, as seen in Figure 7, despite the general expectation of a reduction in compaction by the SAP and pumice, is an important observation. Previous studies have given conflicting results, which is helpful to explain this variability. Some research, such as Zohuriaan-Mehr et al. (2010) noted that the extensive swelling of SAPs when they absorb water can, paradoxically, lead to increase in overall soil bulk density if it causes existing soil particles to compact around the swollen polymer especially in soils with high clay content. This may result in increased mass of soil per unit volume after the soil is dried. Likewise, Cao et al. (2017) observed that the SAPs increased soil bulk densities to between 4.8% and 8.9% relative to the control over a period of nine years in the loess plateau terrace field study and explained it as long-term soil reorganisation.

On the other hand, there are studies in support of the expected reduction in bulk density. The study conducted by El-Nahhal et al. (2019) concluded that the water absorbing capacity of SAPs can help reduce soil compaction and provide more pore space resulting in lower bulk density. Similarly, Gholampour et al. (2016) state that the soil bulk density is reduced through the addition of pumice to soil by increasing the pore space and improving the soil structure. This is because the inherent porosity of pumice makes stable air-filled voids within the pumice which inherently decreases the total mass of soil per unit volume.

The patterns observed in this study, especially the decrease in bulk density for DH, and its similarity to the control, while other combinations increased it, suggests that there is a delicate balance in the interaction between SAP and pumice in the clay soils. The high SAP content in DH, when combined with lower pumice, could have resulted in a better development of macro-pores by the expansion and contraction of SAP, or maybe the specific interaction minimised the tendency for clay particles to compact. The increase in bulk density in other combinations (FH, DD, DF, HD, and HF) suggests that these specific ratios, when interacting with the cohesive nature of clay, may have actually had the opposite effect, such that existing aggregates are destroyed without new stable aggregates being formed. A high bulk density negatively affects soil aeration and porosity, impeding root and microbial respiration. This can lead to shallow rooting of plants, poor plant growth, and reduced vegetative cover and hence reducing crop yield and increasing soil erosion risk from runoff in sloping areas or waterlogging in flatter areas. Therefore, the success of DH in achieving a low bulk density, compared to the control, is a positive outcome for cultivation of bell pepper in the clay soils in Mogotio.

4.1.3 Porosity

Porosity directly determines the ability of soil to store and transmit water and air. Adequate soil porosity is important for efficient infiltration of water, good drainage, sufficient gas exchange (vital for root respiration and microbial activity), and unhindered vegetative growth. Ideally, soil porosity should constitute at least 45 - 55% of the total soil volume in order to provide an optimal air to water phase balance. This balance is important for efficient water and nutrient uptake by plants as dissolved nutrients and water are transported through it. Soil pores are usually classified as macropores (>0.08 mm) and micropores (<0.08 mm). Macropores are mostly responsible for fast drainage of water and aeration, help supply oxygen to roots and the carbon dioxide removal. Micropores, on the other hand, are very important for water retention, holding water against the force of gravity and making it available for plant uptake (Brady & Weil, 2017). An ideal distribution of the macro- and micropores is essential for the healthy functioning of soil and at the same time to prevent waterlogging or excessive drying.

The highest mean porosity was observed in treatment DH (15 kg/ha of SAP and 6250 kg/ha of pumice), which was statistically similar to FD, FF, and CSP but significantly greater than DD and FH. Analysis of Variance showed that the applied treatments significantly affected porosity ($F(9, 20) = 3.03$, $p = 0.0187$). Specifically, the post-hoc analysis with Fisher's tests with an LSD threshold of 2.09 revealed that treatments DH (60.23%), FD (59.92%), FF (59.62%), and CSP (59.30%) resulted in significantly higher porosity than FH (52.93%) and DD (53.07%) ($p < 0.05$ for all these comparisons). For instance, the porosity for DH was significantly higher than FH (Difference = 7.25, $p = 0.0002$). DH recorded a porosity of 60.23% which is a notable and beneficial increase of 0.93% compared to the porosity of the control group, which had a porosity of 59.30%. This increase indicates that the combination and concentration of a higher dose of SAP (Double) with a moderate dose of pumice (Half) successfully formed and sustained a larger volume of stable pore spaces inside the dense clay soil. The mechanism is possibly caused by the dynamics of swelling and shrinking of SAP, which is able to physically disrupt clay aggregates and form new macro- and micropores, as well as the natural porous structure of pumice particles which act as permanent voids. This synergistic action results in a more open and aerated soil structure, which improves both drainage and water holding capacity by forming a more balanced structure of pores.

On the other hand, treatments DD, DF, FD, FH, HD, HF and HH, as seen in Figure 8, resulted in a slight decrease in soil porosity than the control. For instance, the lowest porosity was recorded in the FH (10 kg/ha of SAP and 6250 kg/ha of pumice) treatment at 53%. These conflicting results indicate the complexity and dose-dependency of the effect of superabsorbent materials on soil physical properties. The decrease in porosity in some treatments could be explained by several factors; specific ratios could result in unfavourable rearrangement of soil particles, or the excessive swelling of SAPs in some combinations may have accidentally clogged existing pores, thereby decreasing overall porosity. This shows that although SAPs may open up pores, an imbalance in their application or combination with pumice can result in pore sealings, particularly in clay soils which have numerous fine particles. However, all the porosity values measured remained above 50%, which is considered the commonly accepted ideal value, indicating that although certain treatments reduced porosity, the overall soil still maintained a generally open structure.

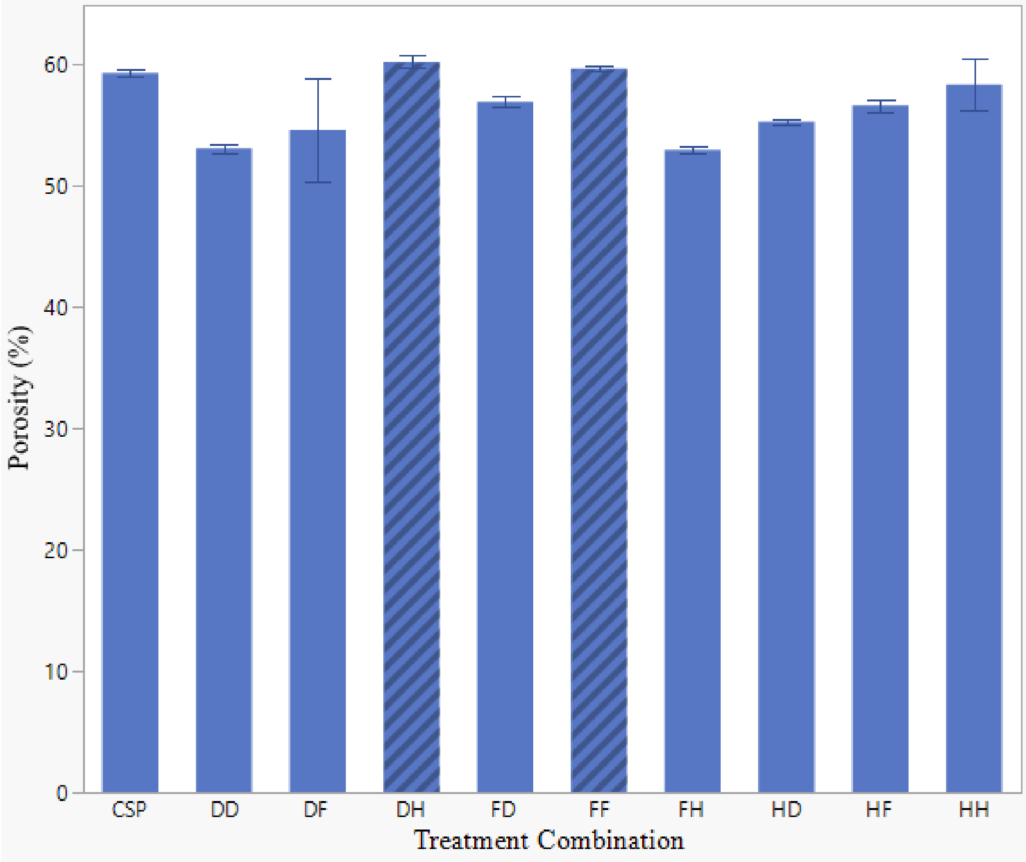

Figure 8: Effect of super absorbent materials on porosity

Note: *The shaded treatments showed higher values of porosity as compared to the control.*

Previous studies, which were carried out on different soil types (e.g., sandy soils, where SAPs increase the water retention without improving porosity) or with superabsorbent materials applied as standalone amendments or blended with organic manure or biochar, have documented mixed results. For example, El-Nahhal et al. (2019) found that pumice alone, increased porosity by establishing stable micropores that increase water flow and aeration. Sahin et al. (2005) likewise found that pumice can enhance soil porosity through the formation of air-filled voids and improving the overall soil aeration. In sandy soils, the water absorption capacity of SAPs has been observed explicitly in order to reduce the loss of water through excessive drainage, resulting into better soil moisture conditions and infiltration rates (Zohuriaan-Mehr et al., 2010). The observed increase in porosity in the DH treatment directly resolves compaction and poor aeration challenges, improves root growth and water flow, thus promoting plant survival and productivity in water-stressed conditions. The unexpected decrease in porosity in the other treatments reinforces the importance of appropriate application rates and combinations since an imbalance can cause undesirable effects.

4.1.4 Hydraulic Conductivity

Hydraulic conductivity is an important soil property that measures the ability of the soil to transmit water. It directly affects the efficiency of irrigation water or rainfall infiltration through the soil profile and its availability to plant roots and is therefore a key indicator for agricultural water management. In this study, the results of analysis of variance showed that the level of influence of the different treatments on hydraulic conductivity was highly significant ($F(9, 20) = 1267.22$, $p < 0.0001$). This indicates significantly pronounced differences in mean hydraulic conductivity values among the combinations of treatments. The high R-squared value (0.99) of the model indicates that almost all of the variability (99.82%) in hydraulic conductivity can be accounted for by the applied treatment combinations. Specifically, results of post-hoc analysis using Fisher's tests with a threshold of 0.05739 revealed that treatment HF (1.83 cm/hr) had significantly higher hydraulic conductivity than all other treatments ($p < 0.0001$ for all comparisons with HF). On the other hand, treatments DD and FD had the lowest hydraulic conductivity and were significantly lower than most of the other treatments ($p < 0.0001$ for many comparisons). These results stress the fact that the treatments have a very significant effect on the hydraulic conductivity of the samples.

