



Designation: D8438/D8438M – 23

# Standard Test Methods for Use of Hyperspectral Sensors for Soil Nutrient Analysis of Ground Based Samples<sup>1</sup>

This standard is issued under the fixed designation D8438/D8438M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reappraisal. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reappraisal.

## 1. Scope

1.1 This test method describes procedures for sampling and testing of soils obtained from ground-based samples using diffuse reflectance spectrometry using handheld portable spectrometers measuring spectra in visible and near infrared (vis-NR) and mid-infrared (MIR) range. The sensor can measure moisture content, PH, organic matter, Cation Exchange Capacity (CEC) as well as macro and micro elemental nutrients in parts per million (PPM) or percentage, including but not limited to nitrogen, phosphorous, potassium, zinc, iron, boron, sulfur, calcium, magnesium, and manganese.

1.2 There are two methods that can be used to perform the test.

1.2.1 *Method A*—The analysis is performed in the laboratory on the sample after the sample has been oven dried and sieved.

1.2.2 *Method B*—The analysis is performed in the field on a moist sample after homogenization. After post-processing of multiple reflectance site data using methods A and B, the moisture content can be measured, and the spectral signature is normalized for moisture content.

1.3 The limitation of this method is that the results of an individual test for elemental analysis would not be the same as exacting reference values from traditional wet chemical lab analysis used by soil scientists. Results of wet chemistry tests or tests from soil science libraries may be used to calibrate a specific site model comprised of many individual tests. Spectral data for organics has shown to be as accurate as conventional methods such as Test Methods D2974.

1.4 For soil nutrient analysis the sample is not finely ground as in typical qualitative spectral analysis as outlined in standard Practice E1252. The spectrometer is checked periodically during testing using procedures in accordance with Guide E1866 performance testing.

<sup>1</sup> This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Investigation.

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1.5 Moisture content is a preferred term in agricultural applications. For this standard, gravimetric water content may be measured in accordance with Test Methods D2216 when drying samples and used to calibrate the site model, but the overall results of spectral analysis are more qualitative, and the term Moisture Content is used in this standard.

1.6 *Units*—The values stated in either SI units or inch-pound units [given in brackets] are to be regarded separately as standard. Wavelengths are stated only in nanometers, nm. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

1.7 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026. The procedures used to specify how data is collected, recorded or calculated in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design.

1.7.1 Spectral data is acquired by electrical data acquisition systems and therefore numeric data is carried through recording and into databases without rounding of numeric data.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

### 2.1 *ASTM Standards*:<sup>2</sup>

- D653** Terminology Relating to Soil, Rock, and Contained Fluids
- D2216** Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
- D2974** Test Methods for Determining the Water (Moisture) Content, Ash Content, and Organic Material of Peat and Other Organic Soils
- D3740** Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
- D4643** Test Method for Determination of Water Content of Soil and Rock by Microwave Oven Heating
- D4700** Guide for Soil Sampling from the Vadose Zone
- D6026** Practice for Using Significant Digits and Data Records in Geotechnical Data
- D6907** Practice for Sampling Soils and Contaminated Media with Hand-Operated Bucket Augers
- E11** Specification for Woven Wire Test Sieve Cloth and Test Sieves
- E1252** Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis
- E1866** Guide for Establishing Spectrophotometer Performance Tests

## 3. Terminology

3.1 *Definitions*—Terminology in accordance with Terminology **D653** and shall be used where applicable.

### 3.2 *Definitions of Terms Specific to This Standard*:

3.2.1 *macro-nutrient, n—in agronomy*, an element required in large amounts for plant growth and development (for example, nitrogen, phosphorous and potassium).

3.2.2 *micro-nutrient, n—in agronomy*, an element required in smaller amounts for plant growth and development (for example, sulfur, calcium, magnesium, manganese, zinc, copper, boron, iron, sodium).

3.2.3 *Power Spectral Density (PSD), n—in spectral analysis*, the energy variation that takes place within a vibrational signal, measured as frequency per unit of mass.

### 3.3 *Acronyms*:

3.3.1 *Vis-NIR*—near infrared light spectrum from 350 to 2500 nm.

3.3.2 *MIR*—mid infrared light spectrum from 2500 to 4000 nm.

## 4. Summary of Test Methods

4.1 The test methods involve obtaining a sample that is homogenized to eliminate the effect of stratification.

4.1.1 Method A the sample is air dried or dried in accordance with Test Methods **D2216** or Test Method **D4643** then homogenized through sieving prior to scanning.

