Egypt. J. Soil Sci. **Vol. 62,** No. 1, pp. 73 - 83 (2022)

Egyptian Journal of Soil Science

http://ejss.journals.ekb.eg/

Soil Magnetism and Magnetically Treated Water and Possible Role for Sustainable Agriculture: A review

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Abstract

THE interest for the application of the magnetic treatment technology in different agronomic aspects is increasing. Most agricultural studies do not take into account an important factor that may have a strong role affects the efficient application of the technology, which is the soil magnetism (SM). The magnetic susceptibility of soil is one of the measurable soil properties and utilized for different applications such as climatic information, pollution, archaeology, and agronomy. It refers to the presence of the iron oxide and oxy-hydroxide minerals, with different types and concentrations. The magnetic field (MF) affects the hydrophilic/hydrophobic character of water toward materials, soaking degree, electric conductivity, and many other properties. Many factors can affect the soil magnetism such as climate, soil drainage, Gleization, temperature, bacterial and microbial action, vegetation, and topography. This review focuses on this promising soil property and the possibility to use it as a prediction tool for a sustainable agriculture. It introduces for the subject, highlights the source of this property and measurement parameters, affecting factors, and some fields of application. It also highlights some characteristics of water when it is magnetically treated to give an overview of different topics that can be further studied to correlate the magnetism of water with the magnetism of soil for an optimum application of the magnetic technology.

Keywords: Magnetic susceptibility; Magnetized water; Soil magnetism; Sustainable agriculture

1. Introduction

The ***soil magnetism*** concept had been mentioned since 1955 (Mullins, 1977). Information about the near surface soil (30 - 50 cm) was developed for the agricultural, environmental, and other applications. Wide range studies with maps had been presented for the soil magnetic properties in the United Kingdom, Australia, China, India, Bulgaria and others. Scientific assessments and theoretical models were carried out to clarify the mechanisms of magnetic mineralogical transformations in soil and the role of soil formation conditions that affect the magnetic characteristics of soil (Dearing et al., 1996; Hu et al., 2020; Maher et al., 2002; Orgeira et al., 2008; Ramos et al., 2017; Virina et al., 2000; Zhang et al., 2021).

Agriculturally, the magnetic treatment technology showed promising applications for fertilization, plant seeds, and water used for irrigation or preparation of solutions of nutrients and fertilizers (Abd-Elrahman and Shalaby, 2017; Abdel-Fattah and Helmy, 2015; El-Basioni et al., 2015; Mohamed, 2020; Sary, 2021). It has improved the seeds germination, plant growth, yield, and yield parameters of many crops especially under stress conditions (Hussain et al., 2020; Samarah et al., 2021). Magnetization of water by passing through a magnetic field (MF) may affect the

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Received: 21/4/2022; Accepted: 15/5/2022

DOI: 10.21608/EJSS.2022.135265.1500

hydrogen bonds and Van der Waal's forces between water molecules, changes the size of clusters and affect some properties of water (Absalan et al., 2021; Karkush et al., 2019). Magnetized water (MW) may turn large moieties into smaller size that facilitate passing through the pores of plants and soils. It increases the nutrients dissolution for absorption by plants with elimination of the dissolved non-nutritive salts that are easily leached from the soil (Doklega, 2017). The magnetic treatment of seeds before sowing was promising to improve the germination and growth through biological and biochemical changes (alternation of enzymes activities). The exposure to a MF may affect the electrical charges, ion concentration, and free radicals in seeds without change in their chemical profile resulting in a more permeable membrane. It improved the emergence and crop growth and yield of the sunflower, lentil, wheat, and tomatoes (Afzal et al., 2021; Harb et al., 2021; Hussain et al., 2020; Samarah et al., 2021).

The effect of the soil magnetism on the use of water or seed magnetization is still a new emerging concept because of which this review was prepared. Studies that handle the soil magnetism property are mainly out of the agricultural field and only little studies are mentioned in the literature (Barrios et al., 2017; Jiménez et al., 2017). On the other hand, agricultural studies about the efficiency of the magnetic treatment on the use of water or seeds are almost far from studying role of the soil magnetism property. Further studies are needed to shed light on effect of soil magnetism on the use of water or seed magnetization technology, at least in the Middle East region.

Some questions may originate that are; does the soil magnetism participate in the efficient application of the magnetic technology in agriculture? Is there any interaction or relation between the soil magnetism and magnetically treated water if used for irrigation? How can the establishment of soil magnetic databases to provide information assist the sustainable agricultural planning? This review tries to answer the questions and highlight the possible role of soil magnetism for a sustainable agriculture.

