

Development of soil organic matter measurement system

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Abstract: We managed to create a self-developed sensor system, which is based on the simultaneous reflectance measurements at a 660 and 940 nm wavelength. The ratio of the reflectance refers to the concentration of the soil organic carbon (SOC). This instrument has a calibration range of 1.19 to 6.05 SOC%. The SOC content of twenty-six soil samples was measured by the self-developed system and a standard spectrophotometric method and we found that the SOC estimation in the self-developed system had a good approximation and the differences ranged from $-27.72\% \sim +6.99\%$. We found a strong correlation between the data of the reference measurements ($R^2 = 0.73$) and the values indicated by our self-developed sensor system (Reference (SOX%) = $1.4857 \times E$ (SOC%) $- 0.7393$). This measurement system is easy to use and displays and records the data in real time. This allows one to map an agricultural production area based on the SOC concentration using its built-in GPS unit.

Keywords: field instrument; reflectance measurement; SOC

Nowadays, there is a growing need to be able to determine certain chemical parameters of the soil, such as the soil organic matter (SOM) content and soil organic carbon (SOC), with near acceptable accuracy in field applications. The SOC is an important measure of the quality of the soil, a key element of its fertility, it also affects the biological activity and microbial biomass of the soils (Beni et al. 2017), it plays an important role in the water holding capacity and soil nutrient supply (Juhos et al. 2021), which all play a significant role in supplying humanity with food. As SOC can also show a greater degree

of heterogeneity within a given agricultural area, accurate knowledge of its patterns can significantly help farmers to develop good tillage practices and ensure an adequate soil strength supply. Laboratory tests, especially for larger sample numbers, are extremely costly and can only be triggered by the use of a developed field instrument. Determining the SOM/SOC also simplifies and makes it much cheaper and faster for researchers to conduct their research.

To achieve this goal, we chose spectroscopic methods. After reviewing the literature, the SOM and SOC estimations can primarily be in the range of

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400–2 300 nm (Brickleyer & Brown 2010; Knadel et al. 2015; Rodionov et al. 2015), i.e., the VIS-NIR (visible, near-infrared) wavelength range. As the soil is not transparent in the wavelength range used, only reflectance measurements can be considered (Fontán et al. 2010). The principle of determining the SOM is based on the fact that the electromagnetic radiation of a certain wavelength is absorbed by the organic matter content of the soil and, therefore, the intensity of the reflected radiation is reduced. Several studies have investigated that there is some mathematical relationship between the SOM at these wavelengths and the decrease in intensity (Vasques et al. 2008). The characteristic wavelengths identified by the step-wise multiple linear regression (SMLR) and partial least squares (PLS) methods of reflectance spectra for estimating SOM are at 654 (660) and 940 nm (Kweon & Maxton 2013; Knadel et al. 2015; Jiang et al. 2016). Therefore, these wavelengths were used to build a sensor for the SOM estimation.

The accuracy of the determination of the SOC is influenced by the soil moisture, soil temperature and texture of the soil. From these, the main factor is the moisture content (Kuang & Mouazen 2013; Nocita et al. 2013; Rienzi et al. 2014). The different soil moisture values decrease the accuracy of SOC predictions. The increasing moisture content increases the soil absorption (Roudier et al. 2017) in the VIS-NIR region, which means a decreasing soil reflectance. Methods exist to reduce the water effect on the SOC measurement, but they require a spectrometer to carry out them (Roudier et al. 2017). The easiest way is the measurement of air-dry soils that improve the accuracy. The surface roughness is also an important factor in the accuracy of measurements because this impact also decreases the accuracy (Roudier et al. 2017). This effect can be reduced by smoothing the soil surface out before the measurement. The variation in the soil temperature also decreases the accuracy of the measurements (Knadel et al. 2015), but a high clay content of the soil increases the accuracy of the SOC (Kuang & Mouazen 2013; Roudier et al. 2017).

MATERIAL AND METHODS

The components built into the SOM prototype instrument are 660 nm (RED) and 940 nm (NIR) LEDs. Furthermore, a VIS (max. 860 nm) photodiode module and an NIR photodiode (760 ~ 1 100 nm) are also included. A non-contact infrared thermometer

module (MLX90614; Hailangniao, China) capable of simultaneously determining the ambient and ground temperatures, which has a measuring range of -70 to $+380$ °C and an accuracy of 0.02 °C is also a part of the equipment. In addition, it includes a capacitive soil moisture sensor with a length of 98 mm and a width of 23 mm. A NEO-7M GPS module (Feng Sheng Xin, China) is used to determine the location of the measurement, to which an external antenna can also be connected. The device displays the measurement results on an LCD display and can record these results together with the GPS coordinates on an SD card with a maximum capacity of 32 GB. During the measurement process, a maximum file size of 4 GB (FAT32) is possible. The recording of the measurement data on the card can be started and stopped with a pushbutton. The instrument control and data collection were performed by an ATmega328p microcontroller (Diy More, China). Arduino IDE software (Ver. 1.8.12., 2020) was used for the source code writing and microcontroller programming. The housing of the optical system was created by a 3D printer.

