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Review
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ON VARIOUS SOIL MOISTURE MEASUREMENT TECHNIQUES AVAILABLE IN THE LITERATURE

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Abstract: The sustainability and health of soil associated with its productivity are closely related to soil moisture. The amount of water in the soil is an important parameter in the mobility of nutrients in the soil, in soil reclamation studies, and in the leaching-transportation and mixing of fertilizers and other chemicals applied to the soil into the groundwater. On the other hand, it has become important today not only to minimize water consumption but also to accurately measure the amount of moisture in the soil so that the proper amount of water that the plant needs can be circulated to the root zone of the plant. In this context, information was given about various measurement methods for determining soil moisture (direct and indirect - thanks to correlations) existing in the literature, and among these studies, especially the studies on microwave methods were examined. Comparison results of the dielectric constant values are obtained for three different soil samples with different gravimetric volumetric moisture rates by one of the calibration-independent non-resonant microwave measurement methods, which have a high application potential and is different from the existing calibration-requiring microwave measurement methods, and the dielectric constant values predicted by the Mironov model in the literature are presented. The comparison result showed that this new type of microwave measurement method has a high potential for measuring the moisture value of soil samples.

Keywords: Soil moisture, Direct and indirect methods, Microwave methods, Calibration-independent

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1. Introduction

The sustainability of the soil, which is related to the productivity and health of the soil, depends on the amount of water it contains (Orgiazzi et al., 2016). The productivity of soils is decreasing day by day due to salinity, desertification and destruction of agricultural lands (TOB, 2019). The World Meteorological Organization predicts that extraordinary weather events caused by climate change will increase day by day. In this context, sustainable and protectionist agricultural policies need to be brought to the fore for the future of our country (Atlı et al., 2021).

The amount of water in the soil is an important parameter in the mobility of nutrients in the soil, in soil reclamation studies, and in the washing-transportation and mixing of fertilizers and other chemicals applied to the soil into the ground water (Hupet and Vanclooster, 2002). Water in the soil can flow both horizontally and vertically. The flow of these two types of water provides not only the amount of water the plant can absorb, but also the mobility of nutrients in the soil and microbial diversity.

On the other hand, understanding the extent to which rainwater passes into the soil profile becomes important, especially in dry farming areas. The amount of water that needs to be given to the soil and the time of giving this water are important in terms of water saving. In this regard, it is necessary to measure the moisture content of the soil along the soil profile at different times in order to increase the soil water cycle. However, making measurements of this type (over different time and different soil layers) is not only costly for large agricultural lands (Moore et al., 1988), but also does not seem to be very profitable even in small lands in our country where agricultural soil properties change frequently.

In addition to the above reasons, it is important to accurately measure the amount of moisture in the soil in order to minimize water consumption and send as sufficient water as the plant needs to the root zone of the plant (Yetik and Aşık, 2021). This is also very important in creating and implementing a plant irrigation program, making fertilizer applications more effectively, saving water, and not putting the plant under water stress or leaving it dehydrated (Çetin, 2003).

When the literature studies on soil moisture measurement are examined (Öztaş, 1997; Uytun et al., 2013; Özbek and Kaman, 2014; Karaca, et al., 2017; Başdemir, 2020; Yetik and Aşık, 2021), it can be seen that these studies have no information about microwave measurement methods that have made significant progress in recent years. It contains no information or partial information. In this study, different methods will be briefly explained regarding the accurate determination of soil moisture, and then detailed information about microwave methods will be presented. Finally, unlike the calibration-requiring microwave measurement methods, the dielectric constant values obtained for three different soil samples with different gravimetric volumetric moisture ratios with a non-resonant measurement method that does not require calibration and has a high potential in determining soil moisture, which has recently entered the literature and has a high potential in determining soil moisture, were compared with the Mironov model in the literature. Comparison results with dielectric constant values obtained from a model known as are presented. The comparison shows that calibration-requiring microwave methods could have the potential to prevent the problems of low measurement sensitivity caused by calibration standards, and calibration-free microwave measurement methods could have a high potential in the accurate determination of soil moisture.

2. Various Direct and Indirect Methods Used in Soil Moisture Determination

There are different methods in the literature for faster and more reliable measurement of soil moisture. These methods can generally be divided into two groups: direct and indirect methods.

