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INVITED REVIEW

EXISTENCE, ORIGIN AND ECOHYDROLOGICAL SIGNIFICANCE OF SOIL WATER REPELLENCY: A REVIEW

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ABSTRACT

Soil water repellency (SWR) is explained as a reduction of wetting rates and water entry into soils. Water-repellent soils does not wet spontaneously when water is placed on the surface. SWR is increasingly being recognized as a common phenomenon impacting the hydrological functions of soil systems. The main hydrological impacts of SWR are reduced infiltration rates, increased overland flow, spatially localized infiltration with fingered flow development, modifications of the three-dimensional distribution, and dynamics of soil moisture. SWR increases overland flow during rainstorms, and subsequently, topsoil erosion. It reduces the water entry into the root zone and retard plant growth, reducing the quantity and the quality of crop production. Water repellency is caused by the presence of hydrophobic organic matter in the soil as coatings on mineral particles intermixed materials. In addition to organic matter, soil moisture content is also an important factor that influences the SWR. Water-repellent nature can be theoretically explained based on the surface free energy and the contact angle of soil. The surface free energy of the soil and the contact angle measures the degree of water repellency, or how much the soil is water-repellent. In this review, the existence, origin, various impacts, theoretical concepts, and management of SWR are discussed using global and local research findings over more than ten decades.

Keywords: Contact angle, Hydrophobicity, Soil water repellency, Soil organic matter, Surface free energy

1.0 Introduction

Soil water repellency (SWR) can be defined as the phenomenon that soil does not wet spontaneously when water is applied on the surface. This condition is generally termed also as hydrophobicity, although slightly water-repellent soils cannot be termed hydrophobic. Under certain conditions, all soils may display water repellency to some degree (Doerr *et al.* 2000). SWR is increasingly being recognized as a common phenomenon impacting the hydrological functions of soil systems (Wallis and Horne 1992). Although water repellency in soils has been recorded since the early 20th century (Schantz and Piemeisel 1917), only limited reports are available prior to the 1960s. Research on SWR reportedly intensified during the latter part of the 20th century, and DeBano (1981; 2000a) provided detailed reviews covering topics specifically on fire-induced SWR and management strategies. Over the past few decades, it has become clear that the SWR is much more widespread than formerly thought. SWR is reported in most parts of the world under varying land uses and climatic conditions.

The wettability of soils is important for many processes concerning the interactions of soil and water (Anderson *et al.* 1995). Water-repellent conditions in soils are related with management practices and biological changes in soil systems that are connected to water flow and transport processes in soils. The main impacts of SWR are the reduction of infiltration rate, increase of overland flow and soil erosion, development of fingered flow in structural or textural preferential flow paths, and creation of unstable, irregular wetting fronts (Hendrickx *et al.* 1993; Ritsema and Dekker 1998). When added to water-repellent soils, water just runs off instead of soaking into the soil (Figure 1). As a result, getting the water into the root zone becomes a major problem. Reduction of water entry to the root zone retards plant growth, reducing the quantity and the quality of crop production. SWR contributes to the land degradation by increasing surface runoff and topsoil erosion

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(Shakesby *et al.* 2000; Ward and Oades, 1993).

Figure 1:Water Applied on the surface flows through the slope without penetrating into the soil

Over the past decades, SWR has been encountered in all inhabited continents (Dekker *et al.* 1998; DeBano 2000a; Doerr *et al.* 2000; Kobayashi and Shimizu 2007; Lichner *et al.* 2018, 2013a,b; Jordán *et al.* 2013; Leelamanie and Nishiwaki 2019; Leelamanie 2016; Leelamanie *et al.* 2021). Although SWR has been reported in almost all major soil types in the world, the occurrence of water repellency in Sri Lankan soils has not been extensively studied or reported so far. Most Sri Lankan soils are readily wettable. This might be due to rapid decomposition rates of organic fraction corresponding to the prevailing high temperature and humidity levels throughout the year. However, SWR conditions are found in soils under several exotic plant species in Sri Lankan conditions (Leelamanie 2016; Leelamanie *et al.* 2021; Piyaruwan and Leelamanie 2020; Piyaruwan *et al.* 2020).

Reviewing the knowledge on water-repellent soils which is scattered into different disciplines and subjected to research throughout the world is important for the general understanding. The purpose of this review is to discuss the various aspects of soil water repellency, summarizing past and present research, and consequently to provide a concise but comprehensive report on SWR, including Sri Lankan conditions to the present reviews. In this review, the existence, origin, various impacts, ecohydrological implications, and management of water repellency are discussed.

2.0 Existence of water-repellent soils

SWR is a widespread phenomenon (Wallis and Horne 1992) and has been mostly reported as the norm rather than an exception (Wallis *et al.* 1991). The existence of water-repellent soils has been known for many decades. It varies non-linearly with soil water content (Figure 2) and is generally found to be most extreme when soils are air-dried, declining, and eventually disappearing as soils become wet (De Jonge *et al.* 1999; Leelamanie and Karube 2007, 2011). Most sandy, loamy, and clayey textured mineral soils and peat are known to exhibit water repellency, at least, to some extent (Doerr *et al.* 2000; Jaramillo *et al.* 2000; Wallis and Horne 1992). Water repellency is found to be causing serious land use problems in agriculture (Blackwell 2000).