The general expectation is that superabsorbent materials should enhance water movement, especially in clay soils, to overcome waterlogging and enhance infiltration. Yang et al. (2021) found that pumice with its porous structure enhances soil structure and aeration which in turn allows more unrestricted flow of water and improve hydraulic conductivity. Similarly, Singh et al. (2015) in general terms explained that SAMs affect the rate of water infiltration and storage in the soil profile, which subsequently affects the water availability, erosion potential, runoff generation, and solute transport.

However, the substantial decrease in hydraulic conductivity in treatments DD and other treatments (HH, FH, FD, DH) is supported by studies that suggest that the overuse of SAP or inadequate mixing of the soil can cause compaction and a decrease of the stable pore space. It therefore could lead to a decrease in hydraulic conductivity (Gholampour et al., 2016). Ostrand et al. (2020) also in fact, noted that the swelling of the SAPs, while desirable for water storage, might increases chances of soil compaction reducing available macropore networks (responsible for rapid flow) and thus reduce hydraulic conductivity. This can occur mostly in fine-textured soils such as clay, where swelled SAPs may occupy existing pore spaces and restrict flow of water.

Alternatively, other research has shown that using SAPs may have a significant increase in the soil hydraulic conductivity, more so in loam and sandy soils. Yang et al. (2020) concluded that the availability of SAPs in sandy soils increases water retention and lessens water loss through excessive drainage to preserve more favourable soil moisture conditions and promote hydraulic conductivity. The important difference is in the type of soil, that in sandy soils SAPs fill large pores which increases water holding, whereas clay soils may have even less large pores to be filled. The combination with pumice is supposed to overcome this.

In this study, the use of treatments HH, FH, FD, and DH produced a decrease in soil hydraulic conductivity compared to the control, which can suggest that the SAP's swelling effect (or the overall physical interaction) in these particular mixes either exacerbated the natural poor drainage of clay or did not create stable conductive pathways accordingly. Conversely, treatments HF, HD, FF, and DF increased the hydraulic conductivity, suggesting that these ratios of SAP and pumice improved the macro-porosity and structural stability of the clay soil, allowing for better transmission of water. The drastic decrease in DD is a cause for concern and suggests that at high concentrations of both amendments can result in severely impeded movement of water. For bell pepper, which requires well-drained soils to prevent waterlogging, high hydraulic conductivity is desirable. The variable results underscore the importance of optimizing mixing ratios for the desired balance of water retention and drainage in clay soils.

4.1.5 Soil Moisture Depletion Rate

The results of this study showed that treatment DH (15 kg/ha of SAP and 6250 kg/ha of pumice) consistently showed the lowest soil moisture depletion rates throughout the early growing period, and FF (10 kg/ha of SAP and 12500 kg/ha of pumice) throughout the late growing period. However, Analysis of Variance did not show a statistically significant effect of the various treatments on the soil moisture depletion rates during both the early ($F(9, 20) = 1.1765$, $p = 0.3608$) and late ($F(9, 20) = 1.4679$, $p = 0.2264$) growing seasons. The R-squared values 0.3462 and 0.3978 indicate that about 34.62% and 39.78% of the variability in the soil moisture depletion rates can be explained by the applied treatments, but this effect was not statistically significant. Other treatments had higher soil moisture depletion rates which could mean that there was competition for water between the plants and the SAP. These results corroborate the fact that the amount and combination of superabsorbent materials are important factors of determining the long-term moisture storage capacity of the soil. The consistently high moisture content in DH indicates that the combination achieved a good balance in terms of both water absorption (SAP) and structural improvement (pumice) which retained moisture well.

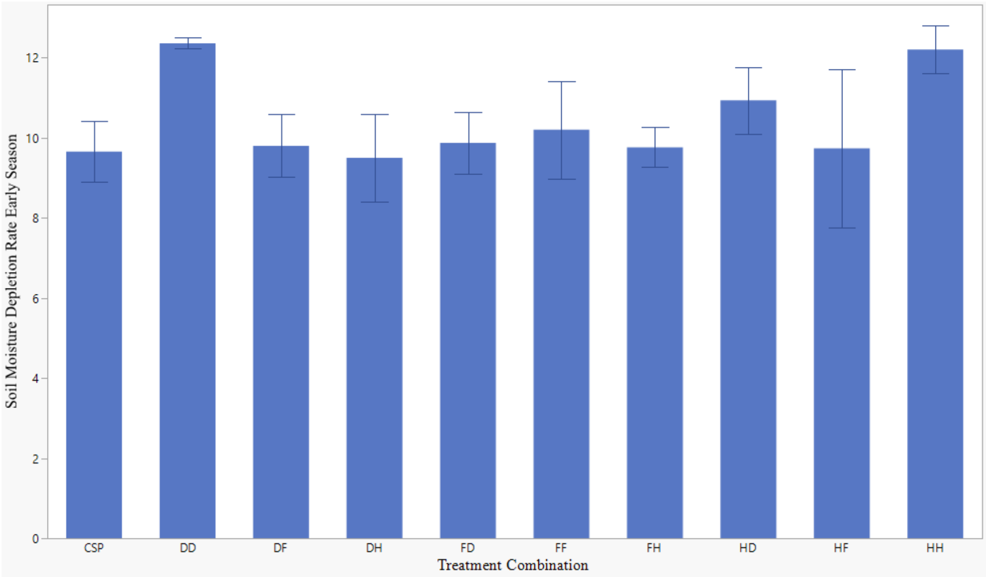

Figure 9: Effect on soil moisture depletion rates during the early growing period

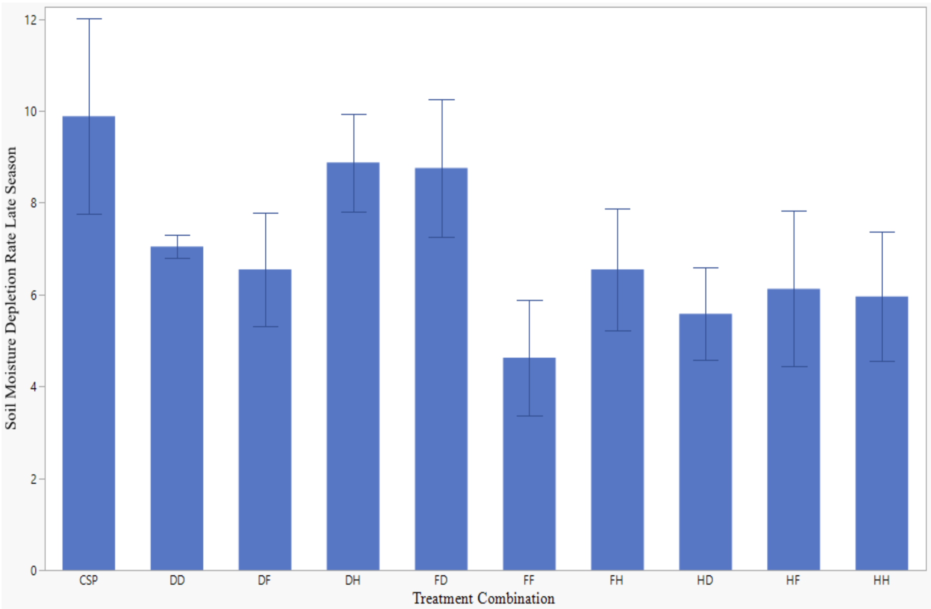

Figure 10: Effect on soil moisture depletion rates during the late growing period

Additionally, during the early growing period the most treatments indicated a higher soil moisture depletion rate than during the later growing period as opposed to the control which indicated a higher soil moisture depletion rate during the late growing period than during the early growing period. Crops need more water during their mid to late growing season in the flowering and fruiting stages (Brouwer & Heibloem, 1986). While moisture is critical during germination and early growing season, the amount of water the plant requires greatly increases as the canopy of the plant grows and the plant heads into the reproductive period.

Water stress at such critical moments can have a negative effect on the final quality and yield (Abbas & Chowdhury, 2016).

The findings of this study agree with results from previous studies. Yang et al. (2021) found that SAPs have the capacity to absorb five times their own weight and are therefore useful in controlled water and nutrient release. Yang et al. (2020) specifically argued that the inclusion of SAPs in the soil helps enhance the soil moisture content by holding and storing the excess water after a rainfall or irrigation event, and releasing it back to plants gradually as needed during drying spells. This improves the soil moisture conditions, minimises water stress on plants, maximises water storage capacity, and maintains moisture against evapotranspiration or drainage losses. This was also validated by Cao et al. (2017), who established that the application of SAPs raised soil moisture content in the range of 3.2% and 43.7% as compared with the control over seven days in loess plateau terraces. In another study, it was found that both pumice and SAPs enhanced the supply of water to plants through moisture uptake and secretion as required (Liao et al., 2016). In bell pepper, which is a very water-sensitive crop, the potential of such amendments in reducing the fluctuations of moisture is vital for the sustained growth and production in ASALs.

4.1.6 Water Retention

Water retention is important in the science of irrigation. It varies with the ability of the soil to retain water against the force of gravity, hence making it available for plant uptake. It is an essential element in plant growth and soil health, especially under dryer climates. Water retention is usually described by a soil water retention curve, which relates soil water content to matric potential (or suction pressure, commonly expressed as pF). In this study, the highest value of saturation (pF 0; near-saturated conditions) was observed in treatment FF (10 kg/ha of sap and 12500 kg/ha of pumice) at 53.37%. As expected, retention of water declined with increased suction pressure, meaning that as the soil dries, it retains less water. However, an interesting observation was that field capacity (FC) values (representing water held at 33 kPa suction) marginally decreased across most treatments. In addition, the treatments HD, FF, FD, and DH showed a slight decrease in FC compared to the control**,** Figure 11. The general principle that water retention rate decreases with an increase in the suction pressure is well-established (Lee et al., 2017). Studies on the effect of soil additives on water holding capacity prove that amendments form water holding pores in soil which help the soil to hold water for extended periods and prevent water losses through evaporation or drainage. Mixing additives with soil enhances the soil texture and structure, which contributes to an increase in the water holding capacity (Zohuriaan-Mehr et al., 2010).