2.1. Direct Methods

These methods are gravimetric methods and are based on the principle of removing moisture from the soil sample by heating, washing, or chemicals and then finding the mass of water (Gardner, 1986). In the gravimetric method, samples are taken from different layers of the soil with the help of a simple hand auger (Figure 1).

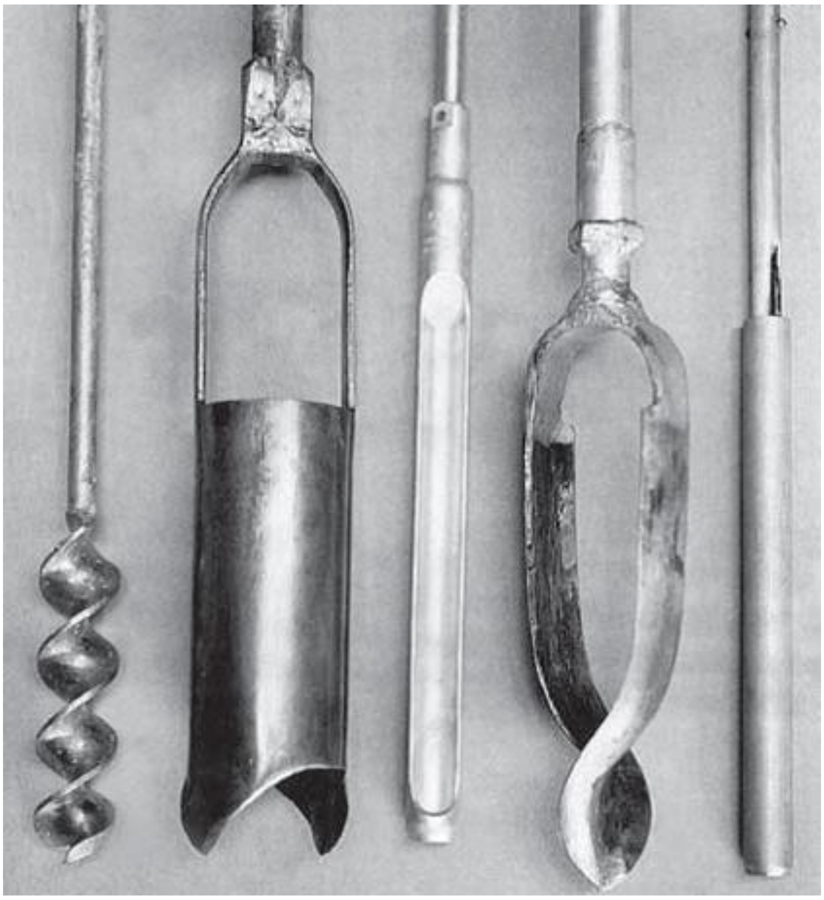

Figure 1. Image of various soil augers and tubes.

Sampling with a soil auger is both easy and allows taking soil samples of the sufficient quality. In measurements made with direct methods, soil moisture is made on a mass or volume basis. However, in cases where the soil area is large, requiring very different measurements, in fragmented lands where the soil has very different textures, and even in dry, hard, stony, and gravelly lands, sampling with a soil auger can be both challenging and time-consuming. At the same time, this situation causes the formation of macropores in the soil and consequently changes the moisture pattern of the soil (Kutilek and Nielsen, 1994).

2.2. Indirect Methods

Soil moisture measurements made by indirect methods are based on associating soil moisture with another property of the soil. In these methods, a correlation is generally tried to be established between the physicochemical properties of the soil and the moisture of the soil. One of the advantages of this method is that the applied sensors can remain in the soil for a long time during the analysis (they can provide information about soil moisture over a wide period of time). Another advantage is that the sensor placed in the soil does not adversely change the soil texture, compared to direct methods that are carried out multiple times. Additionally, measurements made with these methods are generally very fast (Öztaş, 1997).

There are indirect methods with different types and features in the literature: Time-space reflectometer, frequency-space reflectometer, time-space transmissometer, ground penetration radar, neutron meters, tensiometers, porous blocks, electrical resistance blocks and microwave methods (Uytun et al., 2013; Karaca, et al., 2017; Başdemir, 2020).

As one of the most frequently used indirect methods, the time-space reflectometer method determines the moisture content in the soil by means of multiple probes placed in the soil (Figure 2).