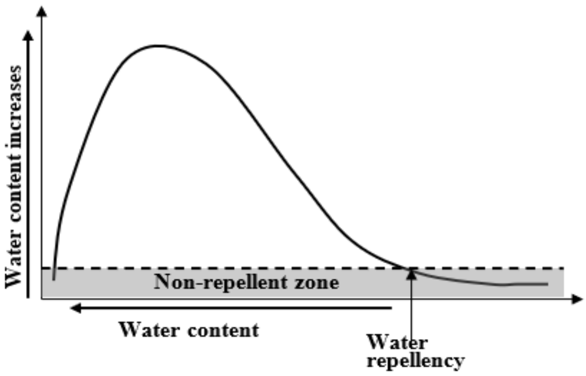

Figure 2:Water repellency varies with soil water content

2.1 Global existence

The worldwide occurrence of soil water repellency has been recognized in most parts of the world (Jaramillo *et al.* 2000). Reports are available to confirm that water repellent soils exist under various natural ecosystems in countries including Australia (Roberts and Carbon 1972), Canada (Dormaar and Lutwick 1975), Egypt (Bishay and Bakhati 1976), Japan (Nakaya 1977; Kobayashi and Shimizu 2007; Kobayashi *et al.* 1996; Leelamanie and Nishiwaki 2019), Italy (Giovannini and Lucchesi 1984), Poland (Orzechowski *et al.* 2013), the Netherlands (Dekker and Jungerius

1990; Hendrickx *et al.* 1993), Slovakia (Lichner *et al.* 2007, 2018), Spain (Imeson *et al.* 1992), Portugal (Doerr *et al.* 1996), Germany (Lichner *et al.* 2018), New Zealand (Wallis and Horne 1992), South Africa (Scott and Van Wyk 1992), Colombia (Jaramillo *et al.* 2000), the USA (Hubbert *et al.* 2006), Greece (Ziogas *et al.* 2005), United Kingdom (Mainwaring *et al.* 2004), China, Israel (Liu and Zhan 2019), India (Das and Das 1972; Mandal and Jayaprakash 2009), and Sri Lanka (Leelamanie 2016; Piyaruwan and Leelamanie 2020; Piyaruwan *et al.* 2020; Leelamanie *et al.* 2021). There are indications that under certain conditions all soils may exhibit SWR to some degree (Doerr *et al.* 2000), basically in all the continents except Antarctica.

2.2 Local existence

Although SWR has been reported for almost all major soil types and ecosystems in the world, the existence of water repellency in Sri Lankan soils has not been extensively studied and reported except for the several studies reported during the past few years (Leelamanie 2016; Leelamanie *et al.* 2021; Piyaruwan and Leelamanie 2020; Piyaruwan *et al.* 2020). Sri Lankan soils are mostly readily wettable. Most soils in the low country wet zone and some soils in the low country dry zone, and the upcountry wet zone of Sri Lanka, including wet zone forest soils are characterized by extremely rapid wetting rates. This is possibly due to the low levels of SOM as a result of rapid decomposition rates of organic matter corresponding to the prevailing very high temperature and humidity levels, throughout the year.

However, some soils in Sri Lanka are characterized by extreme water-repellent conditions. Casuarina (*Casuarina equisetifolia*) is one of the common land covers that can be seen in Sri Lankan coastal sand dunes, which were established as shelter belts for the protection of beach sides. Caribbean pine (*Pinus caribaea*) and Eucalyptus (*Eucalyptus grandis*) are planted in hillslopes of Sri Lanka with the main objective of rehabilitating the degraded lands, and now commonly found in upcountry wet and intermediate zones. Dune sands under Casuarina forests in the low country dry zone (Leelamanie 2016), and soils under exotic Pine forests and Eucalyptus forests in upcountry wet and intermediate zones (Piyaruwan and Leelamanie 2020; Piyaruwan *et al.* 2020) show extreme water-repellent conditions on the surface under natural conditions.

3.0 Origin of water-repellent soils

3.1 The ecological scale

Soil organic matter (SOM) is an important factor, which controls many functions in the soil. Waxes from microorganisms including basidiomycete fungi (Bond and Harris 1964), fungal growth (Chan 1992), plant materials (DeBano *et al.* 1970; McGhie and Postner 1981), and tree litter in vegetation types such as eucalyptus (McGhie and Posner 1980) have been suggested to be involved in the development of water repellency in the field. Potentially hydrophobic organic materials in soils are known to be produced by the plant root exudates, certain fungal species, surface waxes from plant leaves, and decomposing soil organic matter (Hallett *et al.* 2006; Mainwaring *et al.* 2004).

Studies under different climatic regions and various land-use types report numerous impacts of SWR on water systems and hydraulic dynamics in soils. Mostly water-repellent soils are associated with specific plant species that consist of significant quantities of water-repellent materials including polar waxes and/or resins.