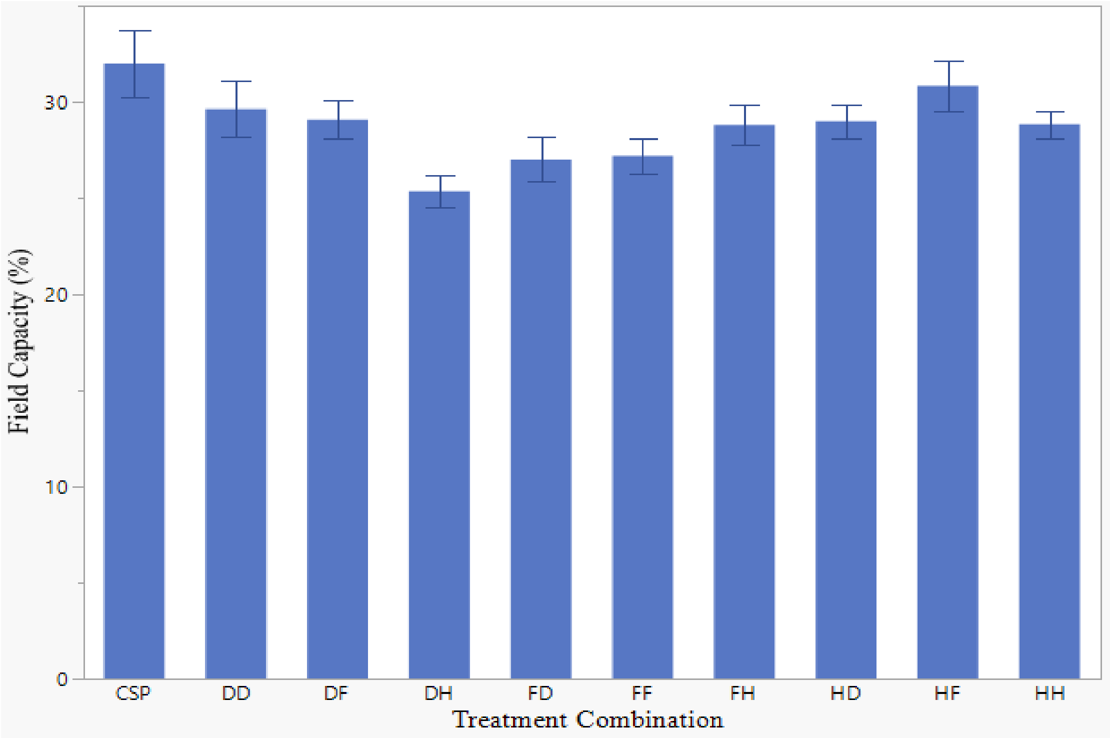

Figure 11: Effect on field capacity

Table 7: Soil moisture retention values (%) of the various treatments

Treatment	**Saturation**	**Field Capacity**	**Permanent Wilting Point**
Suction pressure (kPa)	1	33	1500
pF Value	0	2.5	4.2
CSP	46.60	32.00	20.90
HH	51.18	28.84	17.05
HF	49.50	30.84	18.20
HD	46.78	29.00	18.60
FF	53.37	27.19	17.05
FH	47.70	28.79	16.45
FD	49.62	27.35	17.25
DD	45.55	29.63	17.01
DH	51.65	25.34	16.15
DF	45.13	29.07	18.54

While clay soils have been noted to hold water quite well through their fine silt particles and high surface area, they also contribute to other challenges: water penetration can be slow, and instead of deep infiltration into the soil, it can pool on the surface and be dispersed horizontally (Graber et al., 2006). In some treatments, the decrease in FC was an indication of a complex interaction between the amendments and clay. It is possible that for these mixing ratios, the SAP's swelling, together with the addition of pumice, did not optimally form stable water holding micropores at field capacity. Instead, they may have changed the distribution of pore sizes in such a way that it either allowed for slightly faster gravitational water drainage (water which is held at low suctions, closer to saturation) or less water held at the typical 33 kPa FC tension. This may be a result of an over-aggregation or macropore formation that allows greater water drainage or disrupted clay structure without formation of new stable ones to effectively retain water against gravity at FC.

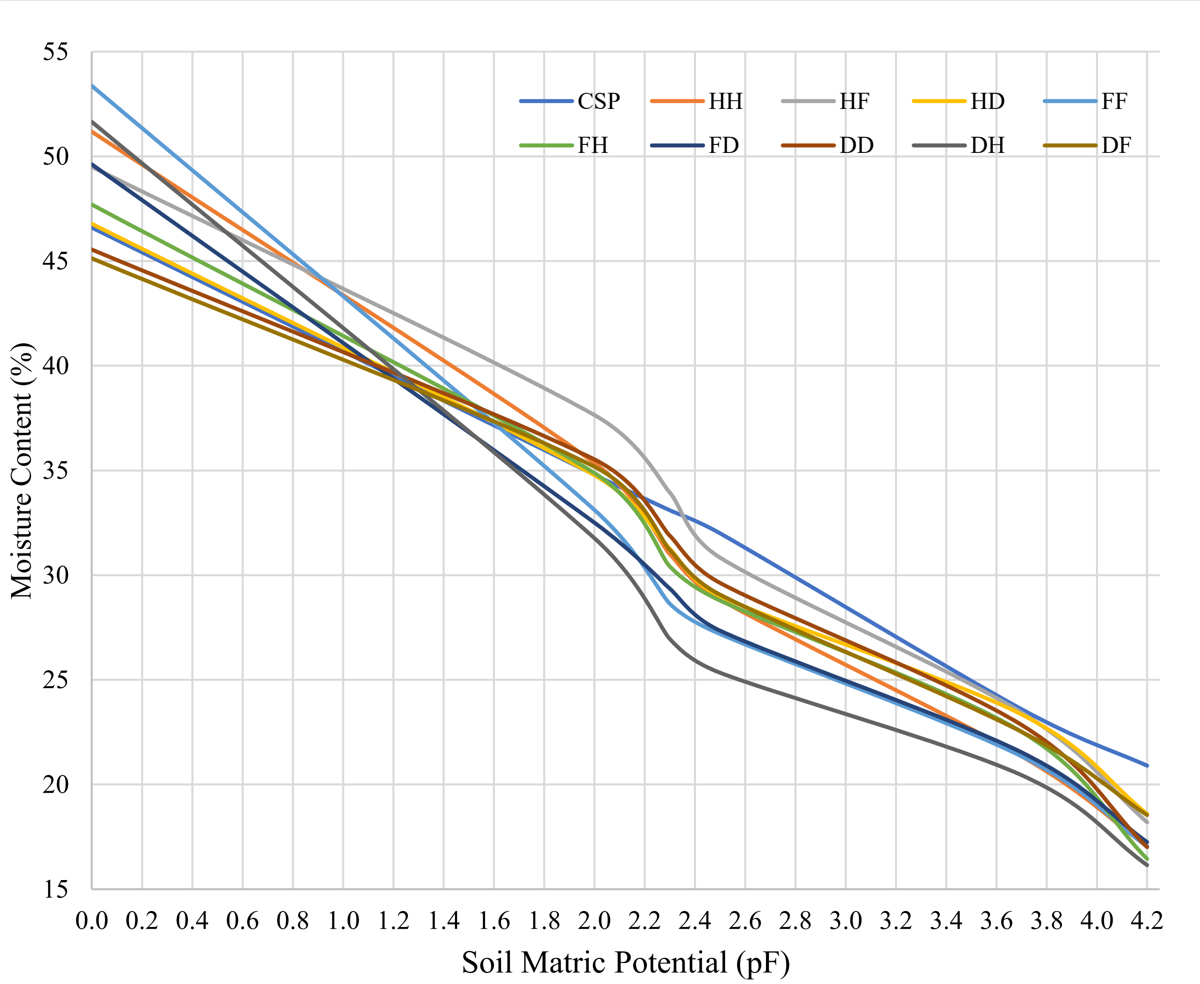

Figure 12: Water retention rate curves for the different treatments

Figure 12 presents a comparison between the water retention curves for the generated curves in the different treatments. The graph strongly suggests that some of the treatments (HH, FH, DD), while starting out much higher in water content, are also increasing the range of plant-available water as compared to unamended clay, in that they hold more water at FC while still releasing some of it before PWP. The steepness of the curve between FC and PWP for these treated soils is important. It should not be too steep as the water may drain too quickly, nor too flat as it may be retained too tightly. The curves for HH, FH, and DD appear to show a more gradual descent in the amount of plant-available than CSP, which is beneficial. The "varying responses" among the different treatments (compare HH to FF) point to the type and amount of SAP, and how it is affected by the specific clay soil, critically important to not only how much water is held, but how it is being released. Some SAPs may hold water too tightly, or release it too quickly. The inflection points and the slope of the curve after is key to understanding this. For example, FF starts quite high, but then its curve drops somewhat steeply in the middle range, and then flattens, which can potentially mean that while it contains a lot of water to start with, a significant amount drains quite rapidly, or the remaining water is held too tightly.

Numerous studies have consistently reported that the augmentation of SAPs have a significant influence on the total water holding capacity of various soil types, especially sandy soils but also loamy and clay soils. This is attributed to the hydrophilic nature of SAPs, which absorb and hold water in their polymer matrix and swell considerably (Zohuriaan-Mehr et al., 2010).