2. Source of the soil magnetism (SM)

The soil magnetism (SM) mainly refers to the presence of iron oxide and oxy-hydroxide minerals, with different types, concentrations, and size distribution affecting the soil characteristics, like appearance, ionic adsorption, aggregates, and pH buffering. Detailed magnetic studies showed that magnetically, soils sometimes contain tiny amounts of coarse magnetic particles, fair magnetic particles due to predominance of the hematite and goethite, and/or powerful magnetism present in some regions.

Iron oxides in the soils originate via miscellaneous pathways dependent on the soil environment and its five forming factors, for instance, pedogenic parent mineral, pH, oxidation/reduction reactions, and water content. In addition, the magneto action of bacteria/microbes, fermentation mechanism (bio-/a bio- transformation of ferri-hydrite into maghemite then into hematite), fires, and thermo conversion of weak magneto iron species into ferri-magnetic species, as well as the anthropogenic actions and climate circumstances. Temperature and rains sometimes negatively affect the superfine ferri-magnetic species by the conversion into hematite and particle immigration enforced by intensive rains in sand soil. Biota and field practices represent additional complicated in-situ effects on the hematite and goethite status in soil (Ahmed and Maher, 2018; Hu et al., 2020).

Weathering of magnetic minerals from basic bedrock and parent material accumulates primary coarse-grain (~ 10 μm) particles (contain Ti and Ni substitutes). Additionally, fermentation of the weathered iron from magnetic and nonmagnetic soil transforms into magnetic phase by soil redox reactions. Such reactions result in finer grains (<0.1 μm) of secondary magnetite / maghemite and super paramagnetic / viscous super paramagnetic (SP) properties. Such 'magnetic enhancement' increases the magnetism of the topsoil compared with the subsoil and its parent minerals (Ahmed and Maher, 2018). Fires also convert the iron oxides that are not magnetic into finer magnetic viscous SP species. Other affecting factors can be polluted atmosphere resulted from industrial combustion of coal and steel, micrometeorites and formulations of magneto bedrock (in-situ) (Hannam et al., 2009).

3. Measurement of the Soil Magnetism

The magnetic character of a soil is mainly defined by the Magnetic susceptibility (MS, $\chi\, 10^{-8}\ m^3\ kg^{-1}$). It is a quantitative parameter indicates if a material tends to accept the magnetic character under the effect of a MF (CWA, 2008; Lu et al., 2012). Low frequency MS (χ_{lf}) as well as the high frequency (χ_{hf}) could be calculated at 0.46 kHz and 4.6 kHz, respectively, by a Bartington MS2 Meter as an example. Basic interpretation of the mentioned magnetic measures has been defined by a number of studies. We can calculate the percent of the frequency-dependent MS (χ_{fd}, %) using the equation:

$$\chi_{fd}(\%) = \left(\frac{\chi_{lf} - \chi_{hf}}{\chi_{lf}}\right) \times \mathbf{100}$$

Where χ_{lf} is the MS at low frequency indicative of concentrations of ferrimagnetic forms, and χ_{hf} is the MS at high frequency. The $\chi_{fd}\%$ represents the concentrations of the super-paramagnetic (SP <0.02 μm) ferri-magnet in the entire ferrimagnetic materials and consequently their particle-size. The $\chi_{fd}\%$ value < 2% imply lack of the fine SP ferrimagnetic particles, while $\chi_{fd}\%$ value 2–10% point out a mixed SP ferrimagnetic with coarser ferrimagnetic particles. $\chi_{fd}\%$ value > 14%, obtained by a Bartingtong-meter frequencies, are rarely in naturally occurring materials. Extremely low χ_{fd} % value, indicate the scarcity of the SP species, may be attributed to powerful post-depositional dissolution. High MS is a function of the concentration of ultrafine ferromagnetic mineral, mostly magnetite and/or maghemite (Table 1). *A concentration-dependent parameter* points out the content of magnetic minerals in a soil sample. The higher its value the higher is the concentration of magnetic minerals. *A mineralogy-dependent parameter* points out the existence of magnetically soft and/or hard minerals. Strong magnetic minerals are considered the magnetically soft minerals (such as magnetite). They are magnetised more rapidly than the magnetically hard ones that possess weak magnetism (such as haematite) and needs a stronger MF to attain magnetization. *A grain size-dependent parameter* points out the predominant size range of magnetic grains in a soil sample either fine-grained SP magnetic minerals or coarse grains (Harshavardhana and Shankar, 2021; Zhang et al., 2021). Table 2 shows some examples for the soil magnetism studied in some regions in the world.