Figure 2. An image of a time-space reflectometer device (Soil Sensor, 2021a).

The lengths of the probes generally vary between 10-30 cm (Soil Sensor, 2021a). In this method, the process of determining soil moisture varies according to the principle of measuring the dielectric constant of the soil (Topp and Reynolds, 1998).

While time-space reflectometer measurements are based on the principle of reflection of short pulses within the soil texture in time space, frequency-space reflectometer measurements are based on reflection measurements in frequency space (Figure 3). Like time-space reflectometer measurements, frequency-space reflectometer measurements are based on dielectric constant measurements. The measurements made vary greatly with the volumetric water density in the soil. This is because radio frequency signals change significantly with the amount of moisture in the soil.

The working principle of the time-space transmissometer is parallel to the working principle of the time-space reflectometer. This method works on the response that occurs as a result of the signals transmitted from the soil sample propagating (travelling) along the length of the line containing the soil sample, as opposed to the response that occurs when the pulse generated in time-space is reflected from the soil sample (Figure 4). Although the shape of the transmitted waveform is not important, measuring the pulse travel time along the transmission line will allow an estimate of the dielectric constant of the medium. The speed of the pulse is related to the dielectric permittivity (Soil Sensor, 2021b).

As another indirect method, ground penetration radar is also frequently used. In this method, both transmission and reflection properties of electromagnetic signals in the range of 106-109 Hz in the soil are used (Figure 5). Operating frequency (center frequency), resolution and penetration depth are the basic parameters used in measurements made with this method (Daniels, 2007). Here, resolution means the ability to distinguish two signals in time space and generally increases with increasing operating frequency (Davis and Annan, 1989; Huisman and Bouten, 2001). On the other hand, the depth range decreases as the electrical conductivity of the soil increases. Measurements made in ground penetration radar measurements are highly affected by the penetration depth and electrical conductivity of the soil; because soil salinity and soil moisture content are two factors that strongly affect soil conductivity (Daniels et al., 1995; Huisman et al., 2003).

Figure 3. An image of a frequency-space reflectometer device (Experimental Hydrology, 2021).

Figure 4. An image of a time-space transmissometer device (Soil Sensor, 2021b).

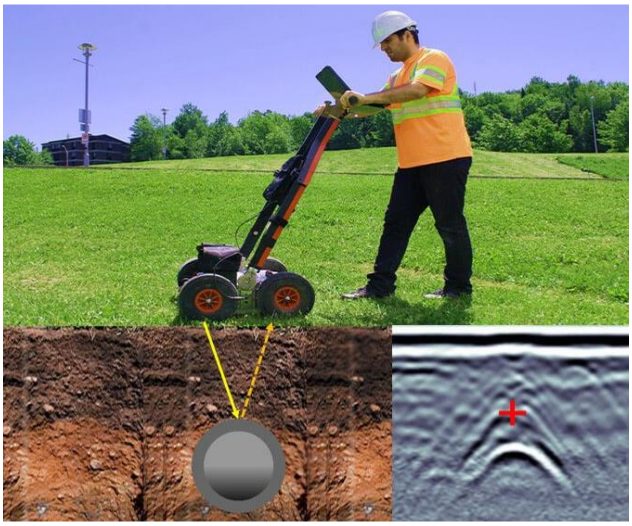

Figure 5. An image of a measurement made with a typical ground penetration radar device (Frimec, 2021).

In addition to the indirect methods mentioned above, neutronmeters are also among the methods used to determine the moisture content of the soil. The difference of this method from other indirect methods is that it provides soil moisture measurements at different times and layers in a simple, reliable, and fast way. Devices using this method consist of a radioactive source, a counter and a detector tube that counts the neutrons coming out of this source, which slow down after hitting the atoms in the soil (Figure 6). Calibration of neutronmeters is very important for reliable humidity determination.

Tensiometers, on the other hand, work with a principle based on soil water tension change. Tensiometers consist of cylindrical tubes with a diameter of approximately 2.54 cm, containing a vacuum at one end and a porous ceramic cup at the other end (Figure 7). The biggest advantage of tensiometers is that they provide data for long periods of time after being placed in the soil (Grattan and Oster, 2003).