The assembled system requires 500 mW, 5 V and 100 mA to operate. The system is powered via a USB-A connector, allowing a standard Power Bank with a Li-ion battery to power the device.

For laboratory testing of the experimental instrument (Figure 1), we used air dried standard soil samples from the Institute of Agrochemistry and Soil Science at University of Debrecen and Calcic chernozem soils from Tépe and Látókép. The laboratory determination of the SOC concentration of

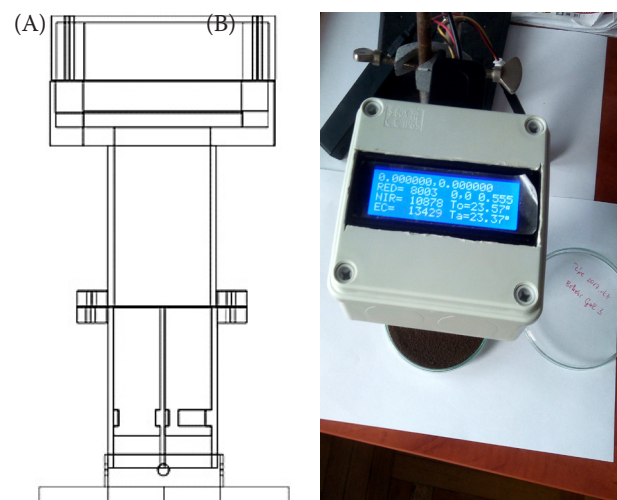


Figure 1. Design (A) of the field instrument and its use in the laboratory measurements (B)

Table 1. Soil properties for the standard soil samples

Sample	K _A	Clay%	pH(H ₂ O)	pH(KCl)	CEC (mmol/kg)	EC (μS/cm)
Mollic Gleysol	47.6	46	7.97	7.25	106.5	1 626
Salic Solonetz	35.7	28	10.46	9.61	48.8	1 127
Calcic Chernozem	50	55	7.61	6.16	155.7	576
Luvic Phaeozem	58.8	58	7.05	6.05	219.3	890
Lamelic Arenosol	27	9	7.16	6.03	51.4	335
Brunic Arenosol	27	10	7.23	5.88	63.0	311

CEC – cation exchange capacity; EC – electrical conductivity

these soils was performed by the Hungarian standard MSZ-08-0210-1977. This Hungarian standard's method for carbon determination is based on the Walkley-Black method (Walinga et al. 1992). The full potential cation exchange capacity (CEC) was determined by the Na-acetate/ethanol/NH₄-acetate replacement method (Chapman 1965). The soil pH (soil/solution ratio of 1:2.5), electrical conductivity (EC), K_A value and clay content were determined according to the Hungarian standards MSZ-08-0206-2-1978 and MSZ-08-0205-1978. These Hungarian standards' methods are based on books by edited Burt and Metson (Metson 1961; Burt 2004). The obtained results were compared with the values obtained with the custom-built instrument. All the soil samples were air-dried, ground, sieved to a size fraction smaller than 200 μm and stored in sealed plastic bags at room temperature. A plastic petri dish (9 × 1.4 cm) filled with about 100 g of soil, and the soil surface was smoothed to minimise the impact of the surface roughness. During the measurements, the field sensor was fixed using a Bunsen stand and a flask holder (Figure 1B). To calibrate the instrument, the Luvic Phaeozem soil was diluted with a known SOC concentration with quartz sand. The instrument was calibrated at 5 points and in the range of 1.19 to 6.05 SOC% and each measurement was performed in 5 replicates.

RESULTS AND DISCUSSION

The instrument measures the red (RED) and near-infrared (NIR) reflectance values. For the different soil types (Table 1), we compared the SOC results determined by the instrument with the reference laboratory test (Table 2).

Based on these studies, the SOC concentration determined by the ratio of the NIR and RED reflectance values best approximated the laboratory

results. Therefore, additional measurement data were evaluated based on the NIR/RED ratio. The equation of the calibration line thus obtained was:

$$y = -0.2237x + 1.4064 \quad (1)$$

where:

y – refers to the signal;

x – indicates the NIR/RED ratio;

$R^2 = 0.9602$.