Along with the rock magnetism, the magnetic properties in soils were also characterized by powder X-ray diffraction (XRD), high-resolution transmission electron microscope (HRTEM), and energy dispersive X-ray analysis (EDX). Some soils exhibited higher concentrations of magnetic minerals at topsoil than parent material. Very high magnetic susceptibilities were recorded for soils of high magnetism created on calcareous rock parent material at Yun-Gui Plateau at west-southern China. High weathering of these soils enriched them by iron oxides and clay minerals mostly gibbsite. Soil MS (χ_{lf}) values were between 2000×10^{-8} and 6000×10^{-8} m^3 kg^{-1}; while some layers showed MS (χ_{lf}) > 6000 to 6500 $\times10^{-8}$ m^3 kg^{-1} representing the maximum soil magnetism measured worldwide. Values of χ_{fd} in the range 210 $\times10^{-8}$ – 720 $\times10^{-8}$ m^3 kg^{-1}, may refer to predominant ultrafine magnetic particles. Gibbsite along with hematite was the major clay minerals as elucidated by XRD patterns. Results of the HRTEM/EDX revealed pedogenic nano magnetite and/or maghemite originated through chemically weathered pedogenesis under wet/dry climate conditions caused elevated MS values. These particles exhibited well crystalline nano-particles (20 to 100 nm). Enhanced magnetism of soil profiles can be attributed to high content of pedogenic super paramagnetic (SP) ferri-magnetic formulations from pedogenesis. The research elucidated the formation of pedogenic magnetite and maghemite formulations in soil on non-magnetic parent material upon pedogenesis (Lu et al., 2012).

4. Factors affecting the soil magnetism

Climate: particularly rainfall, may activate the hydrolysis of a primary mineral, which dissolves the Fe and increase the MS value. Moistured soils motivate some chemical dissolution processes of soil magnetic ores. Parent material affects the Fe availability, soil environment, and igneous rock weathering. Soil utilization, temperature in addition to the organic carbon percent participate in the hematite and goethite development and persistence in situ (Hu et al., 2020).

Drainage conditions: The climate role was studied to measure the variation the magnetism signal with variable drainage status and humidity level. Reduced soil drainage can have a destructive effect on the accumulated magnetite. The drainage extent perhaps induces the reduction/oxidation reactions of the magnetic formulations within the basic environment. Weak relation between soil pH and its magnetism status may be due to the pH dependence on the dynamic equilibrium in soil environment affected by the rain falling, alteration of the water table and nature of the parent mineral. Enhanced formation of SP species was found in basic soils, referring to varied pH values throughout the soil formation route. Changed soil humidity might clarify the change in the SP species generation. Interpretation of miscellaneous and complicated factors influencing the magnetism behavior of a soil should consider geologic and pedologic information (Orgeira et al., 2008; Virina et al., 2000).

Gleization of soil: Soils closely around a built-in reservoir in China were in general gleyed and wetted because of low-level position suffering from water-logging or poor draining opposite to far soil less or not gleyed in consequence of better drainage. Results of magnetic measurements suggested that Gleization might be related to the damage of magnetic species in opposite to pedogenetic creation of magnetic species. Soil Gleization may create a reduction environment dissolves pedogenic ferri-magnetic species rather than their removal by erosion and then surface magnetism has disappeared. However, soil magnetism as MS representing content of pedogenic ferrimagnetic content in soil usually rose when rain falling increased (if it is < 1200 mm), but decreased as rain falling increased (if it is > 1200 mm). The decreased content of soil magnetic materials when rain fall is greater than 1200 mm) often induced by Gleization resulted from moistured soil (Zhang et al., 2021).

Temperature: In the Chinese Loess Plateau (CLP), windblown dust layers of weak magnetism alternating with different magnetic fossil soils, show monsoonal variation throughout millions of years. The soil has contained iron oxides of strong magnetism, produced in-situ, under the contentious mineralogical and paleo-climatic impact. Cycles of soil wetting and drying can induce the iron reduction forming Fe^{2+} bearing magnetite. On the other hand, paleo-temperature can induce the iron oxidation forming Fe^{3+} bearing maghemite that turns into Al-substituted hematite. Another hypothetical theory correlates soil magnetism to the oxidization of maghemite-like phase (hydro maghemite) producing the ferrihydrite that turns into the hematite via ripening and aging not to the redox creation of the Fe^{2+}-bearing magnetite. Such theory would depend on the temperature more than the moisture or redox conditions. A solid solution chain of reactions usually ends with the magnetite and/or maghemite. Maghemite (γ-Fe_2O_3) and hematite (α-Fe_2O_3) have identical chemical formula but different structural formula. Maghemite has a cation-deficient spinal with insufficient Fe^{3+} ions to complete the accessible Fe sites. Ferri-magnetism of maghemite is very similar to the magnetism of magnetite. Meta-stable maghemite converts into the hematite by heating, but can be stabilized at proposed crystallographic symmetries. The structural formula of the nano-ferrite crystal can be characterized by EDXA elemental composition, geometry information on the reciprocal lattice, and planes of symmetry (Ahmed and Maher, 2018).