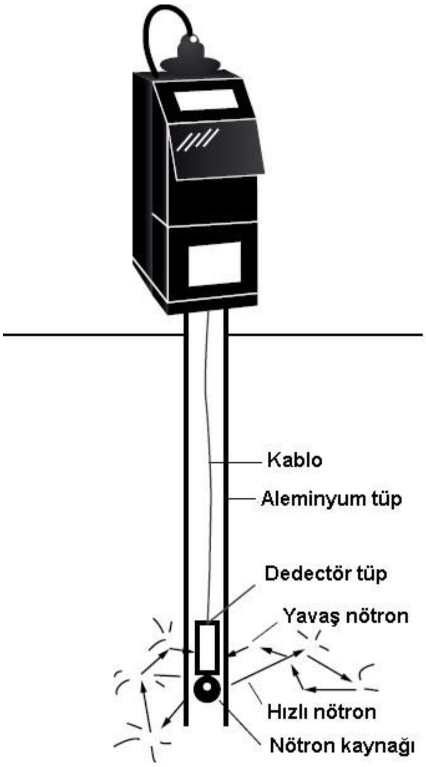

Figure 6. A typical image of the neutronmeter device (General Directorate of Meteorology).

Figure 7. Image of a tensiometer (Esi, 2021).

Another indirect method used to determine soil moisture is porous blocks made of nylon, fiberglass or ceramic. In this method, porous blocks are buried at a certain depth in the soil according to the physical, chemical and texture structure of the soil. In this method, the amount of soil moisture is determined according to the soil-water tension principle. In the indirect method of electrical resistance blocks, soil moisture determination is determined by the resistance value obtained from the principle of measuring the current passing through specific blocks and the voltage between these blocks against the current and voltage applied to the blocks. The sensitivity of the measurements is generally more suitable for determining soil waters with high resistance (Başdemir, 2020).

Another indirect method that can be used to determine soil moisture is measurements made with microwave signals. Microwave signals corresponding to the frequency range of 0.3-30 GHz are electromagnetic signals. The most important feature of microwave signals is that they include the 1-3 GHz frequency range, where the interaction of water in the soil is high (Pozar, 2011). Soil moisture determination using microwave signals is carried out by measuring the microwave signals reflected from and transmitted from the soil. Detailed information about these methods will be mentioned below.

Although they have advantages, the accurate results of indirect methods used in soil moisture determination directly depend on calibration and environmental factors (Topp and Ferre, 2002).

3. Information about Indirect Microwave Methods Used in Soil Moisture Determination

As mentioned above, microwave methods that use the correlation between the electromagnetic properties of soil samples and their moisture content are in the class of indirect methods. We can divide the various microwave measurement methods in the literature into two separate groups: resonant and non-resonant (Chen et al., 2004). In resonant-type microwave methods, the electromagnetic properties of the samples are determined by placing the sample, shifting the resonant frequency and using a combination of the magnitude of the resonant frequency. These methods, which generally work on the principle of the low-loss sample assumption (low perturbation), are more suitable for determining the electromagnetic properties of low-loss samples. Another disadvantage of these methods is that measurements are limited to only a single resonance frequency or frequency range in a narrow band (Lonappan et al., 2009; Sheen 2009).

On the other hand, non-resonant microwave techniques allow electromagnetic characterizations to be made in a much wider frequency range compared to resonant microwave techniques. This is especially important in terms of determining the dielectric constant of soil samples with different moisture contents. In addition to this advantage, unlike resonant microwave methods, non-resonant microwave methods require less sample preparation in determining the moisture of soil samples (Afsar et al., 1986; Baker-Jarvis et al., 1995; Zoughi, 2000; Carriveau and Zoughi, 2002; Chen et al., 2004; Kharkovsky and Zoughi, 2007; Kaatze, 2010;)

Non-resonant microwave measurement methods with various features are also generally included (Nicolson and Ross, 1970; Weir, 1974; Chen et al., 2004; Chalapat et al., 2009; Hasar and Westgate, 2009), wave-directed measurement techniques (Nicolson and Ross, 1974). 1970) and free-space measurement techniques (Ghodgaonkar et al., 1990). In wave-directed methods, a wave-emitting medium is needed to direct the microwave signals generated from the source in a certain direction. Examples of this medium are waveguide or coaxial cables used to transmit microwave signals. In free-space methods, measurements are carried out by transmitting these signals directly in the air (without the need for any physical medium) without the need to direct the generated microwave signals in a certain direction (Varadan et al., 1991).

