RELATIONSHIP BETWEEN SOIL HYDRO-PHYSICAL PROPERTIES AND THE PERSISTENCE OF SOIL WATER REPELLENCY IN AGRICULTURAL SOILS OF KENYA: THE CASE OF MURANGA AND MAKUENI COUNTIES

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Relationship Between Soil Hydro-Physical Properties and the Persistence of Soil Water Repellency in Agricultural Soils of Kenya: The Case of Murang'a and Makueni Counties

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

First, to the Almighty God, whose providence is infinite. Secondly, to my family, my lovely husband and children, my parents Mr. and Mrs. John Ndolo and my siblings Gladys, Kenedy and Joseph.

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ABBREVIATIONS AND ACRONYMS

AIC	Akaike Information Criterion
CRM	Capillary Rise Method
FC	Field Capacity
IRDI	Integrative Repellency Dynamic Index
MED	Molarity of an Ethanol Droplet test
MLR	Multiple Linear Regression
PWP	Permanent Wilting Point
SDM	Sessile Drop Method
SWR	Soil Water Repellency
SWR_{ACT}	Actual Soil Water repellency
SWR_{AREA}	Integrated Trapezoidal area under the SWR-w curve
SWR60	Potential Soil Water Repellency at oven dry conditions (60^{o}C)
SWR105	Soil Water Repellency at oven dry conditions (105^{o}C)
TOC	Total Organic Carbon
WDPT	Water Drop Penetration Time

ABSTRACT

Soil Water Repellency (SWR) is the reduction in the rate of wetting and retention of water in the soil caused by presence of hydrophobic organic matter in the soil. Knowledge of the threshold values at which organic carbon and soil moisture content becomes effective and asserts a negative impact on soil properties especially soil wettability is limited in Kenya. Therefore, this study aimed at characterizing the persistence of SWR using Water Drop Penetration Time Test (WDPT), evaluating the SWR curve as a function of gravimetric water content from the WDPT results and finally developing relationships between SWR parameters. Eighty-four soil samples at 0-15cm and 15-30cm soil depths were collected from agricultural lands in Makueni and Murang'a Counties in Kenya and taken to the laboratory for analysis. The actual SWR was estimated for the samples in their field conditions using the Water Drop Penetration Time Test (WDPT) method. A total of 29% of the soils investigated were water repellent. The results revealed that the WDPT was non-linearly correlated ($r = -0.712$ and $r = -0.238$, $p<0.01$) to soil moisture content (smc) in Murang'a and Makueni soils respectively. The critical soil moisture content (Wc) above which soils with sandy clay loam texture in Murang'a became wettable was found to be between 8 and 16.6% while in soils with loamy sand texture it was 6.2 and 9.0%. In Makueni, for sandy clay loamy soils, the critical soil moisture content was found to be between 3.05% and 7.05 %. The results revealed an extremely strong negative relationship ($r =-0.987$ and -0.982) between saturated hydraulic conductivity and porosity. The total degree of soil water repellency (SWR_{AREA}) ranged from 8.38second/% smc to 24.91 seconds /% smc. Total Organic Carbon (TOC) was the most important soil property in explaining SWR_{AREA} and Wc. Inclusion of clay and silt in the Multiple Linear Regression (MLR) expression of SWR_{AREA} significantly improved the prediction of SWR_{AREA} from 82% to 85%. Further, an upper limit critical water content of 14.6g of water/kg of soil and 7g of water /kg of soil in Murang'a and Makueni County soils respectively was derived from the simple relationship between the Wc and TOC. Murang'a soils were wettable between 2 and 4% TOC and became repellent above 4.0% TOC while Makueni soils were wettable below 2% TOC and became repellent above 3.4% TOC. These thresholds could be used to derive a critical soil moisture content above which SWR and related limitations to soil functions could be eliminated during irrigation.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Soil water repellency (SWR) is the reduced ability of some soils to be wetted and absorb water, in some instances for prolonged periods of time. This has received increased attention in recent years due to the discovery that it is a much more widespread property in soils than previously thought (Urbanek & Doerr, 2017; Müller & Deurer, 2011; Jordán et al., 2013). Soil Water Repellency is a surface property that causes soil to lose its affinity for water. This has an immediate impact on water infiltration and flow through soils. The presence of SWR in soil often influences whether water moves to surface water as runoff, infiltrates into soil water storage, contributes to drainage into groundwater, or evaporates (Smettem et al., 2021).

Soil water repellency has negative impacts on growth of plants and soil hydraulic properties. It decreases the ability of soil to absorb water with the end goal that they oppose wetting for periods extending from a couple of moments to hours, days or weeks which in turn leads to substantial hydrological and geomorphological repercussions (Lozano-Baez et al., 2020). The various impacts on soil hydraulic activities include low infiltration rates in soils, increased runoff hence increased soil erosion, formation of flow paths of preference in the soil which accelerate leaching of fertilizers and other farm chemicals (Cesarano et al., 2016). Generally, soil water repellency poses a limiting factor to soil water availability to plants. Soil water repellency has been reported on both natural and disturbed soils such as agricultural and mining sites (Atanassova et al., 2018). Inevitably, effective characterization of the severity and persistence of soil water repellency on such soils must be conducted to establish the influence on hydrological processes.

There is a widespread occurrence of severe soil water repellency which has been reported to affect agricultural production, social amenity areas such as parks and golf pitches as well as coastal sand dunes. SWR causes patchy grass growth and localized dry spots in golf courts and recreation areas due to the activity of basidiomycete fungi. The activity of the fungi results in formation of water-repellent fairy rings (These are dark green circles that appear on the maintained grass lawns). The fairy rings present a significant management challenge particularly in grasslands (Müller & Deurer, 2011). Similarly, water repellency in unburned soils has been reported from all continents except Antarctica; for climates that range from seasonal tropical to subarctic, soils that are course textured to those that are fine textures, in different types of land uses e.g., in croplands, grasslands, shrub lands and in forests (Zavala et al., 2014, Müller & Deurer, 2011, Deurer et al., 2011). Soil water repellency has been observed in over 50 countries worldwide under various soil types such as sandy, peat, and volcanic soils in various climatic conditions and land uses. Canada, the United States, Colombia, South Africa, Egypt, Poland, Portugal, and India are among them (Hewelke et al., 2018).

The cause of soil water repellency is currently not well understood. The repellency of soil water is a transient property that is related to soil water content. It rises during dry periods and falls or disappears completely during prolonged wet periods (Dekker et al., 2019; Caltabellotta et al., 2022). Soil water repellency is also affected by soil texture as well as physical and chemical soil properties such as soil organic matter content, hydrocarbon concentration, fungi and plant exudates, fire, nitrogen content and pH and water content (Totsche et al., 2018 & Zheng, 2016).

Soils show reduced wettability only when the water content falls below a certain critical value (Deurer et al., 2011). It would be beneficial to define this critical water content (Wc) more precisely in order to allow for more effective irrigation of affected soils by keeping soil water contents above the critical threshold. On the other hand, for more accurate forecasting of situations in which water repellency may occur a better understanding of the relationship between SWR and soil hydrophysical properties is necessary.

1.2 Statement of the Problem

Soil is the foundation of life for plants, animals, and humans, and they provide a wide range of environmental services such as water balance regulation. The soil's ability to allow water infiltration determines its ability to regulate water balance. Certain soils, on the other hand, do not spontaneously wet when water is applied to their surface. This phenomenon disrupts the hydrologic balance. Given the foregoing, numerous remediation strategies for managing hydrophobic soils exist, including surfactant application and claying. However, the benefits of surfactants are debatable, and they have more negative effects on the affected soils. Their performance is heavily influenced by field conditions such as location, weather, application rate, and dilution rate. Another point to consider is economic efficiency. The expensive surfactants must be applied on a regular basis throughout the dry seasons. Heavy irrigation is required after the application of wetting agents to limit their toxicity (Müller& Deurer, 2011).

Claying, on the other hand, is restricted to locations where clay is readily available due to economic considerations and the large amount of clay required for the treatment. Claying is not recommended for heavier soils because it may increase compaction and decrease permeability (Müller& Deurer, 2011). Failure to effectively manage soil water repellency results in reduced infiltration of rainwater, which in turn increases overland flow, reducing plant available water in agricultural fields.

Given the negative effects of soil water repellency, particularly in the soil water balance regulation service, there is a need for a less expensive and more reliable remedy to the negative effects of soil water repellency on soil functions. Despite the fact that many remediation strategies have been proposed and tested in the field, they are not easily accessible to land managers and farmers due to economic constraints. As a result, the purpose of this research is to investigate remediation strategy that involves keeping soil moisture content above the critical level below which soil water repellency occurs, as proposed by Hermansen et al (2019). This strategy will yield consistent results for critical water content in field conditions, and it could be used as a management strategy for repellent agricultural soils.

1.3 Objectives

1.3.1 Main objective

The main objective of this study was to investigate the relationship between soil hydro-physical properties and soil water repellency persistence in agricultural soils from Murang'a and Makueni counties.

1.3.2 Specific objectives

The specific objectives of this study were to:

a) Characterize the agricultural soils from different agro-ecological zones in Murang'a and Makueni Counties.
b) Determine the threshold conditions needed for hydrophobicity to be broken and re-established in the selected agricultural soils.
c) Develop relationships between soil water repellency and the essential soil properties in water- repellent soils.

1.4 Research Questions

a) How do the hydro-physical properties of the agricultural soils vary from the various agro-ecological zones in Murang'a and Makueni Counties?
b) What are the threshold conditions needed for hydrophobicity to be broken and re-established?
c) What is the relationship between soil water repellency and the soil properties for selected agricultural soils?

1.5 Justification

When soil hydrological behavior is affected by water repellency, efficiency of irrigation reduces leading to either increased water requirements to meet plant needs or reduced crop performance. Most agricultural soils e.g., loam, heavy clay, peat, and volcanic ash soils have been reported to experience soil water repellency (Heidary et al., 2018). These are the most common soils in Kenya that are suitable for agricultural activities. It is therefore of great importance to examine the timing, the breakdown and the beginning of water repellency and the effects of soil moisture content on repellency in these soils so as to prevent occurrence of soil water repellency. The concept of critical water content remains very useful in land management, and hydrophobicity is assumed to be absent as long as soil moisture remains above the critical level. The soil moisture-related aspect of SWR has significant implications for land use management due to the effects of SWR in soils that do not meet the critical water content threshold. However, this threshold has not been investigated in much detail, despite its practical implications (Mao et al., 2019) and especially in the Kenyan agricultural soils. The goal of this study, therefore, was to investigate the relationship between soil moisture and the persistence of soil water repellency occurrence which thus reflects reliable results for the critical water content under field conditions.

1.6 Scope and Limitations of the study

The study aimed at evaluating water management options for efficient irrigation in water repellent soils by investigating the critical soil water content above which soil is hydrophilic. The persistence of soil water repellency was estimated using Water Drop Penetration Test Method (WDPT) at air-dry and wet conditions. Multiple linear regression (MLR) analysis was carried out to evaluate the relationship between the properties of the soils and soil water repellency. A linear expression utilizing total organic carbon (TOC), critical soil water content (W_c), percentage clay, silt and sand as input variables was performed in order to obtain a correlation of soil properties as a function of SWR parameters such as total soil water repellency (SWR_{AREA}). The study area comprised various selected sites of unirrigated agricultural lands in Murang’a and Makueni counties in Kenya. In this study, the effect of relative humidity was not considered, since the experiments were carried out under laboratory conditions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Negative Impacts of Soil Water Repellency

Soil water repellency (SWR) is known to be a dynamic phenomenon, which varies in the short term or between seasons. Soil water repellency is believed to be a temporal condition whose temporal nature is often studied based on soil moisture content with an assumption that it is re-established after the soil dries out (Heidary et al., 2018, Bachmann et al., 2021). This state of the soil prevents normal infiltration of water which leads to either ponding on the soil surface, evaporating or moving down preferred pathways /cracks leaving large volumes of localized dry spots in the soil. This uneven wetting of soils results in poor crop germination, pasture and weed plants and also increased risks from wind and water erosion (Roper et al., 2015). Water repellency may increase evaporative losses if moisture is trapped near the surface and may increase drought stress in affected regions (Smettem et al., 2021). SWR causes patchy grass growth and localized dry spots in golf courts and recreation areas due to the activity of basidiomycete fungi. The activity of the fungi results in formation of water-repellent fairy rings which results in reduced grass coverage in golf courts and enhance surface runoff. This has been the driving force for development of management and amelioration techniques for water repellency in agricultural lands (Mao et al., 2019). It is therefore of great practical use to investigate when and how long SWR potentially occurs in the course of a year (Jordán et al., 2013).

2.2 Positive Impacts of Soil Water Repellency

According to recent research, a minor increase in SWR with no-till farming systems can have numerous beneficial consequences on soil and the environment (Miller et al., 2019). The enhanced SWR in no-till soils can contribute to soil structure development and soil erodibility compared to traditionally tilled soils (Blanco-Canqui & Lal, 2007). Indeed, studies have demonstrated that no-till soils have higher wet aggregate stability, macroporosity, and soil organic carbon pools than conventionally tilled soils. These gains may be attributed in part to the minor rise in SWR caused by no-till farming.

2.3 Biological and Physical Factors Controlling Development of Soil Water Repellency

Potentially hydrophobic organic materials are produced by plant root exudates, certain species of fungi, surface waxes produced by plant leaves and decomposing soil organic matter. These materials are strongly hydrophilic when wet but below a critical moisture threshold, the hydrophilic surfaces bond strongly with each other and soil particles, leaving an exposed hydrophobic surface. The specific chemical compounds that can be related with the development of water repellency in soils are not clearly known but they are perceived to be the general organic compounds that accumulate within the soil matrix (Drelich et al., 2011). Soil water repellency occurs in a wide range of soil types (Leelamanie et al., 2010). Sandy soils are the more susceptible to SWR due to their low surface area, so a hydrophobic surface will impact a larger proportion of particles than for a loamy or clayey soil where the surface area is up to three orders of magnitude greater (Nadav et al., 2013; Mao et al., 2019; Jordán et al., 2013). More details of the physical and biological factors controlling the occurrence of soil water repellency are discussed in the following sub-sections.

2.3.1 Physical Factors

Soil water repellency is caused by physical factors such as soil texture, bulk density, and atmospheric conditions such as relative humidity and high temperatures (Müller & Deurer, 2011). Soil water repellency is most common in coarse-textured sandy soils. Since fine soils, such as clay, have a much higher specific surface area, they are less susceptible to organic coatings. Furthermore, the fact that sandy soils are more acidic than clayey soils promote soil water repellency (Roper et al., 2015). On the other hand, Diehl (2013) found no obvious relationship between clay content and soil water repellency and claimed that ‘finer-textured soils should not necessarily be expected to be less repellent’. Large particle sizes, according to Zheng et al. (2016), are associated with low SWR and critical water contents at which the soil becomes wettable.

A strong negative relationship (R= 0.7) between bulk density and the degree of SWR was realized in an experiment conducted by Deurer et al. (2011). This relationship is explained by the accumulation of hydrophobic organic material in the topsoil, which reduces the bulk density of the denser mineral soil. A decrease in bulk density corresponded to an increase in soil water repellency.

Soil organic matter regulates soil water repellency, which has important agricultural implications such as the formation of dry patches due to uneven wetting and increased overland flow, which reduces irrigation efficiency and plant nutrient uptake (Lichner et al., 2018). Soil organic carbon was extremely influential after investigating the effect of soil organic matter on the persistence of water repellency in New Zealand soils as observed by Hermansen et al. (2019). The relationship between soil carbon and moisture contents was used to predict a safe margin of soil water content in order to improve water application practices in such soils. However, this conclusion was made without considering other soil properties that influence water repellency, such as soil texture.

As observed by Jiménez-Pinilla et al. (2016), soil water repellency was strongly related to the amount of soil organic matter, moisture content, and the composition of the plant and soil microbial communities, with soil carbon having the greatest impact on water repellency at a national scale in Wales. Seaton et al. (2019) found that moderate to extreme repellency occurred in 68% of soils at a national scale in temperate ecosystems, with 92% showing some repellency.

Several studies investigated the effect of relative humidity (RH) on SWR and observed that high RH increases soil water repellency. Long-term (>10 days) exposure to high RHs (90-100%) increased the repellency of previously repellent sands as it was observed by Jiménez-Pinilla et al. (2016). The authors also observed a link between water repellency and ambient temperature, concluding that the increase in SWR is caused by a biological process. The effects of short-term exposure to RH of 40% on the water repellency of air-dried soil samples was investigated by Heydari et al. (2016) in the laboratory. It was concluded that physicochemical processes, rather than microbiological processes are responsible for changes in soil behavior because such short-term exposure to high RH has such a large influence on SWR. The study went ahead to speculate that previous studies may have incorrectly classified actually repellent soils as wettable by performing SWR-tests in ambient lab conditions with low RH. From the results, a recommendation was made that, SWR tests be performed after exposing the samples to high RH in order to obtain SWR results that best reflect the most critical field conditions.

High temperatures caused by fire can also induce hydrophobicity. The hydrophobic substances are volatilized and condensed in a concentrated form during combustion (Gardiner, 2019). Water repellency, on the other hand, can be influenced by temperatures much lower than those attained by a fire. Soil samples should therefore be air- dried rather than oven- dried before being tested for water repellency (Kaiser et al., 2015).

2.3.2 Biological Factors

Water repellency is associated with selective microbial plant decomposition, according to Goebel et al. (2011). Parts of plants containing hydrophobic compounds such as waxes, aromatic oils, or resins are generally more resistant to microbial decomposition than hydrophilic parts. According to Miller et al. (2019; 2020) certain crops, grass species, and legumes appear to increase soil water repellency. This could be as a result of specific plant-microorganism interactions. There also exists a link between soil water repellency and land cultivation methods such as ploughing as stated by Li et al. (2021). According to Müller and Deurer (2011), there may be a link between soil water repellency and the presence of mealy bugs. Wetter climate and low nutrient availability alter plant, bacterial and fungal community structure are associated with increased soil water repellency (Seaton et al., 2019).

2.4 Physics of Soil Water Repellency

The occurrence of SWR relies solely on the interaction of cohesion and adhesion forces. The mutual interaction between individual water molecules is described by cohesion while adhesion refers to that between the water molecules and soil particles. Exceedingly high surface tension of 72mN/m (0.072N/m) is possessed in the strongly dipolar molecule structure of water and as such, for water to easily spread on a solid surface, this surface tension must be subdued by the adhesive forces. However, low adhesive forces cause water droplet to assume a spherical nature without wetting the organic surface when interacting (Ahn et al., 2013). Therefore, a contact angle is formed between the liquid and the solid phase as illustrated by Erbil (2021) in Figure 2.1. This interaction is also expressed in Young's equation which considers the balance of interfacial forces between the three phases of solid, liquid (water) and vapor (air) (Equation 2.1).

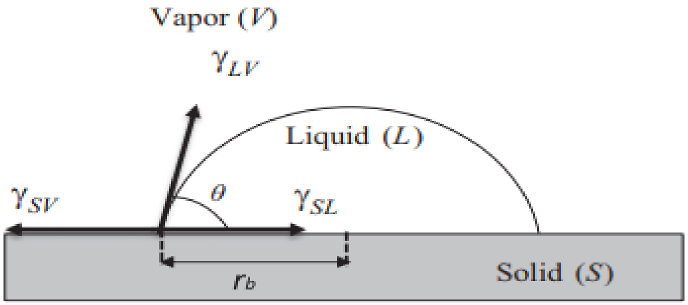


Figure 2.1: The State of a Liquid Droplet on a Solid Surface

$$\gamma LV cos\theta = (\gamma s + \gamma SL \qquad (2.1)$$

Where:

γ_{LV} = Liquid-air surface tension

Θ = Contact Angle

γ_{SV}= Solid-air surface tension

γ_{SL} = Solid-liquid interfacial tension

Less contact angle (<90^0) implies a wettable soil and at a greater contact angle (>90^0), the soil is classified as water repellent. Since all the dominant soil constituents have a higher surface tension than water and are thus wettable, organic compounds such as waxes can have a tension below 72mN/m and hence repel water.

2.5 Measurement of Soil Water Repellency

Many measurement approaches have been developed and tested for the determination of soil water repellency in the laboratory as well as in the field. These include Water Drop Penetration Time (WDPT) test, Molarity of ethanol droplet (MED) test, Repellency index method, Contact angle: Capillary rise method (CRM): Wilhelmy plate method: Sessile drop method as outlined in the following sub-sections.

2.5.1 Water Drop Penetration Time (WDPT) Test

The Water Drop Penetration Time (WDPT) test is used to determine soil hydrophobicity persistence. It has been widely used by researchers in both the laboratory and the field over the last few decades. The WDPT test entails placing water drops onto a flattened soil surface and timing how long it takes for complete penetration. WDPT can range from instant penetration (<5 s) in hydrophilic soils to droplets remaining on the surface for many hours. According to Smettem et al. (2021), if a WDPT measurement exceeds 5 seconds, the soil should be considered water repellent. The WDPT test is still a popular and convenient method for measuring water repellency due to its simplicity (Papierowska et al., 2018). It is also cheap and simple to replicate without the use of specialized equipment.

According to Hallin et al. (2013), many published studies that use the WDPT test fail to indicate the drop volume and number of drops used. It was concluded that larger drop volumes provide a better indication of overall repellency levels in soil, whereas smaller drop volumes reflect the microtopography of the surface and the level of heterogeneity due to the smaller surface area covered by each drop. A recommendation of six drops per sample was given to achieve 95% confidence in the assignment of water repellency class (Hallin et al., 2013).

2.5.2 Molarity of Ethanol Droplet (MED) Test

Drops are applied to the soil surface with increasing surface tensions (decreasing ethanol concentrations) until the drop resists infiltration for an extended period of time. The classification of water repellency is made between the last class where infiltration occurred and the first class where it existed for longer than the time allocated. The variation in concentrations between the aqueous ethanol solutions determines how precise the repellency classification is. Mostly MED test is adapted for contact angles below 90^o (Kořenková et al., 2015). The MED test has a significant advantage over the WDPT test in terms of speed; it eliminates the need for laborious monitoring times in extremely repellent soils and eliminates evaporation issues due to the speed with which the test is performed. The MED test, like the WDPT, is inexpensive and simple to replicate in both the field and laboratory, which makes it a popular choice among researchers (Papierowska et al., 2018).

2.5.3 Repellency Index Method

The Repellency Index (RI) method is used for measuring soil intrinsic sorptivity, which provides an indication of water transport rates. An infiltrometer probe measures wetting rates in soil columns where sorptivity controls water flow (as opposed to gravity). The sorption of ethanol and water is compared, and the index is given by the ratio of the two (Davari et al., 2022). While this is a sensitive method, it has limitations in that it is time consuming and does not provide information on the persistence of water repellency beyond the 5-minute measurement period. A repellency index (RI) value can range from 1 (wettable) to 100 (highly repellent); a RI value greater than 1.95 indicates the presence of water repellency (Papierowska et al., 2018).

2.5.4 Contact Angle under Capillary Rise Method (CRM)

The capillary rise method (CRM) assesses the soil-water contact angle indirectly by measuring the height of water achieved in a soil column (packed powder) via capillary rise. In comparison to the MED and WDPT tests, this is much more time-consuming, and it is best suited for laboratory measurements only due to the nature and set-up of the test. The CRM is only applicable to soils with a contact angle of 90^o making it unsuitable for studying highly repellent soils. This method has however been modified to allow measurement of soil water repellency in soils with contact angles greater than 90^o using the same methodology as CRM (Liu et al., 2016).

2.5.5 Contact Angle under Wilhelmy Plate Method

The Wilhelmy plate method is another soil water repellency study method that is carried out in the laboratory. In this method, soil is applied and secured to a glass slide, which is then attached to a balance and the weight is recorded. The slide is then slowly immersed in the test liquid before being lifted in the opposite direction to calculate the surface tension. The Wilhelmy plate method can determine contact angles ranging from 0 to 180^o and can measure both advancing and receding contact angles (Vogel et al., 2020). This method is applied for relatively homogeneous particles, such as sieved soil fractions. However, measuring the contact angle for heterogeneous services such as whole soils is difficult.

2.5.6 Contact Angle under Sessile Drop Method

The sessile drop method is commonly used to assess the initial degree of soil water repellency by measuring the soil-water contact angle. The balance of interfacial tensions of the three phases of the soil i.e., solid, liquid and vapour, determines the contact angle between a liquid and a solid surface. A high contact angle is produced by a liquid drop with a high surface tension resting on a low surface energy, solid, flat surface. As the solid surface energy increases, the contact angle decreases. As a result, a large contact angle denotes high water repellency, while a small contact angle denotes low water repellency.

The sessile drop method entails creating a monolayer of soil grains that are adhered to a glass slide with double-sided adhesive tape (Bachmann et al., 2003).

A goniometer is used to measure the soil-water contact angle by dispensing a drop of water onto the soil surface. The contact angle of the droplet is determined by analysis software from static images of the drop and can potentially be used to determine contact angles ranging from 0 to 180^o. The method can be time-consuming, but once the equipment is set up, it is simple to replicate (Wijewardanaet al., 2016).

2.6 Persistence and Severity of Soil Water Repellency

The 'initial advancing contact angle,' which is formed at the first appearance of droplet entry into soil, expresses the degree of water repellency during a limited period of time which is termed severity of repellency. It can also be expressed by the 'critical surface tension' at which instantaneous wetting occurs using Young's equation (Erbil, 2021). While the MED- test determines the degree of severity of water repellency, the WDPT-tests determine the degree of persistence. Contact angle is defined as the tangent of the drop profile at the triple point (three-phase contact point) where the liquid-gas interface meets the solid-liquid interface (Erbil, 2014). WDPT is the difference in cohesive energies between this adsorbed film and the water. A large difference in these forces results in a long droplet penetration time. The differences in WDPT and MED between soil types are caused by variable organic films with different cohesive energies (Erbil, 2021; 2014).

The choice of the method for describing hydrophobicity at a specific location depends on the spatial circumstances. If SWR is a year-round issue, the water may not have enough time to reach the equilibrium contact angle. It will quickly run off, so the severity of water repellency is a more accurate description. In flat, low-lying areas, however, prolonged soil/liquid contact time will result in a build-up of hydrostatic pressure, which can then overcome SWR. It is then sufficient to describe hydrophobicity using persistence (Leelamanie& Nishiwaki, 2019).

Numerous studies, however, show that the severity and persistence of water repellency are linked. Persistence and severity of water repellency in soils are correlated as observed by Fér et al. (2016). A strong correlation between persistence and severity of soil water repellency was also reported by Smettem et al. (2021) in most of their soils investigated in a study in Australia. A close relationship between the severity and persistence of soil water repellency in grasslands in Inner Mongolia was also described by Daniel et al. (2019) using a conversion formula.

The knowledge of the persistence of soil water repellency in soil is crucial for understanding and predicting how it affects hydrological processes. However, there is a poor understanding of the persistence of SWR and its effect on soil water flow (Chau et al., 2014; Ganz et al., 2013). Although it is well known that SWR may decrease or disappear during long wetting periods, little is known about the threshold conditions needed for SWR to disappear (Jordán et al., 2013). To assess the relationship between soil water repellency persistence, multiple soils must be tested. Additionally, naturally water-repellent soil material should be tested to assess moisture dependent wettability (Chau et al., 2014).

2.7 Soil Wettability and Water Repellency

The relationship between soil water repellency and soil moisture content is described in detail in the following sections.

2.7.1 The Concept of the Critical Soil Moisture content (Wc)

The Wc is an important transition zone where soil turns from a repellent state to a wettable state (Diehl, 2013). Since the measurement of the persistence of repellent soils are usually performed at single water content, measurements of Wc should be performed because it explains how SWR behaves under different water contents.

Water repellency is a transient property whose variations are thought to be strongly influenced by soil moisture content. Water repellency is most common in dry soils and disappears when soil water content exceeds a critical limit. However, studies have shown that the critical threshold concept alone cannot adequately explain the complex relationship between water repellency and soil water content (Rye, 2018).

Instead of a sharp threshold, Hewelke et al. (2016) proposed establishing a transition zone. Depending on the wetting history, the soil in this transition zone can be hydrophobic or hydrophilic (Liu et al., 2012). The actual water repellency of over 200 field samples of dune sand in the Netherlands was investigated. Results from the study reported a discovery of a transition zone between 0.18 and 0.23 m^3/m^3 volumetric moisture content. In a study site in Southern Brazil, Vogelmann et al. (2013) measured an average critical volumetric water content which of 0.36 to 0.57 $cm^3/\ cm^3$ for Luvisol and Gleysol soil types respectively. Different hydrophobicity thresholds were however used and soils with WDPT < 5seconds were classified as hydrophilic.