Bacterial and microbial action: Soils of strong magnetism at non-polluted regions across England are observed over substrates of weak magnetism with predominant very fine super paramagnetic species. Strong magnetism of soil may not be attributed to burn of crops or presence of non-significant concentration of magneto-tactic bacteria. A suggested mechanism relates the development of secondary ferrimagnetic mineral to abiologic weathering and biologic fermentation reactions. Climate can be considered as a basic motivator in the Fe release mechanism. Iron reducing bacteria possibly convert ferrihydrite into magnetite that is oxidized into maghemite across time (Dearing et al., 1996).

Vegetation: Electromagnetic properties of soil probably affected by surface vegetation as well as roots, rocks, cracks, spaces and pores in soil can raise the fake alarm records of some metal detectors depending on its design. Indicative values of MS (10-5 SI) were suggested: Neutral (< 50), Moderate between 50 and 500, Severe between 500 and 2000, Very severe greater than 2000 (CWA, 2008; Lu et al., 2012). The Digital soil mapping (DSM) technique related with iron oxides can present a mineralogical description for a soil (Ramos et al., 2017).

Topography: living along with non-living organic matter in addition to timing is important factors govern soil formation. Topography is a pedogenic aspect affects the soil physically, chemically, biologically and magnetically because Fe-bearing matrices have strong oxidation-reductions sensitivity. Among the geophysics techniques is the magnetism of rocks that is used to determine the intrinsic MS depending on the content, mineralogy as well as particle size of magneto mineral deposits existing unique for every environmental condition. Topography influences the soil profile magnetism of the hills independent of rains falling or organic matter concentration. Decreased content of magneto formulations and their coarsening to the tops of the profiles indicate the effect of soil erosion (Harshavardhana and Shankar, 2021).

5. Applications of soil magnetism measurements

Climatic information

Soil magnetism became a vital informative tool for climate studies. The pedogenic magnetic concentration in case of non-polluted buffered soil with better drainage sometimes reveals the climate effect in particular, rains falling. New lands spread in the Chinese Loess Plateau show significant but uncertain correlation of the soil pedogenic magnetism with yearly rain falling. Magnetic susceptibility of such soils originates from the minor content of magnetite ~0.3% accompanied by its oxidization subsequent maghemite as extremely fine ≤ 30 nm. Except the vegetation as a climate co-variable, soils formation factors in the region are generally invariable. Therefore, soil magnetism mainly has a climatic dependence. Statistic correlations of the soils magnetism with the main climatic factors recognized the yearly rains falling is the most significant one for the studied region (R2 = 0.93) (Maher et al., 2002).

Pollution: MS mapping has been carried out for around eighty kilo meters square district located at the south-eastern Nile delta, which is characterized by overlapped utilization in the fields of agriculture, residence (urbanization and land reclamation), and numerous industries. Data of the MS matched most of chemistry data of the collected samples near the industrial spots providing an efficient qualitative tool for the spatial distribution of pollutants (Guda et al., 2020). This novel environmental magnetism technique was also an assessment tool of polluting elements in water reservoir sediments (Chaparro et al., 2020).

Surface soil magnetism in Delhi was a characterization tool of the regional pollution levels considering the content of the magnetic materials (Magnetic Domain) as an indicator of toxicants and pollutants. Since contaminated soils contain less paramagnetic and diamagnetic materials than the unpolluted. This study revealed that ultrafine particulates are not necessarily related to high ferrimagnetic content at least in soil. Regions of industries and heavy traffic in Delhi have more concentrated magnetic materials of lower paramagnetic and/or diamagnetic role compared with green and residence regions (Meena et al., 2011).

Seasonal variation of dust flux has been found significantly inversely related to the MS (χ). Results of scanning electron microscope (SEM) with energy dispersive spectroscope (EDS) presented distinct elemental and morphological characteristics of magnetic particulate from different sources. Waste magnetic particles of natural origin exhibited almost levelled surface mainly contains Fe, O, and insignificant existence of Ti. Most of anthropogenic particulates showed angular, spherical, aggregate, and porous shape distinguished by presence of marking elements such as S, Cr, Cu, Zn, Ni, Mn, and Ca. Anthropogenic dust resulted from human activities contained higher levels of poisonous heavy metals like Pb, Zn, Co, Cr, Ni, or As. (Liu et al., 2019a).