3.1.1 Association with plant species: Global context

Eucalyptus (*Eucalyptus globulus*; *Eucalyptus grandis*) (Piyaruwan and Leelamanie 2020; Ferreira *et al.* 2000), Pine (*Pinus caribaea*, *Pinus halepensis*, *Pinus pinaster*, *Pinus sylvestris*) (Iovino *et al.* 2018; Lichner *et al.* 2013a; Piyaruwan *et al.* 2020), Japanese cypress (*Chamaecyparis obtusa*), Japanese cedar (*Cryptomeria japonica*) (Kobayashi and Shimizu 2007; Leelamanie and Nishiwaki 2019), and Casuarina (*Casuarina equisetifolia*) (Leelamanie, 2016; Leelamanie *et al.* 2021; Lin *et al.* 2006) are few examples for tree species that are associated with SWR. Soils under these vegetation types in countries over most parts of the world show water-repellent conditions to various degrees.

3.1.2 Association with plant species: Local context

Plantation forests in Sri Lanka are mainly established using non-native plant species such as pine, eucalyptus, and casuarina due to their fast growth over indigenous species. The main objectives of this exercise were to have an alternative supply of timber resources to safeguard the natural forests and to rehabilitate and protect environmentally damaged or threatened areas within a short period. However, these plantations created dialogues in the past few decades over their unsuitability for the environment as demonstrated by the pieces of evidence such as the drying-out of streams, lowering of groundwater level, absence of undergrowth, and the occurrence of SWR (Leelamanie 2016; Leelamanie *et al.* 2021; Piyaruwan and Leelamanie 2020; Piyaruwan *et al.* 2020). Although these plantation forests provide some of the expected benefits, the presence of water-repellent conditions creates various hydrological consequences.

3.1.2.1 Casuarina shelterbelt, Hambantota

Casuarina equisetifolia is an evergreen, dioecious or monoecious tree 6-35 m tall, with a finely branched crown. One of the common names of Casuarina species, 'she-oak', is widely used in Australia. The sand dune in the Dry zone of Sri Lanka is under a thick cover of *Casuarina equisetifolia* (6°06′ 52″ N 81°05′02″ E). The area falls under the DL5 Agro-Ecological Region (AER). It is one of the driest parts of Sri Lanka with an annual average rainfall of 900 mm. The soil type is sandy Regosols according to the local classification (USDA classification: Ustic Quartzipsamments).

In general, Regosols show no structural development, where both surface and subsurface soils are single-grained, with rapid infiltration and high permeability. However, the sand under this particular Casuarina shelterbelt is extremely water-repellent with very low infiltration rates (Leelamanie *et al.* 2021). The floor of the sand dune is covered with a thick litter layer of dry Casuarina leaves or phylloclades (Figure 3 a, b). The litter layer varies from about 3 to 10 cm in thickness, which seems to be interrelated with the climatic conditions, more specifically, the rainfall.

The decomposition rate of the organic matter is very low in the dry period of the year, resulting in maximum litter thickness, where the surface shows extreme levels of hydrophobic nature. Water drops placed on the sand surface takes more than one hour to penetrate the surface completely. When poured on the surface, water flows over the sand surface without showing any sign of infiltration (Leelamanie 2016; Leelamanie *et al.* 2021). The undergrowth of the area is limited to the prominent and aggressive development of Prickly Pear (*Opuntia monacantha* and *Opuntia dillenii*), which is commonly known to be "Katu Pathok" in Sri Lanka, and to a minimum development of

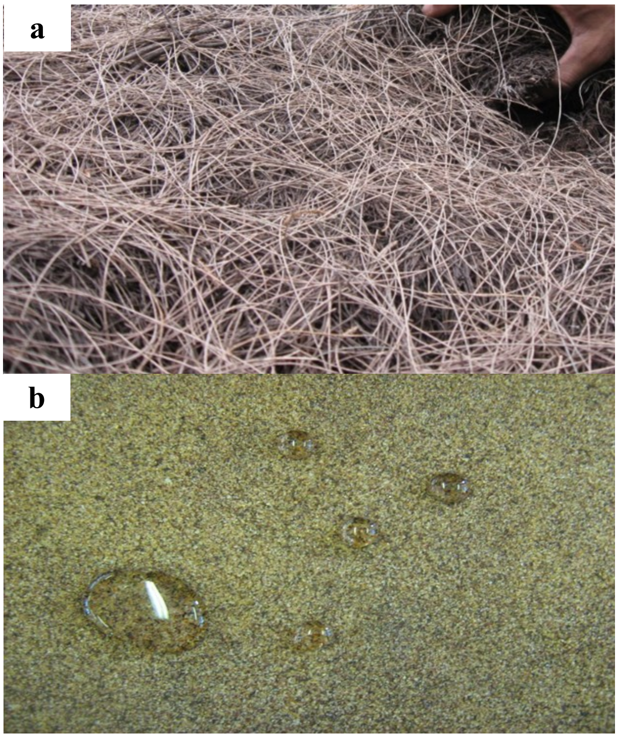

Figure 3 (a): Casuarina forest floor is covered with a thick layer of water-repellent phylloclade litter (b): Water drops applied on the surface remains for more than one hour

several common weeds.