According to Mao et al. (2019), while an upper transition zone threshold indicating the absence of SWR is useful, the lower limit is difficult to specify and may be unreliable. The variability of the critical water content may be caused by the soil's wetting history, which influences the severity of SWR. Another possible cause is the heterogeneous distribution of water in and around soil microaggregates. Furthermore, because of the large differences in available surface area, it is thought to be dependent on soil texture (Caltabellotta et al., 2022).

The soil moisture-related aspect of SWR has important repercussions for land use management due to the effects of SWR in soils which have not reached the threshold of the Wc (Chau et al., 2014). In an effort to better quantify the effect that different SWR has on hydrological processes such as infiltration, it is important to determine relationship between persistence and soil hydro-physical properties in water repellent soils (Olorunfemi &Fasinmirin, 2017). This study therefore aimed at addressing this knowledge gap by investigating the relationship between soil hydro-physical properties, persistence of SWR and the critical water content.

2.7.2 The Relationship Between Soil Moisture Content and Water Repellency

The SWR varies nonlinearly with water content. SWR values increased rapidly with decreasing moisture content between air-dry and wilting point, according to Weber et al. (2021). SWR dropped rapidly to zero as moisture contents approached field capacity upon reaching a peak near the wilting point. On hydrophobic soils, Fu et al. (2021) observed two possible shapes for the curve relating SWR and moisture content. Some soils exhibited 'one- peak behavior,' which means that SWR is very low at low water contents. In this curve, SWR rises as the water content rises, peaks just before the wilting point, and then falls until the soil becomes wettable as moisture approaches field capacity. This theory is consistent with Regalado and Ritter's (2005) statements. Weber et al. (2021) observed a 'double peak- curve' for oven- dried samples as the second possible shape. The first SWR peak occurs at very low water contents, close to zero. The repellency decreases initially with increasing moisture content, but then increases again at low to intermediate soil water contents up to a second peak.

The first peak could be caused by the temperature treatment associated with oven drying (Hermansen et al., 2019). One possible explanation is that when water is lost, the hydrophobic molecules re-orient. However, these effects are irrelevant in the field because such low water contents will never be reached (Rye, 2018 & Smettem et al., 2021). Various studies disagree on the effect of oven drying on soil water repellency. While low oven temperatures like 43°C have been reported to significantly increase SWR, Smettem et al., 2021 observed that SWR remained virtually unchanged when oven dried.

As previously stated, an increase in SWR has been observed with an increase in soil moisture at low soil water contents (Weber et al., 2021). A possible explanation could be that an increase in soil moisture associated with an increase in relative humidity (50%) causes increased activity of microorganisms producing hydrophobic substances (Jiménez-Morillo et al., 2017). This assumption, however, contradicts the findings of Jiménez-Pinilla et al. (2016), who examined samples where contact angles decreased at a maximum relative humidity of 99.9%. As a result of high relative humidity, vapor condensation occurs, resulting in energy release. This energy causes the re-orientation of hydrophobic organic parts of previously disrupted hydrophobic materials.

A very close relationship ($R^2 = 0.997$) between the soil water contents at minimum and maximum soil water repellency and the integrated area below the repellency curve was observed by Weber et al. (2021). Soil water repellency and the integrated area below the repellency curve were combined to create a single parameter that characterizes average soil water dependent repellency which is termed Integrative Repellency Dynamic Index (IRDI). On the other hand, Hermansen et al. (2019) obtained reasonable results using a simple linear approach that presented SWR as a function of water content and soil organic matter while ignoring all other potential influences.

Finally, it should be noted that the timing and processes influencing the variations of SWR with changes in soil moisture content are still poorly understood and should be the focus of future research (Urbanek & Doerr, 2017).

2.8 Actual and Potential Soil Water Repellency

As informed by the non-linear relationship between water content and SWR, a distinction has been made between 'actual water repellency,' which is measured in field moist soil, and 'potential water repellency,' which is measured in an oven-dry or air-dry state and is assumed to be the maximum SWR that can be achieved. Standardized tests measure the potential water repellency so that the results can be compared. However, potential water repellency cannot provide information about the critical water content below which SWR begins to occur, and it may not be the highest possible SWR that a soil can achieve. Water repellent soils were found to be wettable after using the standard method of pre-treatment prior to SWR measurements, which involves oven-drying the samples at 60°C for 48 hours and equilibration for 24 hours (Weber et al. 2021). As a result, Hermansen et al. (2019) recommend measuring the actual water repellency and determining the critical water content, which is more practical than the potential water repellency. This approach was also used in this study.

However, the correlation of persistence and severity between actual and potential water repellency differs. This was confirmed by Jiménez-Pinilla et al. (2016) who observed that WDPT values remained unchanged while contact angles were smaller in intact soils than in heat-treated soils

2.9 Temporal Variation of Soil Water Repellency

On study sites in Portugal, Malvar et al. (2016) observed the seasonal occurrence of soil water repellency in the field. The authors observed a strong relationship between soil water content and SWR and concluded that SWR can be avoided by keeping soil water content above the critical threshold. Soil water repellency occurred only during the summer season, from May to mid-August. Since the soil in the field did not dry out completely, the authors could only see the first peak of SWR and not the second. The authors observed that soil water content is an important determinant of the severity of soil water repellency at a study site in Portugal. However, it is insufficient to explain the temporal variations in SWR, which appears to be influenced by factors other than soil moisture.

The re-establishment of SWR following thorough wetting was investigated by Urbanek et al. (2015). While SWR is expected to be absent above a certain soil water content, it is not certain that it returns when the soil water content falls below this value. It was concluded that predicting the temporal behavior of hydrophobicity is thus extremely difficult. The relationship between soil moisture and hydrophobicity may not be useful in climates where the occurrence of dry periods is unpredictable. This could also explain the disparities in results reported by Malvar et al. (2016) who investigated study areas in very different climate zones.

2.10 Re-establishment of Soil Water Repellency

The impact of wetting history on the re-establishment of soil hydrophobicity is a critical question in SWR evaluation. In general, SWR is expected to be restored when the soil dries out after a wetting period (Caltabellotta et al., 2022). The re-establishment of amphiphilic coatings is expected to cause this process. When soil moisture levels fall, the polar ends re-orient and interact via hydrogen bonds, while the nonpolar, hydrophobic ends point outwards, resulting in soil water repellency (Wu et al., 2020).

Many studies have however yielded conflicting results. The re-establishment of hydrophobicity after extended periods of dryness was reported by Smettem et al. (2021), Wu et al. (2020) and Caltabellotta et al. (2022). Some normally water-repellent soils as observed by Weber et al. (2021), were both dry and hydrophilic at the same time. Further, Mao et al. (2019) reviewed laboratory experiments in which SWR did not re-establish after drying, necessitating a completely new input of hydrophobic substances to render the soil hydrophobic. The effect of cyclic wetting and drying on hydrophobic soils was investigated by Caltabellotta et al. (2022) and noticed that the MED and WDPT values decreased progressively as the number of cycles increased. The observed trend was similar for air-dried and oven-dried soils.

As a result, the re-establishment of SWR is a very complex process and cannot be adequately explained. It may be more dependent on biological processes than on soil-moisture-driven ones (Miller et al., 2019; 2020). However, the concept of critical water content remains very useful in land management, and hydrophobicity is assumed to be absent as long as soil moisture remains above the critical level. Soil water repellency tests on re-wetted samples were performed in this study to observe the re-establishment of hydrophobicity in laboratory conditions as well as possible changes in the critical moisture level.

2.11 Impact of Sample Disturbance on Soil Water Repellency

The representativeness of laboratory results for soil water repellency in the field was demonstrated by Li et al. (2021) by measuring WDPT on undisturbed and disturbed soil samples at a study site in Israel. The authors were unable to find a close relationship between the results obtained from measurements on undisturbed and disturbed samples. The current study builds on the work of Iovino et al. (2018), who investigated SWR in disturbed soil samples. However, the goal of this study is to determine the temporal appearance and duration of soil water repellency in the laboratory, which necessitates reliable results for the critical water content under field conditions. Soil water repellency measurements are thus performed on disturbed samples in order to obtain reliable results that can be used to develop a simple irrigation model based on critical moisture content.

2.12 Effects of Water Repellency on Agriculture

There are many detrimental effects of soil water repellency on agricultural soils which are likely to affect crop performance if no amelioration strategies are taken in time and which could also be very expensive to remedy (Roper et al., 2015). One of the consequences is drainage and leaching of nutrients through the areas of weakness in the water repellent layer as influenced by the amount of rainfall with time or irrigation event. In this process, any soluble fertilizers in the soil are also carried beyond the plant root zone and are not accessible to the plant (Weber et al., 2021). On the other hand, due to the uneven wetting experienced in the water repellent soils, there is uneven distribution of chemicals and fertilizers and hence in some localized dry areas plants experience water and nutrient stress (Roper et al., 2015). In the recent past adoption of minimum tillage and no-tillage practices have led to the build-up of soil organic carbon near the soil surface that has increased the occurrences of repellency induced complications in agricultural soils (Roper et al., 2013).

Crop management strategies, as noted by Blanco-Canqui and Lal (2007), may influence or induce SWR. Water repellency was shown to be higher in a no-till silt loam soil in Scotland than in traditionally tilled soils (González-Pealoza et al., 2012). No-till practices, according to the authors, may generate slight to severe water repellency in soils due to crop residue return and minimal soil disturbance. To examine the effects of no-till farming on SWR, they advocated thorough research on SWR in long-term no-till soils. Depending on the soil type, no-till agriculture causes 1.5 to 40 times more SWR than conventional tillage. This could be owing to the near-surface accumulation of hydrophobic organic carbon compounds formed from agricultural leftovers, as well as increased microbial activity and decreased soil disturbance. While high SWR may have negative effects on soil hydrology and crop yield, the amount of SWR under no-till versus conventional tillage may contribute to aggregate stabilization and intra-aggregate carbon sequestration (Blanco-Canqui, 2011).

The scarcity of good quality irrigation water has posed a significant threat to current irrigated agriculture. This has increased the demand for a reliable source of fresh water for both industrial and municipal needs. The shortage has resulted in the use of low-quality water for crop application. Treated wastewater contributes majorly as an alternative water source like in the case for Israel. Soil physical and hydraulic properties are affected by the complex mixture of constituents in the treated effluent especially the soil hydraulic and infiltration rates as it was confirmed by Liu et al. (2019). Also, use of treated sewage as an alternative water source for irrigation for a long period has been observed to enhance soil water repellency at the top layers of the soil (Ogunmokun and Wallach, 2021).

Use of treated wastewater has been recognized as an alternative water resource in areas experiencing freshwater shortage. Many studies have been done to investigate the effects of long-term irrigation with treated wastewater on soil wettability and spatial flow changes in the soil matrix whereas less attention is accorded to the spatial distribution of water repellency on the soil surface. The distribution of water repellency was reported to have been greatly influenced by the location of the emitters. This is because high water repellency was observed on the areas irrigated by adjacent emitters while low repellency was recorded under the emitters. However, estimations of soil water repellency and its measurement technique underneath the drippers was not presented. The high repellency was attributed to the use of treated wastewater which could also be alleviated by use of freshwater (Liu et al., 2019; Ogunmokun and Wallach, 2021).

After conducting a two-year summer maize irrigation experiment to determine the effects of soil water repellency on soil moisture content, crop development and yields, and evapotranspiration, Li et al. (2019) reported that more persistent water repellent soils resulted in a decrease in summer maize growth. The results revealed that the values of

Water Drop Penetration Time (WDPT) of all treatments increased significantly as the sowing days increased and reached peaks before the subsequent irrigation, though the peak decreased as the number of irrigation events increased. It was also observed that crop growth decreased proportionally to repellency. However, irrigation scheduling was not clearly defined since irrigation was applied when Volumetric (θ_v) soil moisture content was below 70% of filed capacity (θ_f) i.e., 30mm at the former stages and 20mm around later stages.

Similar findings were reported by Wang et al. (2021) who investigated the possible mechanisms that impede the growth of summer maize in repellent soils. The results showed a daily cumulative decrease in root water uptake with increasing soil water repellency. It was suggested that the WDPT be considered as a key parameter in smart irrigation systems for determining an irrigation schedule, i.e., when and how much to irrigate, irrigation quota, and irrigation frequency. More research is needed to uncover root uptake processes and determine appropriate irrigation amounts in water repellent soils.

Despite extensive research, soil water repellency remains a significant barrier to plant establishment and growth. It is still a difficult problem for which few solutions have been developed (Ruthrof et al., 2019). However, Ruthrof et al. (2019) proposed that soil water repellency in agriculture and ecological restoration can be viewed as an opportunity rather than a problem to be solved. It was observed that soil water repellency can be temporarily alleviated at the micro-scale to successfully establish plants and then be harnessed at larger spatial scales to improve soil water storage to act as a "drought-proofing" tool for plant survival in water-limited soil. However, because the condition of repellency is temporary, it is not stated how this shift will affect farming and the sustainability of the transition to water harvesting.

Water repellent soils are a significant constraint to horticultural production in southern and south-western Australia, where more than 10 million hectares of arable sandy soils are affected (Davies et al., 2019). In Australian farming systems, water repellency is responsible for a 40% annual loss in crop productivity (Ghadim, 2000). These sandy soils exhibit repellency characteristics, such as dry fixes on the soil surface following heavy precipitation. This has a significant impact on farming activities by causing uneven field germination and limiting fertilizer accessibility. Similarly, amazed weed germination undermines effective weed control, and delayed harvest and field germination increase the risk of wind erosion (Roper et al., 2015).

Dominance of soil water repellency has likewise been seen in areas where conservation agriculture such as no-till farming is practiced (Humberto and Sabrina, 2018). This can be linked to the excessive collection of natural materials from deteriorating plant matter superficially. Water repellency has been observed to seriously affect soils especially with the reception of non-till cultivation which prompts dominance of soil natural materials at the soil surface (Roper et al., 2013).

2.13 Effects of Soil Water Repellency on Soil Hydrologic Properties

A review study was carried out by Heidary et al. (2018) to identify gaps in existing research studies on the effects of soil water repellency on hydrological and disintegration processes. Some of the gaps identified include inconsistencies in the assessment of important implications of water repellency on soil productivity and management, the essential soil moisture content, and the actual water repellency in reviews and assessments. This information is useful in preventing the occurrence of soil water repellency. It was observed that there was indeed a need to investigate the effects of soil water repellency on runoff generation and soil erosion under different rainfall intensities and spatial scales.

Infiltration experiments were carried out by Schwen et al. (2015) for one hydrophilic and four artificially hydrophobized materials. They also calculated the static wetting and drainage water saturation curves. In their experiments, they reported that the degree of WR affected the wetting curves. In particular, for the water saturation vs. matric potential curves, the water entry pressures increased with increase in the degree of WR, reaching a positive value for extremely hydrophobic materials. Their drainage curve results revealed that only the non-repellent sand differed from the artificial hydrophobic mixtures.

In an experimental and theoretical study, Moret-Fernández et al. (2019) investigated the wettability effect on both water retention and hydraulic conductivity curves. They began with wet materials and obtained drying and wetting curves. They developed a model that could accurately predict the saturated soil hydraulic conductivity of soil mixtures with varying wettability. Experiments to the drainage and imbibition water saturation curves of various soil types with varying degrees of water repellency were conducted by Hammecker et al. (2022). The findings of this study revealed that the effect of WR in drainage is less pronounced than in imbibition. The results also showed that increasing the contact angle reduced the saturated hydraulic conductivity. A model was also developed which can predict water infiltration into water repellent soils with moderate and strong repellency, as well as fingering features.

A study to investigate the effect of soil water repellency on slope hydrological response was conducted by Zheng et al. (2017). Twenty-four flume tests were conducted in model slopes under artificial rainfall, with soils of varying wettability levels. To model the response of natural and man-made slopes to rainfall, different rainfall intensities were used. The analysis of experimental data from 24 flume tests in completely decomposed granite at various soil water repellency levels, rainfall intensities, slope angles, and relative compactions. The results revealed that an increase in water repellency led to a significant drop in both the wetting front rate by 40% and 100% for the subcritical water repellent and water repellent soil, respectively and total water storage by 42% and 77% for the subcritical water repellent and water repellent soil, respectively.

In summary, the knowledge of the persistence of soil water repellency in soil is crucial for understanding and predicting how it affects hydrological processes. However, there is a poor understanding of the persistence of SWR and its effect on soil water flow (Chau et al., 2014; Ganz et al., 2013). Although it is well known that SWR may decrease or disappear during long wetting periods, little is known about the threshold conditions needed for SWR to disappear (Jordán et al., 2013). To assess the relationship between soil water repellency persistence, multiple soils must be tested. Additionally, naturally water-repellent soil material should be tested to assess moisture dependent wettability (Chau et al., 2014). Another important factor controlling SWR is the critical water content (Wc). The Wc is an important transition zone where soil turns from a repellent state to a wettable state (Diehl, 2013). Since the measurement of the persistence of repellent soils are usually performed at single water content, measurements of Wc should be performed because it explains how SWR behaves under different water contents. The soil moisture-related aspect of SWR has important repercussions for land use management due to the effects of SWR in soils which have not reached the threshold of the Wc. In an effort to better quantify the effect that different SWR has on hydrological processes such as infiltration, It is important to determine relationship between persistence and soil hydro-physical properties in water repellent soils. The purpose of this study was to determine the relationship between the soil hydro-physical properties, persistence and the Wc in soils with varying SWR. The study hypothesized that there is indeed a relationship between soil hydro-physical properties, persistence of SWR and the critical water content.

2.14 Remediation Strategies for Soil Water Repellency

While amendments are not the focus of this thesis, it is important to recognize their importance in addressing the issue of soil water repellency. Claying as well as surfactant applications, have been identified as potential water repellent soil amendments to date.

2.14.1 Claying

Soil water repellency can be reduced by adding Kaolinite and Na-montmorillonite clay to the soil (Lichner et al., 2006; McKissock et al., 2000). Clay contributes to the formation of hydrophilic surfaces by attaching to soil grains and hydrophobic compounds (Diamantis et al., 2017). Clays applied to water repellent soils were effective at reducing repellency levels, according to Roper et al. (2015), though the degree of effectiveness varied with clay type. Similarly, Daniel et al. (2019) proposed that higher clay contents in soils (around 5%) could reduce water repellency by creating flow pathways of surface water through the soil profile via an increase in surface area available for wetting.

In a recent study by Diamantis et al. (2017) kaolinite-rich clay soil was used for repellency mitigation. The wet clay method resulted in a 74% reduction in soil water repellency levels when compared to dry clay additions that required subsequent wetting/drying cycles to become as effective.

2.14.2 Surfactant Applications

Soil surfactants are amphiphilic molecules that can be applied to soils to reduce water surface tension and thus the contact angle between the water and soil surface, allowing the soil to wet more easily (Dekker et al., 2019). Surfactants are particularly popular as treatments on turf grass and golf courses to eliminate water repellency issues such as preferential flow pathways and patchy grass cover. Surfactants, according to Dekker et al. (2019), help to restore the wettability of soils in root zones, and regular treatments throughout the growing season may result in the elimination of water repellency issues.

A two-year field experiment was carried out to assess the effects of six different chemical wetting agents on soils with existing soil water repellency and planted with creeping bentgrass. These wetting agents were Cascade Plus (10% alcohol ethoxylates and 90% polyethylene and polypropylene glycols); Hydro-Wet (87.5% poloxanlene, 2-butoxyethanol); Matador (100% alkyl block polymer); OARS (80% polyoxyalkylene polymers and 10% potassium salt of alkyl substituted maleic acid); pH Acid (100% blend of acidifying agents and a high molecular weight nonionic surfactant) and Tournament-Ready (62% alkyl polyglycoside and siloxane solution, and 38% polyalkoxylate blend). In the second growing season, four of the six wetting agents increased soil volumetric water content, while the others had no effect. These results were found to be negatively related to the development of localized dry spots (LDS) and positively related to the occurrence of an air-borne turf disease. Soil phospholipid fatty acid (PLFA) analysis revealed that none of the treatments used caused a shift in microbial populations between fungi and bacteria, or between gram-positive and gram-negative bacteria. The wetting agents used had no effect on stress indicators such as saturated to mono-unsaturated fatty acids. However, a wetting agent containing alkyl block polymers (ABP; Matador) with known ability to remove soil organic coatings inhibited microbial populations at one evaluation timing. These results suggest that repeated ABP application reduced soil carbon availability for soil microorganisms, which likely contributed to the elevated LDS development observed (Song et al., 2019).

Water repellency amelioration strategies are categorized into two types: direct and indirect strategies, as shown in Table 2.1 by Müller and Deurer (2011). The mechanisms of the amelioration strategy can be direct (D) or indirect (ID). They have been developed and tested in the laboratory (L) or in the field (F). Indirect remedies are used to manage the apparent symptoms by offering a temporal solution by improving the infiltration capacity of the repellent soil. On the other hand, direct remediation strategies aim at either reducing the input of hydrophobic substances to soil or increasing their decomposition or both.

Table 2.1: Overview of the Remediation Strategies for Soil Water Repellency

Remediation strategy	**Mechanism**	**Disadvantages**	**Advantages**	**Negative Side Effects**	**Use**	**Scale (F/L)**
Surfactants	ID	Continuous applications are needed to sustain effect; high costs	Turf quality, seedling emergence, yields, efficacy of agrichemicals, homogeneous wetting of soil, water storage and distribution	contamination of water resources, effects on soil structure and biological communities	Yes	F/L
Claying	ID (D)	Costs if clay is not available in subsoil or close to site	Yields, pH, CEC, soil fertility, microbial activity, water holding capacity	Soil structure; compaction, copper immobilization, other trace elements	Yes	L/F
Liming	D	Costs	pH, soil fertility, microbiological activity, microbial diversity, earthworms	Not known	No	F
Vegetation choice	ID	Not everywhere feasible	Water harvesting	May lead to changes in land use system	Yes	F
Irrigation	D	Costs; water availability	Yields		Yes	F
Cultivation	ID	Short-term effect		Sub-soiling decreases SOM-content of topsoil, elevated greenhouse gas emissions, erosion	Yes	L/F
Soil aeration	ID	Short-term effects, labor-intensive	Stimulation of microbial communities	Not known	Yes	F
Compaction	ID			Soil structure, soil quality	No	L

ID-indirect amelioration mechanism; D-direct amelioration mechanism; L-tested in the Laboratory; F- tested in the field

2.15 Research Gap

There has already been a lot of study done to determine the influence of SWR on the soil ecology in forest and fire-affected soils (Weninger et al., 2019). However, because the degree of SWR in farming tillage soil is lower than in forest and fire-affected soils (Lucas-Borja et al., 2019), there has been lack of research on SWR in farmland, particularly on how conservation agriculture affects SWR. The presence of a small degree of SWR, known as subcritical water repellency, can have a significant impact on soil structure and hydraulic parameters (Tadayonnejad et al., 2017). Understanding the factors that influence SWR is therefore vital for improving soil quality. This study was carried out to address this knowledge gap with the following objectives: (i) identifying the interactions between the different soil properties controlling development and persistence of soil water repellency in a hydrophobic soil and (ii) determine the critical soil water content (Wc) beyond which hydrophobic soils become hydrophilic and define a safety margin for Wc as a management strategy for improving irrigation practices in repellent agricultural soils in Kenya.

2.16 Conceptual Framework

The variables studied relate as shown in Figure 2.2 the persistence of soil water repellency is controlled by various soil hydrophysical properties. The availability of hydrophobic soil matter and the pre-treatment temperatures influence the occurrence of water repellency in a soil. A safety margin of soil water content that needs to be maintained in the soil to avoid soil water repellency inducing conditions can be obtained from the relationships between soil properties and soil water repellency.

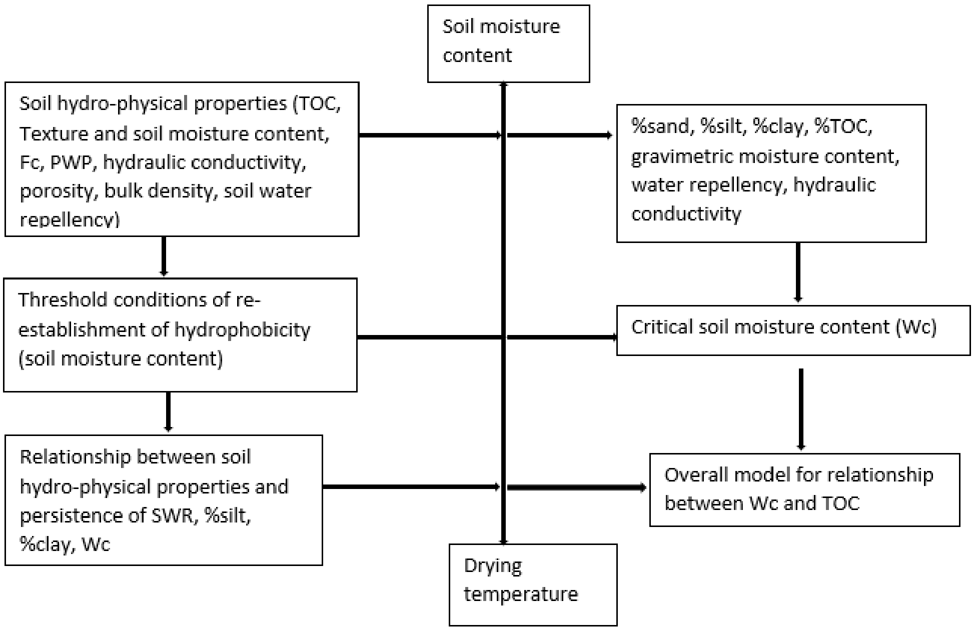


Figure 2.2: Conceptual Framework

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of Study Area

Soil samples were collected from Murang’a and Makueni counties located in Kenya as shown in Figures 3.1 and 3.2 respectively. Murang’a county is located in the central region of the Republic of Kenya between latitudes 0^{o} 34’ and 1^{o} 7’ South and 36^{o} 00’ and 37^{o} 27’ East and covers an approximate area of 2,558.8 km^{2}. It borders Nyeri to the North, Kirinyaga, Embu and Machakos to the East, Kiambu to the South and Nyandarua to the West. Murang’a is characterized as semi-humid with average annual rainfall ranging between 800-1400mm and mean annual temperatures ranging between 18-20^{o}C (Murang’a CIDP, 2023/2027). The county is characterized by nine (9) agro-ecological zones (Jaetzold et al., 2006) and receives two rainy seasons MAM andOND. The high rainfall is experienced on the high lands and favors coffee and tea farming (Figure 3.1).

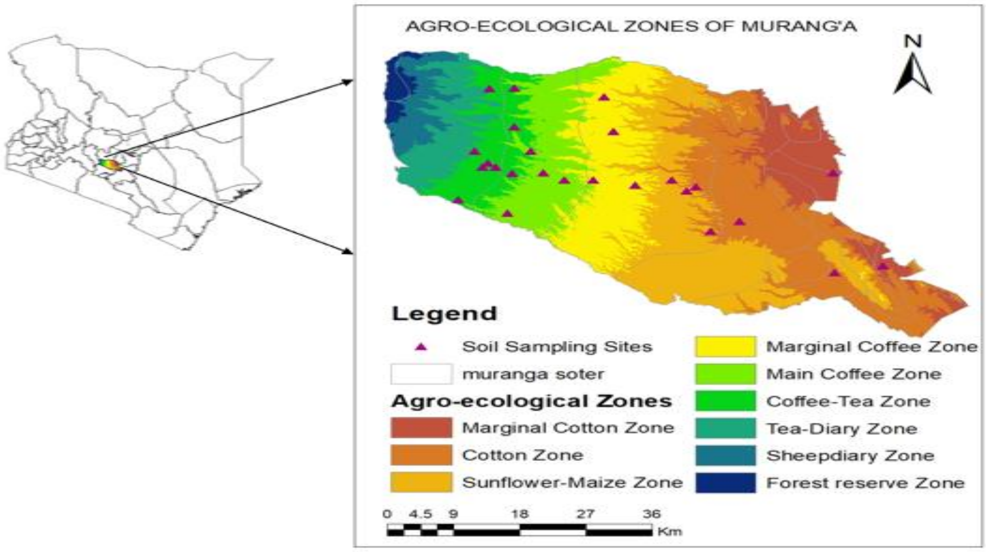


Figure 3.1: Agroecological Zones of Murang'a County in Kenya and the Location of the Sampling Sites in the Various Soil Types

Kangema, Gatanga and the higher parts of Kigumo and Kandara are generally humid and wet due to the influence of the Nyandarua Ranges. The eastern region receives less rainfall and crop production requires irrigation. The western part of the county is characterized by upper highland humid and upper highland perhumid while Lower highland humid, upper midland sub humid, and humid agro ecological zones cover the central region of the county. Lower midland semi-humid, transitional, and semi-arid agro-ecological zones characterize the eastern region of the county. The nine agro-ecological zones are as presented in Table 3.1 as adopted from Jaetzold et al. (2006).