Digital soil mapping (DSM): MS measurement can be applied to digital soil mapping (DSM) to support the identification of soils forming conditions and the distinction of different pedogenic environments. The mineralogy identification of the soil profiles referred to that the content of iron oxide formulations depend on the profile location at a hill slope (Ramos et al., 2017). High litho-logical variability could be linked to the difference in magnetism characteristics and other factors, like lithology, micro-morphology, particle size distribution, and total organic carbon (TOC) percentage (Lisa et al., 2012).

Archaeology: Magnetometry is widely used as scientific toolkits utilized by archaeologists (Bigman, 2014; Fassbinder, 2015a). Magnetic prospecting as an archaeological method helps to detect and map archaeological sites and analyze landscapes because most of surface soils show signs of MS. Advanced computerized technologies as well as satellite navigation allow the utilization of instrumental multi-sensors with real-time GPS. Concentration of iron oxides and organic matter in soils determine their colour. A measurable variation in the MS requires just a small change in the ppm-scale of ferrimagnetic Fe- oxides (Fassbinder, 2015b).

Soil magnetism affects metal detectors and ground penetrating radar (GPR) specially hampering processes through landmines clearance. Magnetic properties of soil affect the electromagnetic induction and performance of magnetic sensors. Super paramagnetic minerals in soil have frequency dependent (FD) characteristics exhibit signals comparable to the metallic components of land mines that give fake alarms. Such characteristics may occur uniquely for iron oxides resulted from natural formation over time in the soil profiles. Soil maps can describe various kinds of soils without magnetic information (Hannam et al., 2009).

Agronomy: MS can play a role in the soil survey and evaluation to improve crop production and planning sustainable agricultural practices. Magnetic susceptibility was highly correlated with some soil characteristics such as sand and clay percentages, field capacity, thermal conductivity, bulk density, and total pore space (Virina et al., 2000). Differences were attributed to soil tillage. Consequently, para-magnetism as a physical property measured both in-situ and ex-situ can help in the estimation of some soil characteristics. The precision of soil MS being dependent on many physical properties is influenced by the extent to which the soil is physically disturbed (Jiménez et al., 2017).

Sugarcane management practices were found to be interfering with dynamics of soil magnetism. Magnetic susceptibility can be a soil quality indicator in sugarcane cultivation areas. Magnetic signature expressed by MS was beneficial in the mineral quali-quantitative analysis in tropical soils to sign the emitted CO_2 indicating the environment quality, identifying land boundaries and areas of potential erosion in sustainable farming. It identifies differences in physical, chemical, and mineralogical characters of Latosols (Oxisols) upon sugarcane harvesting either have earlier burns or not, i.e. cropped and exposed to fire (Barrios et al., 2017).

Far from the soil magnetism concept, the MF applied agronomically has improved the conventional systems of plant production (Table 3). It increased the rate of germination, root, and shoot development, photosynthesis of pigments, cell division, yield, water, and nutrient uptake (Liu et al., 2019b). Clear explanation of the induction mechanism through which the plant responses to the MFs controlling the signal transduction pathway is still incomplete. The magneto biological effect and the geno-toxic side effects of MFs need further studies (Sarraf et al., 2020).

The MF treatment of water changed its boiling point, specific heat, and evaporation, at MF strength of 300 mT. This is useful in industry since magnetized water (MW) can better cool power generators and increase their efficiencies (Wang et al., 2018). Magnetic fields change the hydrophilic/hydrophobic character of water toward materials, soaking degree, electric conductivity, viscosity, depress its surface tension forces, enhance water flowing, increase its refraction index, and dielectric constant. Novel properties of water and different electrolytes (for example, Table 4, (Absalan et al., 2021)) are promising agriculturally, industrially, and medicinally (Xiao-Feng and Boa, 2008).

The MF action on the molecular and atomic structures of water was defined by the FT-IR, Raman, Vis-UV spectroscopy, and X-ray light analysis. Water after magnetization showed shifted peak in the X-ray diffractogram and differences were observed in the Raman scattering as well as the FT-IR and UV absorption compared with the non-magnetized water. Peaks intensity and frequency were changed, and some new peaks appeared at 25 °C after water was magnetized. Shifts are correlated to the magnetization time, MF strength, and water temperature. Furthermore, the contact angles of MW on the hydrophobic surfaces decreased. The molecular clusters of H-bonded chain structures and polarizability of water were changed when subjected to a MF (Xiao-Feng and Bo, 2008).