4.1.7 Available Water

Available water content (AWC) is a direct measurement of the amount of water available for plant growth between field capacity and permanent wilting point. It is therefore an important indicator of soil quality in terms of its capacity to store and provide water for growing plants, which in turn has a direct bearing on the productivity of crops. In this research treatment HF had the highest value of available water of 12.64%, which indicates its ability to provide water to plants. The lowest values were recorded in the treatment DH at 9.19%, while the control had an available water content of 11.10%. Particularly, treatment HF caused a 20.63% increase in available water content than the control as shown in Figure 13.

Apart from treatments HH, FF, FD, DF and HD, all other treatments had more available water as compared to the control. This suggests that a number of treatments have successfully increased water availability. Analysis of Variance showed no statistically significant effect of the various treatments on available water ($F (9, 20) = 0.9456$, $p = 0.5095$). The R-squared value of 0.2985 indicates that only about 29.85% of the variability in available water can be explained but this effect was not statistically significant. Ostrand et al. (2020) explains that SAPs tend to result in an increase in available water content by increasing the amount of water held at field capacity and increases the water retention capacity of the soil against gravity and evaporation. In accordance with this, there was a high FC value of 34.15% in treatment HF. The general mechanism is that soil additives improve soil texture and structure, leading to an increase in the amount of water held by the soil in the plant-available range.

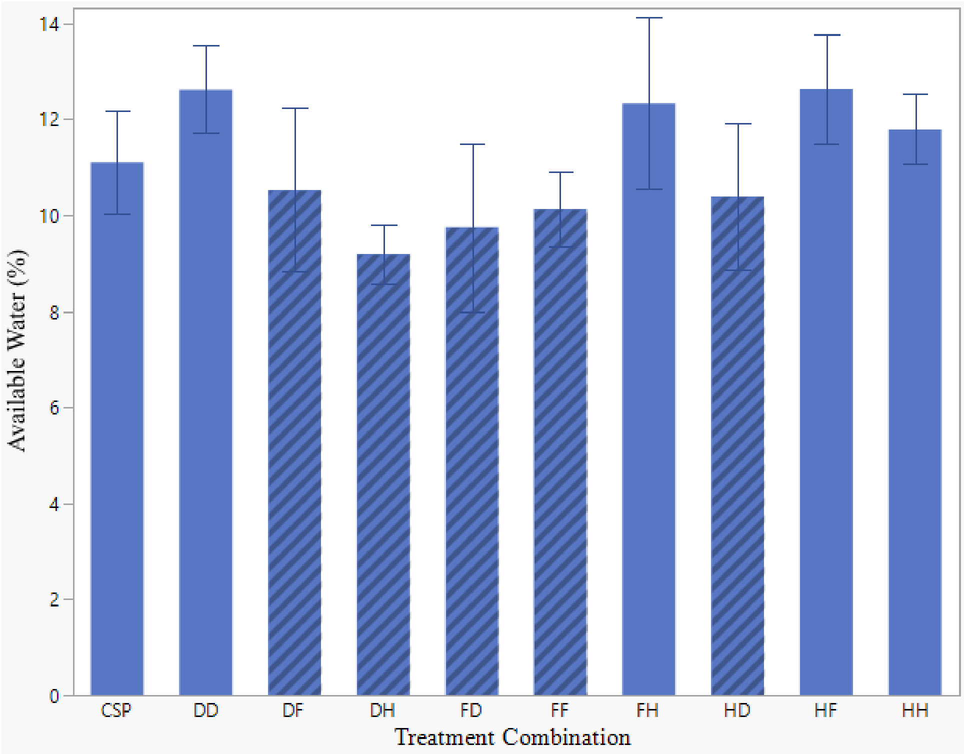

Figure 13: Effect on available water

Note: *The highlighted treatments DF, DH, FD, FF, and HD had a slight drop in available water compared to control.*

The observed decrease of available water in HH, FF, FD, DF and HD treatments as compared with the control is a critical and unexpected finding. This may be explained by the synergistic effect of both the SAP and pumice. As SAP absorbs and releases moisture gradually over extended periods, pumice prevents the soil from oversaturating by keeping it aerated. However, El-Nahhal et al. (2018) explains that the type and ratio of soil additives used can have negative effects on the physical properties of soil, the soil water potential, or the water uptake by plants, consequently leading to a decrease in available water content. This agrees with the results in this study where some treatments may have produced non-optimal pore sizes or resulted in other problems.

SAPs and pumice provide a very desirable and balanced soil environment. SAPs function as on-demand water reservoirs in that they provide a steady supply of moisture, especially during dry periods. At the same time, pumice ensures good aeration and drainage of the soil, preventing the excessive saturation of the soil, which would otherwise be caused by the SAPs and by the excessive use of pumice in clay soils. This synergistic effect helps to compensate both drought stress and waterlogging, hence giving an optimized water use efficiency and better growth conditions of plants. The incorporation of pumice buffers against the possibility that the presence of SAPs would create excessively moist conditions that may impair root health because of a lack of oxygen.

4.2 Effect of the Superabsorbent Materials on Growth and Yield of Bell Pepper

To determine the effect of the superabsorbent materials on the growth and yield of bell pepper, key morphological and yield parameters were measured. These included change in plant height, number of leaves, stem diameter, and the total number and weight of the fruits per plant. Analysis of Variance showed no statistically significant effect (plant elongation rate ($F(9, 20) = 0.7778$, $p = 0.6387$), stem enlargement ($F(9, 20) = 1.0542$, $p = 0.4348$), and change in the number of leaves ($F(9, 20) = 1.4279$, $p = 0.2416$)). While the ANOVA did not show any statistically significant effect of the treatments, it is important to mention the presence of observable numerical trends. These are presented and discussed in the following sections.

4.2.1 Plant Height

Plant height is an important indicator of overall plant growth and vigour and reflects the overall ability of a plant to accumulate biomass and response to environmental conditions including water availability. The results showed that the elongation rate of plant height was highest in treatment FF (Full SAP, Full Pumice) at 6.27%, while the lowest was observed in treatment HD (Half SAP, Double Pumice) at 4.53%. The control group exhibited an elongation rate of 5.21%. The analysis also revealed that treatments HH, HF, FH, FD, DD, DH, and DF registered average elongation rates of 4.69%, 5.72%, 4.65%, 5.69%, 5.63%, 5.59%, and 5.35% respectively.

While a variety of studies have been conducted to analyse the effects of superabsorbent materials on the aspects of plant growth, such as total yield, water use efficiency and photosynthetic characteristics, the specific effect of superabsorbent materials on plant height has not always been the primary focus of extensive individual exploration. Nonetheless, it is generally recognised that improved soil conditions like enhanced water retention, better nutrient availability and improved soil structure favour good root development and a general healthy plant that contributes significantly to plant elongation (Lee et al., 2017). Studies by Smith et al. (2018) and Garcia et al. (2019) generally support the findings that SAPs enhance crop yield, water productivity, and soil quality through enhanced water retention, nutrient availability, and soil structure. These additive-induced improvements in soil aeration, drainage, and nutrient accessibility indirectly support plant growth and contribute to plant elongation. The diverse responses in height in this study, despite overall soil improvements, indicate that optimizing plant height in bell pepper on clay soils is sensitive to the exact amendment ratios, possibly indicating that there is some trade-off between vegetative growth and reproductive growth (fruit production) in some combinations.

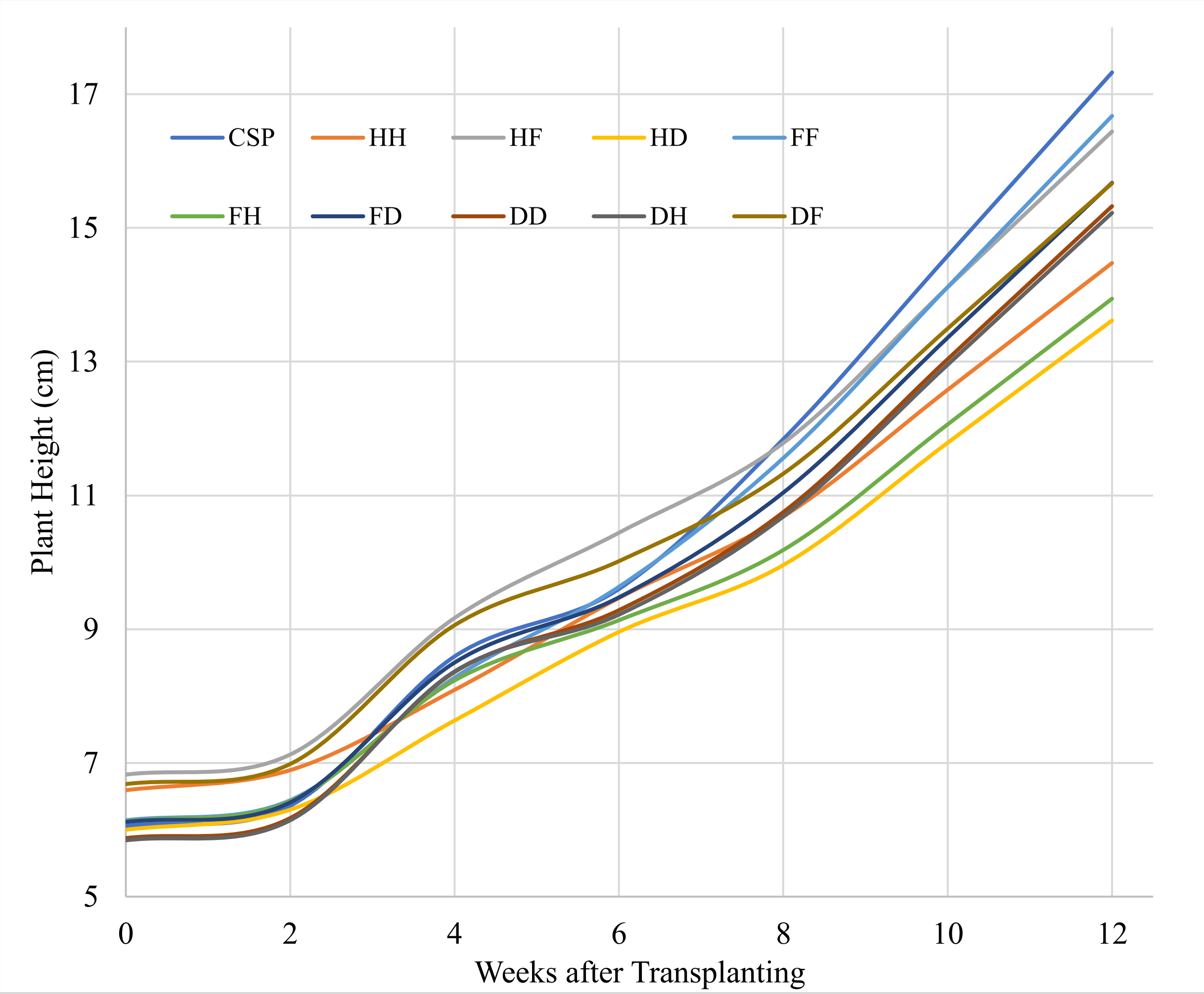

Figure 14: Curves of plant elongation rate for the different treatments

4.2.2 Number of Leaves

The number of leaves is an important physiological indicator of growth performance and biomass production in plants, that reflects their photosynthetic capacity and vigour. The highest average change in the number of leaves was registered under treatment DH with 42.31%. On the other hand, the lowest change was noted in treatment HD at 34.13%. The averages for treatments CSP, HH, HF, FF, FH, FD, DD, and DF were also revealed from the analysis as 39.35%, 37.10%, 35.66%, 40.53%, 38.69%, 35.76%, 36.06%, and 37.15% respectively.