3.1.2.2 Pine forest: Thangamale Sanctuary, Haputale

Thangamale Sanctuary, Haputale, was started with the objective of restocking the existing forests in the slope lands as a measure of preventing erosion and subsequent land degradation. A part of the Thangamale Sanctuary (6°46'16" N 80°55'52" E) in the Upcountry Intermediate zone (IU3 AER) of Sri Lanka (National Atlas of Sri Lanka, 2007) is covered with a thick growth of Pine. *Pinus caribaea* is 20-30 m tall with a generally straight and well-formed trunk and is established in Sri Lanka in 1965. The IU3 AER is the driest part of the region with an annual average rainfall of 1150 mm. The forest floor is covered with a thick layer of litter consisting of slippery dried pine leaves (Figure 4 a, b) that show extreme water-repellent characteristics. The topsoil is extremely water-repellent and the repellent level decreases towards the lower layers of the soil (Leelamanie *et al.* 2021; Piyaruwan *et al.* 2020).

Although the influence of Pines on soil hydro-physical parameters and heterogeneity of water flow is still not known to the general public in Sri Lanka, it created a dialogue over its unsuitability due to the drying out of streams, reduction of groundwater level, etc. As a result, the Forest Department has taken a policy decision not to establish new pine plantations in Sri Lanka.

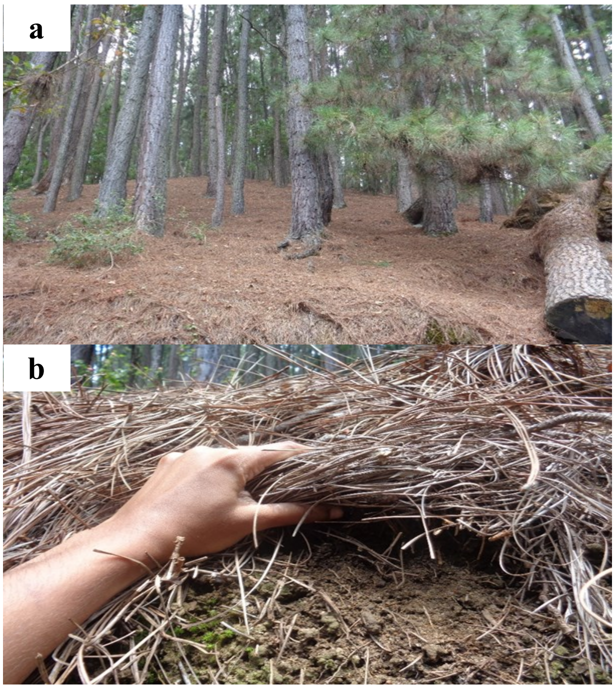

Figure 4 (a): Pine plantation at Thangamale Sanctuary, Haputale (b): Forest floor is covered with a thick layer of water repellent leaf litter

3.1.2.3 Eucalyptus forest: Diyathalawa

A water-repellent *Eucalyptus grandis* plantation forest is located in the Upcountry intermediate zone (IU3c AER, National Atlas of Sri Lanka, 2007), Diyathalawa, Sri Lanka, (06° 47′ 42″ N 80° 57′ 57″ E) with an area of around 100 ha. The area is characterized by steep slopes (~10–40°). The mean annual temperature of the area is in the range of 20–22.5°C with a mean annual rainfall of >1700 mm.

Similar to other forests with water-repellent soils, a thick mat of litter layer with 3–4 cm thickness covers the forest floor (Figure 5 a, b). The soils are sandy loam in texture and can be classified under Red Yellow Podzolic according to the local classification (Hapludults, USDA classification, Soil Survey Staff, 2014).

The surface soil is extremely water-repellent

Figure 5 (a): Eucalyptus plantation at Diyathalawa (b): Forest floor is covered with a thick layer of leaf litter

and the magnitude of repellency tends to decrease with increasing soil depth (Leelamanie *et al.* 2021; Piyaruwan and Leelamanie 2020; Piyaruwan *et al.* 2020).

3.2 The macroscale

SWR is mostly vegetation-induced because water repellency of soil is often a function of the type of organic matter incorporated in it, and organic matter is, in general, vegetation-derived in nature. The litter material collected on forest grounds with stable types of organic material such as various hydrophobic aromatic compounds shows very slow decomposition rates leading to the accumulation of such litter materials in forest soils, forming a superficial layer of vegetal residues. These litter layers continuously release various hydrophobic organic compounds into the underlying soils.

The development of SWR is associated with both the content and the composition of SOM (Doerr and Thomas 2000). Repellency occurs when originally wettable mineral particles are hydrophobized by coatings of organic substances or with the presence of intermixed organic matter with mineral soil particles (Bisdom *et al.* 1993; Bachmann *et al.* 2000b; DeBano 1981; Leelamanie 2016; Wallis and Horne 1992). SWR is known to follow short-term or seasonal variations (Doerr and Thomas, 2000).