Table 3.1: Agro-ecological zones of Murang'a County

Agro-ecological zones	Main land use activity
UHO	forest reserve
UH1	Sheep, dairy
LH1	Tea, dairy
UM1	Coffee, tea
UM2	Mainly coffee
UM3	marginal coffee
UM4	Sunflower, maize
LM3	cotton
LM4	marginal cotton

The geology of the county consists of volcanic rock structure and most of the soil has developed from the volcanic activities. The soils are generally fertile and have good drainage. These soils include Humic Nitisols, Rhodic ferralsols, ferralic cambisols, umbric Andosols and some patches of vertisols which are poorly drained (Batjes and Gicheru, 2004).

Makueni County on the hand is situated in the Southeastern part of the country. It borders Machakos to the North, Kitui to the East, Taita Taveta to the South and Kajiando to the West. It is located between latitudes 1^{o} 35’ and 3^{o} 00’ South and longitudes 37^{o} 10’ and 38^{o} 30’ East and covers an area of 8,008.7km^{2} (Makueni CIDP, 2023/2027). Makueni County lies in the arid and semi-arid zones and receives two rainy seasons MAM and OND with an average annual rainfall ranging between 450-900mm and mean annual temperatures falling between 20-22^{o}C. The hilly parts of Mbooni and Kilungu receive 800-1200mm annually while the lower side of the county which is very dry receives little rainfall ranging between 300mm to 400mm annually.

It is also characterized by high temperatures of 35.8^{o}Cin the low-lying areas (Makueni CIDP, 2023/2027).

Makueni has eight AEZ zones ranging from LM2, UM3, UM4, LM3, LM4, LM5, LM6 and UM6. The ASALs are LM4, LM5, LM6, and UM6, which account for more than 80% of Makueni County (Jaetzold et al., 2006). It receives between 200 and 1200 mm of rainfall each year, which can be erratic at times, resulting in crop failures. The agro-ecological zones of Makueni are as presented in Table 3.2 as adopted from Jaetzold et al. (2006).

Table 3.2: Agro-ecological zones of Makueni County

Agro-ecological zones	Main land use activity
High potential LM2	Coffee, maize, peas, citrus, fruits, afforestation
Medium potential LM3, UM3, LM4, UM4	Coffee, maize, pigeon peas, cotton, sunflower, sorghum and fruits
Lower potential LM5, LM6, UM6	Livestock rearing, maize, sorghum, pigeon peas, beans, cotton, sunflower, forests

The most dominant soils include Rhodic ferralsols, Chromic Cambisols, Eutric Vartisols, Haplic Lixisols and Chromic Luvisols (Batjes and Gicheru, 2004). These types of soils cover most of the arable land of 5,042.69km^2 which is approximated as 74% of the total county area (Makueni CIDP, 2023/2027. The types of crops grown include maize, beans, cow peas and green grams. Small scale irrigation is done for maize, beans and vegetables. The largest area of Makueni County is covered by mixed farming which mostly consists of food crops (Figure 3.2). The farmers use small scale irrigation to produce these food crops since the rains are erratic (Makueni CIDP, 2023/2027).

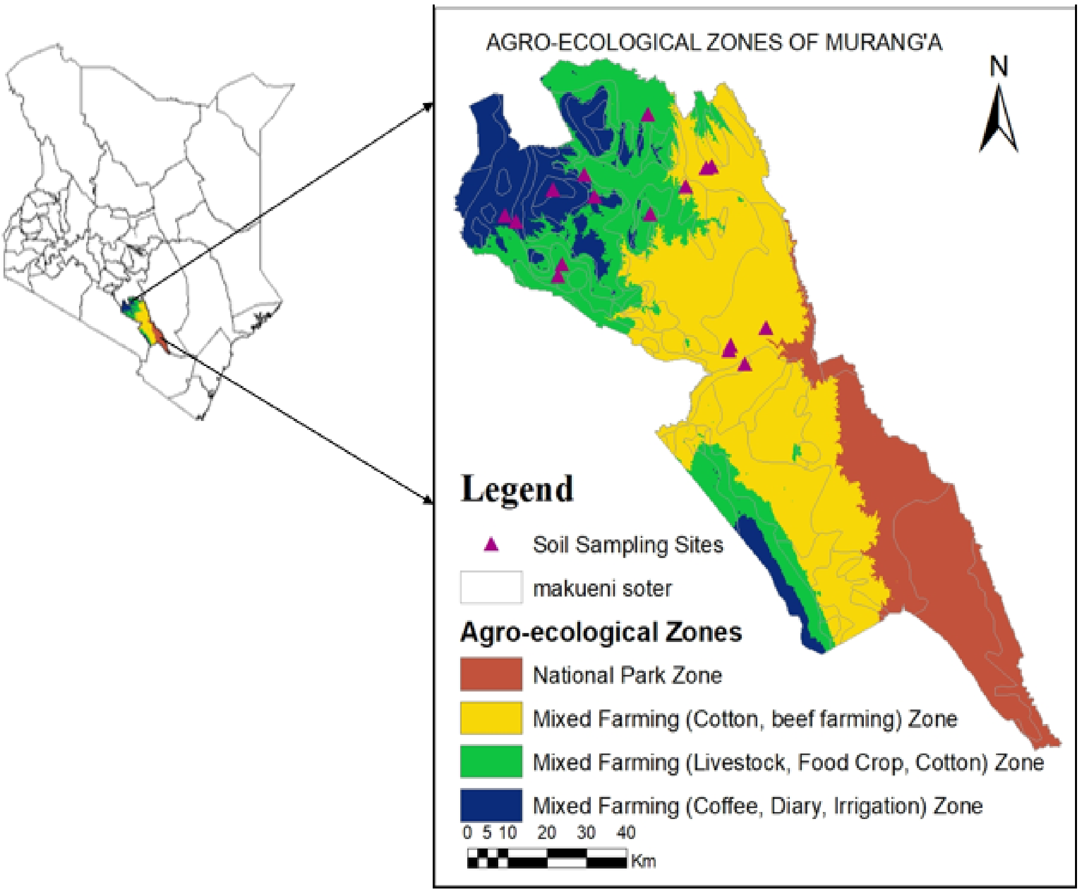


Figure 3.2: The Agroecological Zones of Makueni County of Kenya and the Location of the Sampling Sites in the Various Soil Types

These study areas fall in different agroecological zones which are characterized by different climatic conditions ranging from rainfall, evapotranspiration, and temperatures. All these factors influence the soil forming process which means that the soils in these study areas differ in their hydrophysical properties. The soil formation factors such as the parent material, vegetation and land use (Müller & Deurer, 2011) are also varied and therefore the physical factors that influence soil water repellency such as soil texture, bulk density and organic matter also vary. Given the agricultural significance of these two counties in Kenya and bearing in mind the negative impacts of soil water repellency in agriculture, it was necessary to study the soil hydrological behavior, especially the development of soil water repellency in their setting.

3.2 Agricultural Soils in Kenya

Kenya has 25 major soil groups based on soil properties which are as a result of the interplay between climatic conditions, land terrain, underlying rock material, organisms and time. Soil is the most valuable and widespread natural resource which supports agriculturally based livelihoods. Soil resources in Kenya range from all textures, depth and fertility but most of the soil resources are limited for agricultural production due to salinity/sodicity, acidity, drainage and fertility. Soils that are used for agriculture in Kenya include Ferralsols, Vertisols, Acrisols, Lixisols, Luvisols and Nitisols (Dondeyne et al., 2021). Use of animal excrement as manure is encouraged to help in conserving the soil moisture content by improving the soil water holding capacity of the soil. Consequently, addition of soil amendments can lead to the formation and occurrence of water repellency (Farrick et al., 2018).

3.2.1 Description of the sampled soil types

In the following sub-sections, the sampled soil types and the specific sampling sites are described in detail.

Andosols

They are also called volcanic ash soils because they develop from volcanic ejecta. They develop on undulating to mountainous environments and in humid to tropical climatic conditions. These soils support a wide range of vegetation. The profile of the Andosols is developed from rapid weathering of the porous volcanic ejecta which results in accumalation of argano-mineral complexes or short-range-order minerals such as allophanes, imogolite and ferrihydrite. These argano-mineral complexes decreases soil wettability by rendering the soil surface hydrophobic (Achtenhagen et al. 2015). Andosols have a high potential for agricultural production since they are easy to cultivate and have a good rootability and water storage properties. However, they have not been utilized to capicity due to their strong phosporus fixation capacity which hinders adsorption of orther essential nutrients by plants. This type of soil was sampled from six sampling sites in Murang’a county.

Cambisols

Cambisols are found in all types of climate in terrains ranging from mountainous to level surfaces. They are generally medium to fine textured and show horizon differentiattion in terms of structure, color and clay content derived from a wide range of rocks. Cambisols are generraly intensively utilized for agricultural purposes. They however have a limitation in their use due to the absence of appreciable quantities of illuviated clay, organic matter and aluminum and/or iron compounds. They are also restricted for use due to the usual characteristics associated with shallowness, stoniness and low base status (Awange, 2022).This soils were sampled from six sampling sites in Makueni County.

Ferralsols

Ferralsols are red and yellow tropical soils with high content of clay minerals, mainly aluminum and iron. They develop on level to undulating land surfaces and are strongly weathered soils. These soils have desirable physical structure such as stable micro-structure but are poor chemically. Ferralsols have low capacity to fix phosphates and therefore have low natural fertility. For this case, liming and fertilization is used for sustainable agricultural production. Generally, most ferralsols are clayey hence have a strong water retention at the permanent wilting point. On the other hand, the presence of micro-aggregates reduces moisture storage at the field capacity. This is the main reason why this type of soil has limited capacity to hold available moisture for the crops. For some of the ferralsols, the available moisture is 10mm/10cm soil depth which is typical. Ferralsols with low levels of iron and/or organic matter are susceptible to surface sealing and compaction if subjected to cultivation. Those with high levels of iron and/or organic matter are susceptible to reduced particle wettability due to the processes associated with aggregate stability where clay and organic matter bind together to form organo-mineral complexes (De Melo et al., 2018).

Nitisols

Nitisols are normally deeper than 150 cm and dusky red or dark red in color with more than 30 percent clay content. They are well drained soils with a fair retention of plant available moisture of (5-15 percent by volume). The main clay that dominates these soils is kaolinite and are rich in iron. The presence of iron (Fe) limits water dispersion in the soils. These soils are very clayey with a subsurface made of high aggregate stability. Stable soil aggregates have a wide range of pore space, allowing for good water and air flow as well as root penetration. Aggregate stability has been in many cases boosted by the addition of organic matter into the soil. However, it has been proven that aggregate stability is positively correlated to soil water repellency (Zheng et al., 2016). This was proven by Sarker et al. (2018) who observed that increase in soil organic matter content and its hydrophobic properties gradually increased the soil aggregate stability.

Lixisols and Acrisols

These are soils that have a higher clay content in the sub-surface due to leaching. They are limited by low Cation Exchange Capacity of less than 24cmol/kg clay (Kögel-Knabner and Amelung, 2021). The eluviated top surface has unstable soil structure and therefore for these soils to be used in farming, their organic matter should be conserved, and erosion controlled. For this reason, many farmers employ conservation agriculture to manage the soil which could introduce hydrophobic substances in the soil and their negative impacts. These soils were sampled from the lower region of Makueni County.

3.3 Soil Sampling Design and Procedure

The sampling sites comprised 26 and 16 unirrigated agricultural sites in Murang’a and Makueni Counties respectively. Sampling was conducted in Murang’a County from 15th to 20th July 2020 and in Makueni from 8th to 18th August 2020. The selection of the soils to be sampled was based on the soil type. The soil types that cover most of the areas in the county and are closely related to agricultural production as mapped by Kenya Crop Land Layer were selected. These soil types were Umbric Andosols, Humic Nitisols, Rhodic Ferralsols, Rhodic Nitisols Chromic Cambisols, Haplic Lixisols, Haplic Acrisols, Dystric Cambisols and Humic Cambisols as classified in the Soil Map of Kenya, (1982) as shown in Figure 3.3 adopted from Sombroek et al. (1982).

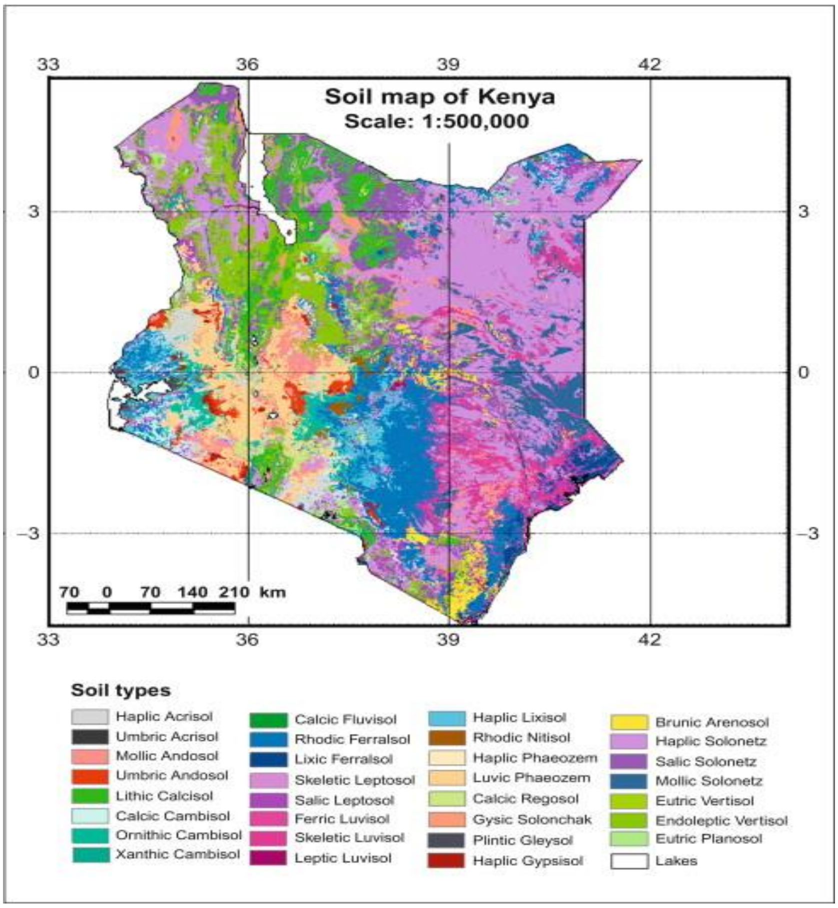


Figure 3.3: Map of the Major Soil Types in Kenya

The soil types were mapped using soil layers from Kenya Soils and Terrain Database (Batjes, & Gicheru, 2004). The various soil types fell within the agro-ecological zones (AEZs) in the study areas. A combination of stratified and systematic sampling methods was employed to draw representative soil samples from different AEZs, land use/land cover and soil types. The study areas were first stratified into Agro-ecological zones.

Then, three land use/land cover types, such as forest land, farmland and National parks were identified in each study area by overlaying the Kenya crop land layer and AEZs on the soil map in ArcGis (version10). Subsequently, farmlands were divided into two, irrigated and unirrigated lands. Soil samples were only collected from the unirrigated lands to avoid the influence of irrigation on the actual soil water repellency measured in the field. Random sampling was then employed to pick the unirrigated lands within the farmlands and soil types. This means that each unirrigated farm land and soil type, had an equal chance of being sampled. In each sampling site, two disturbed samples were collected at a depth of 0-15cm and 15-30cm. This is because most plant roots, biological activity and nutrient levels occur mainly in the topsoil (0-25cm) which is also the recommended depth of tillage (Fery and Murphy, 2013). Also, for the purposes of this study, it is within this depth where microbial plant decomposition takes place and is strongly associated with the occurrence of water repellency (Miller et al., 2020). Approximately 1kg of each disturbed soil sample was collected and placed in sampling bags and the bag labelled with the location of sampling, type of soil and the depth of sampling. Undisturbed core samples were also collected from each sampling location for hydraulic conductivity determination. The samples were then transported to Kenya Agricultural and Livestock Research Organization (KALRO), Nairobi laboratory for analysis.

3.3.1 Characteristics of the Sampling Sites

The twenty six (26) sampling sites in Murang’a were characterized by six (6) different soil types namely Umbric Adndosols, Humic Nitisols (UP), Humic Nitisols (IB2), Rhodic nitisols, Rhodic Ferralsols and Ferralic Cambisols. On the other hand, Makueni sampling sites were characterized by Chromic Cambisols, Rhodic Ferralsols, Haplic Lixisols, Haplic Acrisols, Dystric Cambisols and Humic Cambisols. Further, the coordinates of each sampling site, site code and soil types in Murang’a and Makueni are represented in Table 3.3 and 3.4.

Table 3.3: Site Characteristics of Sampling Sites in Murang'a County

Site code	GPS Coordinates	Soil Type	LIT	Sample code	Geology
KE92	S0 39 50,E35 49 44	Umbric Andosols	UP	ANu	pyroclastic
KE92	S0 37 44, E36 50 9	Umbric Andosols	UP	ANu	pyroclastic
KE92	S0 50 40, E36 47 52	Umbric Andosols	UP	ANu	pyroclastic
KE92	S0 46 27, E36 49 40	Umbric Andosols	UP	ANu	pyroclastic
KE113	S0 47 7, E36 51 47	Humic Nitisols	UP	NTu	pyroclastic
KE113	S0 47 51 , E37 3 32	Humic Nitisols	UP	NTu	pyroclastic
KE113	S0 51 32, E36 51 28	Humic Nitisols	UP	NTu	pyroclastic
KE113	S0 42 00, E36 52 00	Humic Nitisols	UP	NTu	pyroclastic
KE113	S0 37 41, E36 51 59	Humic Nitisols	UP	NTu	pyroclastic
KE162	S0 38 41, E36 58 34	Humic Nitisols	IB2	NTu	Basalt
KE162	S0 53 32, E37 6 22	Humic Nitisols	IB2	NTu	Basalt
KE162	S0 52 26, E37 8 30	Humic Nitisols	IB2	NTu	Basalt
KE162	S0 42 30, E36 59 13	Humic Nitisols	IB2	NTu	Basalt
KE245	S0 47 5, E37 15 22	Rhodic Nitisols	IB	NTr	basic igneous
KE238	S0 57 20, E37 19 1	Rhodic ferralsols	MA2	FRr	gneiss
KE233	S0 58 7, E37 15 28	Ferralic cambisols	II1	CMo	andesite
KE92	S0 44 41, E36 49 5	Umbric Andosols	UP	ANu	pyroclastic
KE92	S0 45 59, E36 50 3	Umbric Andosols	UP	ANu	pyroclastic
KE113	S0 46 25, E 36 50 38	Humic Nitisols	UP	NTu	pyroclastic
KE113	S0 44 42,E 36 53 10	Humic Nitisols	UP	NTu	pyroclastic
KE162	S0 47 53, E36 57 45	Humic Nitisols	IB2	NTu	Basalt
KE162	S0 49 6, E 37 4 36	Humic Nitisols	IB2	NTu	Basalt
KE113	S0 47 6, E36 54 5	Humic Nitisols	UP	NTu	pyroclastic
KE113	S0 47 52, E 36 55 40	Humic Nitisols	UP	NTu	pyroclastic
KE162	S0 48 27, E 37 0 51	Humic Nitisols	IB2	NTu	Basalt
KE162	S0 48 38, E 37 5 19	Humic Nitisols	IB2	NTu	Basalt

Table 3.4: Site Characteristics of Sampling Sites in Makueni County

Site Code	GPS Coordinates	soil type	LIT	Sample Code	Geology
KE235	S1 57 13, E37 23 8	Rhodic Ferralsols	MA2	FRr	gneiss
KE191	S1 47 16, E37 40 1	ChromicCambisols	II1	CMx	andesite
KE252	S2 5 25, E37 50 51	Haplic Lixisols	MA2	LXh	gneiss
KE235	S1 50 60, E37 15 22	Rhodic Ferralsols	MA2	FRr	gneiss
KE230	S1 51 46, E37 16 47	Haplic Acrisols	MA2	ACh	gneiss
KE252	S2 9 59, E37 48 2	Haplic Lixisols	MA2	LXh	gneiss
KE191	S1 44 55, E37 42 48	Chromic Cambisols	II1	CMx	andesite
KE235	S1 38 7; E37 34 51	Rhodic Ferralsols	MA2	FRr	gneiss
KE80	S1 50 50, E37 25 11	Dystric Cambisols	MA2	CMd	gneiss
KE80	S1 58 44, E37 22 39	Dystric Cambisols	MA2	CMd	gneiss
KE252	S2 7 41; E37 46 3	Haplic Lixisols	MA2	LXh	gneiss
KE191	S1 44 42, E37 43 30	Chromic Cambisols	II1	CMx	andesite
KE83	S1 47 45, E37 21 51	Humic Cambisols	MA2	CMu	gneiss
KE230	S1 45 48, E37 26 9	Haplic Acrisols	MA2	ACh	gneiss
KE235	S1 48 35, E37 27 32	Rhodic Ferralsols	MA2	FRr	gneiss
KE252	S2 8 15, E37 45 51	Haplic Lixisols	MA2	LXh	gneiss

3.4 Determination of Soil Hydro-physical Properties

The determination of the soil's physical properties is described in detail in the following sections.

3.4.1 Determination of Soil Texture

The soil texture was determined in the laboratory using a hydrometer method. 50.0 g of each soil sample was oven dried and put in a baffled stirring cup and the cup filled to half with distilled water before adding 10ml of sodium hexametaphosphate solution. The cup was then placed on to a stirrer and the contents stirred for about 10.0 minutes until soil aggregates were broken down. The suspension was transferred to the settling cylinder and the cylinder filled to the lower mark with distilled water after placing the hydrometer in the liquid. The hydrometer was the drawn and the suspension shaken vigorously to prevent any impact on the settling rate. The reading of the hydrometer was taken after 40.0 seconds and 2.0 hours for sand and clay contents respectively (Bouyoucos, 1962).

The percentage sand was computed using Equation 3.1:

$$\%Sand = \frac{50 - C_{hr} * 100}{50} \tag{3.1}$$

Where:

C_{hr} = corrected hydrometer reading after 40.0 seconds

Percentage clay was calculated using Equation 3.2 given as:

$$\%Clay = \frac{C_{hr} * 100}{50} \tag{3.2}$$

Where:

C_{hr} = corrected hydrometer reading after 2.0 hours

Percentage silt was calculated using Equation 3.3 given as:

$$\%Silt = 100 - (\%sand + \%clay) \tag{3.3}$$

The USDA soil textural triangle was used to determine the soil textural classes.

3.4.2 Determination of Porosity and Bulk Density

First, a cylinder with a known volume 100 cm^3 (diameter of 5cm and height of 5.1cm) was weighed to determine its weight. The cylinder was then filled with sieved soil (<2mm) and tapped at the bottom to ensure that it was well packed. More soil was added into the cylinder and compaction was repeated until the cylinder was well packed and its volume attained as it is described by Tan (1995). Once again, the cylinder was weighed to determine its weight with soil. The soil moisture content of the sample was evaluated by oven-drying and the dry weight in the cylinder was weighed again.

The bulk density was then calculated using Equation 3.4 given as:

$$\rho_b = \frac{Mwet - Mdry}{Vcylinder} \qquad (3.4)$$

Where:

ρb=Bulk density (g/cm^3)

M_{wet} =Mass of the cylinder plus soil before oven drying (g)

M_{dry} = Mass of the cylinder plus oven-dried soil (g)

$V_{cylinder}$ = volume of the cylinder ($100cm^3$)

For each soil sample, two replicates were averaged to get a reliable bulk density value which was recorded.

Porosity was determined from the bulk densities using Equation 3.5 given as:

$$\phi = 1 - \frac{\rho_b}{\rho_s} \qquad (3.5)$$

ρ_s = Particle density = 2.65 g/cm^3

3.4.3 Determination of Total Organic Carbon (TOC)

Total Organic Carbon in the soil samples was determined using Calorimetric Method as adopted by Anderson and Ingram (1993). It is the most economical on time and can be used for soils with higher levels of organic carbon (>0.2%). Soil was ground and sieved through a sieve of 0.15mm in size. 1.0g of the sieved soil was weighed into a labelled 100ml digestion tube and 2ml of water was added. 10ml of 5% potassium Dichromate solution was added and allowed to completely wet the soil and dissolve the standards. 5.0ml sulphuric acid was added from a burette and the mixture swirled. The mixture was then digested at 150^{o}C for 30 minutes. It was then removed and allowed to cool before adding 50ml of 0.4% Barium Chloride. The contents were mixed thoroughly and allowed to stand overnight so as to leave a clear solution. An aliquot of the clear solution was transferred into a calorimeter cuvette and each standard as well as the sample absorbance was measured and recorded at 600nm (wavelength).

A graph of the absorbance against standard concentration was plotted and solution concentrations for each unknown and blanks were determined. Mean blank value was subtracted from the unknowns which gave a value for corrected concentration, K. Total Organic Carbon content for each sample was calculated as given in Equation 3.6 given as:

$$\%TOC = \frac{(K*0.1)}{W} \qquad (3.6)$$

Where:

W= Weight of the soil (g)

K= corrected concentration.

3.4.4 Determination of Saturated Hydraulic Conductivity (K_s)

Saturated hydraulic conductivity was determined using the falling head permeameter method (Chapuis et al., 2007). The undisturbed core ring soil samples were prepared by first saturating them in water for 24hours from the bottom by placing in samples in a tray with water. Water was tapped through the samples to ensure no air is trapped in the soil matrix. Water was then allowed to drain into the soil sample through the standpipe by first filling it to the mark and then allowing the water to drain slowly to the lower mark in the standpipe. The initial height and final head were recorded, and the experiment was repeated three times. The average time interval for the head change was calculated and the saturated hydraulic conductivity of the various samples computed by use of Equation 3.7 given as:

$$K_s = \frac{2.3aL}{At}\log_{10}\frac{h_1}{h_2} \tag{3.7}$$

Where:

Ks = saturated hydraulic conductivity (mm/hr)

a = Cross-section area of glass tube (cm^2)

A = Cross-section area of soil sample (cm^2)

L = the length of flow (cm)

t = the time interval (sec)

h_1 = the initial water level (cm)

h_2 = the final water level (cm)

3.5 Determination of Soil Moisture Characteristics

A procedure by Klute (1986) was adopted for determination of field capacity and permanent wilting point (PWP) and the experiment was conducted in Kenya Agricultural and Livestock Research Organization (KARLO).

3.5.1 Field Capacity

It is the maximum amount of water a soil can hold after the gravitational water is drained. It is estimated that the soil water content held by the soils after 2-3 days following saturation but before evapotranspiration has depleted the water in the soil. The disturbed soil samples were prepared and saturated for overnight as shown in the Plate 3.1

Plate 3.1: Saturation of the undisturbed Soil Samples

The soils were then removed from the pool of water and left to drain for 3days. The samples were weighed, and the weight of the wet sample and the core ring was recorded as W1.the samples were then oven-dried for 24hours at 105°C and the dry weight of the soil and core ring recorded as W2. The gravimetric soil moisture content at the field capacity was calculated from Equation 3.8 given as:

$$FC(\%) = \frac{w1 - w2}{w2} * 100 \tag{3.8}$$

Where:

W1=weight of the wet soil in a core ring (g)

W2=weight of the dry soil in a core ring (g)

3.5.2 Permanent Wilting Point (pF-4.2)

Permanent wilting point is defined as the soil water content at a pF 4.2 or 15 bar matrix potential. Soil samples were saturated, and the samples were put in a pressure membrane apparatus to allow the soils to drain through the porous ceramic plate. High humidity was maintained by covering the soils with a dump cloth while allowing them to equilibrate. Air pressure was slowly applied to the chamber until 15 bars was attained. The samples were then allowed to equilibrate for 4 days.