Non-resonant microwave techniques can be divided into two groups: calibration-requiring and (ordinary) calibration-free methods. As the name suggests, calibration-requiring non-resonant microwave methods require the calibration of the measurement system before performing sample-related measurements (characterization processes). Since calibration standards are used in calibration processes, the slightest deviation from the ideal in these standards may negatively affect the sensitivity of the calibrations (Wan et al., 1998a; Wan et al., 1998b). The calibration process performs the calibration by including the calibration environment in which the measurements are made. This means that microwave measurements performed with calibration will be affected by environmental factors such as humidity and pressure in the measurement environment. To simultaneously eliminate these two disadvantages of calibration-requiring methods, calibration-free microwave methods can be used in sample characterization processes (Wan et al., 1998a; Wan et al., 1998b; Janezic and Jargon, 1999; Reynoso-Hernandez et al., 1999; Huynen et al., 2001; Guoxin, 2015; Hasar et al., 2023).

By way of example, Figure 8 shows a schematic view of the soil sample placed on the sample holder inside the coaxial cable from non-resonant microwave coaxial cable measurements. Under normal circumstances, before non-resonant microwave coaxial cable measurements, it is necessary to calibrate the measurement system, the schematic of which is shown in Figure 8. For example, the calibration method suggested in the recent study (Lewandowski et al., 2019) can be used for this calibration. Figure 9 shows a photograph of the non-resonant microwave coaxial cable measurement setup proposed in (Hasar et al., 2023).

Figure 10 illustrates dielectric constant values for three different soil samples (SI, SII, and SIII) with different gravimetric volumetric moisture rates (θ_V), at a frequency of 1.4 GHz with the calibration-free non-resonant microwave coaxial cable measurement method proposed in the study of (Hasar et al., 2023). All the soil samples have 90% or more sand content and were taken from various places in Gaziantep in 2021. The realized dielectric constant values (ε'_{rs}) are reported in the literature by Mironov et al. (2013) shows the comparison ($\Delta\varepsilon'_{rs}$ - difference in determined ε'_{rs} values) with the dielectric constant values obtained from the model developed. As can be seen from this figure, ε'_{rs} values measured for 3 different soil samples with different gravimetric volumetric moisture rates and those values predicted by the Mironov et al., model developed are in good agreement with each other (less than 5% difference). In light of the information given in Figure 10, it can be said that the sensitivity of microwave non-resonant methods that do not require calibration is at a good level.

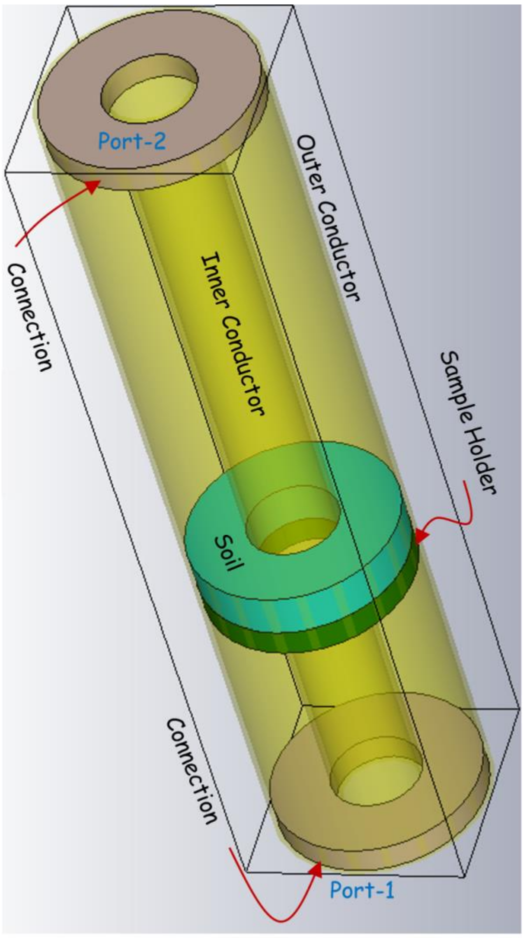

Figure 8. The schematic of a non-resonant microwave coaxial cable measurement setup (Hasar et al., 2023).