Certain types of organic matter induce water repellency in soils by several means. Coatings of hydrophobic plant decompositional, microbial, or fungal byproducts around mineral soil particles may induce water repellency (DeBano 2000a; Doerr *et al.* 2000). Franco et al. (1995) described that wax-containing particles and wax-coated sand surfaces contribute to the development of SWR. Furthermore, intermixing of mineral soil particles with particulate organic matter, such as remnants of roots, leaves, and stems, may also induce severe water repellency (Bisdom *et al.* 1993).

Doerr *et al.* (2005) reported that some compounds extracted from wettable soils can induce hydrophobicity in wettable sand. Accordingly, hydrophobic compounds (Doerr *et al.* 2005; Leelamanie and Karube 2007 2009) or the amount and the proportion of hydrophobic functional groups in the SOM (McKissock *et al.* 2003) may not always relate to the water repellency. Yet, SOM is the most important factor affecting soil water repellency, without which the repellency would not exist.

3.3 The microscale

Alkanes, alkanoic acids, and esters are some of the common organic chemical compounds in SOM that are associated with vegetation-induced water repellency (Hansel *et al.* 2008). Water repellency is not an absolute concept because there is no surface in nature that actually exerts repelling forces on any liquid. A surface displays hydrophilic or hydrophobic characteristics depending on the level of attraction towards the liquid (water). In general, there is always some level of attraction present between any kind of liquid and any solid, and therefore, entirely hydrophobic surfaces do not exist (Tschapek 1984). When a surface is hydrophilic, it allows water placed on the surface to spread over as a thin film showing wettable behavior. In contrast, on a hydrophobic surface, water balls up to form separate droplets displaying a water-repellent nature (Adam 1963). Hurraß and Schaumann (2006) suggested that the occurrence of amphiphilic substances might also be an important factor involved in creating soil water repellency.

The presence of both free and esterified long-chain, C_{16} to C_{32} fatty acids is reported in hydrophobic extracts of non-wetting sands (Ma'shum *et al.* 1988). Franco *et al.* (2000b) reported that the components of the waxes isolated from non-wetting sand, tree litter, and other plant materials consist of un-branched and branched C16 to C36 fatty acids and their esters, alkanes, phytanols, phytanes, and sterols. It is accepted that long-chain aliphatic compounds such as long-chain fatty acids, alcohols, esters with extended polymethylene chains, and alkanes in SOM are associated with SWR (Franco *et al.* 1995, 2000a; Ma'shum *et al.* 1988). The presence, as well as the cohesion and packing of hydrocarbon chains, are important parameters in creating hydrophobic surfaces (Uddin *et al.* 2019). SWR occurs as a result of various interactions between water molecules and the molecules in hydrophobic organic coatings on soil particles or intermixed organic materials. According to some conceptual models, interactions of organic compounds with water at the surfaces can be explained properly at the nanoscale.

4.0 Theoretical aspects of water repellency

4.1 Surface free energy and contact angle

The contact angle is a quantitative measure of SWR that increases with an increasing magnitude of repellency. It is defined geometrically as the angle formed by a liquid at the three-phase boundary where a liquid, gas, and solid intersect. Surface free energy (or surface tension) is the force that operates on a surface and acts perpendicular and inward from the boundaries of the surface, tending to decrease the area of the interface (Heimenz and Rajagopalan 1997). It can be explained as the free energy per unit area or the force per unit length. The surface free energy of a solid is a characteristic factor that affects the surface properties and interfacial interactions such as adsorption, wetting, adhesion, etc.

Contact angle and surface free energy are two different parameters although they are closely related. Both are consequences of intermolecular interactions. Surface free energy is a property of the interface between two phases, and therefore, two phases must be specified to describe the property. Contact angle describes the edge of the two-phase boundary where it ends at a third phase (Figure 6).
Therefore, three phases are needed to explain

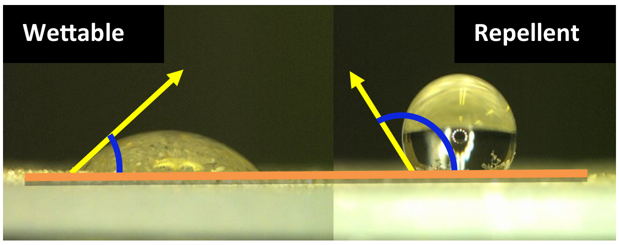

Figure 6: Soil-water contact angles of water drops placed on soil surfaces

the contact angle. Whether a liquid spread on a surface or will break up into small droplets depends on these properties (Heimenz and Rajagopalan 1997).

4.2 Liquid-solid interactions

Chemical affinities between a solid surface and a liquid at the molecular level determine the wettability of the surface and the resulting shape of the liquid drop (Heimenz and Rajagopalan 1997). Water repellency appears in low-energy surfaces, where the attraction between solid and liquid phases is weak (Leelamanie *et al.* 2007; Roy and McGill 2002). If the attraction between the molecules of a liquid (e.g. water) and the molecules of a solid surface (e.g. soil) is stronger than the attraction between liquid molecules towards each other, the contact angle becomes smaller and surface wetting occurs (Figure 7). These kinds of solid surfaces are known as high-energy surfaces, where the adhesion force is larger than the cohesion force. Alternatively, if the attraction between the molecules of a liquid and the molecules of a solid surface is weaker and liquid molecules are more strongly attracted to each other (low-energy surfaces, adhesion < cohesion), the liquid tends to bead up making a higher contact angle, showing water repellency.