TABLE 1. Some parameters of soil magnetism measurements with interpretations (Harshavardhana and Shankar, 2021)

Parameter with units	Indicative of
Mass-specific low- and high-frequency magnetic susceptibility (χ_{lf} and χ_{hf}, 10^{-8} m^3 kg^{-1})	Concentration of ferri-magnetic minerals
Frequency-dependent magnetic susceptibility (χ_{fd}, 10^{-8} m^3 kg^{-1}) χ_{fd} ($\chi_{lf} - \chi_{hf}$) Frequency-dependent magnetic susceptibility percentage (χ_{fd} %, dimensionless) Proportion of SP grains	Concentration of ultra-fine grained super-paramagnetic (SP) minerals
Susceptibility of an-hysteretic remnant magnetization (χ_{ARM}, 10^{-5} m^3 kg^{-1})	Concentration of single domain (SD) ferrimagnetic minerals
Isothermal remnant magnetization (IRM) and Saturation IRM (SIRM) (10^{-5} A m^2 kg^{-1})	Concentration and grain size of remnant -carrying minerals

TABLE 2. Examples for soil magnetism measurments in some regions

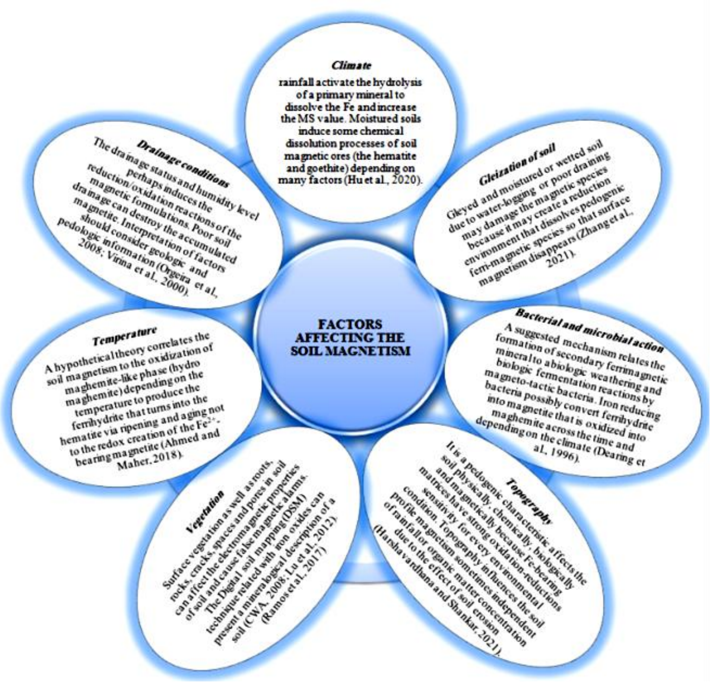
Country/Region	Magnetic susceptibility (χ, m^3 kg^{-1})	Origin of magnetism	Reference
Yun-Gui Plateau of west-southern CHINA	$\chi_{lf} = 2000 - 6000 \times 10^{-8}$ m^3 kg^{-1} $\chi_{fd} = 210 - 720 \times 10^{-8}$ m^3 kg^{-1}	pedogenic nano-scale magnetite/maghemite 20 – 100 nm in size and exhibited well crystalline nano particles pedogenic super paramagnetic (SP) ferrimagnetic minerals upon pedogenesis. calcareous rock parent materials	(Lu et al., 2012)
Guizhou Plateau, SW CHINA	$41 - 95 \times 10^{-8}$ m^3 kg^{-1}	Ferri magnets and their SSD grains proportions of the total ferri magnets in the total magnetic minerals SP ferri magnets in the sediments	(Zhang et al., 2021)
Doddabathi-Siddeshwara Hill and Elimale Hill, Karnataka, INDIA	$\chi_{lf} = 261.67 - 67.70 \times 10^{-8}$ m^3 kg^{-1} $\chi_{fd} = 27.36 - 7.46 \times 10^{-8}$ m^3 kg^{-1}	Ferrimagnetic minerals with different concentrations and grain size	(Harshavardhana and Shankar, 2021)
Southern Part of the Russian Plain	$\sim 20 \times 10^{-8}$ m^3 kg^{-1}	In situ formation of fine grains of Magnetite (maghemite) with pedogenic origin through Sedimentary processes and Terrigenous magnetic minerals.	(Virina et al., 2000)
Transect spanning the RUSSIAN steppe from the N. Caucasus to the Caspian Sea	$\sim 10 - 95 \times 10^{-8}$ m^3 kg^{-1}	ferrimagnetic grains that are so fine grained ($\leq$ 20 nm) as to be super paramagnetic (SP) magnetite/maghemite	(Maher et al., 2002)