Pressure was released slowly and carefully avoiding contact with drained water. The moisture content at the wilting point was calculated using the weight difference as expressed in Equation 3.9 given as

$$PWP(\%) = \frac{w1 - w2}{w2} * 100 \qquad (3.9)$$

Where:

PWP = Permanent wilting point (%)

W1= weight of wet soil in a core(g)

W2= weight of dry soil in a core (g)

3.5.3 Determination of the Initial Soil Water Content

Soil moisture content was determined in the laboratory using the gravimetric method (Black, 1965). 50g of soil samples were placed in weighed aluminum dishes and the weight of the soil plus that of the dishes recorded. The soil samples were then dried in an oven for 24hours at 105ºC. The samples were allowed to cool before weighing the dry soil in the dishes. Soil water content was then calculated using Equation 3.10 given as:

$$\%SMC = \frac{W_{tm} - W_{td}}{W_{td}} * 100 \qquad (3.10)$$

Where:

SMC = soil moisture content (%)
W_{tm} =weight of moist soil (g)
W_{td} =weight of dry soil (g)

3.6 Determination of Soil Water Repellency Using Water Drop Penetration Time (WDPT) Test

The disturbed soil samples were first prepared prior to measurement of the soil water repellency. They were passed through a 5mm sieve to remove undecomposed material such as leaves and grass. The sieved soil samples were then divided into 3 portions of about 20g and the actual water repellency was then measured on the disturbed soil samples. Water drop penetration time test (WDPT) was the standard method of measurement of this soil property. It was conducted on soils samples by placing 2ml drops of distilled water. The 2ml volume of water was first measured into a measuring cylinder (10ml) and then placed at about 10mm height randomly on the surface of the sample in an aluminum dish with a depth of approximately 1.0 cm as shown in Plate 3.2.

Plate 3.2: WDPT-Test Showing behavior of Water Droplet on Repellent Soil Sample

The time it took for the drop of water to completely disappear into the soil was then recorded. There were three replications for each sample. This data was analyzed as per classification of Soil Water Repellency based on severity (Contact angles: Erbil (2014).) and persistence (WDPT: Deurer et al., 2011) as shown in Table 3.5.

Table 3.5: Classification of Soil Water Repellency Based on Severity (Contact angles) and Persistence (WDPT)

Severity		**Persistence**	
Contact angles (^{o})	**SWR Classification**	**WDPT(s)**	**SWR Classification**
<75*	Not significantly water repellent	<5	wettable
75-80*	Very low water repellent	5-60	Slightly repellent
81-86*	Low water repellent	60-600	Strongly water repellent
87-93*	Moderately repellent	600-3600	Severely water repellent
94-97	Severely repellent	>3600	Extremely water repellent
>97	Very severely repellent		

*Subcritical soil water repellency (0^o>contact angle<90^o)

In this study, repellency classification by Deurer et al. (2011) was adopted where soil was considered water repellent when the infiltration time exceeded 5 seconds. However, the observed water droplet penetration times mainly showed values smaller than 10 Seconds.

3.7 Determination of Critical Soil Moisture Content by the Water Droplet Penetration Time (WDPT) Test

The threshold conditions for braking and re-establishment of soil water repellency were determined by observing the dynamic changes of soil moisture. Air and oven dried (60^oC) soils gives an estimate of the potential soil water repellency, and this is the highest level that it can reach when the soil dries out completeletly (Deurer et al., 2011). Estimation of the potential soil water repellency provides an insight into the potential consequences of soil hydrophobicity in case of a drought. On the other hand, it is only the insitu measurements at the field moist conditions that gives the actual soil water repellency (Müller et al., 2014). High drying temperatures have been observed to influence the formation of organic materials coatings responsible for water repellency (Jordan et al., 2017). Therefore, drying of soils at 105^{o}C can give an incorrect estimate of repellency. Air drying was suggested as the best approach to study the soil water repellency-moisture relationship in different studies (Doerr & Thomas, 2000). This was the approach adopted in this study.

3.7.1 Wet Phase

Actual soil water repellency was determined by conducting a Water Drop Penetration Time Test (WDPT) on the field moist soil samples before oven drying them at 60^{o}C for 48 hours after which the soil moisture content reduced to absolute zero (Weber et al., 2021). The oven dried soil samples were divided into three replicates before saturating them for 24 hours in the laboratory. The samples were then exposed to air-dry in a greenhouse to simulate the ideal field conditions.

3.7.2 Dry Phase

Soil samples were left uncovered under greenhouse conditions (24^{o}C-39^{o}C) to allow for gradual drying. Measurements of the persistence of SWR were conducted every day until there was no significant change in soil moisture content recorded. This happened after about 7 days of the experiment. Soil moisture loss was determined by weighing the samples each day before the soil water repellency measurements were taken. WDPT was carried out on each soil sample by placing 2ml of deionized water on a smoothed soil surface and recording the full drop penetration time in seconds (Papierowska et al., 2018). Three replicates were done for each soil sample until the soil moisture content reached a stable minimum i.e., the samples attained a constant weight. Air dried samples were then oven dried at 105^{o}C to estimate the soil's dry weight.

The measurements obtained for SWR were plotted against the corresponding soil moisture content (w). The total SWR of each sample (SWR_{AREA}) was calculated as the trapezoidal integrated area under the SWR-w curve. The critical soil moisture content (Wc) was determined as the water content where the soil turned hydrophilic (Figure 3.4). The SWRAD is determined at air-dried conditions. SWR60 was determined after oven-drying soil samples at 60°C.

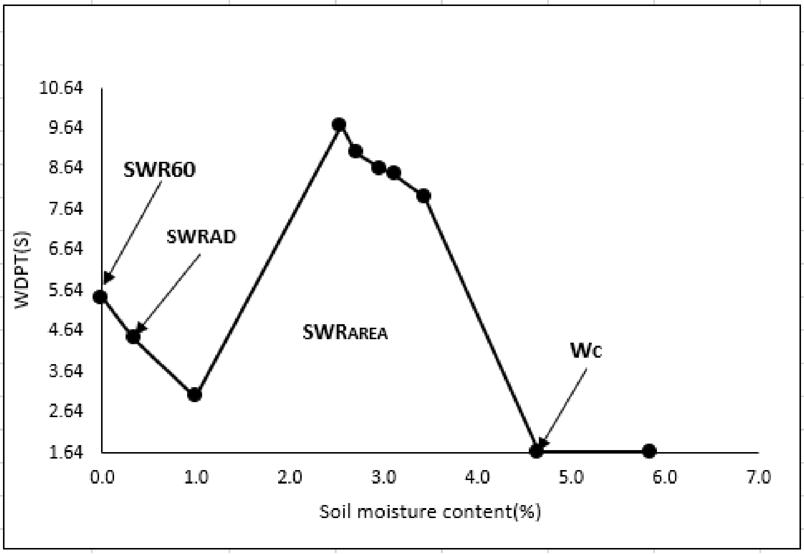


Figure 3.1: Soil Water Repellency (SWR) as a Function of Soil-Water Content and the Derived Parameters

Soil samples that were hydrophilic were excluded from further analysis.

3.8 Development of Relationships between Soil Water Repellency and Soil Properties

Since, soil organic carbon, textural composition and soil moisture content have been reported to control soil wettability (Doerr et al., 2006), regression and correlation analysis was performed using these variables as the possible predictors of soil water repellency. Simple linear and forward multiple linear regression (MLR) analysis was carried out on the soil properties that contribute significantly ($p<0.05$) to explain the variation in total soil water repellency in the investigated soils. Linear correlations were evaluated by the coefficient of determination (R^2). The least square method was used to develop estimates of the model parameters and the model that presented the lowest root mean square error was considered the best.

3.9 Statistical Analyses

Descriptive statistics such as mean, minimum, maximum and standard deviation were calculated for all the variables. Pearson's coefficients of correlation between the analyzed soils properties and soil water repellency were also calculated using SPSS ver.16.0.

The Integrative Repellency Dynamic Index (IRDI) was used to calculate the average soil water repellency function, which gives a measure of the mean water repellency in the soil moisture interval between zero (at oven dry condition) and critical soil moisture content (when soil turns hydrophilic) (Regalado and Ritter, 2005). The average was calculated as shown in Equation 3.11 given as:

$$\mathrm{IRDI} = \frac{\mathrm{SWR_{AREA}}}{\mathrm{Wc}} \qquad (3.11)$$

Where:

IRDI = Integrative Repellency Dynamic Index (seconds)

$\mathrm{SWR_{AREA}}$ = Trapezoidal integrated area under the SWR-w curve (seconds/% soil moisture content)

Wc = Critical soil moisture content at which the soil turned hydrophillic (seconds)

The Akaike Information Criterion (AIC) is a measure of the fitness of a model used to correlate data (Bozdogan, 1987). It was applied to evaluate the accuracy of the SWR and Wc correlations with soil properties. The best model is considered to be the one with a low AIC value. This value was calculated using Equation 3.12, given as:

$$\mathrm{AIC} = \mathrm{n}[\ln(2\pi) + \ln\left(\sum_{\mathrm{i}=1}^{\mathrm{n}} \frac{(\mathrm{di})^2}{\mathrm{n}-\mathrm{K}}\right) + 1] + \mathrm{K} \qquad (3.12)$$

Where:

K = number of input variables

n = number of samples

d_i = residual value between the measured and obtained value from the model.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 The Soil Physical and Hydrological Characteristics

The soil physical and hydrological properties as determined in the laboratory are presented in Appendix I and II. Six soil types were studied in each of the two study areas. The average soil porosity for the soils collected in Murang’a ranged between 39.7 and 52.4% while the corresponding saturated conductivity (log Ks) ranged between 1.48 and 0.21mm/hr. Saturated conductivity (log Ks) was negatively correlated (r= -0.987; p<0.01) with porosity at both depths (0-15 and 15-30cm) as shown in Figure 4.1.

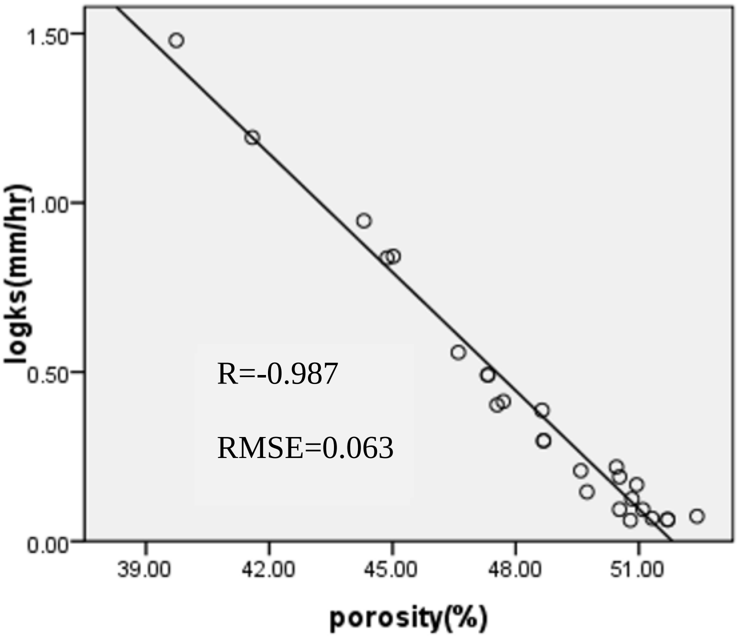


Figure 4.1: Relationship Between Saturated Hydraulic Conductivity and Porosity of the Sampled Soils in Murang'a County

Makueni soils had a porosity ranging between 30.2 and 47.9% while the average hydraulic conductivity (log Ks) for the sampled soil types varied between 2.18 and 0.32 mm/hr respectively. This translated to a negative correlation R= 0.982; p<0.01 at both depths as shown in Figure 4.2.

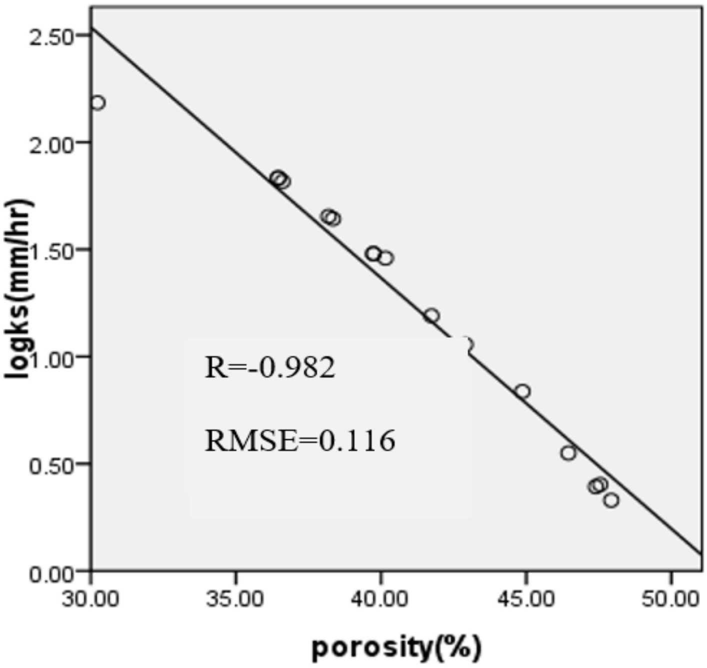


Figure 4.2: Relationship between Saturated Hydraulic Conductivity and Porosity of the Sampled Soils in Makueni County

This negative trend of decreasing hydraulic conductivity with an increase in porosity can be attributed to two main reasons: the effective grain size and packing arrangements , and disturbance of the contonuity of soil macropores. Firstly, an increase in porosity with increasing effective grain size is reversed when the percentage of fines exceeds some threshold. It is at this point that the hydraulic conductivity decreases systematically as the coarse-grained percentage decreases (Morin, 2006).

Shepherd (1989) summarized the relationship between permeability and grain size diameter in the following expression (Equation 4.1)

$$P = Cd^2 \tag{4.1}$$

Where:

P= Permeability (cm/s)

d = Grain size (cm)

C = Dimensionless constant of proportionality

For natural materials, grain size has proved to be of great influence on the porosity. The smaller the grain size, the higher the surface area to volume and mass ratio which translates to greater porosity. Also, it is important to note that the highest porosity is commonly achieved when grains are of the same size. According to Zhang et al. (2011), addition of fine particles tends to reduce porosity to a minimum by completely filling the pores in a coarse-grained material. This happens due to creation of a looser packing as the number of fine grains that bridge around the curvature of the surface of the large grains increases. The sand content of the sampled soils was relatively high and therefore, it becomes impossible for the fine grains to pack closely and tightly to each other meaning that the creation of the looser packing increases the porosity of the soil. However, the number of uniform small sized grains which can be packed in any one-unit volume of voids in a packing of uniform large size grains varies widely with the relative diameter of the two sizes. As the unit void is filled with smaller and smaller grains, the diameter of the smaller grains is decreased but in a faster rate than the porosity. Consequently, if the hydraulic conductivity of a granular material is purely based on the grain size and considering Equation 4.1, then the permeability of the material will decrease with increasing porosity under changes in grain packing patterns. This therefore confirms why the investigated soil samples exhibited high saturated hydraulic conductivity with a decrease in porosity. This relationship has also been confirmed by Ren et al. (2016) in an experimental set-up on undisturbed soil samples conducted in the field.

The other reason is that, at the start of the season, conventional tillage loosens the soil, resulting in the formation of macropores. By increasing the proportion of soil transmission pores, soil aeration and water permeability can be significantly increased. However, the enhanced porosity is only short-term because continual rainfall causes finer fractions to fill the pores (Osunbitan et al., 2005). Tillage also disrupts the continuity of the soil macropores, limiting the movement of water from the soil surface into the soil matrix (Li et al., 2020).

The soils' hydraulic conductivity was also related to total organic carbon. The hydraulic conductivity of the soils collected from Makueni ranged between 2.1 and 152.9 mm/hr with corresponding total organic carbon of 0.94 and 0.38% respectively. On the other hand, Murang'a soils had a hydraulic conductivity ranging between 1.15 and 30.2 mm/hr with corresponding Total organic carbon of 0.77 and 0.67% respectively. Although saturated hydraulic conductivity (Ks) is generally assumed to be positively correlated with organic carbon (Sepehrnia et al. (2017), in this study a negative relationship ($R= -0.467$, $p<0.01$) was found for the Makueni soils while the negative relationship was stronger ($r= -0.115$), $p<0.01$) for the Murang'a soils. The likely reason for the negative correlation could be reduced wettability presumably related to the development water repellency caused by soil organic matter which outweighs the effects of any increase in hydraulic conductivity caused by soil aggregation (Jarvis et al., 2013). Also, the low soil organic carbon and the large particle size of the sand may limit the effect of soil organic matter on soil aggregation process in the examined soils (Wang et al., 2009).

In Murang'a County, the soils were sampled from Umbric Andosols, Humic Nitisols UP, Humic Nitisols IB2, Rhodic Nitisols, Rhodic Ferralsols and Rhodic Cambisols soil types. The various soil types and the corresponding WDPT (seconds) are presented in Figure 4.3. Four soil types had samples that were repellent with the highest recorded WDPT been 10seconds for one sample of Humic Nitisols, IB2. Rhodic Nitisols, Rhodic Ferralsols and Ferralic Cambisols also had repellent samples with WDPT above 5 seconds which are classified as slightly repellent.

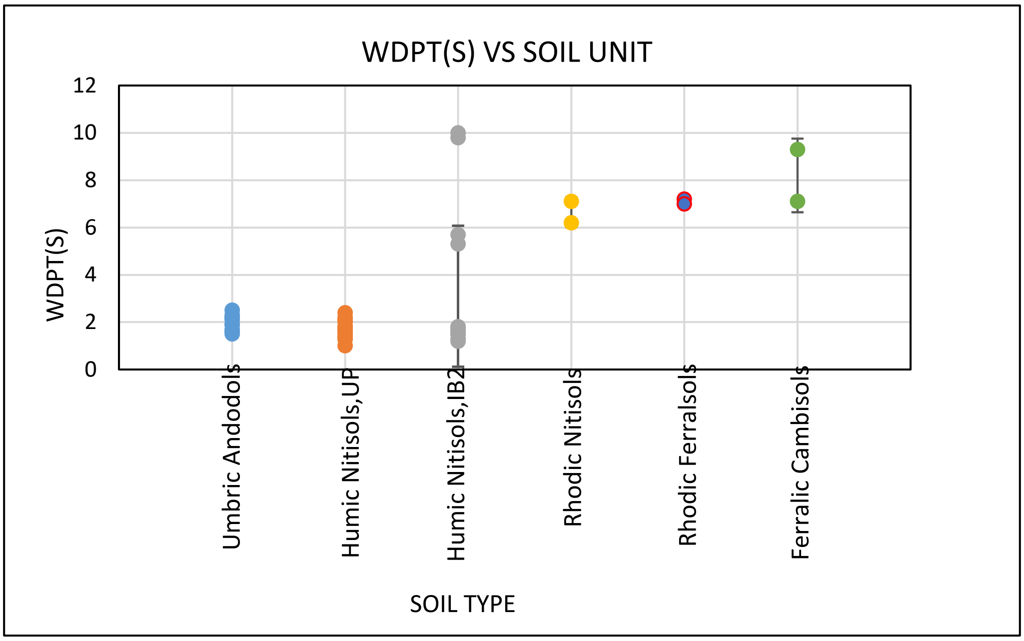


Figure 4.3: Wettable and Repellent Soil Types in Murang'a County

All the soil types had some repellent samples at field conditions except for Umbric Andosols and Humic Nitisol, Up soil types. This could be associated with the high soil moisture content that was detected in all the samples from these soil types which ranged between 42.3% and 71% (Table 4.1). Among the six soil types investigated in Murang’a County, the perrsistence of soil water repellency with regards to soil moisture content increased in the following order: Umbric Andosols> Humic Nitisols UP> Humic Nitisols IB2> Rhodic Nitisols> Rhodic ferralsols> Ferralic cambisols.

On the other hand, three out of the six soil types studied from Makueni County showed some slight soil water repellency. These were Rhodic Ferralsols, Haplic Acrisols and Dystric Cambisols soils (Figure 4.4). One sample of Rhodic Ferralsols had a WDPT of 10.8 seconds with a corresponding moisture content of 4.2%. Samples with WDPT above 5seconds are slightly repellent.

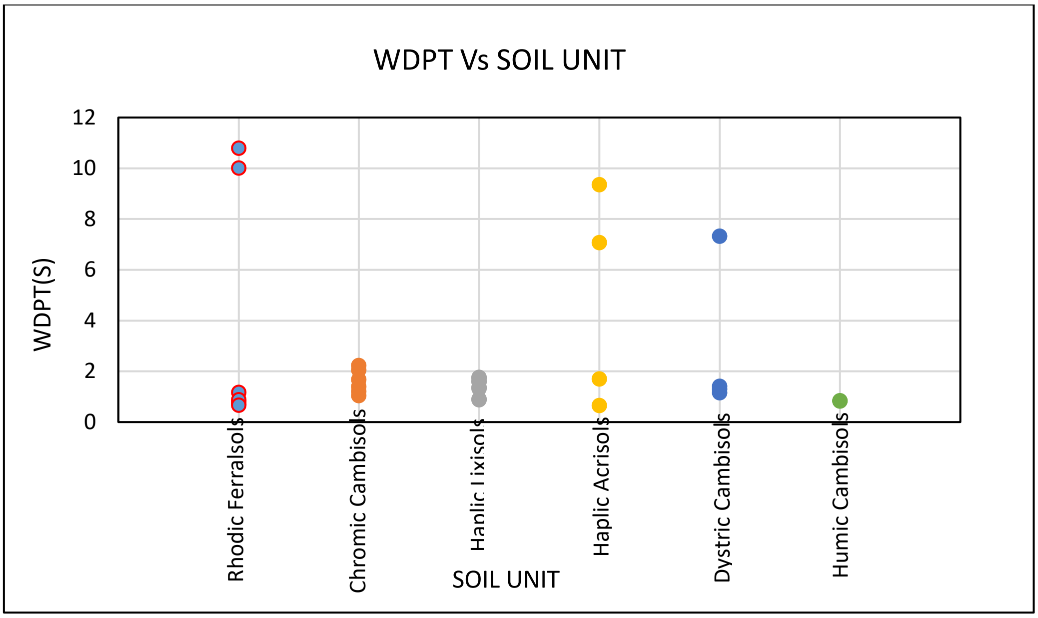


Figure 4.4: Wettable and Repellent Soil Types from Makueni County

The persistence of soil water repellency in the soils sampled from Makueni County increased in the following order: Humic Cambisols> Haplic Lixisols> Chromic Cambisols>Dystric Cambisols> Haplic Acrisols>Rhodic Ferralsols. This is because soil moisture content generally decreased in the same order for the different soil types.

The soil types from Murang’a exhibited a wide range of textures when fitted in the USDA Textural Triangle as shown in Figure 4.5. According to the parent material, the soils were generally sandy loam to clayey with a wide range of sand (40-86%) and clay (10-54%) contents. Most of the soil samples (50%) fitted in the sandy clay loam textural class. The highest soil water repellency (10 seconds) was recorded for the Humic Nitisols IB2 which had the highest sand content (86%) and 6% soil organic carbon. There was no repellency depicted in the soils with a sand content below 52%.

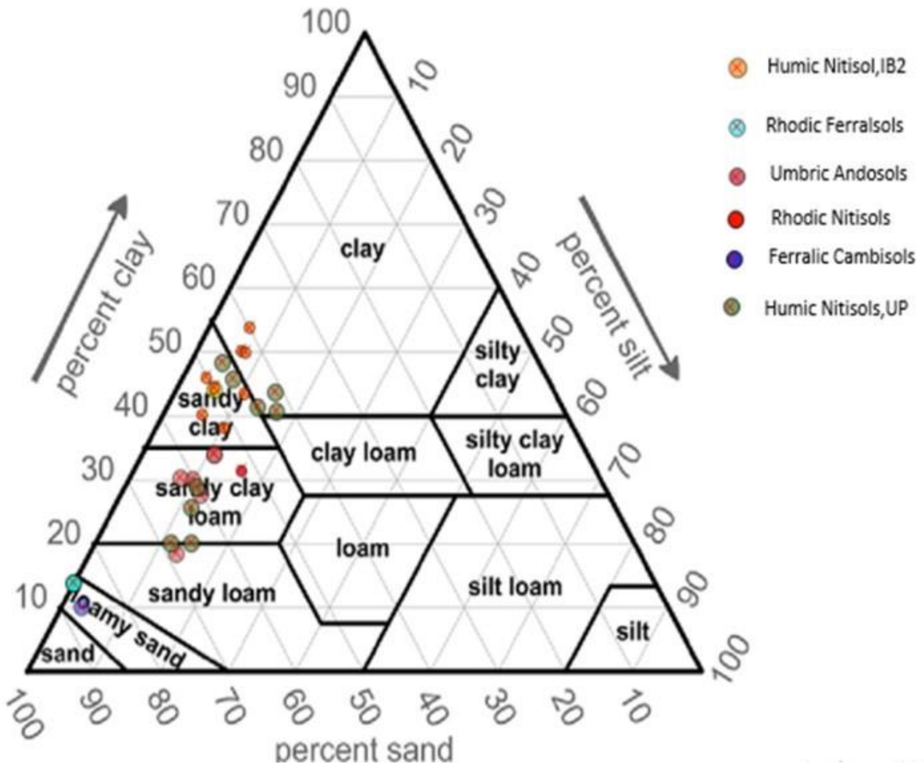


Figure 4.5: Distribution of the 26 soil samples in Murang'a County across the USDA Textural Triangle

Similarly, the 16 soil samples from Makueni County were analyzed for texture and fitted in the USDA Textural Triangle as presented in Figure 4.6. The fine earth fraction here was classified as sandy loam (2 samples), sandy clay loam (5 samples), loamy sand (4 samples) and sandy (5samples). The highest WDPT of 10.8 seconds was recorded for a Rhodic Ferralsol soil type whose sand and clay content were 66% and 26% respectively in Makueni County.

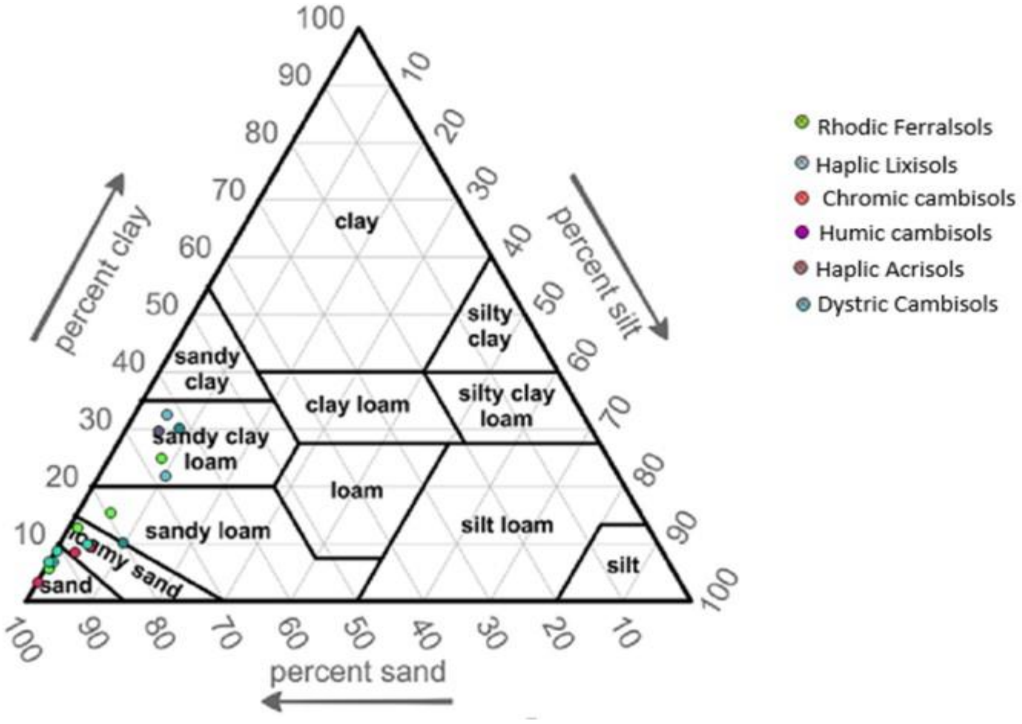


Figure 4.6: Distribution of 16 soil samples of Makueni County Fitted in USDA Textural Triangle

All the repellent soil samples (5 samples) fell in sandy clay loam textural class while 60% of the repellent soils in Murang’a fell in this textural class. The soils in Makueni had high mean sand contents of 80% while the mean sand content in Murang’a soils was 55.7%. For this reason, soils of Makueni were more prone to water repellency due to the lower surface area of sand particles which is easily coated by hydrophobic matter (Mao et al., 2019).