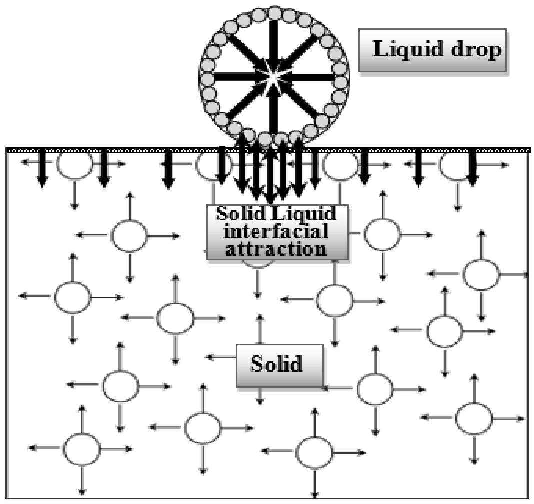

Figure 7: Surface free energy of solid and the liquid that indicate the cohesive forces, and the interfacial attractions between solid and liquid that indicate the adhesive forces

5.0 Ecohydrological behavior and implications

Water repellency in soils can have serious environmental implications, including reduced seed germination and plant growth, lowered irrigation efficiency, accelerated soil erosion, enhanced leaching of agrochemicals through preferential flow, and reduced agricultural production (Dlapa *et al.* 2004; Lichner *et al.* 2006; Shakesby *et al.* 2000; Ward and Oades 1993). It can cause delayed germination of pasture and crops, leaving soil prone to erosion. All these impacts are interrelated with the hydrological implications of SWR.

Usually, dry soils are readily absorbing water due to the strong attraction between mineral particles and water molecules. Highly wettable soils show liquid-solid contact angles of almost zero. The affinity of soil particles towards water molecules is retarded by coatings of mineral soil particles with hydrophobic substances. This will increase the liquid-solid contact angle and make soil water-repellent or hydrophobic. This phenomenon changes the capillarity of soil and influences the hydrological dynamics in soils.

5.1 Moisture content dependency

SWR is a characteristic that is highly moisture -dependent. In general, it breaks down after the soil is in contact with water for some period (Rye and Smettem 2015). The exact mechanisms behind this phenomenon are not clearly understood. However, it is generally accepted that organic molecules at the soil surface reorientate and reorganize when contacts with water droplets, where the hydrophilic groups in amphiphilic molecules start to orient toward the water, transforming the soil towards more wettable (Kleber *et al.* 2007; Kaiser *et al.* 2015; Doerr *et al.* 2000; Smettem *et al.* 2021). Consequently, the attraction through adhesion becomes stronger than the cohesion of water molecules breaking the spherical shape of water droplets leading to quick absorption of water into the soil.

SWR varies non-linearly with soil moisture content (Figure 2). In general, soils are non-repellent at high moisture contents close to saturation and start to show water-repellent characteristics with drying at a marginal water content that is specific to a particular soil (Doerr and Thomas 2000; Kobayashi and Shimizu 2007; Leelamanie and Karube 2011). Further drying usually increases the SWR to a maximum level, and extreme drying may decrease the repellency to a lower or non-repellent level (De Jonge *et al.* 1999; Regalado and Ritter 2005; Leelamanie and Karube 2007, 2011).

The water-dependent repellency curve is used to introduce water repellency parameters such as the critical water content (the marginal water content where SWR appears with drying), the water content at the maximum repellency, and the integrated area below the curve (Doerr and Thomas 2000; Regalado and Ritter 2005). Many internal and external factors such as organic matter (Franco *et al.* 1995; Leelamanie and Karube 2007), clay (McKissock *et al.* 2002; Lichner *et al.* 2006; Leelamanie *et al.* 2010), and drying temperature (Dekker *et al.* 1998) affect the SWR and the water-dependent repellency behavior of soil.

The origin of this nonlinear behavior of the relationship between soil water repellency and water content is not well understood, although some proposed hypotheses exist (Regalado and Ritter 2005). An enhanced microbial activity with increasing relative humidity, that is, the soil water content, may cause an increase in soil water repellency (Jex *et al.* 1985). Wallis *et al.* (1990) proposed that molecular conformational changes in the organic matter may responsible for the changes in hydrophobicity with water content. Doerr and Thomas (2000) suggested that the attachment/detachment of hydrophobic molecules from the soil mineral particles as water content varies might cause the water-dependent repellency. Doerr *et al.* (2002) proposed that the increased repellency with increasing relative humidity might be owing to the displacement of hydrophobic organic moieties into soil pores as the mineral and organic bonds were disrupted by the energy released from water vapor condensation.