TABLE 3. Examples for application studies of magnetically treated water (MTW) in crops cultivation

Country	Type of study	Type of plant under study	Magnetic treatment (MT)	The most important findings	Reference
Cuba	Field experiment	Dry onion seeds	Pre -sowing magnetic treatment of seeds (160 mT milli Tesla -15 min)	The onion productivity was significantly improved due to enhanced germination, seedling emergence, plant growth, bulb formation, and yield. Bulb yield per area for the control was 2.56 kg m^{-2}, while for the magnetically treated seeds was 3.58 kg m^{-2}	(De Souza et al., 2014)
Pakistan	Field experiment	Sunflower	1- Seeds exposed to magnetic field strengths of 50, 100 and 150 mT for 5, 10 and 15 min 2- Seeds priming with magnetically treated water contains 3% moringa leaf extract (MLE+MTW) for 12 h	Magnetic seed treatment with 100 mT for 10 min and seed priming with 3% MLE solution in magnetically treated water (MTW + MLE) significantly improved the emergence, sunflower growth rate and yield. Achene yield for the control was 1321 Kg ha^{-1} and for seeds primed in the magnetically treated water was 1760 Kg ha^{-1}	(Afzal et al., 2021)
Iran	Pot experiment	Maize seeds germination	Irrigation by magnetically treated saline water (0.5, 2, and 6 dS m^{-1}) by a magnetic field 1,500 mT	Irrigation by the magnetically treated water increased the vegetative growth of maize seeds in all treatments. The Dry weight (g) of seeds in case of the magnetized-saline water was 0.75 g compared to 0.68 g in case of the saline water (6 dS m^{-1})	(Abedinpour and Rohani, 2017)
Egypt	Field experiment	Cowpea	Irrigation by magnetically treated saline water (salinity levels (3.14, 6.25 and 9.37 dS m^{-1}) by a magnetic field 1.4 Tesla	The irrigation by magnetically treated saline water (9.37 dS m^{-1}) has increased the seeds yield from 560 kg fed^{-1} (Control) to 970 kg fed^{-1} for the treatments irrigated by the magnetically treated water	(Sary, 2021)
Jordan	Laboratory experiment	Tomato	1- Irrigation by magnetically treated NaCl salt solutions (0, 5, 10, and 15 dS m^{-1}) through a magnetic field (3.5–136 mT) 2- Exposing tomato seeds to the magnetic field (3.5–136 mT) for 20 min before sowing	Magnetic treatment of saline water or seeds has improved the germination, plant growth, and fruit yield of tomatoes under saline conditions. The fruit yield was increased from 701 g/plant for the untreated to 1106 g/plant for the magnetically-treated salt water (5 dS m^{-1})	(Samarah et al., 2021)
Egypt	Field experiment	Faba been	Fertilization by spraying magnetized (at 1.4 Tesla) aqueous K- humate solutions (KHM) in presence of soil applied phosphate fertilizers	Treatments have enhanced the efficiency of the phosphorus fertilization under the sandy soil conditions. Seed yield was increased from 2.28 Mg ha^{-1} (control) and/or 2.52 Mg ha^{-1} (control K-Humate) to 2.60 Mg ha^{-1} for the magnetically treated K-humate solution (KHM)	(Mohamed, 2020)

TABLE 4. Zeta potential of some magnetized electrolytic solutions (Absalan et al., 2021)

Electrolytes	Zeta Potential (mV)	
	Magnetized	Not-Magnetized
KF	64.7	68.1
KOH	68.2	69.2
NaOH	70.5	74.4
KCl	62.9	65.0
KBr	63.4	67.4
KI	66.1	71.6
KSCN	68.1	71.8
NaCl	65.9	67.6



FACTORS AFFECTING THE SOIL MAGNETISM

Climate

rainfall activate the hydrolysis of a primary mineral to dissolve the Fe and increase the MS value. Moistured soils induce some chemical dissolution processes of soil magnetic ores (the hematite and goethite) depending on many factors (Hu et al., 2020).

Gleization of soil

Gleyed and moistured or wetted soil due to water-logging or poor draining may damage the magnetic species because it may create a reduction environment that dissolves pedogenic ferri-magnetic species so that surface magnetism disappears (Zhang et al., 2021).