The wettable soil in Murang’a had a considerably high sand content (64%) and soil organic carbon of 3.19% while those that were wettable in Makueni had a sand content of 80% and Organic carbon of 0.5%. Sand content was found to be positively correlated to soil water repellency ($r = 0.422$, $p<0.01$). This can be attributed to the low specific surface area of the sand particles. Low surface area provides ease of coating by hydrophobic substances which is related to a specific portion of the total organic carbon present in the soil (Doerr et al., 2000; Woche et al., 2005). However, this obvious relationship between sand and soil water repellency was not found in the soil samples from Makueni County. These specific soils had a unique sand/soil water repellency relationship in that the two properties were negatively (r= -0.562, p<0.01) correlated. These results agree with the findings by Zheng et al. (2016) who observed that high particle sizes expressed low soil water repellency as compared to finer soil fractions. This phenomenon can be explained by the fact that while the non-polar components of finer soil fractions are of the same size to those of the big aggregate fraction of the soil, the polar components of the big aggregate fraction are significantly smaller than the polar components of the finer fractions. This leads to reduced wettability in the finer soil particles (Goebel et al., 2004).

In Murang'a soils, clay content ranged between 10 and 54%. Generally, soil water repellency increased significantly with decrease in the soil clay content (r = 0.352, p < 0.05) in these soils. Similar results were obtained in studies done by Mirbabaei et al. (2013) who reported low coefficients, r = 0.35 between soil water repellency and clay contents. Since it has been demonstrated that increase in sand content increases soil water repellency, for soils with high clay content to be repellent, high organic matter content is required. Despite the negative correlation, two samples of Humic Nitisol IB2 (clay contents of 38% and 40%) and one sample of Rhodic Ferralsols (clay contents of 26%) in Murang'a were repellent. The three samples had an average corresponding organic carbon of 5.8% and 5.8% for the Humic Nitisol IB2 and Rhodic Ferralsol soil types respectively. On the other hand, Makueni soils had an average clay content ranging between 2 and 32%.

The repellent samples however had a high clay content of 30% and 32% for Haplic Acrisols and Dystric Cambisols respectively and a corresponding organic carbon of 3.8% and 2.8% respectively. The clay content was positively correlated with soil water repellency (r= 0.564, p<0.01) in these soils. This inconsistency could be attributed to the high soil organic carbon due to the coating of soil clay particles by hydrophobic substances which renders the soil non-wettable. This was supported by Czachor et al. (2013) who reported that even a small increase in organic matter content can change soil hydrological properties from a completely wettable to a partially water-repellent state.

4.2 Bulk Density and Soil Water Repellency

From Appendix I and II, soil bulk densities for the soils sampled from Murang'a were relatively low ranging from 1.261 to 1.476 g/cm^3 for the wettable samples and 1.332 to 1.592 g/cm^3 for the repellent soils at both depths (0-15 cm and 15-30 cm). Notably, the repellent soil samples had a slightly higher average bulk density (1.435 g/cm^3) than the wettable soils, which had an average bulk density of 1.349 g/cm^3. In contrary, the wettable soils from Makueni had higher bulk densities of 1.596 g/cm^3 than the repellent soils which showed an average bulk density of 1.49 g/cm^3. Generally, a negative relationship ($r = -0.488$, $p < 0.01$) between soil water repellency and bulk density was observed in the studied soils which suggests that a decrease in bulk density leads to an increase in soil water repellency. This behaviour can be attributed to the accumulation of hydrophobic organic substances on the topsoil which reduces the bulk density of the denser mineral soil and in turn increases the soil water repellency (Deurer et al., 2011). Low bulk densities were also reported by Clothier et al. (2000) for water repellent soils with high soil organic carbon although low bulk density was also recorded for the wettable soils with less soil organic carbon. Similar results were also reported by Nesper et al. (2015) for cultivated soils. A similar trend was observed by Deurer et al. (2011) who reported a close negative relationship between degree of soil water repellency and bulk density with a coefficient of determination of 0.7.

4.3 Soil Moisture and Soil water Repellency

The studied soils samples from Murang'a County had a range of soil moisture contents with a minimum of 4.5% and a maximum of 71%. The soils from Makueni County were very dry with moisture contents ranging from 0.7% to a maximum of 5.1%. All the wettable samples had a high soil moisture content than the repellent samples at both depths with the higher soil moisture content at the subsurface depth (15-30cm). Water Drop Penetration Time increased significantly ($r = -0.712$, $p<0.01$) with decreasing soil moisture as presented in Figure 4.7. According to Regalado and Ritter (2005), the peak of soil water repellency occurs near the wilting point, and the state of wettability occurs when the moisture content approaches field capacity. A decreasing soil water repellency with increase in soil water content was also observed by Vogelman et al. (2010), Chau et al. (2014) and Bayad et al. (2020).

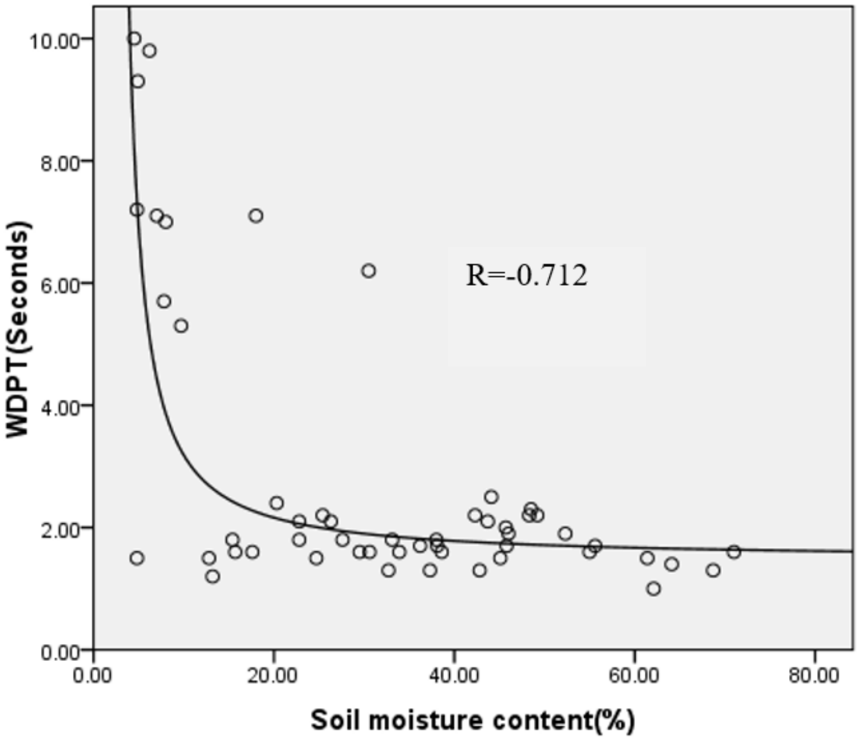


Figure 4.7: Relationship between Soil Water Repellency and Soil Moisture Content in Murang'a Soils

The highest WDPT was associated with the driest soils. This is because Water repellency generally occurs in dry soils and disappears when the soil water content exceeds a certain critical limit. This limit is a transition zone rather than a sharp threshold (Dekker et al., 2001). The critical gravimetric moisture content of the soils with sandy clay loam texture in Murang'a was found to be between 7.0 and 17.6% which translated to an average critical water level of 11.87%. On the other hand, soils with loamy sand texture had an average critical gravimetric moisture content of 8.7%. The variability of the critical water content may have been caused by the wetting history of the soil which has an influence on the persistence of SWR. The heterogeneity in the distribution of water in and around the micro aggregates could be another cause of variation (Dekker et al., 2001).

The soils from Makueni County on the other hand, were very dry with moisture contents ranging from 0.7% to a maximum of 5.1%. Soil water repellency increased significantly ($r = -0.238$, $p < 0.01$) with decrease in moisture content as shown in Figure 4.8.

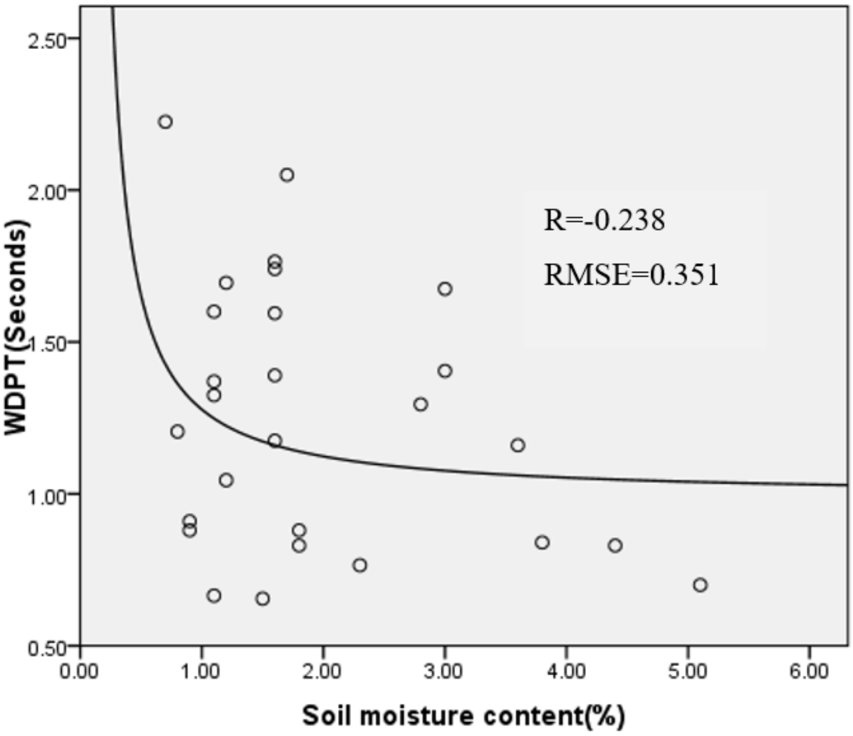


Figure 4.8: Relationship between Soil Water Repellency and Soil Moisture Content in Makueni Soils

Makueni soils showed repellency far from their field capacity and wilting point which was found to be 18.22% and 11.96% respectively. This means that the water repellency condition can be avoided by ensuring that soil moisture content is kept above the wilting point. During irrigation, in most cases, irrigation scheduling is done at 40 to 60% management allowable depletion, meaning that the soils still have about 40 to 60% safe margin from the wilting point.

The average critical gravimetric soil moisture content at which the repellent soils turned wettable was found to be 5.16 % which was lower than the average critical moisture content of 9.93% in Murang’a soils. This could be attributed to the higher average total organic carbon of 4.8% in Murang’a soils as compared to the 3.6% in

Makueni soils which means that a likely larger portion of hydrophobic matter could be contained in Murang’a soils. The transition zone of more than 200 field samples on dune sand in the Netherlands was found to fall between 18% and 23% gravimetric moisture content water repellency (Dekker et al. 2001). Täumer et al. (2005) also set the transition zone between gravimetric water content values of 3% and 18.0% for medium- sized sand under grassland in eastern Germany. Generally, critical moisture content of various soil types is thought to depend on the soil texture because of the huge differences in available surface area (Doerr & Thomas, 2000).

4.4 Relationship between Soil Water Repellency, Soil Properties and Depth

Surface soil (0-15cm) generally exhibited higher soil water repellency as compared to the subsurface layer (15-30cm). A significant decrease in WDPT with depth was also observed by Weerasinghe and Thivyatharsan (2020) which was attributed to the decrease in soil organic carbon with depth. The repellent soil types included Humic Nitisols 1B2, Rhodic Nitisols, Rhodic Ferralsols, Ferralic Cambisols, Dystric Cambisols and Haplic Acrisols. All the repellent samples showed repellency at both depths except for one Dystric Cambisol sample that was repellent at only one depth (0-15cm). Kořenková et al. (2015) and Šimkovic et al. (2009) also observed presence of water repellency in Cambisols among others like Luvisols, Fluvisols and Leptosols that were studied.

The Total Organic Carbon (TOC) for all samples collected from Murang’a ranged between 0.67% and 6.08% as presented on Appendix I with Rhodic Nitisols expressing the highest mean total organic content of 5.82%. The highest WDPT of 10 and 10.8 seconds was recorded in Murang’a and Makueni soils with a correponding TOC of 6% and 3.61% respectively. Water repellency was also observed in soils with lower soil organic carbon and high sand contents. In the case of the Rhodic ferralsols sampled from Murang’a, the soil organic carbon was as low as 1.16% at 0-15 cm depth and 1.1% at 15-30 cm depth while the corresponding WDPT was 7.2 and 7 seconds respectively at the two depths. Similar observation was made for the repellent Dystric Cambisols sampled from Makueni which had a Water Drop Penetration Time Test of 7.3 seconds with 2.8% total organic carbon.

The persistence of water repellency increased with increase in the soil organic carbon although the strength of the relationship was low for soils in Murang'a County as compared to that found in the soils from Makueni County. The WDPT exhibited a linear increase with increase in the total organic carbon of the soil (Figures 4.9 and 4.10). A positive correlation (r = 0.650 p<0.01) between soil organic carbon and soil water repellency for the Murang'a soils was observed while soils from Makueni presented a stronger positive correlation (r = 0.932, p<0.01) between soil organic carbon and soil water repellency (Figures 4.9 and 4.10).

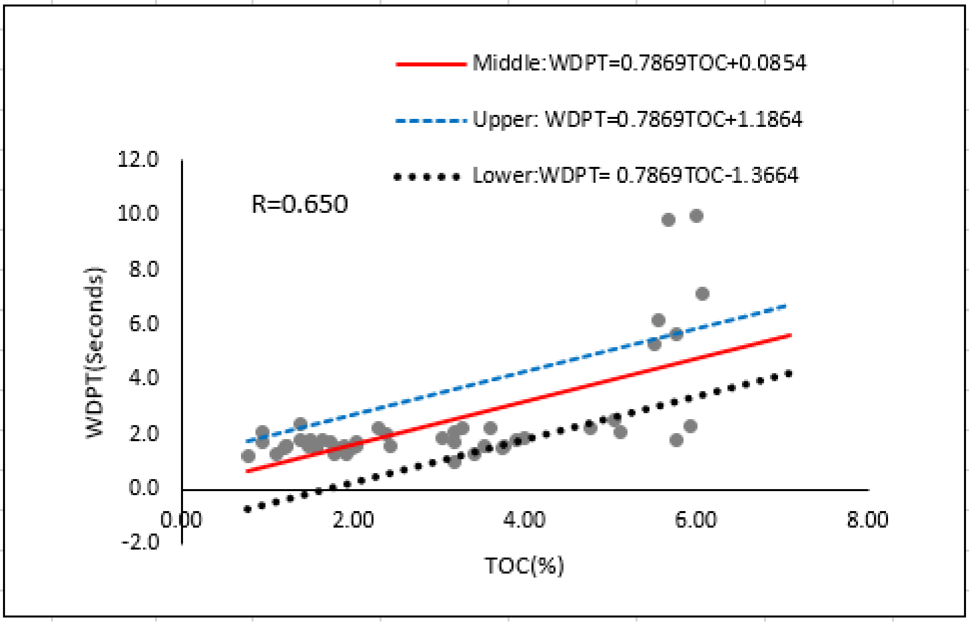


Figure 4.9: Relationship between WDPT and TOC with Calculated Correlation Coefficient for Soils Samples from Murang'a County

The behaviour of soil water repellency with increase in soil's total organic carbon can be explained from the soil aggregate stability perspective. A highly positive correlation between soil organic carbon and soil aggregate stability has been reported severally by many authors. One of the authors that observed such a relationship is Aksakal et al. (2020) who investigated aggregate stability of 26 soils from agricultural areas and found a highly significant linear correlation (r = 0.934, p< 0.001) between aggregate stability and organic matter content. Similarly, Chaplot and Cooper (2015) and Sarker et al. (2018) found a steady increase in aggregate stability of r = 0.989, p < 0.001 and r = 0.969, p < 0.01 respectively with soil organic matter. The authors attributed the soil aggregate stability to the presence of humic substances which are usually hydrophobic (water-repellent). The reason for the beneficial effect of humic substances to aggregate stability is due to formation of clay-humic complexes which orient carboxyl and phenol groups of humic materials towards the interior of the aggregates. This leaves an aliphatic and aromatic hydrophobic component of the humic substances to face outward. This leads to formation of a water-repellent coating with high surface tension, effectively reducing water infiltration into the aggregates (Krull et al., 2004). This therefore suggests that soil water repellency increases with increase in soil aggregate stability (Zheng et al., 2016).

A similar trend was also reported by Leelamanie (2014) who observed that in the studied soils, soil organic matter was positively correlated ($r = 0.969$-0.995) with soil water repellency. Similarly, Atanassova et al. (2018) reported a positive correlation of ($r = 0.699$, $p<0.05$) with soil water repellency. However, water repellency was also recorded in soils with low organic carbon as it was reported by Deurer et al. (2011). This is because even little amounts of hydrophobic compounds can cause water repellency and this is not usually proportional to the actual amount of organic matter present in soil (Atanassova et al., 2018). According to Vogelmann et al. (2010), the highest persistence of water repellency may also be present in soils with low organic carbon content, implying that the hydrophobic character is related to the quality rather than the quantity of these organic compounds.

According to Dorji et al. (2020), the mean weight diameter (MWD) of aggregate exhibited a curvilinear increase with increase in carbon content, indicating an upper limit of influence of soil organic carbon. Using Emerson crumb test, Krull at al. (2004) found that below 2% soil organic carbon (<2%) soil aggregates were unstable, and most soils are prone to structural destabilisation either by cultivation, compaction or irrigation. Soils were considered moderately stable at 2-2.5% and very stable at soil organic carbon >2.5%. Maximum stability was observed at 4.5% soil organic carbon. The behaviour between WDPT and total organic carbon in Murang'a soils (Figure 4.9) seemingly followed the threshold already reported. The soils were wettable between 2-4% total organic carbon where the soil aggregates are considered stable. Above 4% total organic carbon, the WDPT drastically increased with increase in organic carbon.

This could be attributed to the formation of a water-repellent lattice around the aggregates enhancing the water stability of the aggregates (Krull at al., 2004).

For sandy soils such as those obtained from Makueni County (Figure 4.10), the critical threshold of soil organic carbon depends on the percentage clay content present in the soils and was observed to be below 3.5%.

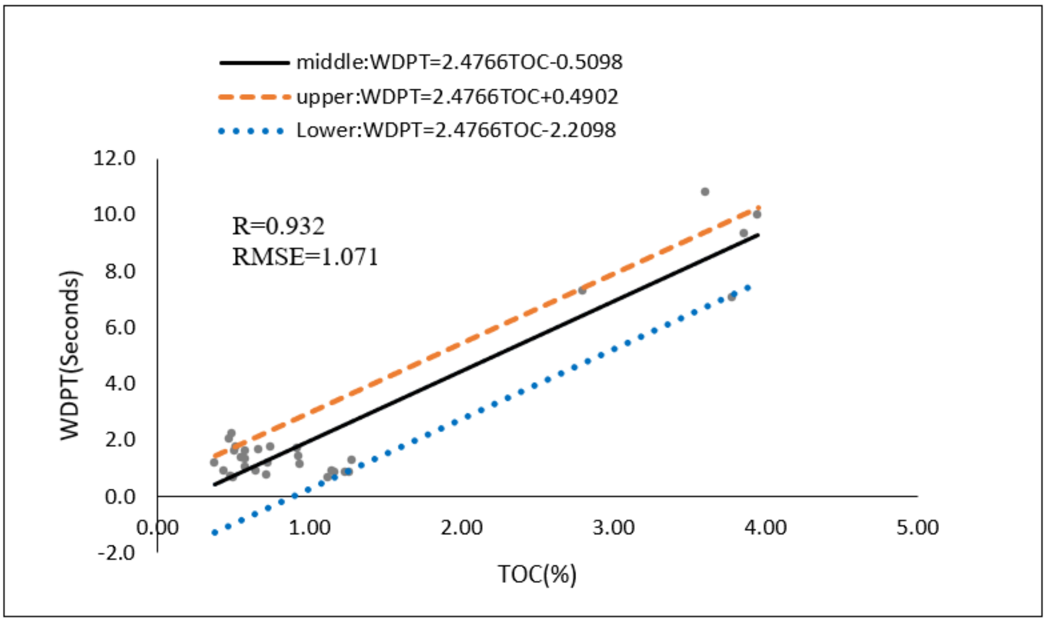


Figure 4.10: Relationship between WDPT and TOC with Calculated Correlation Coefficient for Soil Samples from Makueni County

The wettable soils had an average clay content of 12% and a mean total organic carbon of 0.75%. On the other hand, the mean clay content of the repellent soils was 28.8% with an average total organic carbon of 3.6%. This was supported by Loveland and Webb (2003) who found that optimum crop production for soils with 4% clay was maintained at upper and lower limits of 1 to 1.5% soil organic carbon while for soils with 38% clay contents the respective limits were 3.5 and 4.4% respectively. This can be seen from Figure 4.10 where, the wettable soils (WDPT<5seconds) appear below the 2% TOC while the repellent soils (WDPT>5 seconds) appeared above 3.5% TOC threshold. At low soil organic carbon (1%) the sensitivity of water repellency to changes in organic carbon increases with increase in clay content up to 50%. This is because the higher the content of clay especially for montmorillonite and kaolinite/

halloysite type of clay, the greater is the content of water held in the soil. However, soil water repellency of coarse textured soils is more sensitive to changes in organic carbon than in fine textured soils (Moral et al., 2005).

Coarsely textured sandy soils such as the ones sampled from Makueni County are very susceptible to becoming water repellent. In a study by Atanassova et al. (2018), it was found that water repellency only occurred in soils with <10 % clay and was most severe for soils with <5 % clay. Although not as common, water repellency can occur in certain soils with a finer texture if the soil has a strongly aggregated structure (Mao e al., 2019). This is a typical case for the Murang'a soils that had an average clay content of 34.92%. The repellency occurs when the aggregates become coated with a hydrophobic material (Krull at al., 2004). The difference in the critical TOC levels in the two study areas can be attributed to the differences in the amounts of clay content of 14.6% and 34.92% for Makueni and Murang'a sampling sites respectively. With low clay content as was the case with soils from Makueni County, hygroscopic water may condense and produce isolated tiny clods through the process of surface tension. This draws clay particles together leaving air spaces around them which might restrict the surface water entry of sandy soils (Leelamanie and Karube, 2007). At higher clay content clay clods might not be isolated and may provide a path for surface water entry, reducing the persistence of water repellency as was the case with Murang'a soils and therefore giving a weaker relationship as compared to Makueni soils.

4.5 The Threshold Conditions Needed for Hydrophobicity to be Broken and Re-established

4.5.1 Soil Water Repellency Persistence

The actual soil water repellency of the field moist samples varied between 1.0 second and 355 seconds which means that SWR ranged from wettable to strongly repellent. This is according to Deurer et al. (2011) who used a similar classification for the water repellency. Among the 52 soil samples from Murang'a, 19 out of 52 samples i.e., 37% were hydrophobic. The hydrophobic soils from Murang'a showed an actual water repellency (SWR_{ACT}) of between 5 and 355seconds and had a total organic carbon content with a range of between 1.38 and 6.08%. These soils were classified into sand clay loam (13 samples), clay (2 samples) and sandy loam (4 samples). The potential water repellency of the samples was also measured at 60^{o}C and 105^{o}C as presented in Table 4.1 and Figure 4.11.

Table 4.1: Soil Characteristics and SWR after Oven Drying at 105^{o}C

	n	Sand (%)		Clay (%)		Silt (%)		SWR105 (seconds)		IRDI (Seconds)	
Soil Unit		**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
Murang'a County											
Umbric Andosol	3	59	2.3	31	2.3	10	2.5	1.94	0.57	2.1	0.20
Humic Nitisol, Up	6	59	12	27	10.3	14	8.9	1.76	0.77	1.4	0.48
Humic Nitisol, IB2	4	53	1.2	39	1.2	8	1.1	1.75	0.77	1.9	0.37
Rhodic Nitisol	2	52	0	32	0	16	2.4	1.42	0.03	2.1	0.07
Rhodic Ferralsols	2	86	0	14	0	0	0.9	0.84	0.07	1.1	0.02
Ferrallic Cambisols	2	86	0	10	0	4	0.2	1.91	1.05	1.5	0.23
Makueni County											
Rhodic Ferralsols	2	66	0	26	0	8	0	1.75	0.18	10	0.56
Haplic Acrisols	2	62	0	30	0	8	0	1.43	0.7	8.2	1.61
Dystric Cambisols	1	62	0	32	0	6	0	0.71	0.71	7.3	7.32

NB: Soil Characteristics (sand, silt and clay) and SWR after Oven Drying at 105^{o}C (SWR105) for Murang'a and Makueni Soils

Determination of the potential SWR entailed estimating the highest level of repellency that can be reached when the soil dries out completely. Potential soil water repellency is considered the most appropriate parameter for comparing soils in terms of their sensivity to water repellency and was assessed at 60^{o}C and 105^{o}C to eliminate the differences in soil moisture content which influences the persisitence of soil water repellency. The actual soil water repellency (SWR_{ACT}) was observed to be higher than the potential soil water repellency after heating (SWR_{60}) across all the soil samples from Murang'a County. Humic Nitisols, UP showed the highest mean actual soil water repellency of 20 seconds with Rhodic Nitisols showing the least mean actual repellency of 6.7 seconds in Murang'a as presented in Figure 4.11. Although high temperatures have been observed to influence hydrophobicity due to re-orientation of the hydrophobic molecules (Jordan et al., 2017; Bachmann et al., 2021), these particular soils studied, had lower soil water repellency at oven dry state (60°C) as presented in Figure 4.11. This however is an underestimate of the maximum persistence of soil water repellency that can occur in these soils when they are completely dry as reported by Dekker et al. (2001). Data in Figure 4.11 is presented as mean and standard deviation of three replicates.

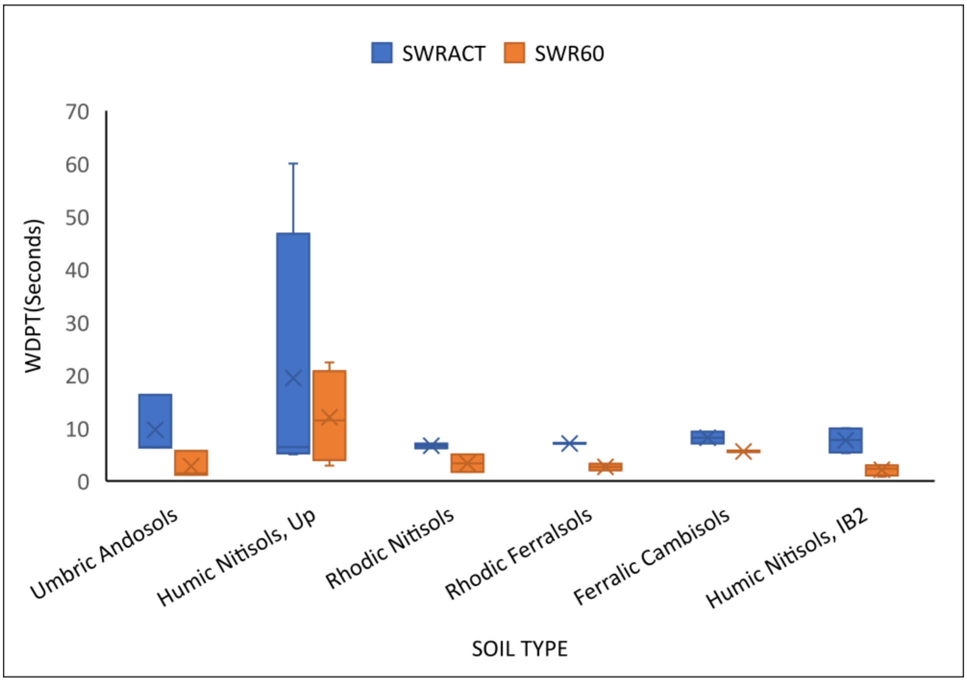


Figure 4.11: Soil Water Repellency for the Repellent Soil Types in Murang'a County

Umbric Andosols and Humic Nitisols,UP exhibited a relatively high maximum SWR_{60} of 5.69 and 22.41 seconds respectively despite the the high contents of clay of 34% and 40% respectively. This could be attributed to the coating of the soil clay particles by the hydrophobic substances in the soils. These findings are supported by Czachor et al. (2013) who reported that even a small increase in organic matter content can change soil hydrological properties from a completely wettable to a partially water-repellent state. This is further supported by results from a study by Weber et al.(2021) and Hermansen et al. (2019) who observed lower soil water repellency in soils at their oven dry conditions. This is because the soil organic carbon tends to loose its stabilising effect during drying (Urbanek et al., 2014). The relationship between the potential and the actual soil water repellency is however not evident and therefore actual soil water repellency cannot be derived from the potential soil water repellency as it has also been stated by Graber et al. (2006).