Reduction of the surface free energy of soil particles due to an increase of adsorbed water molecules on high-energy mineral surfaces or the formation of thin water films (Derjaguin and Churaev 1986; Goebel *et al.* 2004; Leelamanie and Karube 2007; Leelamanie *et al.* 2008) may increase the contact angle and the water repellency soils.

5.2 Reduction in infiltration rates

The primary effect of soil water repellency is the reduction of infiltration rates creating unstable, irregular wetting fronts (Dekker and Ritsema 1994; Wallis and Horne 1992). The infiltration patterns in repellent and wettable soils are different (Feng *et al.* 2001; Tillman *et al.* 1989). Wettable soils typically have high initial infiltration rates, which decrease and become constant with time.

In contrast, the infiltration rate of water-repellent soils is initially slow and increases with time (Bond 1964; Wallis *et al.* 1991). Initial very low infiltration rates in water-repellent soils are due to lower attraction between soil and water. Infiltration rate increases with time due to molecular level changes and the dissolving of water-soluble material and consequently increasing the wettability of the surface. In addition, movement of water vapor, diffusion towards less water vapor, and available sites of particles improve the wettability of the entire soil and makes the infiltration rate higher.

5.3 Irregular wetting and preferential flow

The occurrence of water repellence in highly macroporous soils creates the potential for extreme spatial variability in infiltration rates (Figure 8). Under natural conditions, water-repellent soils do not show a continuous repellant layer on the surface, and therefore incomplete wetting and irregular waiting patterns can be identified in water-repellent soils. This changes the water distribution patterns in soils.

Water-repellent layers allow the water to enter the soil in discreet weak areas or "fingers" forming zones of preferential flow (Ritsema and Dekker 1996). Perturbations at an infiltrating wetting front might grow into 'fingers' or 'preferential flow paths' instead of flattening out by lateral diffusion (Annaka 2006; Baker and Hillel 1990; Kobayashi *et al.* 1996).

Figure 8: Selective penetration of water into the soil causing irregular wetting patterns

5.4 Overland flow and erosion

Erosion can be explained as a result of many factors, which can either be natural or manmade and largely associated with poor infiltration capacity of soils and extreme rainfall. As SWR reduces infiltration rates, it can contribute to land degradation caused by increasing surface runoff and topsoil erosion (Sadeghi *et al.* 2008).

The reduced infiltration capacity of soils leads to excess water accumulation, or ponding, on the soil surface that will consequently be grown into the overland flow or the surface runoff. This is usually most pronounced after strong dry periods (Doerr *et al.* 2000; Ferreira *et al.* 2000). Significant increases in overland flow cause increased erosion of the topsoil on slopes. There is also a loss of nutrients and sediments, which may end up in surface streams and waterways with the potential to cause significant pollution. There are pieces of evidence to show severe detachments of sediments in hydrophobic soils compared to hydrophilic soils (Shakesby *et al.* 2000). Therefore, the accumulation of water on the soil surface makes hydrophobic soil aggregates float. The floating aggregates can wash out from the fields in massive amounts with the increased overland flow and this will consequently increase the topsoil erosion

(Piyaruwan and Leelamanie 2020).

5.5 Water pollution

SWR can lead to the leaching of agrochemicals, increasing the risk of groundwater pollution. The preferential flow paths created due to SWR lead to the accelerated transport of contaminants in the soil matrix, specifically agricultural chemicals such as pesticides and fertilizers, to the groundwater (Blackwell 2000; Hendrickx *et al.* 1993; Smettem *et al.* 2021). SWR can contribute to land degradation caused by increasing surface runoff and top-soil erosion due to increases in overland flow as a result of diminished infiltration capacity of soils (Sadeghi *et al.* 2008). These nutrients and sediments may end up in surface streams and waterways with the potential to cause significant pollution. However, there are reports suggesting that although SWR is effective in generating considerable runoff, it would be over short distances (Sheridan *et al.* 2007). It is further noted that surface hydrophobic layers rarely cover the soil throughout over large distances some micro wettable regions can facilitate infiltration (Smettem *et al.* 2021).

5.6 Impeding plant growth and crop quality

Water repellency in soils can result in numerous problems caused by poor water movement patterns. Distribution of applied water and chemicals to agricultural fields, including soluble fertilizers or various pesticides, can be quite irregular and incomplete due to uneven wetting patterns of water-repellent soils (Doerr *et al.* 2000). This may lead to non-uniformity in crop quality.

Vertical solute leaching is greater in these preferential flow paths. Being small in area, preferential pathways through the soil lead to water movement deeper into the soil profile and to remove the water from the root zone depending on the intensity of the rainfall or irrigation event. Water draining below the root zone is lost to the plants and can be considered wastage. Not only is water wasted, but any soluble applied fertilizers in the soil will also be carried out of the plant-accessible range (Ritsema and Dekker 2000). Decreased amounts of water and nutrient availability for plant growth cause considerable losses in agricultural production.