The fact that the mixing ratios of superabsorbent materials could both improve and, in some cases, limit bell pepper leaf growth is a significant observation. The better growth of DH is comparable to what is established for the best soil conditions, which increase the supply of water and nutrients, and directly contribute to vegetative development. Garcia et al. (2019) observed that pumice acted as a nutrient reservoir, releasing its nutrients slowly over time to the roots of the plant, which induced nutrient intake of key significance in development of leaves. Additionally, Singh et al. (2015) observed that application of SAPs and pumice enhanced root development and as such created an ideal medium for leaf development as well as lessened water stress.

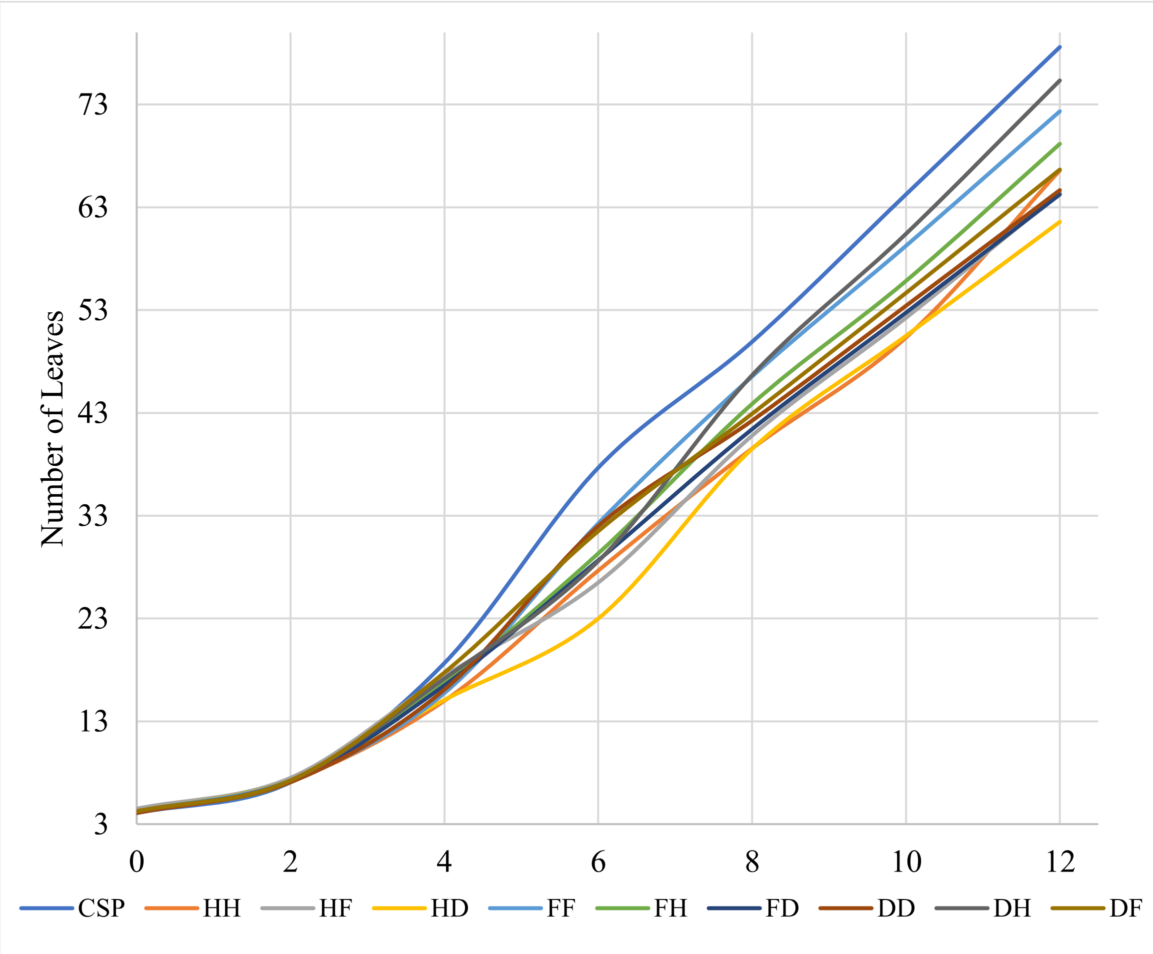

Figure 15: Curves of the change in leaf count for the different treatments

On the contrary, the negative effect recorded in HD (and less productivity in other treated blocks compared to control) is consistent with Gholampour et al. (2016). They found that applying excessive amounts of SAPs may create an imbalanced supply of nutrients or a form of stress responsible for deficiencies. These imbalances or stresses may limit total plant growth and inhibit important physiological processes, such as leaf development. In clay soils, if the amendment causes excessive water retention that leads to temporary anoxia, or if it binds specific nutrients too strongly, it could hinder leaf development.

4.2.3 Stem Diameter

Measures of the stem diameter help determine changes in the structural and functional characteristics of plants. This often correlates with the overall plant vitality and biomass accumulation. A wider stem diameter may point to the health and strength of the plant and its ability to support more leaf and fruit bulk. In this study, the highest average stem enlargement was recorded in treatment DH at 0.30%. On the other hand, the lowest average stem enlargement was observed in the control group at 0.19%. It was further observed that the average stem enlargement rate registered for treatments HH, HF, HD, FF, FH, FD, DD, and DF were 0.25%, 0.22%, 0.20%, 0.27%, 0.26%, 0.24%, 0.28%, and 0.23% respectively. All the treated plots showed an increase in the stem enlargement compared to the control.

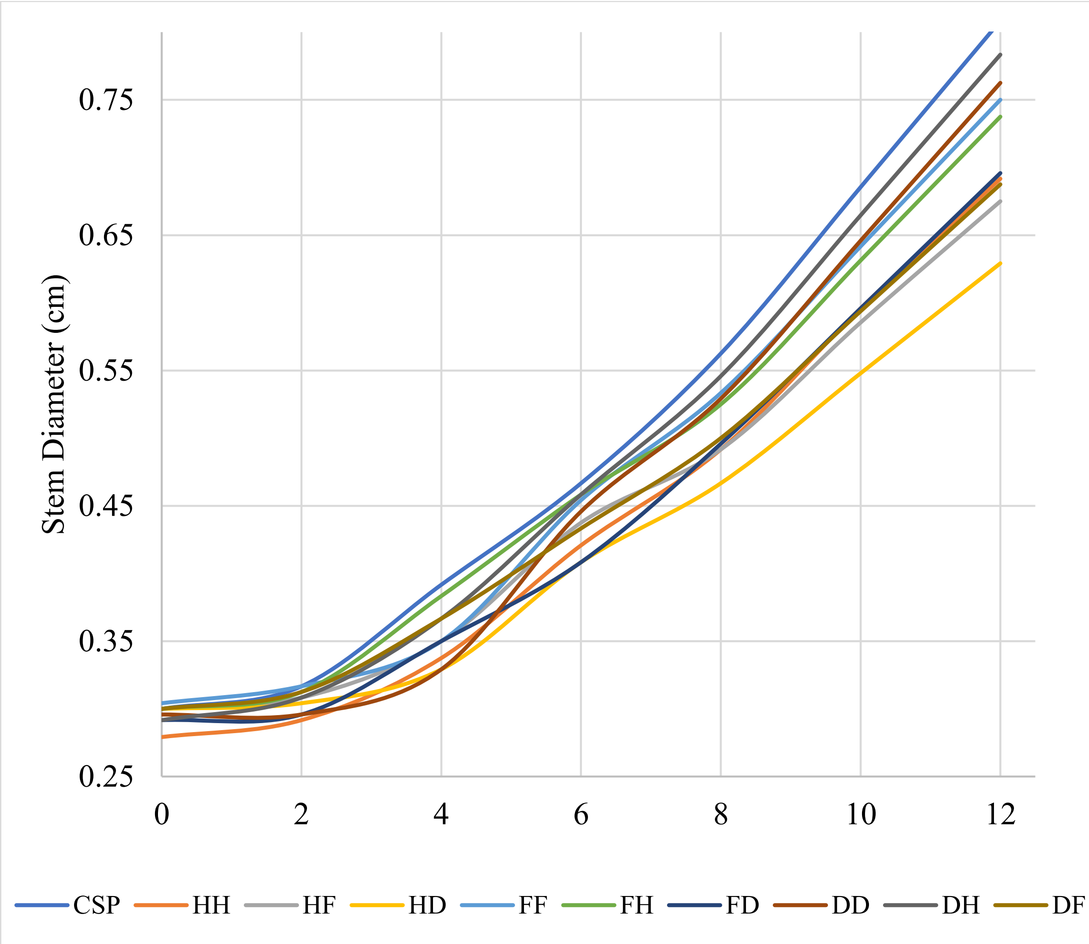

Figure 16: Curves of stem enlargement for the different treatments

The positive effect on stem diameter is in agreement with the known benefits of these amendments. El-Nahhal et al. (2018) stated that the porous nature of pumice facilitates soil aeration and drainage. This helps to prevent waterlogging (a major problem in clay soils) and allows adequate oxygen to get to the roots, which is essential for healthy root respiration and, strong stem growth. Furthermore, Lee et al. (2017) explained that the positive effect of SAPs in water absorption and retention helps maintain optimal soil moisture levels, substantially decreasing water stress in plants. This continued availability of water helps promote healthier root development, improve nutrient absorption, and contribute to overall plant health, which will ultimately lead to increased stem diameter. DH displayed the best results, not forgetting its subsequent low bulk density and high leaf count, indicating that the specific combination of high SAP and moderate produced the most conducive physical and hydrologic environment for structural development of bell peppers in the clay soil.