Despite the fact that Humic Nitisols, Up and Humic Nitisols IB2 are classified similarly, Humic Nitisols, Up had a greater average SWR_{ACT} (19.4 seconds) than Humic Nitisols, 1B2, which had an average SWT_{ACT} of 7.7 seconds. This observation can be related to the higher clay content of Humic Nitisol, IB2, which was 39% compared to 26% for Humic Nitisols, Up. Small increases in clay content can reduce the persistence of water repellency. Thus, a 1-2% increase in clay in highly sandy soils can be utilized to prevent occurrence of water repellency according to McKissock et al. (2002). Claying water-repellent topsoil increases soil surface area, dilutes the hydrophobic organic matter responsible for repellency, and improves soil wettability (Daniel et al., 2019).

On the other hand, Rhodic Ferralsols of Makueni County exhibited a mean SWR_{ACT} of 10.4 seconds which was the highest as compared to the Haplic Acrisols and Dystric Cambisols (Figure 4.12). Data are presented as mean and standard deviation of three replicates.

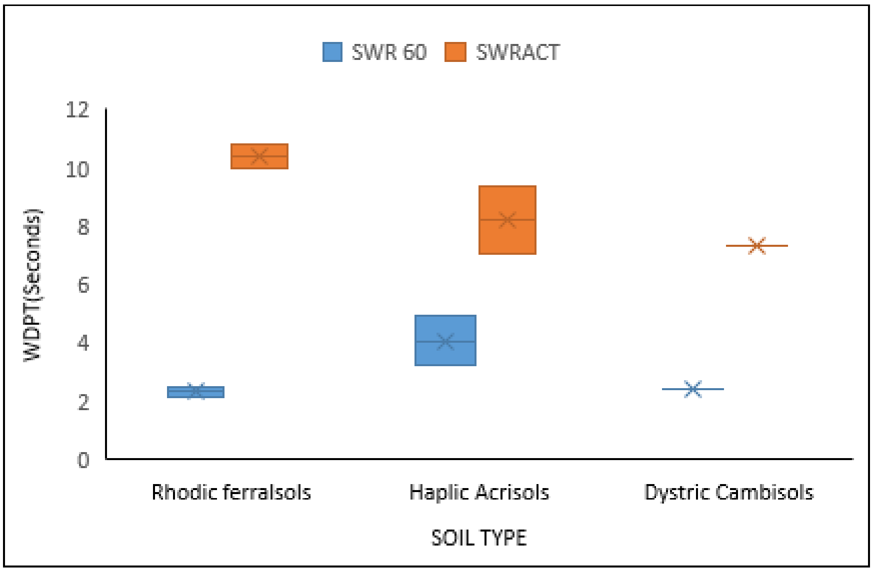


Figure 4.12: Soil Water Repellency for the Repellent Soil Types in Makueni County

In these soils, the potential soil water repellency was also observed to be lower than the actual soil water repellency for the three investigated repellent soil types. This observed behavior is attributed to the loss of the stabilising effect of soil organic carbon during drying (Urbanek et al., 2014).

4.6 Soil Water Repellency-Soil Moisture Content Curves (SWR-w Curves)

The soils presented in Figure 4.14 and Figure 4.15 expressed a range of behaviors with respect to repellency and soil moisture content dynamics. In each graph, three curves shown represent the three replicates examined for each soil sample at depths of 0-15 cm and 15-30cm. As shown in Figure 4.14 and Figure 4.15, the soils investigated exhibited a wide range of SWT-w curves as those published in literature. The curves were either unimodal or bimodal as it was observed by Kawamoto et al. (2007). SWR persistence increases from dry conditions until it reaches a maximum level either before wilting point, around wilting point, between wilting point and field capacity, or close to field capacity for unimodal curves (de Jonge et al., 2007; Karunarathna et al., 2010; Regalado and Ritter, 2009; Regalado et al., 2008).

The single peak SWR-w curves were represented in Fig.4.14A, Fig. 4.14B, Fig. 4.14 G, Fig. 4.14O, Fig. 4.14P, Fig. 4.14Q, Fig. 4.14R, Fig. 4.14S and Fig. 4.15B. On the other hand, the double peak SWR-w curves were represented in Fig. 4.14C, Fig. 4.14D, Fig. 4.14E, Fig. 4.14F, Fig. 4.14H, Fig. 4.14I, Fig. 4.14J, Fig. 4.14K, Fig. 4.14L, Fig. 4.14M, Fig. 4.14N and Fig. 4.15A, Fig. 4.15C, Fig. 4.15D and Fig. 4.15E. SWR-w curves were either rising from a repellent (e.g., Figure 4.14 D) or a wettable state (e.g., Figure 4.14 B) at oven dry conditions (60^{o}C). Further for the bimodal curves, the persistence of soil water repellency decreased to a local minimum with an increasing moisture content but still retaining some degree of hydrophobicity as shown in Figure 4.14I. In addition, there are also some bimodal SWR-w curves whose repellency decreased with an increase in soil moisture content to become temporarily wettable (WDPT < 5 seconds) before rising to a maximum repellency from oven dry conditions (e.g., Figure 4.14 C-D). Some soils exhibited water repellency near their field capacity as presented in Figure 4.14 I. The soil sample represented in Figure 4.14I showed repellency of 5.1 seconds at 11% soil moisture content which is very close to its field capacity (11.8%). Most of the soil samples however, reached maximum water repellency at soil moisture content levels below their wilting point.

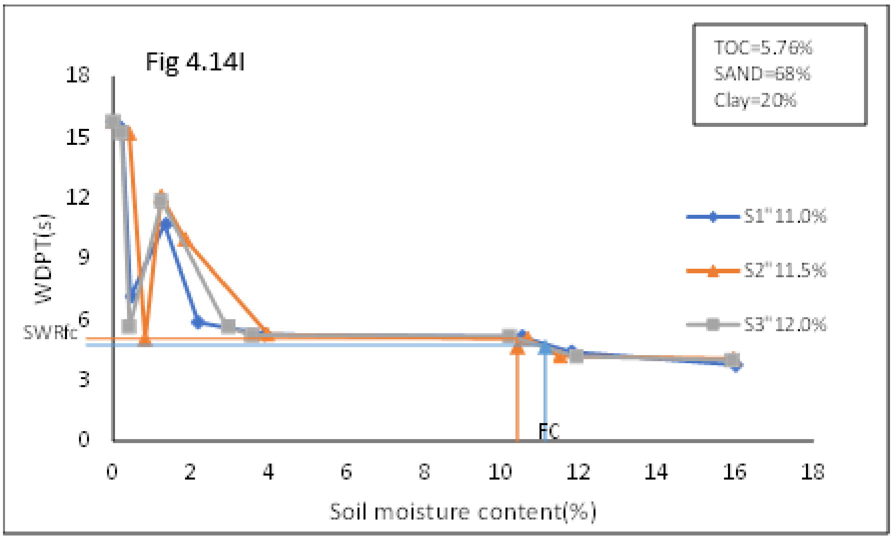


Figure 4.13: Soil water repellency (SWR) near field capacity

NB: FC denotes the Field capacity (SMC=11.8%) and SWRfc represents the interpolated SWR near the field capacity (SWRfc=5.1 seconds at 11% moisture content).

Generally, it was observed that SWR first decreased from the oven dry state of the soils to a local minimum with increasing soil moisture contents. Immediately after attaining the local minimum, SWR increased again with increasing soil moisture content to a second peak. This particular behavior was observed by Smettem et al. (2021). Some possible processes and mechanisms have been proposed to explain this unusual behavior. This behavior was attributed to enhanced microbial activity with increasing relative humidity (Jiménez-Pinilla et al., 2016). Solvent-induced changes in molecular conformation of soil organic matter is also accountable for increased soil water repellency at increasing soil moisture content levels (Daniel et al., 2019). The same behavior was also attributed to re-orientation of hydrophobic functional groups that had been previously disrupted during oven-drying process (Jordan et al., 2017). For the double peak curves, the first peak of soil water repellency occurred at low water contents which are close to zero, however, with increase in soil moisture content, the repellency first decreased and then increased again to an intermediate soil water content up to a second peak after which it decreases again until the soil becomes wettable above the critical moisture content (Figure 4.14). For the double peaked curves, the behavior of the first peak is attributed to the re-orientation of the hydrophobic molecules due to water loss associated with the temperature treatment during oven-drying (Jordan et al., 2017; Bachmann et al., 2021).

Fig 4.14A

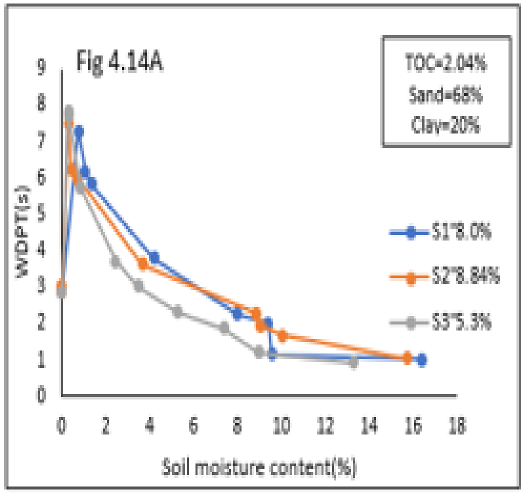


Fig 4.14B

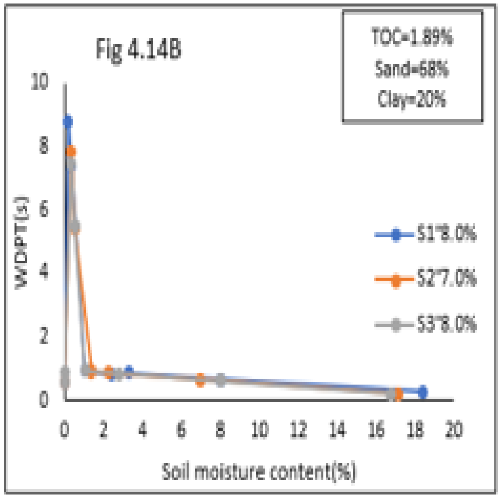


Fig 4.14C

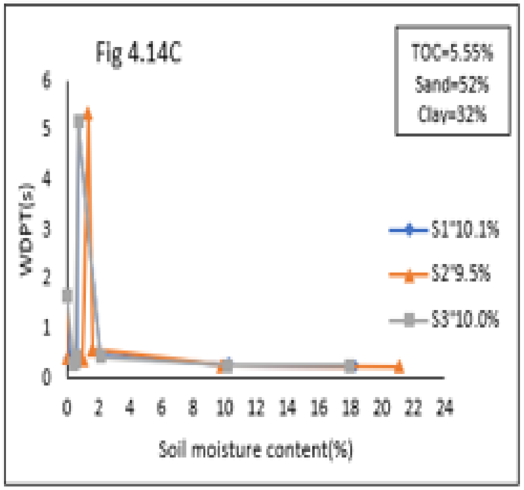


Fig 4.14D

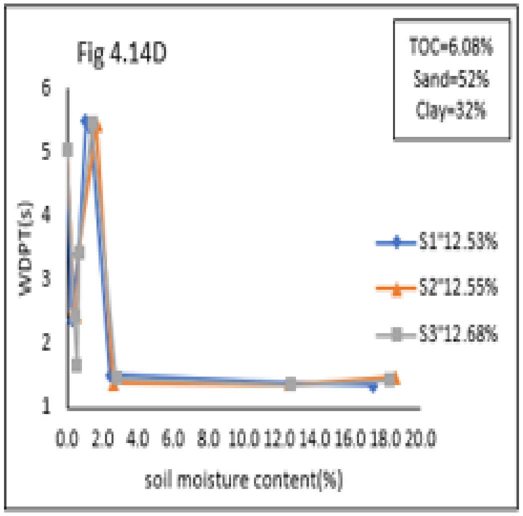


Fig 4.14E

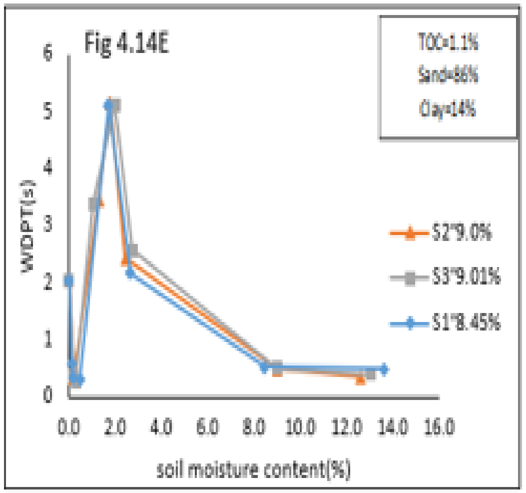
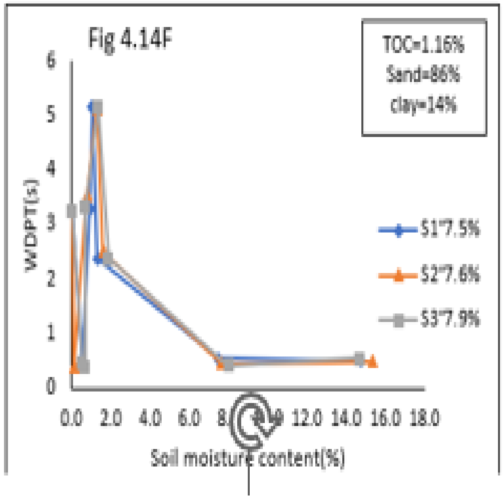


Fig 4.14F



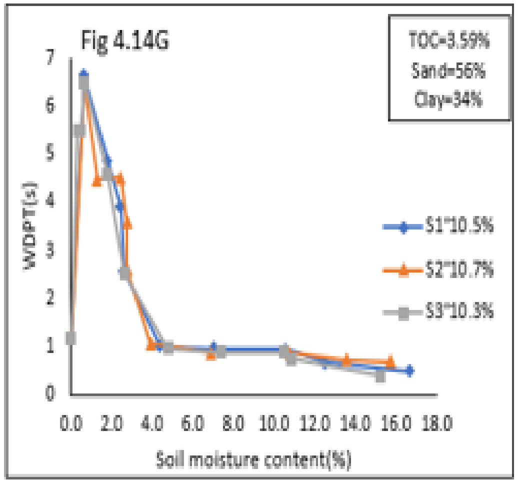


Fig 4.14G

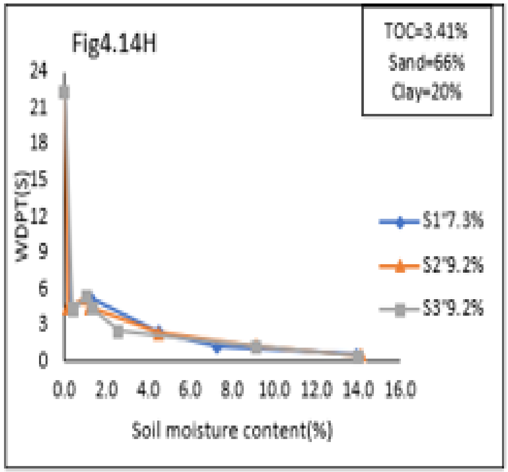


Fig4.14H

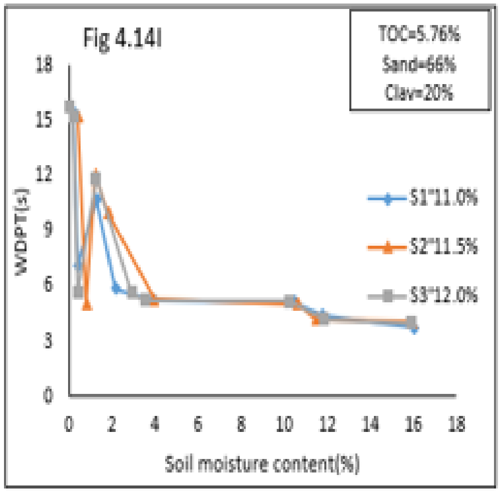


Fig 4.14I

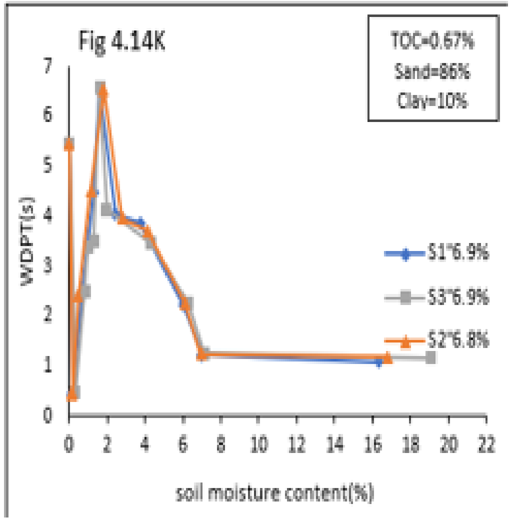


Fig 4.14K

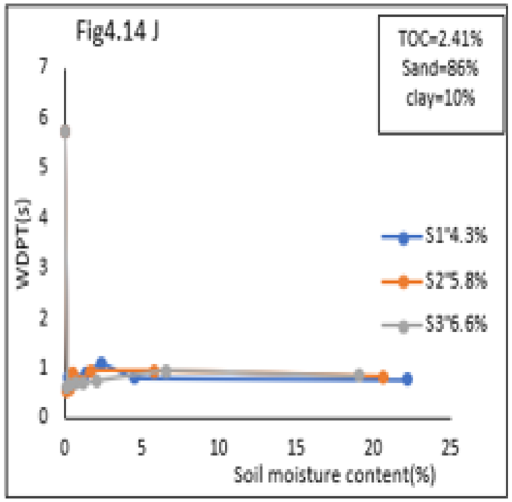


Fig4.14 J

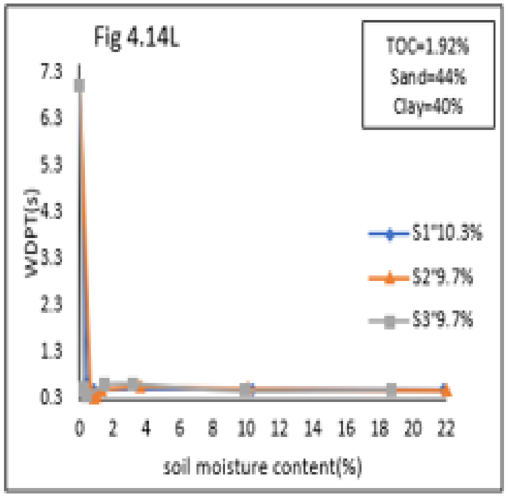


Fig 4.14L

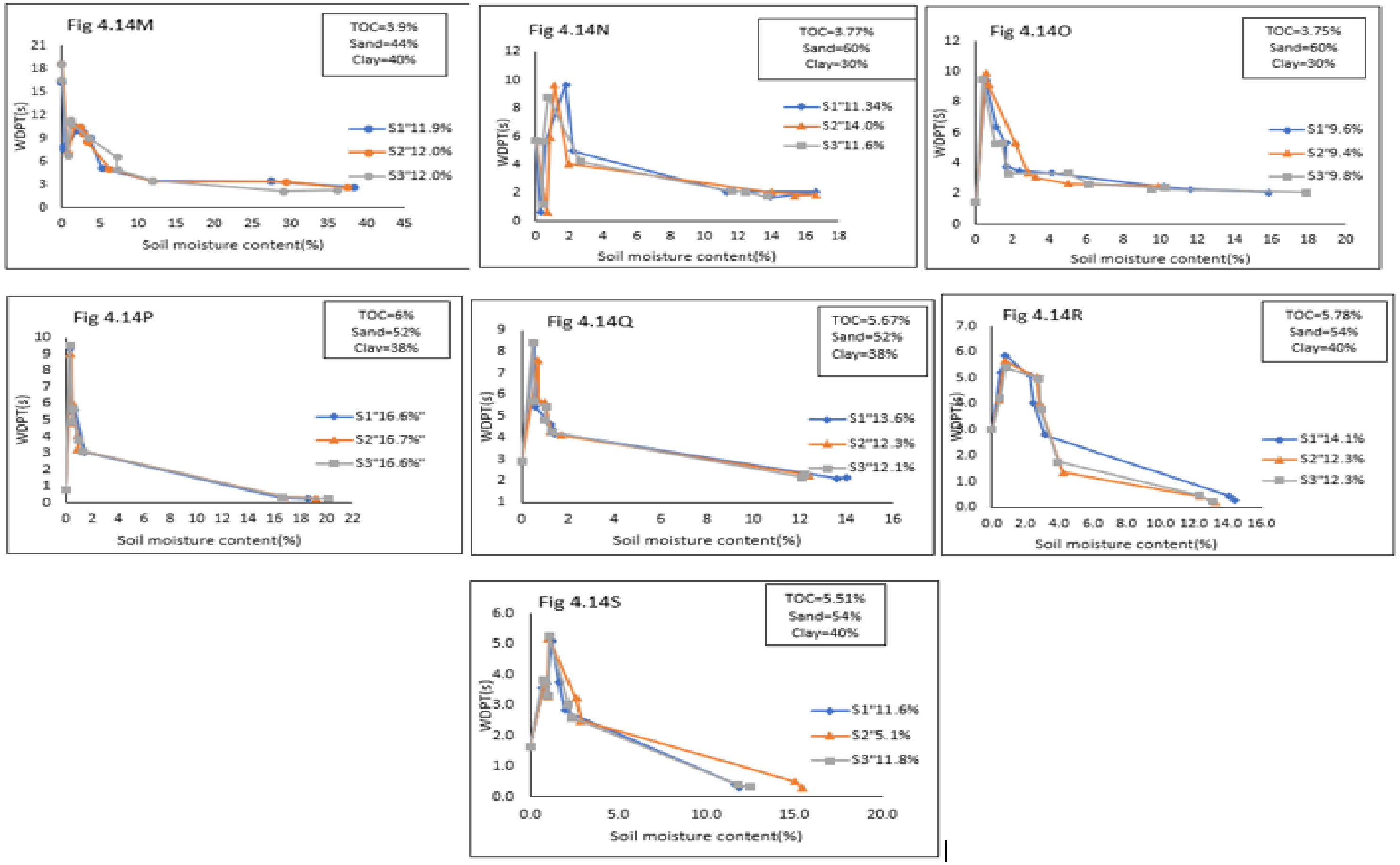


Figure 4.14: A-S: Soil Water Repellency as a Function of Soil Water Content in Murang'a Soils

NB: S1, S2, S3 indicates the critical moisture content for the three replicates examined for each soil sample at depths of (0-15cm) and (15-30cm).

It was evident that soils whose curves were bimodal, their global maximum (the largest overall value of WDPT) was observed in the second peak and therefore, it is necessary to measure the whole SWR-w curve inorder to estimate the highest degree of repellency that can be reached in the soil (Hermansen et al.,2019). Similarly, SWR-w curves of soils of Makueni were either single or double peaked as shown in Figure 4.15.

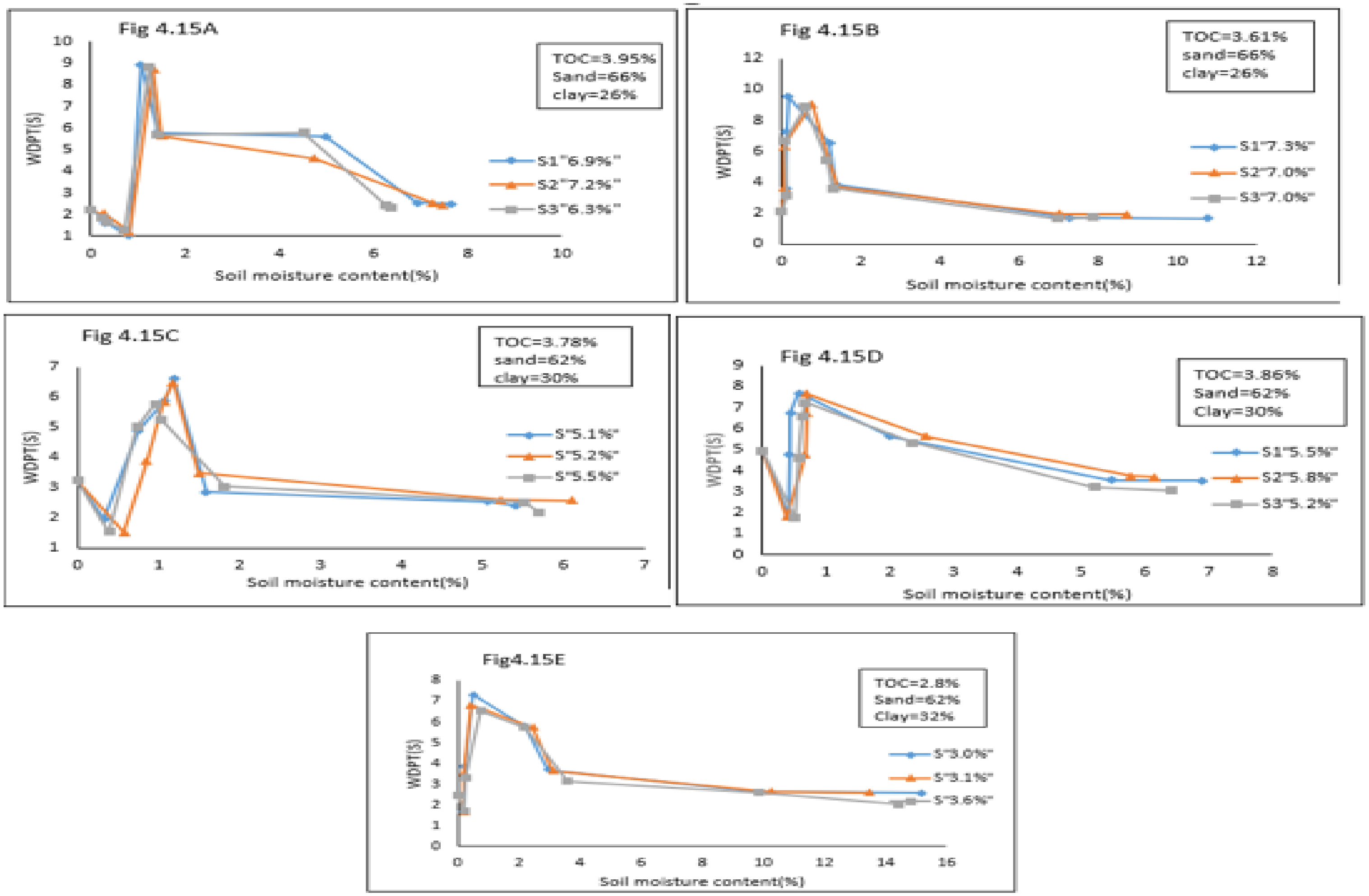


Figure 4.15: A-E: Soil water repellency as a function of soil water content in Makueni soils

NB: S1, S2, S3 indicates the critical moisture content for the three replicates examined for each soil sample at depths of (0-15cm) and (15-30cm).

The average Soil water repellency function was therefore determined from Integrative Repellency Dynamic Index (IRDI). IRDI gives a measure of the mean water repellency in the soil moisture interval between zero (pre-treament by oven drying at 60^{o}C for 48hours) to critical soil moisture content (when soil turns hydrophillic) (Regalado and Ritter, 2005). Generraly, Humic Nitisols, IB2 and Umbric Andosols recorded a maximum IRDI of 2.25 and 2.33 seconds respectively while Rhodic Ferralsols had a IRDI of 1.14 seconds (Figure 4.15d).