5.7 Improvement of aggregate stability

In contrast to the significant amount of research that has been carried out on the detrimental effects of water repellency on soils, the impact of water-repellent substances on improving aggregate stability has been much less investigated. Recent studies have demonstrated that subcritical or mild water repellency in soils can improve the resistance of aggregates against disruption (Goebel *et al.* 2011).

Slaking is linked with rapid pressure buildup within aggregates. In general, there are four key processes involved in aggregate deterioration; (i) slaking when dry aggregates are suddenly rehydrated; (ii) mechanical breakdown by the raindrop impact; (iii) mellowing after wetting-drying cycles; and (iv) differential swelling/dispersion when the soil is in contact with free water for a prolonged period. Water repellency (hydrophobicity) of soil aggregates reduces their affinity for water and their infiltration capacity by the presence of hydrophobic substances and their configurations (Eynard *et al.* 2006; Kořenková and Matúš 2015). By reducing the rate of infiltration into the aggregates, water repellency helps hamper the pressure buildup within aggregates, which will reduce the aggregate disruption by slaking and mechanical impact of raindrops. High stability of soil aggregates is expected to be caused.

However, improving aggregate stability using hydrophobic organic matter is not a simple process as it appears to be. If the consequence of hydrophobic organic matter is excessive, aggregates would become too much hydrophobic, and consequently increase the topsoil erosion by the removal of floating aggregates with runoff water. In addition, highly hydrophobic soils will create all the problems that a water-repellent soil would do. Therefore, care should be taken not to exceed this critical hydrophobic condition.

6.0 Management and amelioration

Water repellency is a consequence of the decomposition of organic materials, which are an essential component of healthy soil. Therefore, the entire removal of these organic materials from the system would not be a practical solution. However, it is essential to control organic matter build-up for the reasons of maintaining adequate infiltration and drainage.

Soil management practices may affect soil water repellency. Water repellency can be reduced by management factors that reduce the total organic carbon content (Harper *et al.* 2000). Increased disturbance by cultivation reduces the repellency. No-till soils were found to have higher repellency compared with plowed soil.

Minimum tillage and zero till systems may cause an increase in water repellency due to the accumulation of organic matter in the soil surface horizon (Harper *et al.* 2000). Cultivation may decrease water repellency by both mixing and mineralization of organic matter. It may increase the clay content of the topsoil by mixing with deeper more clayey materials and thereby reducing the water repellency (Harper *et al.* 2000). Furthermore, liming may provide additional fine material and stimulate the mineralization of organic matter. This reduction in organic matter and increase in finer fraction may reduce the water repellency (Harper *et al.* 2000; Wallis and Horne 1992).

The usefulness of wetting agents as a remedial treatment for water repellency has been discussed worldwide. Remedial treatments other than wetting agents are reported to be used more extensively in many countries. Mechanical methods, such as direct drilling and wide furrow sowing, and biological methods, such as the use of microorganisms and fertilizers to stimulate the microbial breakdown of water repellency, are included in these treatments (DeBano 2000 and references therein). The effectiveness of kaolinite and montmorillonite in reducing SWR has been tested over years (McKissock *et al.* 2002, 2003; Dlapa *et al.* 2004). With the addition of fine materials such as clays, the surface area of the soil is expected to be increased (Ward and Oades 1993; Roberts 1966). However, it may cause problems in drainage (Wallis and Horne 1992). The application of surfactants can increase the infiltration of water-repellent soils. These are long-chain polymers of varying complexity with hydrophilic and hydrophobic ends. However, these compounds are not commonly used to manage soil water repellency (Wallis and Horne 1992 and references therein).

7.0 Conclusions

SWR is increasingly being recognized as a common phenomenon impacting the hydrological functions of soil systems. Studying the different related issues would be supportive for the improved understanding of the SWR. This review explains various aspects of SWR, including origin, development, theoretical concepts, impacts, and amelioration of water repellency in soils using selected research findings over ten decades.

SWR is explained as a reduction of wetting rates and water retention that is caused by the presence of hydrophobic organic matter in the soil, especially as coatings on mineral particles. However, in many locations, the exact causes of the SWR are still not clearly understood. Water repellency is theoretically explained based on the contact angle and the surface free energy of soil. Water repellency reduces the water entry into the root zone and retard plant growth, reducing the quantity and the quality of crop production. Therefore, the various detriments of soil water repellency are discussed from an agricultural viewpoint. Different amelioration techniques as the methods to overcome these problems are described at the end of this review. However, at present, there is no optimum management strategies exist for the complete removal of water-repellent conditions from soils. Any technique used in water-repellent soils should be focused on minimizing environmental hazards while maintaining high crop productivity.

SWR is highly important because it interacts and interrelates five spheres in nature. SWR is caused by the presence of organic material derived from plants or microorganisms (*biosphere*) as coatings of surfaces of, or intermixed with, mineral soil particles (*lithosphere*). It changes with prevailing atmospheric and climatic (*atmosphere*) and influences hydrological dynamics (*hydrosphere*). SWR can be altered by anthropogenic activities (*anthroposphere*). Therefore, the effects of the water-repellent conditions on the hydrophysical characteristics of soil are specific and highly important, and is an issue that requires the attention of the general public of Sri Lanka.

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