4.2.4 Total Number and Weight of Fruits per Plant

Measuring the number and weight of fruits directly determines the effect of the superabsorbent materials on plant yield. The average number of fruits per plot was significantly higher in DH than in all other treatments, with an average of 216 fruits. The lowest average number of fruits per plot was recorded in FD at 108 fruits, while 144 fruits were recorded as an average for the control group. Treatments HH, HF, HD, FF, FH, DD, and DF had an average of 156, 132, 132, 180, 168, 192, and 120 fruits per plot, respectively. Analysis of Variance showed that there was a statistically significant effect on the number of fruits ($F(9, 20) = 4.96$, $p = 0.0014$). This means that the different treatments produced significantly different mean fruit counts. The R-squared value of 0.69 indicates that a large proportion of about 69.06% of variability in the number of fruits can be explained by the applied treatments, signifying a strong relationship. In particular, the results of post-hoc analysis based on Fisher's tests with a threshold of 2.09 for LSD revealed that treatment DH (72.00) led to significantly higher fruit count than treatments FD (36.00), DF (40.00), HF (44.00), and HD (44.00) (all $p < 0.001$). Furthermore, treatments DD (64.00) and FF (60.00) also displayed substantially higher fruit count than treatments FD ($p = 0.0034$ and $p = 0.0119$, respectively), DF ($p = 0.0053$ and $p = 0.0195$ respectively), HD ($p = 0.0119$ and $p = 0.0387$, respectively), and HF ($p = 0.0119$ and $p = 0.0387$, respectively). On the other hand, FD had the lowest fruit count which was significantly less in comparison to DH, DD, FF, FH, and CSP.

Similarly, the maximum total yield (in terms of weight) was observed in treatment DH at 3.27 kg /m^2, while the least was from treatment FD at 1.62 kg/m^2. In the control group, the yield was 2.13 kg/m^2. Analysis of Variance showed that there was a statistically significant effect of the different treatments on the weight of the fruits ($F(9, 20) = 3.6874$, $p = 0.0072$). This means that the treatments gave rise to in significantly different values of mean weight. The R-squared value of 0.6239 implies that around 62.40% of the variability in weight can be explained by the applied treatments, signifying a strong relationship. Specifically, post-hoc analysis using Fisher's tests with an LSD threshold of 0.057 indicated that treatments DH (3.27

kg/m^2) and DD (2.87 kg/m^2) led to a significantly higher yield compared to treatment FD (1.62 kg/m^2) ($p = 0.0004$ for DH vs FD; $p = 0.0075$ for DD vs FD), DF (1.82 kg/m^2) ($p = 0.0028$ for DH vs DF; $p = 0.0125$ for DD vs DF), HD (1.96 kg/m^2) ($p = 0.0054$ for DH vs HD; $p = 0.0273$ for DD vs HD), and HF (2.01 kg/m^2) ($p = 0.0084$ for DH vs HF; $p = 0.0357$ for DD vs HF). The highest yield was observed in treatment DH, which was statistically similar to DD, FF, FH, CSP, and HH, but significantly greater than FD, DF, HD, and HF.

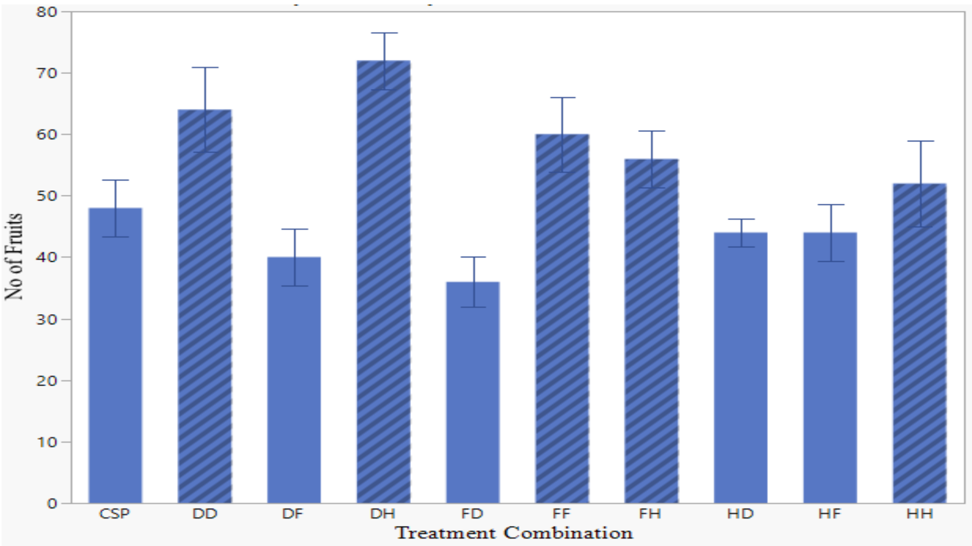

Figure 17: Effect on fruit count for different treatments

Note: *The shaded treatments DD, DH, FF, FH, and HH had lower values of fruit count compared to the control.*

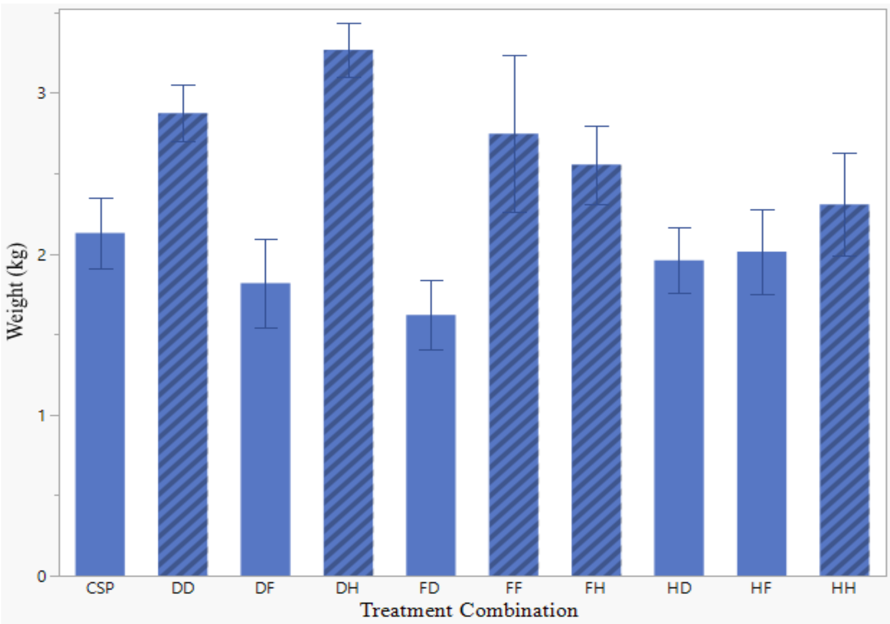

Figure 18: Effect on weight of fruits in kg/m^2

Note: *The shaded treatments DD, DH, FF, FH, and HH had higher yield values compared to the control.*

Most treatments, compared to the control, resulted in an increase in the total yield, with DH showing a remarkable 53.36% increase. This emphasises the importance of using the correct proportion of soil additives to generate optimal crop yield. However, it is important to note that treatments FD, HD, HF, and DF led to decline in the total yield compared to the control. Treatment DH emerged the best performer in both fruit number and weight indicating that this particular combination created the most favourable conditions for bell pepper in the clay soil. This can be explained, in part, by the fact that the high SAP held more water while the lower pumice offered the right structural effect (aeration and drainage) without losing too much porosity and without affecting the water availability at critical stages. The high SAP concentration possibly provided maximum uptake and retention of water in the root zone for extended periods, which is essential for the continuous fruiting of the bell pepper.

On the other hand, the decline in yield recorded in treatments FD, HD, HF, and DF can be related to the complex and sometimes harmful interactions between the amendments and the clay soil. High concentrations of SAP, especially in combination with moderate to higher pumice ratios, may have caused over-swelling in the clay, causing localised compaction or pore clogging that limits root access to water and nutrients (Ostrand et al., 2020). If certain ratios significantly lowered infiltration rates (as observed in DD), less water may have entered the root zone, resulting in overall water deficits even with subsequent irrigation. In contrast, if some combinations resulted in too much drainage due to unintentional macropore formation, this could have led to nutrient leaching.

The activity of soil microbial communities, which are responsible for important processes such as nutrient recycling and disease suppression, is strongly dependent on the proportion and chemical composition of soil (Smith et al., 2018). As a result, this induces higher or lower nutrient availability which in turn affects crop yield. Nnadi & Brave (2011) assessed the influence of SAP on crop yield, water productivity, and soil properties in a semi-arid region and reported that it resulted in a 12.8% increase in yield compared to the control. They attributed this to soil quality improvement in terms of water-holding capacity, infiltration rate, bulk density, and porosity (Karuku, 2018).