The results of laboratory methods and calibrated experimental instrument are summarised in Table 3.

The differences ranged from –27.72% ~ + 6.99%. The negative difference may be due to the need for extrapolation for the evaluation because the results fell outside the calibration range.

We found a strong correlation between the data of the reference measurements and the values indicated by our self-developed sensor system (Reference (SOX%) = 1.4857 × E (SOC%) – 0.7393) (Figure 2). Based on 26 measurements, it can be stated that, below an SOC concentration of about 1.55, the instrument developed by us, under the applied calibration conditions, measured slightly higher values than the reference values, while in a range above this value,

Table 2. Comparison of the soil organic carbon (SOC) results with reference values ($n = 5$)

Sample	SOC%			
	reference	RED	NIR	NIR/RED
Mollic Gleysol	3.01	1.51	2.72	2.95
Salic Solonetz	0.64	2.89	0.11	0.55
Calcic Chernozem	1.83	1.50	1.61	1.59
Luvic Phaeozem	2.05	–3.08	3.91	2.31
Lamelic Arenosol	0.87	–0.34	1.34	1.03
Brunic Arenosol	0.96	–0.44	1.80	1.35

Soil names based on IUSS Working Group WRB (2015)

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Table 3. Comparison of the results of Calcic chernozem soils from Tépe and Látókép, Hungary ($n = 5$)

Sample	Standard laboratory methods						Experimental instrument		
	K_A	clay (%)	pH(H ₂ O)	pH(KCl)	CEC (mmol/kg)	EC (μS/cm)	SOC (%)	SOC difference (%)	
Tépe 1	43		8.21	6.59	149.4	1 159	2.34	1.79	-23.53
Tépe 2	43.5		7.53	5.98	134.7	1 030	2.49	2.16	-13.36
Tépe 3	39		6.80	5.57	146.4	1 060	2.47	1.96	-20.76
Tépe 4	42.5		7.46	6.06	161.4	1 304	3.06	2.47	-19.12
Tépe 5	44.8		7.50	6.32	153.9	1 310	3.26	2.35	-27.72
Tépe 6	42	30	7.09	6.03	143.3	1 252	3.25	2.36	-27.25
Tépe 7	43		6.92	5.17	167.8	1 142	2.03	1.86	-8.44
Tépe 8	42.8		7.38	6.23	153.7	1 254	2.08	2.08	0.32
Tépe 9	44		8.38	6.48	174.6	1 233	2.22	1.90	-14.16
Tépe 10	43		7.90	6.28	165.8	1 176	2.34	2.16	-7.93
Tépe 11	44		7.02	5.75	151.7	1 195	2.98	2.45	-17.93
Tépe 12	43.5		7.00	5.68	125.0	1 137	3.18	2.50	-21.28
Látókép 1	40		7.30	5.60	89.4	1 072	1.61	1.64	2.13
Látókép 2	39		7.26	6.19	84.9	1 064	1.58	1.69	6.99
Látókép 3	42		7.47	5.99	99.5	1 112	1.84	1.88	2.21
Látókép 4	42.5	28	7.43	6.41	94.2	1 134	1.86	1.83	-1.87
Látókép 5	42		7.01	6.37	106.7	1 149	2.11	2.00	-5.49
Látókép 6	41		7.42	6.53	117.9	1 104	1.91	1.98	3.65
Látókép 7	39.5		7.35	6.99	113.1	1 048	1.69	1.81	6.85
Látókép 8	39		7.52	6.46	86.4	941	1.66	1.76	5.92

CEC – cation exchange capacity; EC – electrical conductivity; SOC – soil organic carbon

the instrument gave lower values (Figure 3). For this sample of three intrazonal soil types (Mollic Gleysol from a wetland area, Haplic Solonetz from a saline area and a Luvic Phaeozem also exposed to a water

effect), no such effect was observed. For these three soils, on the other hand, the difference between the data of the reference soils and our corresponding measurements made with the device was smaller