The total soil water repellency (SWR_{AREA}) and the critical soil moisture content (Wc) were also determined from the SWR-w curves. SWR_{AREA} was determined as the total trapezoidal intergrated area under the SWR-w curve while Wc was resolved as the minimum moisture content where soils turned hydrophilic. SWR_{AREA} and Wc were highly variable, ranging from a mean of 8.89 to 24.91sec/%moisture content and 13.23 to 6.56% respectively. Humic Nitisols, IB2 exhibited the highest mean SWR_{AREA} of 24.91(sec/% smc) while Ferralic Cambisols had the lowest total soil water repellency of 8.89 (sec/% smc) as presented in Figure 4.16 (a) and (b). Soil samples which had lowest and highest SWR_{AREA} also had a corresponding low and high TOC contents (Figure 4.16(c)) depicting a strong influence of TOC on the persistence of SWR (Weber et al, 2021). The differences in total organic carbon content in the soil samples affected the SWR_{AREA} for the various soil types which inturn influenced the total soil water repellency (IRDI) as presented in Figure 4.16 (a-d).

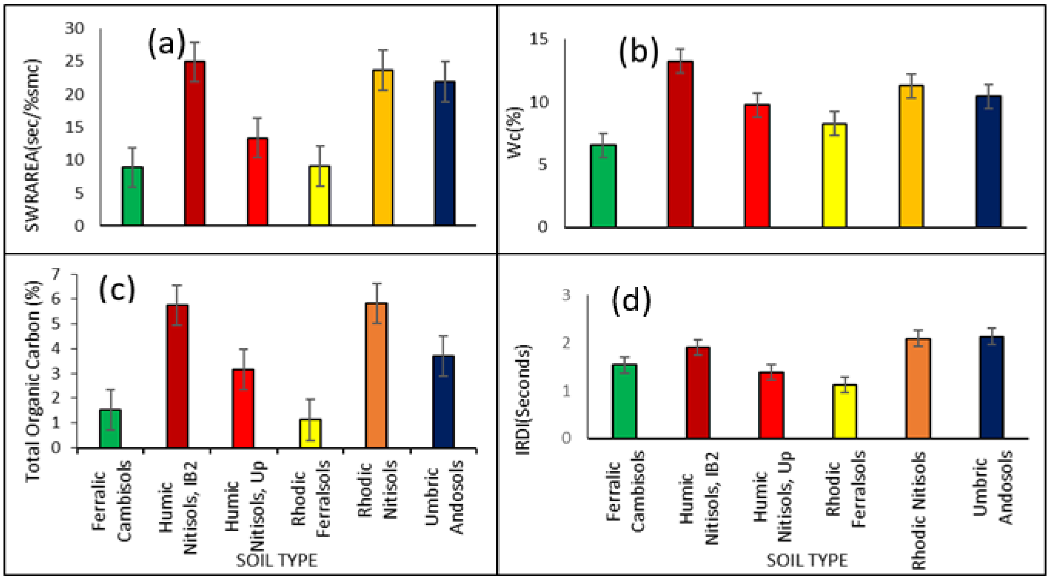


Figure 4.16: (a) total degree of soil water repellency (SWRAREA), (b) the critical soil water content (Wc) (c) Total organic carbon (TOC)and (d) Repellency Dynamic Index (IRDI) of the six soil types of Murang'a County

NB: The Error Bars Represent the Standard Error.

Rhodic Ferralsols in Makueni exhibited the highest average SWR_{AREA} of 18.518 sec/% smc with a coresponding TOC of 3.83%. With regards to critical moisture content the Rhodic Ferralsols were significantly ($p < 0.01$) higher than the Haplic Acrisols (Figure 4.17b). Further, the Rhodic Ferralsols had a significantly ($p < 0.01$) higher SWR_{AREA} and Wc than the Dystric Cambisols (Figure 4.17 a and b). It was evident that Rhodic Ferralsols had a significantly ($p < 0.05$) higher average TOC which coresponded to the high SWR_{AREA} and Wc, thus, the high SWR_{AREA} and Wc could be attributed to the relatively high TOC content as compared to the other soil types.This relationship is in agreement with other similar studies that reported a similar significant corelation between SWR_{AREA} and TOC (De Jonge et al., 2007; Kawamoto et al., 2007; Regalado and Ritter, 2005; Regalado et al., 2008; Czachor et al. 2013).

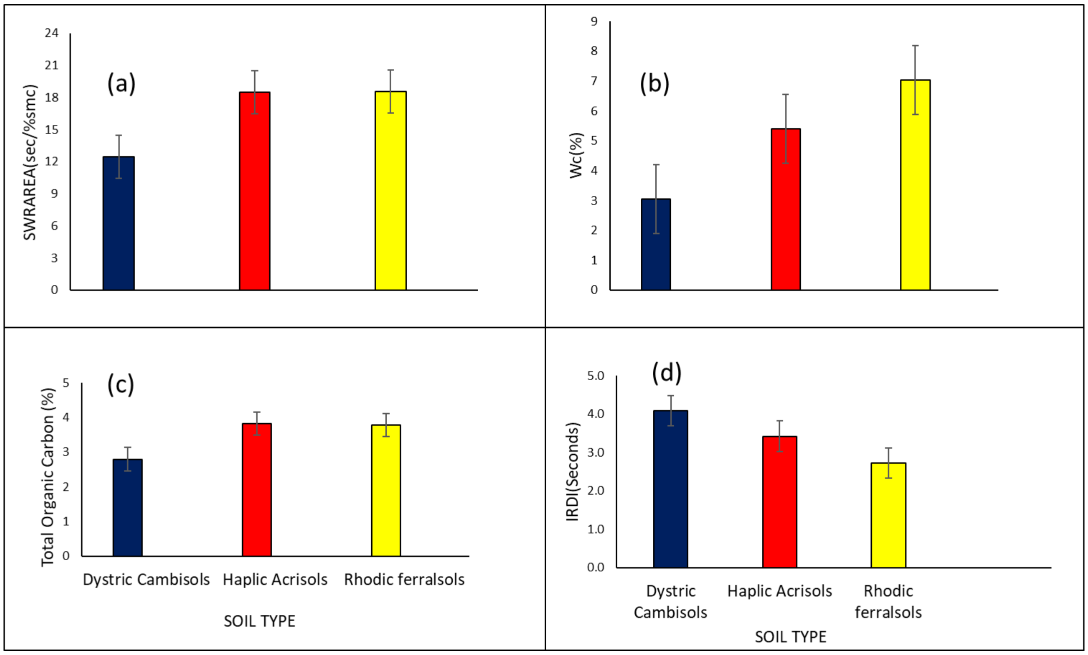


Figure 4.17: (a) total degree of soil water repellency (SWR_{AREA}), (b) the critical soil water content (Wc) (c) Total organic carbon (TOC)and (d) Repellency Dynamic Index (IRDI) of the six soil types of Makueni County

NB: The error bars represent the standard error.

Among the three repellent soil types studied in Makueni County, the persistence of SWR with regards to SWR_{AREA} decreased in the following order; Rhodic Ferralsols> Haplic Acrisols> Dystric Cambisols.

4.6.1 Critical Soil Moisture Content

The critical soil moisture content at which soil water repellency is broken was determined as a transition zone rather than a sharp threshold as proposed by Hewelke et al. (2016). In this transition zone the soils can either be hydrophobic or hydrophilic depending on the wetting history and therefore two control limits were obtained from the transition zone. An upper threshold of the transition zone indicates the absence of soil water repellency, and the lower limit which indicates the re-establishment of the repellency. However, this lower limit cannot be specified well and may be an unreliable predictor of the re-establishment of soil water repellency (Rye, 2019).

Soil water repellency was observed to be broken at various critical moisture content levels (Wc). Humic Nitisols, IB2 were observed to turn hydrophillic at higher average critical moisture content of 13.23% while on the other hand, Ferrallic Cambisols turned wettable at a lower soil moisture content level of 6.56%. This means that Humic Nitisols, IB2 would be more difficult to remediate as more surfacants or water would be needed to overcome the repellent nature of the soil. The critical water contents ranged between 9.5% and 11.5% for Umbric Andosols, 8% and 12.0% for Humic Nitisols,Up, 11.7% and 16.7% for Humic Nitisols,IB2, 10.0% and 12.5% for Rhodic Nitisols, 7.5% and 9.0% for Rhodic Ferralsol and 6.2% and 6.9% of soil for Ferrallic Cambisols as presented in Table 4.2. The average critical water content values were way higher than the mean permanent wilting point and closer to field capacity of the soils as presented in Table 4.2.

Table 4.1: Soil type specific average Critical Soil Water Content (Wc) and soil moisture characteristics

Soil moisture characteristics	**Umbric Andosols**	**Humic Nitisols, UP**	**Humic Nitisols, IB2**	**Rhodic Nitisols**	**Rhodic Ferralsols**	**Ferraliic Cambisols**
Wc (%)	10.47	9.75	13.23	11.29	8.27	6.56
Field capacity (%)	14.54	23.25	22.84	13.23	10.23	11.81
PWP(%)	6.74	6.08	8.05	6.82	3.98	3.23
Saturation(%)	25.72	35.51	39.17	22.62	22.02	28.40
Field moisture content (%)	52.8	41.5	7.05	24.25	5.25	5.95

NB: The average Critical Soil Water Content (Wc), Field Capacity, Permanent Wilting Point (PWP), Degree of Saturation and the Moisture Content during Sampling in the Field (Field Moisture Content) for the Repellent Soil Samples in Murang'a

It was found that the critical soil moisture contents of Umbric Andosol , Rhodic Ferralsols and Rhodic Nitisols were very close to the field capacities of these soils. This could be attributed to overestimations of the critical water content due to inhomogeneous moisture distribution during the wetting-drying regime in these soils (Bachmann et al., 2021). It is also thought to depend on the soil texture because of the huge differences in available surface area between clay and sand particles (Nadav et al., 2013; Mao et al., 2019).

The minimum soil moisture content that needs to be maintained in the Rhodic Ferralsols of Murang'a to prevent the occurrence of soil water repellency was found to be significantly higher ($p<0.01$) than that of Rhodic Ferralsols of Makueni County Table 4.3 . This could be attributed to the differences in the texture especially the average clay content which was higher in Rhodic Ferralsols (26%) of Makueni as compared with 14% in Rhodic Ferralsols of Murang'a County. Soil sand content has been reported to correlate positively with the soil water repellency parameters such as SWR_{AREA} and Wc while the clay content correlates negatively with these parameters (Diamantis et al., 2017; Fu et al., 2021). Hydrophobic organic matter fractions can increase aggregate stability, presumably due to hydrophobic coatings around the aggregates, which could explain the high SWR in these clay-rich soils (Wijewardana et al., 2016).

Table 4.2: Soil type specific average Critical Soil Water Content (Wc) and soil moisture characteristics

	Dystric Cambisols	**Haplic Acrisols**	**Rhodic Ferralsols**
Wc(%)	3.05	5.4	7.03
Field capacity (%)	12.84	20.56	21.26
PWP(%)	8.67	13.57	13.65
Saturation (%)	22.87	37.31	40.60
Field moisture content(%)	3.5	4.4	4.1

NB: The average Critical Soil Water Content (Wc), Field Capacity, Permanent Wilting Point (PWP), Degree of Saturation and the Moisture Content during Sampling in the Field (Field Moisture Content) for the Repellent Soil Samples in Makueni County

The critical water contents ranged between 7.0% and 7.1% for Rhodic Ferralsols, 5.2% and 5.7% for Haplic Acrisols and 3.1% of soil for Dystric Cambisols. Taking the critical water contents of all replicate samples from all other soil types, an ANOVA test was performed (Appendix III). There was a significant difference ($p = 0.006 < 0.05$) between the critical water contents for the different soil types in Murang'a County. Further, the critical soil moisture content for the three repellent soils of Makueni was less significant ($p = 0.012 < 0.05$) (Appendix IV) bewteen the soil types compared to that of Murang'a soils.

4.6.2 Relationship Between Soil Water Repellency and Soil Properties

The soil samples investigated exhibited a strong linear relationship between SWR_{AREA} and Total organic carbon. The SWR_{AREA} and TOC were strongly correlated ($r= 0.90$; $p<0.01$) with r^2 of 0.82 as summarised and presented in Figure 4.18. A simple linear regression utilizing $SWR_{AREA,}$ and TOC only resulted in a RMSE of 3.07sec/% soil moisture content and is expresses in Equation 4.2. The high correlation agrees with other studies which also found a similar positive correlation between SWR_{AREA} and TOC (Kawamoto et al., 2007; Regalado et al., 2008).

$$SWR_{AREA} = 3.4072TOC+4.7775 \tag{4.2}$$

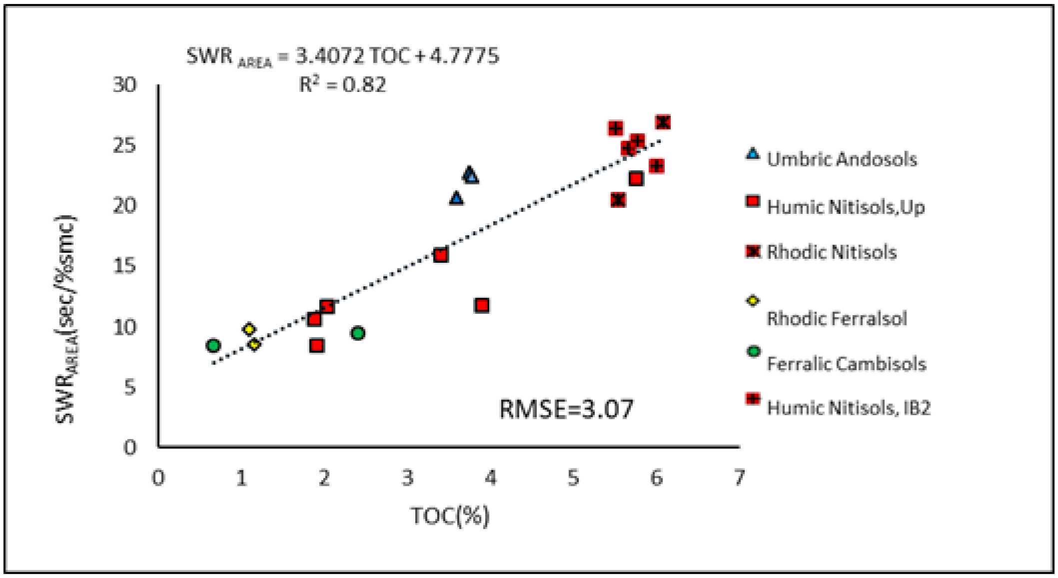


Figure 4.18: The Total Degree of Soil Water Repellency (SWR_{AREA}) in Six Soil Types of Murang'a

On the other hand, a weaker relationship ($r = 0.82$; $p < 0.01$) with r^2 of 0.66 (Figure 4.19) was obtained between the total repellency and TOC in soils of Makueni County. This could be attributed to the corresponding low average TOC from Makueni soils when compared to Murang'a county soils. The simple linear regression yielded the following Equation 4.3 and a RMSE of 2.81sec/% soil moisture content as shown in Figure 4.19.

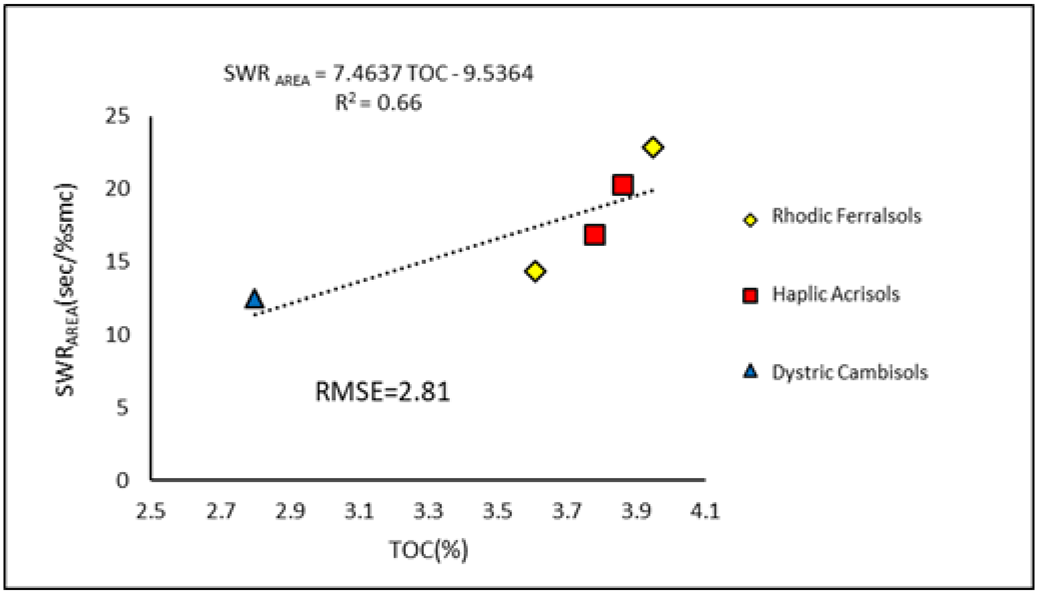


Figure 4.19: The Total Degree of Soil Water Repellency (SWR_{AREA}) in Three Repellent Soil Types of Makueni

$$SWR_{AREA} = 7.4637\ TOC - 9.5364 \qquad (4.3)$$

The results of this study suggest and supports the fact that the SWR_{AREA} depends on the total amount of TOC present in the soil. Similarly, critical soil moisture content was found to be strongly correlated with Total Organic Carbon ($r = 0.86$, $p < 0.01$) with ^{2} of 0.73 and RMSE of (1.04) 10.4g/kg of soil. This soil property can be described by a linear expression using TOC as the variable as presented in Figure 4.20 with the corresponding Equation 4.4. Notably, a linear regression ($r = 0.80$) between Wc and Organic Carbon was found by De jonge et al. (2007) for soils sampled from Denmark while Kawamoto et al. (2007) developed a linear regression yielding an r of 0.87.

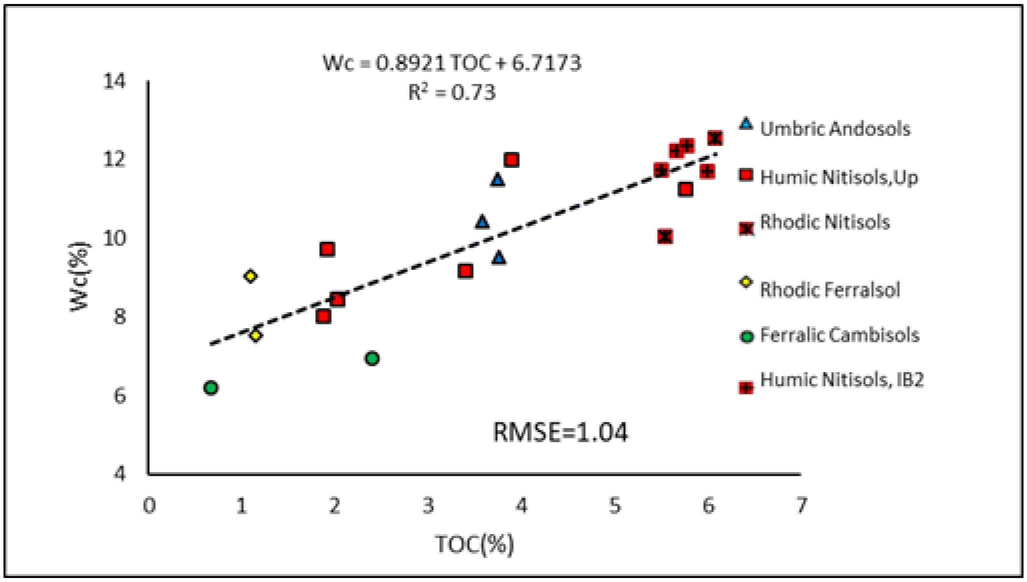


Figure 4.20: The Critical Soil Water Content (Wc) as a Function of Total Organic Carbon in Murang'a soils

$$W_c = 0.8921TOC + 6.7173 \qquad (4.4)$$

The contribution of TOC on soil water repellency was also investigated for the repellent soils of Makueni county and it was found that increasing TOC significantly ($r = 0.82$, $p < 0.01$) contributed to the increase in the minimum soil water content that was required to prevent the occurrence of soil water repellency. The simple linear relationship between Wc and TOC can be expresses as shown in Equation 4.5 with a RMSE of 1.09 % soil moisture content as presented in Figure 4.21.

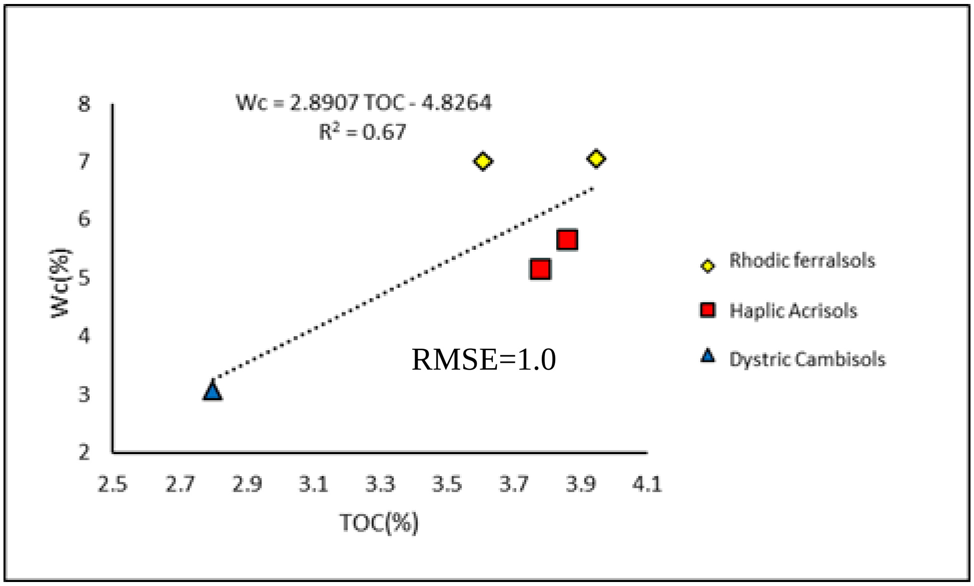


Figure 4.21: The Critical Soil Water Content (Wc) as a Function of Total Organic Carbon in Makueni Soils

$$Wc = 2.8907TOC - 4.8264 \tag{4.5}$$

The critical soil moisture content shows an important soil moisture level above which onset of soil water repellency can be avoided. For practical purposes an upper and lower control limits were obtained. The upper limit is applicable in soil water repellency remediation since a safety margin will be integrated into the critical moisture content to show the level of soil water content that should be maintained to avoid soil water repellency as shown in Figure 4.22.

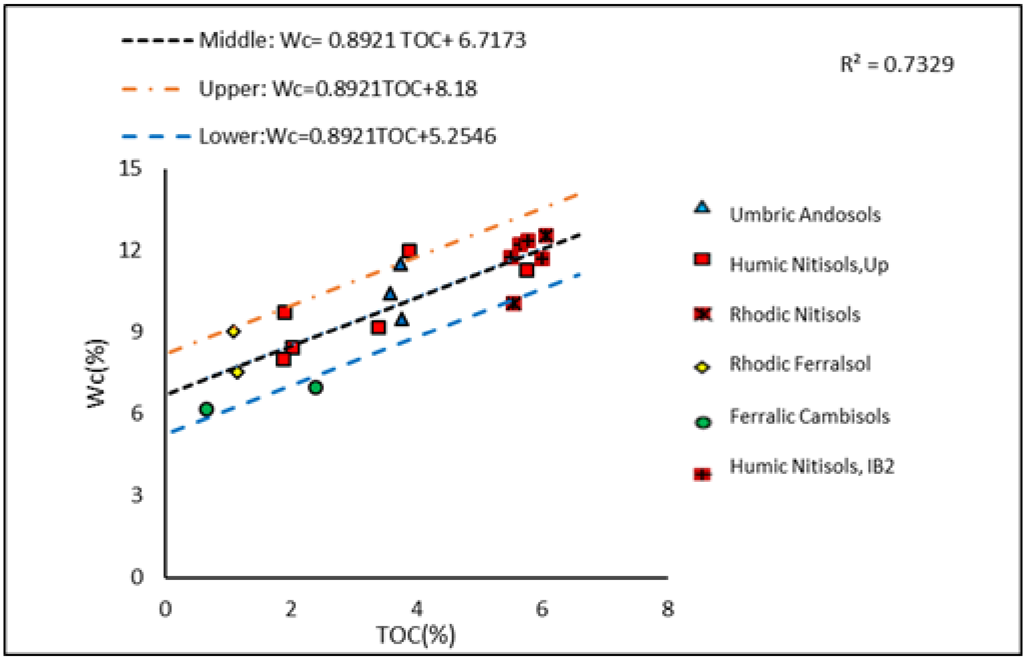


Figure 4.221: An Upper and Lower Control Limits to Represent the Spread Around the Regression Coefficient in Murang'a Soils

To get the upper control limit, a safety margin of 1.46% moisture content was added. Ferrallic Cambisols and Rhodic Nitisols appeared below the middle regression line which means that they require higher extent of irrigation compared to the other four soil types to avoid the onset of SWR. This is because they are located closer to the lower control limit moisture content. However, the general behaviour of the six soil types suggests that the overall irrigation support model; W_c= 0.89TOC + 6.7183 can be utilized to avoid water repellency in those soils. However, it is advisable to develop soil type specific models for W_c as a function of TOC when more comprehensive data is available for each soil type.

Similarly, safety margin of 0.7% was integrated into the simple linear regression between Wc and TOC to show the spread around the middle regression in Makueni soils. Haplic Acriols and Dystric Cambisols appeared below the middle regression line while the Rhodic Ferralsols apperared above. The same behavior was observed for the Rhodic Feralsols of Murang'a. This means that Rhodic Ferralsols may not need the same extent of irrigation as compared to Haplic Acriols and Dystric Cambisols to avoid the onset of water repellent conditions. For now however, the overall irrigation models as expressed in Equation 4.5 (W_c = 2.8907TOC - 4.8264) and in Figure 4.23 can be applied sufficiently to avoid soil water repellency occurrence in the studied repellent soils of Makueni.

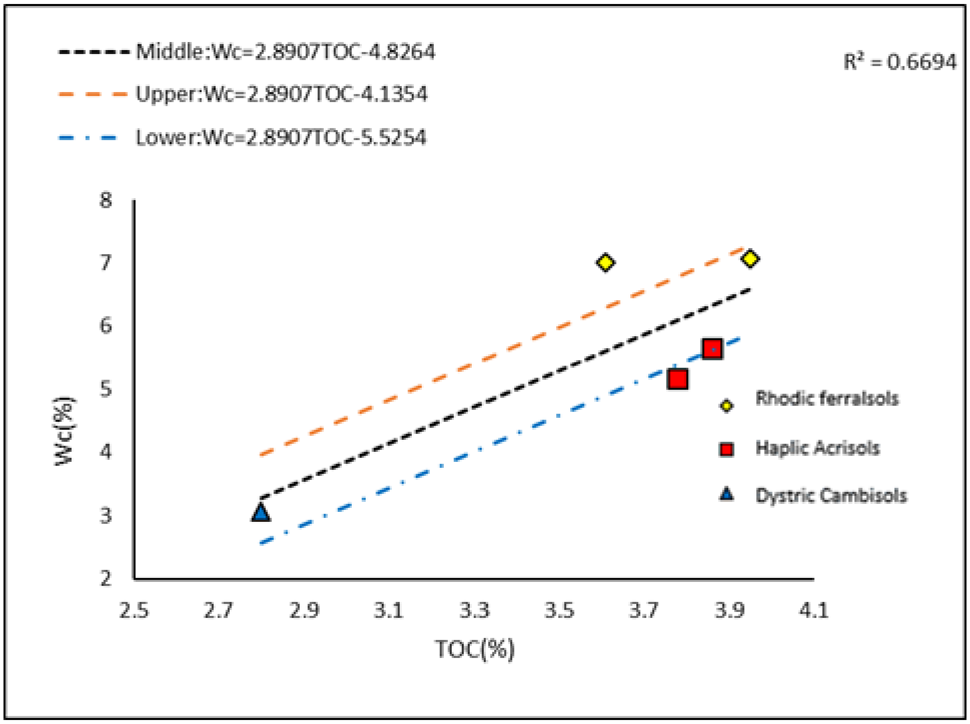


Figure 4.23: An Upper and Lower Control Limits to Represent the Spread around the Regression Coefficient in Makueni Soils

The correlation between SWR_{AREA} with soil texture and TOC are as presented in Appendix V. Sand content was however not included in the regression analysis. This is because there existed a multicollinearity between clay, silt and sand as the predictor variables of soil water repellency in their respective correlations as shown in Appendix V and VI. Collinearity in a statistical model refers to predictor variables that are linearly connected and it can lead to the identification of incorrect relevant predictors and hence erroneous results (Dormann et al., 2013).