4.3 Determining the Optimal Mixing Ratio

Here, the best/optimal mixing ratio of superabsorbent polymer and pumice for use in clay soils that will maximise the resulting soil water-yielding capacity and bell pepper crop productivity for the study area, was determined. The analysis of the various soil properties and crop productivity provides a clear picture. Physical optimization was performed to identify the optimal application rate of SAP and pumice which maximizes yield and minimizes irrigation water demand at the same time.

The desirable results are increased yield and decreased irrigation water requirement because of lower bulk density, higher porosity, and lower field capacity and permanent wilting point. Treatment DH (15 kg/ha of SAP and 6250 kg/ha of pumice) was considered to be the best for this parameter. This is an indication that under this specific concentration the combined application of SAP and pumice optimally regulates soil water dynamics. The lower available water content is an indication that the increased drainage and aeration imparted to the soil by pumice eliminates the possibility of excessive water accumulation and hence reduces the likelihood of waterlogging. This balance allows for aeration, prevents oversaturation and allows for retention of moisture by SAPs to the plants.

The controlled release of water by the SAPs makes them effective (Mignon et al, 2019). As the soil dries and the water potential decreases below the potential that exists within the SAP polymer matrix, the water is slowly released from the SAP and made available to the roots of the plant. This release pattern is optimised in order to provide water to the plants for a longer duration, thereby reducing the water irrigation requirement and alleviating the water stress, which is important during the critical times of plant growth (Montesano et al., 2015). Most plant roots are harmed by prolonged periods of moisture, which causes anaerobic soil conditions. In contrast, pumice improves aeration and soil microporosity by the numerous open pores present within the particles of pumice. In addition to this, pumice can also provide excellent drainage, which is not possible in saturated soils. This is because pumice has a highly porous structure which allows water to flow freely and avoid waterlogging and root rot conditions, among other diseases caused by soil over-saturation of soil (Jimenez et al., 2004).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

i. The amendments improved the hydraulic properties of soil. The porosity increased with decreasing bulk density thus improving soil structure and water flow. The low available water content decreases the demand for irrigation water thus preventing oversaturation and creating a more conducive environment for plant growth.

ii. There was a significant increase in crop yield, as shown by an increase in the number and total weight of fruits in the study area.

iii. The treatment 15kg/ha of SAP and 6250kg/ha of pumice was found to be the best. This ratio met the desired outcomes of the study.

5.2 Recommendations

a) Recommendations for policy making and management of soil and water resources

   i. Farmers in regions with similar farmers in areas with similar soil textural characteristics as those of clay soils should be sensitised to adopt the application rate of SAP 15kg/ha and pumice 6250kg/ha.

   ii. The local extension officers should be provided with the materials and training to promote the adoption of SAP and pumice for agricultural soil and water management.

b) Recommendations for further research

   i. A detailed economic analysis to assess feasibility and profitability of using SAP and pumice.

   ii. The physical and chemical interactions of the amendments with the soil, focusing on their effects on soil structure, water-holding capacity, and microbial activity.

   iii. The relationship between water quality and the amendments, specifically how irrigation water salinity and pH as they affect overall soil health.

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APPENDICES

7.1 APPENDIX A: Summary of One-way ANOVA for Objective 1 & 2

Response Variable	F-Ratio	Prob>F	R^2	Sig	Key Interpretation
Porosity	3.0277	0.0187	0.5767	Yes	DH, FD, FF, CSP significantly higher than DD, FH
Bulk Density	3.8510	0.0058	0.6341	Yes	DD, FH significantly higher than DH, HH
H Conductivity	1267.224	<0.0001	0.9982	Yes	HF significantly higher than all the rest FF, HD higher than several others
E Moist Depletion R	1.1765	0.3608	0.3462	No	No statistically significant differences observed
L Moist Depletion R	1.4679	0.2264	0.3978	No	No statistically significant differences observed
Saturation	6.8209	0.0002	0.7543	Yes	FF significantly higher than others but almost similar to HH, DH
Field Capacity	2.8376	0.0250	0.5608	Yes	CSP significantly higher than other treatments
Permanent Wilt P	3.3407	0.0118	0.6005	Yes	CSP significantly higher but almost similar to DF, HD, HF
Available Water	0.9456	0.5095	0.2985	No	No statistically significant differences observed
Plant Elongation R	0.7778	0.6387	0.2593	No	No statistically significant differences observed
Stem Enlargement R	1.0542	0.4348	0.3218	No	No statistically significant differences observed
Leaf Count	1.4279	0.2416	0.3912	No	No statistically significant differences observed
Fruit Count	4.9592		0.6906	Yes	DH significantly higher than others followed by FF
Yield	3.6874	0.0072	0.6240	Yes	DH and DD significantly higher than FD, DF, HD, HF

$\alpha = 0.05$, df = 9, 20

7.2 APPENDIX B: Mean and Standard Error Values for Each Response Variable

Trt	Porosity	Bulk Density	H Cond	Saturation	FC	PWP	Fruit Count	Yield
CSP	59.25 ±1.53^{ABC}	1.05 ±0.04^{D}	0.17 ±0.026^{D}	46.60 ±1.87^{BC}	32.00 ±1.14^{A}	20.90 ±0.76^{A}	48 ±5.11^{D}	2.13 ±0.27^{D}
HH	58.29 ±1.53^{CD}	1.10 ±0.04^{CD}	0.11 ±0.026^{E}	51.18 ±1.87^{AB}	28.84 ±1.14^{B}	17.05 ±0.76^{B}	52 ±5.11^{D}	2.31 ±0.27^{D}
HF	56.60 ±1.53^{BCD}	1.15 ±0.04^{BCD}	1.83 ±0.026^{A}	49.50 ±1.87^{B}	30.84 ±1.14^{A}	18.20 ±0.76^{AB}	44 ±5.11^{E}	2.01 ±0.27^{E}
HD	55.26 ±1.53^{CD}	1.19 ±0.04^{ABC}	0.237 ±0.026^{B}	46.78 ±1.87^{C}	29.00 ±1.14^{B}	18.60 ±0.76^{AB}	44 ±5.11^{E}	1.96 ±0.27^{E}
FF	59.62 ±1.53 ^{ABC}	1.07 ±0.04^{D}	0.23 ±0.026^{B}	53.37 ±1.87^{A}	27.19 ±1.14^{B}	17.05 ±0.76^{B}	60 ±5.11^{B}	2.75 ±0.27^{B}
FH	52.93 ±1.53^{D}	1.26 ±0.04^{A}	0.10 ±0.026^{E}	47.70 ±1.87^{BC}	28.79 ±1.14^{B}	16.45 ±0.76^{B}	56 ±5.11^{C}	2.55 ±0.27^{C}
FD	59.92 ±1.53^{AB}	1.10 ±0.04^{CD}	0.03 ±0.026^{F}	49.62 ±1.87^{B}	27.00 ±1.14^{B}	17.25 ±0.76^{B}	36 ±5.11^{F}	1.62 ±0.27^{F}
DD	53.07 ±1.53^{D}	1.25 ±0.04^{A}	0.01 ±0.026^{F}	45.27 ±1.87C	29.63 ±1.14^{AB}	17.01 ±0.76^{B}	64 ±5.11^{AB}	2.87 ±0.27^{B}
DH	60.18 ±1.53^{A}	1.03 ±0.04^{D}	0.05 ±0.026^{F}	51.65 ±1.87^{AB}	25.34 ±1.14^{C}	16.15 ±0.76^{B}	72 ±5.11^{A}	3.27 ±0.27^{A}
DF	54.57 ±1.53^{CD}	1.20 ±0.04^{AB}	0.19 ±0.026^{C}	45.13 ±1.87^{C}	29.07 ±1.14^{B}	18.54 ±0.76^{AB}	40 ±5.11^{F}	1.82 ±0.27^{E}
P v	0.0187	0.0058	<0.0001	0.0002	0.0250	0.0118	0.0014	0.0072
LSD	2.08596	0.05739	0.05739	2.08596	2.08596	2.08596	2.08596	2.08596

7.3 APPENDIX C: Key Data for Objective One

Plot ID	Trt	SAP (kg/ha)	Pumice (kg/ha)	Porosity (%)	B.D (g/cm3)	Sat (%)	F.C (%)	PWP (%)	AW (%)	H C (cm/hr)	Ave M.D (E) (%)	Ave M.D (L) (%)
CSP1	CSP	0	0	58.69	1.07	48.50	35.00	22.00	13.00	0.16	11.14	13.88
CSP2	CSP	0	0	59.77	1.03	44.90	29.00	19.69	9.31	0.2	9.10	6.63
CSP3	CSP	0	0	59.30	1.05	46.40	32.00	21.00	11.00	0.15	8.72	9.13
HH1	HH	5	6250	61.83	1.00	51.10	27.53	17.10	10.43	0.12	11.80	7.50

HH2	HH	5	6250	58.49	1.10	52.65	30.00	18.00	12.00	0.1	13.36	3.13
HH3	HH	5	6250	54.55	1.20	49.80	29.00	16.05	12.95	0.11	11.43	7.25
HF1	HF	5	12500	57.36	1.13	50.00	31.00	16.61	14.39	1.9	7.97	2.75
HF2	HF	5	12500	56.77	1.15	47.00	28.53	18.00	10.53	1.79	7.54	7.88
HF3	HF	5	12500	55.68	1.17	51.50	33.00	20.00	13.00	1.8	13.69	7.75
HD1	HD	5	18750	54.89	1.20	47.03	27.50	20.00	7.50	0.26	9.51	3.75
HD2	HD	5	18750	55.68	1.17	49.00	29.00	18.00	11.00	0.23	12.39	7.25
HD3	HD	5	18750	55.22	1.20	44.30	30.50	17.80	12.70	0.22	10.90	5.75
FF1	FF	10	12500	59.93	1.07	54.80	28.86	17.96	10.90	0.2	8.58	3.25
FF2	FF	10	12500	59.09	1.08	51.80	26.90	16.00	10.90	0.25	9.42	7.13
FF3	FF	10	12500	59.85	1.06	53.50	25.80	17.20	8.60	0.24	12.59	3.50
FH1	FH	10	6250	53.56	1.24	45.90	30.63	15.00	15.63	0.09	9.22	7.88
FH2	FH	10	6250	52.81	1.26	48.20	28.75	16.80	11.95	0.1	9.30	7.88
FH3	FH	10	6250	52.42	1.28	49.00	27.00	17.56	9.44	0.11	10.76	3.88
FD1	FD	10	18750	57.65	1.08	51.90	25.00	17.00	8.00	0.02	8.45	10.13
FD2	FD	10	18750	57.03	1.10	47.90	27.00	19.00	8.00	0.04	11.11	10.38
FD3	FD	10	18750	56.08	1.12	49.06	29.00	15.74	13.26	0.03	10.04	5.75
DD1	DD	15	18750	52.83	1.25	43.90	29.90	15.90	14.00	0.009	12.21	7.50
DD2	DD	15	18750	52.61	1.27	47.00	32.00	19.03	12.97	0.01	12.62	6.63
DD3	DD	15	18750	53.76	1.23	44.90	27.00	16.10	10.90	0.011	12.24	7.00
DH1	DH	15	6250	59.92	1.03	49.00	25.10	15.40	9.70	0.04	10.06	6.75