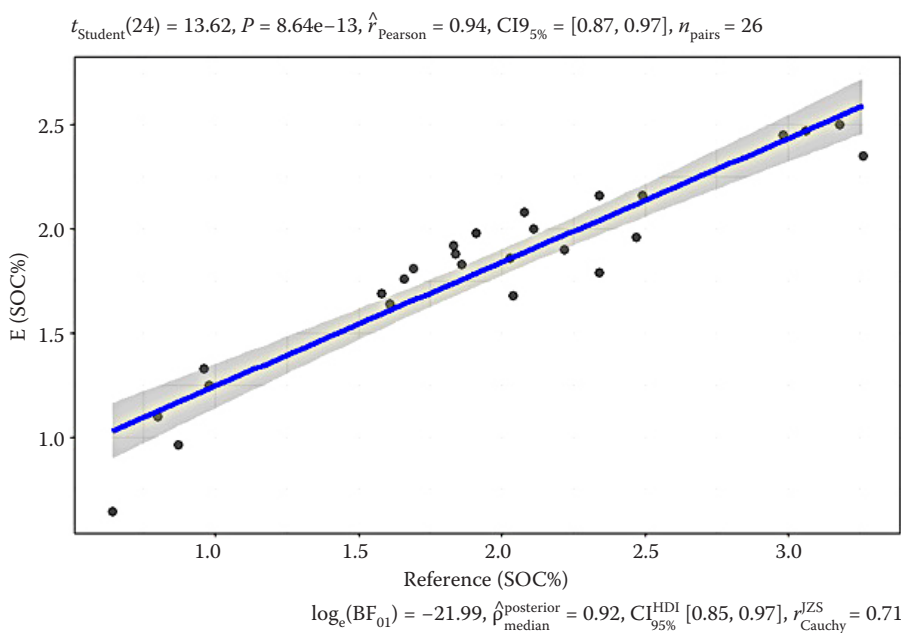


Figure 2. Correlation of the soil organic carbon (SOC) values of the studied soils measured by the sensor with the reference values

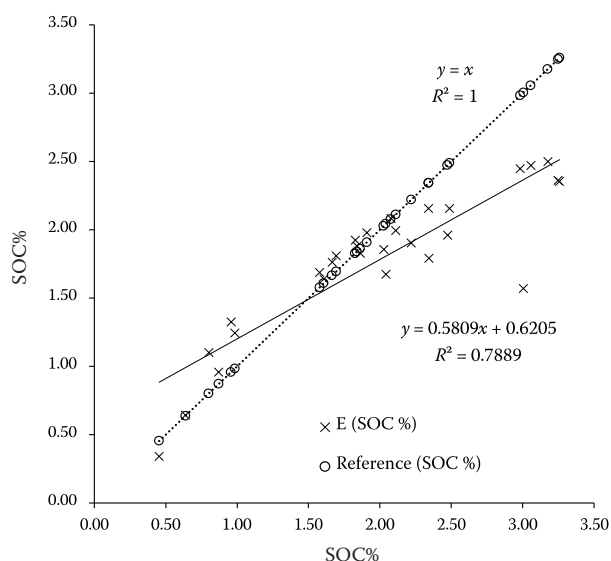


Figure 3. The soil organic carbon (SOC) values measured by the sensor (E (SOC%)) of the studied soils and the reference values (Reference (SOC%)) with their own trendlines

(2%, 16%, 13%, respectively) than the average of the difference between all the measurement pairs.

Before determining the SOC by the elemental analysis, the soil is firstly pre-treated with concentrated H_3PO_4 acid and left to wait for 12 h to remove the carbonate. After that, the carbon content of the sample can be determined by an elemental analyser. (Wang et al. 2012). This technique is simple and accurate, but the capital and running cost is high.

The Walkley and Black wet chemical oxidation method depend on external heating. A correction factor of 1.33 was applied for estimated SOC without the external heating (Sleutel et al. 2007). With the external heating, the amount of SOC approximately 100% is recovered, therefore, it is as accurate as of the automated elemental analyser technique except for extremely low SOC soils (Wang et al. 2012). In conclusion, no significant effect was found to occur on the sensor accuracy. This work used the spectrophotometric method to determine the SOC of the standard soils.

CONCLUSION

In this study, an SOC sensor was used to measure archived dried soil samples in a laboratory environment. This setup is able to quickly and non-destructively measure the SOC concentration of the soils. The calibration of this sensor with standard

soils was used to more accurately determine the soil types and to use a separate calibration function for very different soil types. Furthermore, very different moisture contents also affect the accuracy of the determination, which requires a moisture correction.

Besides the laboratory application, this system is also suitable for field measurements thanks to other built-in sensors (soil moisture, temperature and GPS). The testing of the functions of the device will be modelled in the next phase of the research. This sensor system seems to be a very promising development, which makes soil mapping much easier according to the SOC% values with low running costs, proportionally estimating the extent of the variations within the area.

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