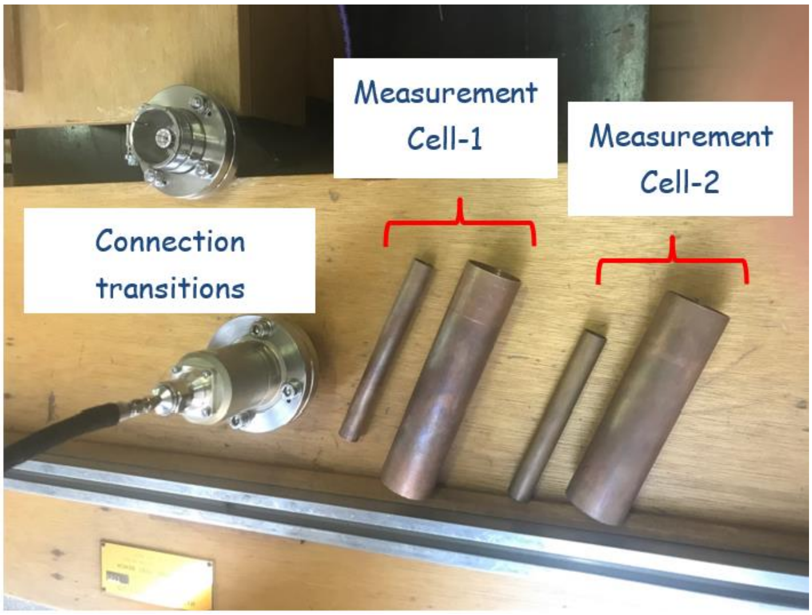

Figure 9. The photograph of non-resonant microwave coaxial cable measurement setup (Hasar et al., 2023).

	θ_V	Meas	Model	$\Delta\varepsilon'_{rs}$ (%)	θ_V	Meas	Model	$\Delta\varepsilon'_{rs}$ (%)
S_{I}	$0,31$	$18,272$	$19,155$	$4,610$	$0,38$	$24,951$	$25,027$	$0,304$
S_{II}	$0,25$	$14,918$	$14,746$	$1,166$	$0,34$	$21,529$	$21,576$	$0,218$
S_{III}	$0,21$	$11,732$	$12,126$	$3,249$	$0,42$	$27,334$	$28,735$	$4,876$

Figure 10. The dielectric constant values obtained at 1.4 GHz frequency with the calibration-free non-resonant microwave coaxial cable measurement method proposed in the study of (Hasar et al., 2023) are similar to those in the literature by Mironov et al., Comparison with the dielectric constant values obtained from the model developed (Mironov and Fomin, 2009; Mironov et al., 2013).

4. Conclusion

In this study, information is given about indirect and direct measurement methods used to determine soil moisture. In this regard, firstly the gravimetic method, which is a direct method, is explained, and then the time-space reflectometer, frequency-space reflectometer, time-space transmissometer, ground penetration radar, neutron meters, tensiometers, which are frequently used in the literature as indirect methods (thanks to the provision of correlations) for the determination of soil moisture. Information is given on porous blocks and electrical resistance blocks. Subsequently, general information is presented about microwave measurement methods, which have just begun to take their place in the literature and have great potential for the determination of soil moisture. Finally, information about non-resonant microwave measurement methods that do not require calibration, which constitute a special class of microwave measurement methods, is presented. The dielectric constant values obtained by one of these methods for 3 different soil samples with different gravimetric volumetric moisture rates were compared with those in the literature. It is compared with the dielectric constant values obtained from the developed model. As a result of the comparison, it was observed that for three different soil samples with different gravimetric volumetric moisture rates, the dielectric constant value obtained from the measurements and the dielectric constant values obtained from the model were in agreement with each other (less than 5% difference). This shows that calibration-free microwave measurement methods, which have the potential to avoid the problems of low measurement sensitivity caused by calibration standards, have high potential in the accurate determination of soil moisture.

Author Contributions

The percentage of the author(s) contributions is presented below. The author reviewed and approved the final version of the manuscript.

	H.H.
C	100
D	100
S	100
L	100
W	100
CR	100
SR	100
PM	100

C=Concept, D= design, S= supervision, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management.

Conflict of Interest

The author declare that there is no conflict of interest.

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