DH2	DH	15	6250	61.15	1.01	51.80	26.90	17.00	9.90	0.07	7.39	10.00
DH3	DH	15	6250	59.46	1.05	54.14	24.03	16.05	7.98	0.04	11.04	9.88
DF1	DF	15	12500	47.37	1.40	45.09	30.10	17.63	12.47	0.22	8.54	8.88
DF2	DF	15	12500	61.98	1.00	44.30	27.12	20.00	7.12	0.19	11.23	6.13
DF3	DF	15	12500	54.37	1.20	46.00	30.00	18.00	12.00	0.16	9.61	4.63

7.4 APPENDIX D: Sample of Mean Values of Daily Volumetric Moisture Cont

Plot ID	Trt	SAP (kg/ha)	Pumice (kg/ha)	Days									
				1	2	3	4	5	6	7	8	9	10
CSP1	CSP	0	0	37.88	31.13	26.38	43.50	36.00	32.00	42.25	33.50	29.00	38.88
CSP2	CSP	0	0	37.25	31.13	24.88	38.13	34.25	30.25	34.88	30.88	28.50	38.25
CSP3	CSP	0	0	37.38	30.38	32.25	35.50	31.63	27.63	41.13	31.75	32.88	38.38
HH1	HH	5	6250	37.88	31.88	31.75	46.00	36.00	32.00	41.00	38.00	29.88	38.88
H2	HH	5	6250	38.50	32.25	20.63	44.25	33.38	29.38	36.13	29.75	30.00	39.50
HH3	HH	5	6250	37.38	32.75	26.13	34.13	31.00	27.00	46.75	27.63	28.00	38.38
HF1	HF	5	12500	31.75	28.88	23.38	31.00	26.75	22.75	34.75	29.13	28.75	32.75
HF2	HF	5	12500	35.38	27.13	22.50	33.00	31.25	27.25	35.50	30.75	27.88	36.38
HF3	HF	5	12500	28.63	28.75	19.00	34.88	29.38	25.38	47.75	31.50	31.00	29.63
HD1	HD	5	18750	32.38	29.50	23.38	31.88	31.75	29.75	39.75	32.00	28.25	33.38

HD2	HD	5	18750	32.25	33.63	21.25	43.00	34.38	30.38	42.13	29.00	29.75	33.25
HD3	HD	5	18750	34.88	28.88	21.50	28.75	29.75	25.75	40.63	27.75	29.75	35.88
FF1	FF	10	12500	33.50	31.63	24.13	35.63	30.25	26.25	33.75	29.00	28.38	34.50
FF2	FF	10	12500	34.13	28.25	31.38	35.25	29.00	25.00	42.00	29.50	30.25	35.13
FF3	FF	10	12500	31.25	34.00	19.88	33.75	39.38	35.38	46.13	33.63	29.25	32.25
FH1	FH	10	6250	31.50	29.88	22.38	33.00	24.38	20.38	32.88	29.88	25.13	32.50
FH2	FH	10	6250	33.25	30.00	26.25	41.00	35.25	31.25	38.13	36.13	32.38	34.25
FH3	FH	10	6250	30.13	36.13	31.13	38.50	32.88	28.88	42.25	29.88	29.50	31.13
FD1	FD	10	18750	32.38	28.38	21.00	29.25	29.63	25.63	29.63	27.88	32.50	33.38
FD2	FD	10	18750	30.13	28.50	27.25	44.88	32.50	28.50	40.88	33.00	32.13	31.13
FD3	FD	10	18750	34.25	27.50	24.38	40.25	30.50	26.50	38.38	35.00	30.88	35.25
DD1	DD	15	18750	36.38	30.63	24.38	37.63	30.88	26.88	40.88	34.38	28.13	37.38
DD2	DD	15	18750	34.88	28.88	20.38	36.88	25.75	21.75	40.13	29.50	29.88	35.88
DD3	DD	15	18750	32.25	28.38	19.25	42.13	37.63	33.63	40.25	32.00	31.38	33.25
DH1	DH	15	6250	33.88	28.88	25.75	36.00	30.00	26.00	39.75	32.25	30.75	34.88
DH2	DH	15	6250	33.88	28.25	28.50	34.00	32.38	28.38	42.88	33.63	32.88	34.88
DH3	DH	15	6250	31.75	38.50	24.50	33.50	38.25	34.25	39.13	31.25	28.13	32.75

DF1	DF	15	12500	31.63	29.13	24.25	41.63	36.88	32.88	34.63	32.50	26.63	32.63
DF2	DF	15	12500	36.00	26.75	25.50	43.50	39.00	35.00	38.88	33.25	28.13	37.00
DF3	DF	15	12500	34.25	28.38	27.50	50.88	47.13	43.13	40.50	30.00	28.63	35.25

7.5 APPENDIX E: Relative Growth Rate of Plant Growth Parameters

		Relative Growth Rate		
Plot ID	**Treatment Combination**	**Plant Elongation (%)**	**Stem Enlargement (%)**	**Change in No Leaves (%)**
CSP1	CSP	0.07	0.08	0.23
CSP2	CSP	0.08	0.08	0.25
CSP3	CSP	0.12	0.09	0.26
HH1	HH	0.05	0.06	0.24
HH2	HH	0.05	0.07	0.22
HH3	HH	0.09	0.09	0.23
HF1	HF	0.08	0.07	0.22
HF2	HF	0.06	0.07	0.22
HF3	HF	0.08	0.07	0.22
HD1	HD	0.08	0.07	0.22
HD2	HD	0.05	0.06	0.23
HD3	HD	0.08	0.05	0.21
FF1	FF	0.07	0.08	0.23
FF2	FF	0.09	0.09	0.24

FF3	FF	0.09	0.05	0.24
FH1	FH	0.07	0.09	0.23
FH2	FH	0.07	0.07	0.25
FH3	FH	0.06	0.06	0.23
FD1	FD	0.07	0.08	0.23
FD2	FD	0.08	0.06	0.22
FD3	FD	0.08	0.07	0.23
DD1	DD	0.10	0.08	0.25
DD2	DD	0.07	0.08	0.22
DD3	DD	0.07	0.08	0.21
DH1	DH	0.08	0.08	0.22
DH2	DH	0.09	0.09	0.26
DH3	DH	0.06	0.07	0.24
DF1	DF	0.06	0.08	0.24
DF2	DF	0.07	0.06	0.22
DF3	DF	0.08	0.06	0.23

7.6 APPENDIX F: Abstract Page of the Publication Paper

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EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Effect of Mixing Ratio of Super Absorbent Materials on the Growth and Yield of Bell Pepper in the Ferric Luvisols of Mogotio, Kenya

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Crop Growth, Pumice, Super Absorbent Polymer, Soil Additives, Soil Properties, Yield.

ABSTRACT

Agriculture in arid and semi-arid regions (ASALs) faces challenges due to limited water and problematic soils. This study investigates the potential of superabsorbent materials like Super Absorbent Polymers (SAPs) and pumice to enhance water retention and agricultural productivity in Ngubreti in Mogotio Sub-County, Kenya, representing ASALs. Using a randomized design with different material ratios and a control group, the research analysed soil parameters and plant growth indicators. Incorporating superabsorbent materials increased soil porosity, reduced bulk density, and improved water retention. Bell pepper production notably increased by 53.4%, with the SAP Pumice Double Half (SPDH) treatment showing the highest yield. This research underscores superabsorbent materials' ability to enhance ASAL soil conditions and agricultural output, particularly SPDH treatment. Precise material concentration control and consideration of their impact on soil penetration rates are crucial for optimal results. The study contributes to sustainable agriculture in water-scarce regions, emphasizing soil management's role in crop productivity. Further research and region-specific experiments are needed for broader applicability. Farmers are advised to assess their soil characteristics and consider a recommended median soil-additives mixing ratio of 1:833. Long-term effectiveness warrants additional investigation.

APA CITATION

Muriithi, F., Onyando, J. & Okwany, R. O. (2024). Effect of Mixing Ratio of Super Absorbent Materials on the Growth and Yield of Bell Pepper in the Ferric Luvisols of Mogotio, Kenya. *East African Journal of Agriculture and Biotechnology*, 7(1), 204-215. https://doi.org/10.37284/eajab.7.1.1885

CHICAGO CITATION

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HARVARD CITATION

Muriithi, F., Onyando, J. & Okwany, R. O. (2024) "Effect of Mixing Ratio of Super Absorbent Materials on the Growth and Yield of Bell Pepper in the Ferric Luvisols of Mogotio, Kenya.", *East African Journal of Agriculture and Biotechnology*, 7(1), pp. 204-215. doi: 10.37284/eajab.7.1.1885.

IEEE CITATION

F. Muriithi, J., Onyando & R. O. Okwany "Effect of Mixing Ratio of Super Absorbent Materials on the Growth and Yield of Bell Pepper in the Ferric Luvisols of Mogotio, Kenya", *EAJAB*, vol. 7, no. 1, pp. 204-215, Apr. 2024.

7.7 APPENDIX G: Research Permit

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