Clay content however correlated positively and significantly to SWR_{AREA} and Wc (r = 0.62 and 0.77, respectively) ($p < 0.01$) as shown in Appendix V. Clay content further improved the relationship between Wc and SWR_{AREA} to TOC in the forward multiple linear regressions (Fig 4.24 and 4.25). These findings are in contrast with the findings of Hermansen et al. (2019), who did not observe any significant positive effect of clay content on Wc. Notably, there was no significant correlation between SWR_{AREA} and texture in the repellent soils of Makueni. However, Wc was strongly (r = 0.944; $p < 0.01$) correlated with clay content. A strong positive correlation between TOC and silt content (r = 0.963;$p < 0.01$) was also observed in these soils as presented in Appendix VI.

A strong negative multicollinearity (r = -0.953; $p < 0.01$) between sand and clay was also recorded for these soils and therefore the sand and clay content cannot be utilized together in multiple linear regression to explain variation in soil water repellency parameters. This is because the high multicollinearity between the variables could lead to over-fitting of the model.

Multiple linear regression was performed utilizing percentage contents of TOC, Silt and Clay which significantly explained 85 % of the variation in SWR_{AREA} (RMSE = 3.02 sec/%Soil moisture content) as shown in Figure 4.24 and an expression of SWR_{AREA} as a function of the three parameters is is given as Equation 4.6.

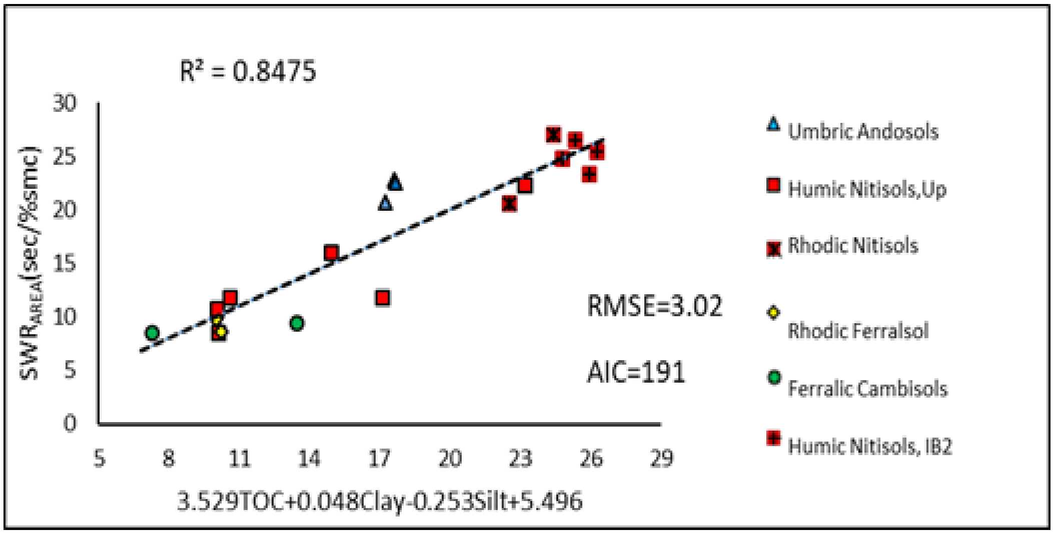


Figure 4.24: Multiple Linear Regression (MLR) for Trapezoidal Integrated Area under the Soil Water Repellency Curve (SWR_{AREA}) using %TOC, Clay and Silt in Murang'a Soils

$$SWR_{AREA}= 3.529TOC+0.048Clay-0.253Silt+5.496 \qquad (4.6)$$

Regarding forward MLR, percentage contents of TOC, silt and clay contributed significantly to explain 98% of the variation in SWR_{AREA} with a RMSE of 0.97sec/%soil moisture content in Makueni soils (Figure 4.25). The forward MLR yielded Equation 4.7 which shows that silt and clay played an important role in predicting SWR_{AREA} meaning that higher clay and silt content reduced the SWR_{AREA}.

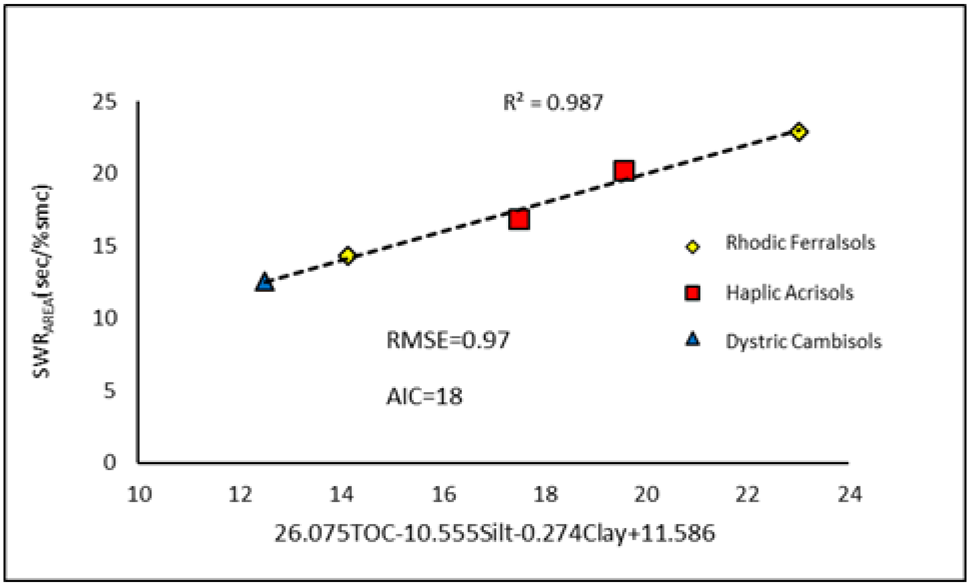


Figure 4.25: Multiple Linear Regression (MLR) for Trapezoidal Integrated Area under the Soil Water Repellency Curve (SWR_{AREA}) using %TOC, Clay and Silt in Makueni Soils

$$SWR_{AREA} = 26.075TOC - 10.555silt - 0.274Clay + 11.586 \tag{4.7}$$

Concerning the critical soil moisture content, MLR was performed by utilizing the same factors i.e. Silt, Clay and TOC and the results are presented in Figure 4.26.

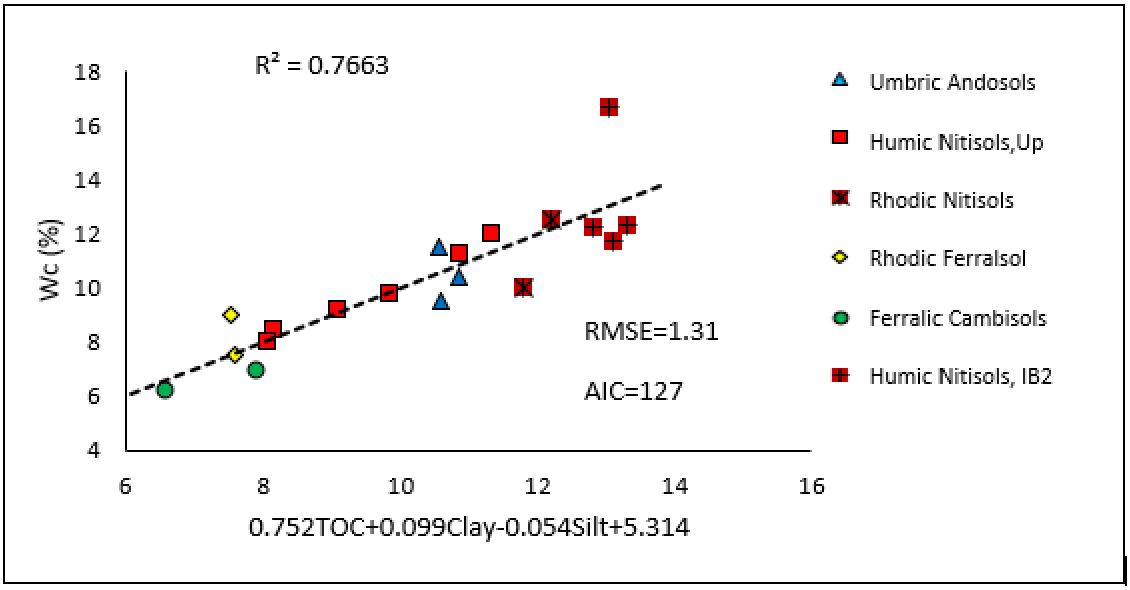


Figure 4.26: MLR for critical Soil Water Content Using %TOC, Silt and Clay as Input Variables in using % TOC, Clay and Silt in Murang'a Soils

Similarly, 77% of the variations in the critical soil moisture content could be attributed to the Clay, silt and TOC contents in the soil (RMSE = 13.1g/kg of soil). Also, a high correlation between SWR_{AREA} and Wc was found ($r = 0.74$; $p < 0.01$) (Appendix V) as reported by Kawamoto et al. (2007). TOC, silt and clay also significantly explained variation of Wc in Makueni soils by 99% with a RMSE of 0.34% soil moisture content (Figure 4.27).

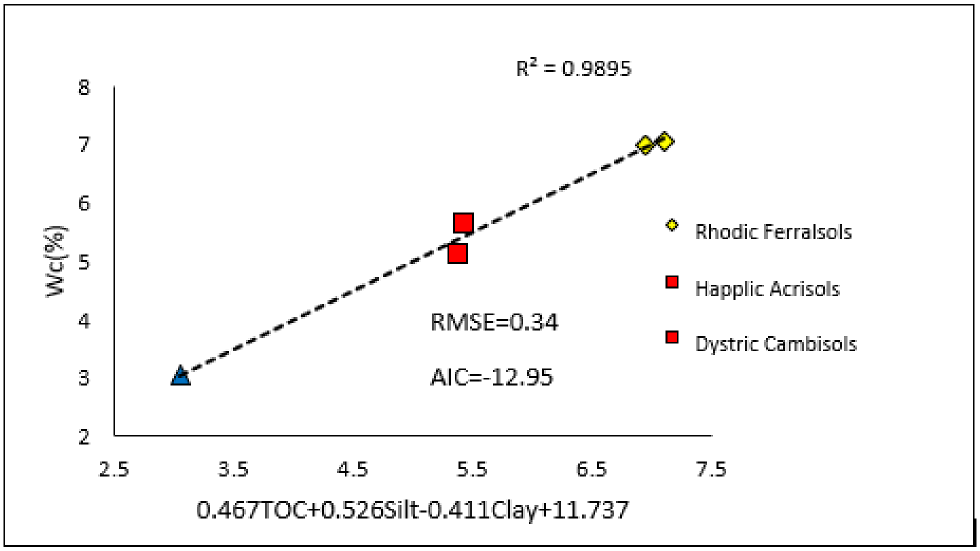


Figure 4.27: MLR for critical soil water content using %TOC, Silt and Clay as input variables in Makueni Soils

As shown in the pearson correlation matrix Appendix V and Appendix VI respectively, Wc was positively ($r = 0.770; p < 0.01$) correlated to clay while for Makueni soils, clay was observed to be strongly negatively correlated ($r = -0.944;p < 0.01$) with Wc. This shows an opposing role in influencing the occurrence of soil water repellency in soils from the two study areas. The average clay content in Murang'a soils was 27.5% while that of Makueni soils was 28.8% which implied that Murang'a soils needed a higher Wc to be maintained to avoid repellency as compared to that required for Makueni soils. These results concurred with those of Lichner et al. (2006) who observed that addition of 1, 2 and 3 % by mass of respective clays rendered repellent sandy soils wettable. In addition to increasing the surface area of soils, clay is thought to be effective in ameliorating repellency by masking the hydrophobic surfaces in the soil matrix and exposing the hydrophillic clay surfaces (Diamantis et al., 2017).

On addition of Wc as an input variable, the MLR expression of SWR_{AREA} resulted in R^2 of 0.85 (Figure 4.28) and the expression of SWR_{AREA} as a function of TOC, sand, silt and Wc is as presented in Equation 4.8. The addition of Wc in the MLR expression of SWR_{AREA} improved the accuracy of the expression from AIC of 191 to AIC of 190 to which the variation of the total soil water repellency with TOC, clay and silt could be explained in the case of Murang'a soils.

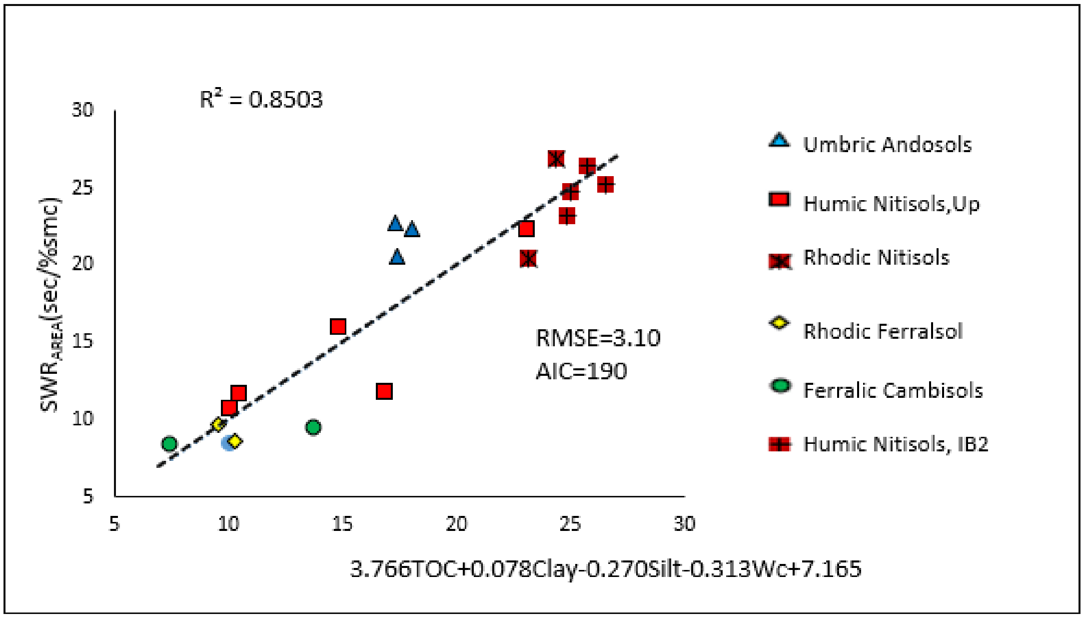


Figure 4.28: MLR for SWR_{AREA} using % TOC, Sand, Silt and Wc as the Input Variables in Murang'a soils

$$SWR_{AREA}=3.766TOC + 0.078Clay - 0.270Silt - 0.313Wc+7.165 \qquad (4.8)$$

Further, a significantly high correlation between SWR_{AREA} and Wc was found ($R = 1$; $p < 0.01$) as already described in several previous studies (Kawamoto et al., 2007; Regalado and Ritter, 2005). Accordingly, the addition of Wc resulted in a significant increase in the accuracy of the the MLR expression for SWR_{AREA} from AIC of 18 to AIC of 1 as shown in the Figure 4.29. This expresion is given in Equation 4.9

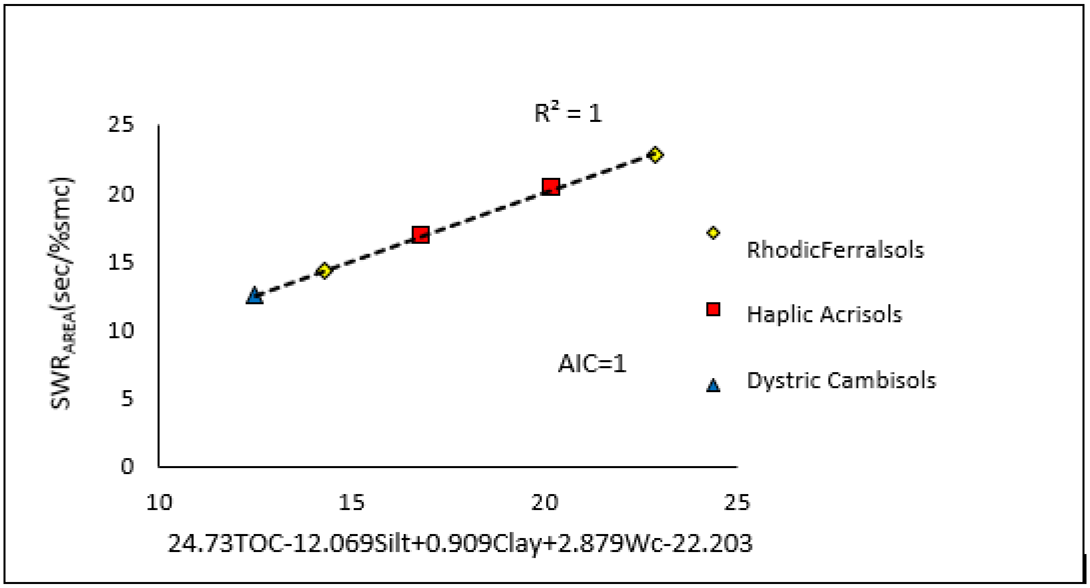


Figure 4.29: MLR for SWRAREA using %TOC, Sand, Silt and Wc as the input variables in Makueni Soils

$$SWR_{AREA}=24.73TOC-12.069Silt+0.909Clay+2.879Wc-22.203 \quad (4.9)$$

Addition of Wc as an input variable contributed to a slight positive variation in SWR_{AREA}. Similarly, Regalado et al. (2008) also utilized TOC and Wc to improve the prediction of SWR_{AREA} other than utilizing only organic carbon.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Nineteen (19) 37% of the soil samples collected from the 26 sampling sites were hydrophobic. Humic Nitisols, IB2 exhibited the highest WDPT of 10 seconds and Wc within the 6 soil types studied in Murang'a. On the other hand, five (5) 16% of soil samples from Makueni were repellent with Rhodic Ferralsols recording the highest WDPT of 10.8 seconds.
2. Soil water repellency was observed to be broken at various critical moisture content levels (Wc). However, there was a significant difference ($p = 0.006 < 0.05$) and ($p = 0.012 < 0.05$) between the critical water contents for the different soil types in Murang'a and Makueni counties respectively. The SWR_{AREA} and the Wc were highly linearly correlated to TOC which was identified as the best predictor of these two repellency parameters.
3. TOC was the most important soil property in explaining the total degree of SWR (SWR_{AREA}) and Wc since it showed 82 and 73% of the variability respectively in Murang'a soils and 67% for both SWR_{AREA} and Wc in Makueni soils. With regard to the linear Wc relationship with TOC, a safety margin of 1.46% and 0.7% moisture content for Murang'a and Makueni soils was added to capture the spread around the regression line.

5.2 Recommendations

1. The upper limit critical water content obtained from Murang’a soils: W_c= 0.89TOC + 6.7183 and Makueni soils: W_c = 2.8907TOC - 4.8264 could be used to derive a threshold water content above which SWR and the related degradation in soil functions could be eliminated.
2. Since soil water repellency is dependent on a variety of interconnected and dynamic factors, future research should focus on large scale soil type-specific field experiments to help improve the understanding of the occurrence of soil water repellency.

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APPENDICES

Appendix I: Soil Characteristics the 84 Soil Samples from 46 Sampling Sites for the Various Soil Types in Murang'a and Makueni Counties. The results are presented in the form of mean and Standard Deviation

Study area	Soil Type	Depth(cm)	Attr.	Sand (%)		Clay (%)		Silt (%)		SMC (%)		WDPT (s)	
			n	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Murang'a County	ANu	0-15	6	60.00	4.90	29.00	5.90	11.00	2.10	45.30	2.50	2.10	0.30
		15-30	6	60.00	4.90	29.00	5.90	11.00	2.10	54.90	8.70	1.80	0.20
	NTu, Up	0-15	9	54.00	10.60	35.00	11.20	12.00	3.20	35.60	12.60	1.90	0.30
		15-30	9	54.00	10.60	35.00	11.10	12.00	3.20	45.50	16.20	1.50	0.30
	NTu, IB2	0-15	8	48.00	4.70	46.00	5.30	7.00	2.10	18.70	11.00	3.20	3.10
		15-30	8	48.00	4.70	46.00	5.30	7.00	2.10	18.10	11.90	3.00	3.10
	NTr	0-15	1	52.00	0.00	32.00	0.00	16.00	0.00	18.00	0.00	7.10	0.00
		15-30	1	52.00	0.00	32.00	0.00	16.00	0.00	32.50	0.00	6.20	0.00
	FRr	0-15	1	86.00	0.00	14.00	0.00	0.00	0.00	4.80	0.00	7.20	0.00
		15-30	1	86.00	0.00	14.00	0.00	0.00	0.00	8.00	0.00	7.00	0.00
	CMo	0-15	1	86.00	0.00	10.00	0.00	4.00	0.00	4.90	0.00	9.30	0.00
		15-30	1	86.00	0.00	10.00	0.00	4.00	0.00	7.00	0.00	7.10	0.00
Makueni County	FRr	0-15	4	80.00	11.00	16.00	8.20	5.00	3.00	2.10	1.30	3.10	4.60
		15-30	4	80.00	10.10	16.00	8.20	5.00	3.00	3.40	1.60	3.30	5.00
	CMx	0-15	3	89.00	4.10	7.00	4.10	4.00	0.00	1.20	0.50	1.60	0.60
		15-30	3	89.00	4.10	7.00	4.10	4.00	0.00	1.80	1.10	2.00	0.30
	LXh	0-15	4	90.00	2.50	8.00	1.90	3.00	1.20	1.00	0.10	1.10	0.30
		15-30	4	90.00	2.50	8.00	1.90	3.00	1.20	1.50	0.30	1.70	0.10
	ACh	0-15	2	71.00	12.70	20.00	14.10	9.00	1.40	2.70	2.10	4.40	3.80
		15-30	2	71.00	12.70	20.00	14.10	9.00	1.40	3.00	2.10	7.00	6.20
	CMd	0-15	2	65.00	4.24	26.00	8.49	9.00	4.20	3.20	0.50	4.40	4.20
		15-30	2	65.00	4.24	26.00	8.49	9.00	4.20	3.30	0.40	1.20	1.00
	CMu	0-15	1	64.00	0.00	30.00	0.00	6.00	0.00	3.80	0.00	0.80	0.00
		15-30	1	64.00	0.00	30.00	0.00	6.00	0.00	4.40	0.00	0.80	0.00

Appendix II: Hydro-physical Characteristics for the various Soil Types in Murang'a and Makueni Counties. The Results are Presented in the form of Mean and Standard Deviation

Study Area	Soil Type	Depth	Attr.	TOC (%)		KS (mm/hr)		BD (g/cm3)		Porosity (%)	
Murang'a County	ANu	0-15	6	4.13	1.11	3.50	2.65	1.40	0.04	47.40	1.61
		15-30	6	3.71	0.62	3.50	2.65	1.40	0.04	47.40	1.61
	NTu, Up	0-15	9	2.90	1.50	3.10	2.30	1.36	0.10	48.70	2.70
		15-30	9	2.04	0.78	3.10	2.34	1.36	0.07	48.70	2.71
	NTu, IB2	0-15	8	2.70	2.00	1.30	0.16	1.30	0.03	50.90	0.95
		15-30	8	2.25	2.08	1.30	0.16	1.30	0.03	50.90	0.95
	NTr	0-15	1	6.08	0.00	2.40	0.00	1.36	0.00	48.60	0.00
		15-30	1	5.55	0.00	2.40	0.00	1.36	0.00	48.60	0.00
	FRr	0-15	1	1.16	0.00	16.00	0.00	1.50	0.00	41.60	0.00
		15-30	1	1.10	0.00	16.00	0.00	1.50	0.00	41.60	0.00
	CMo	0-15	1	2.41	0.00	30.20	0.00	1.60	0.00	39.70	0.00
		15-30	1	0.64	0.00	30.20	0.00	1.60	0.00	39.70	0.00
Makueni County	FRr	0-15	4	1.77	1.48	24.60	29.40	1.54	0.11	41.90	4.14
		15-30	4	1.31	1.54	24.60	29.40	1.54	0.11	41.90	4.14
	CMx	0-15	3	0.54	0.05	75.90	66.90	1.60	0.24	36.10	5.12
		15-30	3	0.51	0.15	75.90	66.90	1.60	0.24	36.10	5.12
	LXh	0-15	4	0.73	0.28	52.20	17.90	1.65	0.04	37.70	1.54
		15-30	4	0.59	0.11	52.20	17.90	1.65	0.04	37.70	1.54
	ACh	0-15	2	2.35	2.02	15.70	18.50	1.49	0.14	43.90	5.22
		15-30	2	2.18	2.38	15.70	18.50	1.49	0.14	43.90	5.22
	CMd	0-15	2	2.04	1.07	4.50	3.35	1.41	0.08	46.40	2.16
		15-30	2	0.94	0.01	4.50	3.35	1.41	0.08	46.40	2.16
	CMu	0-15	1	1.17	0.00	2.50	0.00	1.39	0.00	47.40	0.00
		15-30	1	1.24	0.00	2.50	0.00	1.39	0.00	47.40	0.00

SMC-Soil Moisture Content; WDPT-Water Drop Penetration Time; n-Number of Samples; Attr. -Attribute; sd-standard deviation; CMu-Humic Cambisols; CMd-Dystric Cambisols; ACh-Haplic Acrisols; LXh-Haplic Lixisols; CMx-Chromic Cambisols; FRr-Rhodic Ferralsols; CMo-Ferrallic Cambisols; NTr-Rhodic Nitisols; NTu- Humic Nitisols and ANu-Umbric Andosols; TOC- Total Organic Carbon; Ks-Hydraulic Conductivity; BD-Bulk Density

Appendix III: ANOVA Results, Comparison of Critical Water Contents for different Soil Types in Murang'a County

ANOVA

Wc	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	74.560	5	14.912	5.580	.006
Within Groups	34.741	13	2.672		
Total	109.300	18			

Appendix IV: ANOVA Results, Comparison of Critical Water Contents for different Soil Types in Makueni County

ANOVA

Wc	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	10.642	2	5.321	84.291	.012
Within Groups	0.126	2	0.063		
Total	10.768	4			

Appendix V: Pearson Product Moment Correlation Matrix of Total Organic Carbon, Clay, Silt, Sand, IRDI, Wc, SWRAREA, SWR105 and SWR60 for 19 Hydrophobic Soil Samples in Murang'a

	Sand	Clay	Silt	TOC	Wc	IRDI	SWR$_{AREA}$	SWR105	SWR60
Sand	1								
Clay	0.678**	1							
Silt	0.442	0.483*	1						
TOC	1.000**	0.678**	0.442	1					
Wc	0.819**	0.770**	0.350	0.819**	1				
IRDI	0.604**	0.238	0.113	0.604**	0.252	1			
SWR$_{AREA}$	0.906**	0.620**	0.264	0.906**	0.735**	0.809**	1		
SWR105	0.156	0.220	0.220	0.156	0.043	0.315	0.166	1	
SWR60	0.035	-0.084	0.403	0.035	-0.018	-0.149	-0.152	0.242	1

**. Correlation is significant at the 0.01 level(2-tailed)

*.Correlation is significant at the 0.05 level(2-tailed)

Appendix VI: Pearson Product Moment Correlation Matrix of Total Organic Carbon, Clay, Silt, Sand, IRDI, Wc, SWRAREA, SWR105 and SWR60 for 19 Hydrophobic Soil Samples in Makueni

	Sand	Silt	Clay	TOC	Wc	IRDI	SWR_{AREA}	SWR60	SWR105
Sand	1								
Silt	.408	1							
Clay	-.953*	-.667	1						
TOC	.354	.963**	-.610	1					
Wc	.804	.862	-.944*	.818	1				
IRDI	-.652	-.588	.729	-.371	-.697	1			
SWR_{AREA}	.267	.640	-.431	.818	.593	.136	1		
SWR60	-.594	.301	.385	.382	-.071	.374	.409	1	
SWR105	.553	.703	-.686	.746	.820	-.283	.748	.333	1

**. Correlation is significant at the 0.01 level(2-tailed)

*.Correlation is significant at the 0.05 level(2-tailed)