Bacterial and microbial action

A suggested mechanism relates the formation of secondary ferrimagnetic mineral to abiologic weathering and biologic fermentation reactions by magneto-tactic bacteria. Iron reducing bacteria possibly convert ferrihydrite into magnetite that is oxidized into maghemite across the time and depending on the climate (Dearing et al., 1996).

Topography

It is a pedogenic characteristic affects the soil physically, chemically, biologically and magnetically because Fe-bearing matrices have strong oxidation-reductions sensitivity for every environmental condition. Topography influences the soil profile magnetism sometimes independent of rainfall or organic matter concentration due to the effect of soil erosion (Harshavardhana and Shankar, 2021).

Vegetation

Surface vegetation as well as roots, rocks, cracks, spaces and pores in soil can affect the electromagnetic properties of soil and cause false magnetic alarms. The Digital soil mapping (DSM) technique related with iron oxides can present a mineralogical description of a soil (CWA, 2008; Lu et al., 2012) (Ramos et al., 2017)

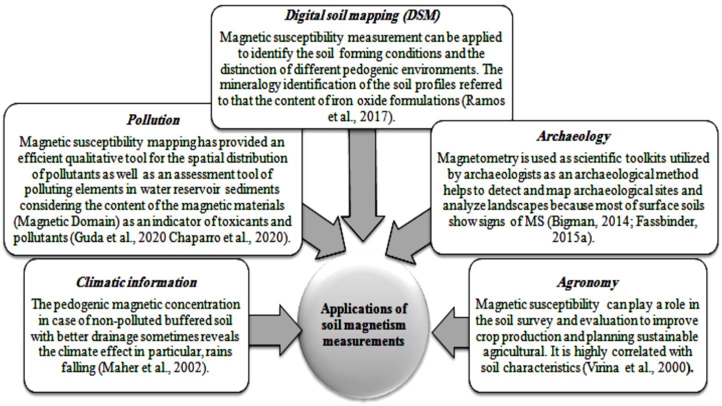
Temperature

A hypothetical theory correlates the soil magnetism to the oxidization of maghemite-like phase (hydro maghemite) depending on the temperature to produce the ferrihydrite that turns into the hematite via ripening and aging not to the redox creation of the Fe^{2+}-bearing magnetite (Ahmed and Maher, 2018).

Drainage conditions

The drainage status and humidity level perhaps induces the reduction/oxidation reactions of the magnetic formulations. Poor soil drainage can destroy the accumulated magnetite. Interpretation of factors should consider geologic and pedologic information (Orgeira et al., 2008; Virina et al., 2000).

Fig. 1. Factors affecting the soil magnetism



Digital soil mapping (DSM)

Magnetic susceptibility measurement can be applied to identify the soil forming conditions and the distinction of different pedogenic environments. The mineralogy identification of the soil profiles referred to that the content of iron oxide formulations (Ramos et al., 2017).

Pollution

Magnetic susceptibility mapping has provided an efficient qualitative tool for the spatial distribution of pollutants as well as an assessment tool of polluting elements in water reservoir sediments considering the content of the magnetic materials (Magnetic Domain) as an indicator of toxicants and pollutants (Guda et al., 2020 Chaparro et al., 2020).

Archaeology

Magnetometry is used as scientific toolkits utilized by archaeologists as an archaeological method helps to detect and map archaeological sites and analyze landscapes because most of surface soils show signs of MS (Bigman, 2014; Fassbinder, 2015a).

Applications of soil magnetism measurements

Climatic information

The pedogenic magnetic concentration in case of non-polluted buffered soil with better drainage sometimes reveals the climate effect in particular, rains falling (Maher et al., 2002).

Agronomy

Magnetic susceptibility can play a role in the soil survey and evaluation to improve crop production and planning sustainable agricultural. It is highly correlated with soil characteristics (Virina et al., 2000).

Fig. 2. Applications of the soil magnetism measurements

6. Conclusions and recommendations

The response of soil to the magnetically treated water (MW) in view of soil magnetism (SM) measurement and mapping can be used as an efficient guide for the application of the magnetic technology for sustainable agriculture. Optimum application of the technology based on SM needs more studies to assess the technology use efficiency for different crops especially under different stress conditions and climate change.

7. Conflicts of interest

"There are no conflicts to declare".

8. Formatting of funding sources

This review was prepared free of public or commercial fund.

9. Acknowledgments

The author thanks very much the staff members at the Sandy and Calcareous Soil Research Department for their continuous help and support.

10. Author's Contribution

Rama T. Rashad designed the manuscript, carried out the literature survey, wrote the draft, read, and approved the final manuscript.

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