4.1.2 Method B the samples are only homogenized via mixing and stirring.

4.2 The samples are then scanned with a hyperspectral sensor to collect the spectral signature in the soil sample.

4.3 A reflectance and adsorption record for each test is obtained for each sample and all data are combined into a site database for post processing modeling calibration.

## 5. Significance and Use

5.1 Spectral analysis of soils for agricultural use is being used worldwide to obtain rapid data on soil nutrients. for the purpose of agricultural management including fertilizer application and other amendments such as pH adjustment, organic supplements, etc. Satellite, aerial, and ground-based sampling methods are being used. This test method applies to ground-based, terrestrial field applications where samples are taken from the ground, generally in the root zone. Use of these rapid remote sensing techniques allow for more detailed and economic data acquisition than older cumbersome sampling and wet chemistry testing methods used in the past by soil scientists for soil nutrient evaluations.

5.2 This test method describes procedures for sampling and testing of field soils using diffuse reflectance spectrometry using handheld portable spectrometers measuring spectra in visible and near infrared (vis-NR) using dried sieved or wet samples. There is a worldwide effort to collect spectral databases of soils. The procedures specified here follow procedures as outlined in the United Nations Food and Agricultural Organization (FAO) primer on Vis-NIR and MIR spectroscopy of soils **(1)**<sup>3</sup>. Other organizations such as IEEE are actively working on additional guidance documents that will be incorporated in future revisions of this test method.

5.2.1 This standard describes the procedures (Section **12**) for using hyperspectral sensor data to measure moisture content as a percentage, pH, Organic Matter (OM) as a percentage, Cation Exchange Capacity (CEC) measured in 10 cmol c /kg could hold 10 cmol of Na + cations (with 1 unit of charge per cation) per kilogram of soil, but only 5 cmol Ca 2+ (2 units of charge per cation), as well as micro and macro nutrients in soils measured in PPM (parts per million) or a percentage, including, but not limited to nitrogen, phosphorous, potassium, boron, zinc, iron, sulfur, calcium, magnesium, and manganese.

5.2.2 Research has shown that the Vis-NIR data for OM content is as accurate as other tests such as the burn off test in Test Methods **D2974(2)**. Analysis of natural moisture samples using method B can provide faster testing and better estimates of OM are normalization for moisture **(3)**. Wet sampling allows for many more samples to be rapidly scanned in the field and therefore more samples and more detailed coverage of the site.

5.3 This standard does not address sensors that measure in the mid infrared range, MIR, are more expensive and there is less spectral data available. MIR spectral analysis is performed on dried samples that are finely grinded **(4)**. MIR modeling

<sup>2</sup> For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

<sup>3</sup> The boldface numbers in parentheses refer to a list of references at the end of this standard.

requires a high level of calibration against recognized laboratory procedures and physical properties.

5.4 Spectral data can differ from older reference tests typically based on wet chemistry methods such as pore fluid extractions such as those outlined in soil survey manuals (5). These old methods require extensive labor costs and long turnaround times. However, soil scientists are accumulating large databases of spectral libraries which have been checked and calibrated with baseline chemical data. The soil survey manual (5) also has early (2014) procedures for Vis-NIR testing methods on dry specimens.

5.5 The accuracy of the measurement is determined by the accuracy of the calibration of the baseline measurements that are calibrated by chemical processing. On critical/new projects the sampling plan may include samples for wet chemistry testing to help calibrate the site model. The large amount of data that is collected at a site is combined into a site-specific database which is subject to complex model training to optimize the dataset. This standard will not provide detailed guidance on modeling and the FAO document (1) provides a good overview of the current procedures for dataset modeling. Dataset modeling requires adjustments for texture, water content, and geology and generally is linked to other appropriate spectral libraries available from many sources (6).

5.5.1 Horizon and Soil taxonomic order as auxiliary variables improve prediction accuracy of models. Regional, local, and past site-specific data, and taxonomic historic data base libraries may be used to help calibrate a site model.

NOTE 1—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

## 6. Apparatus

6.1 *Hyperspectral Vis-NIR Sensor*—Any spectral sensor that meets the requirements of Table 1 can be used. There are a variety of desktop systems that can meet these specifications but a sensor with contact probe with a minimum field of view of 10 mm [0.4 in.] is recommended for field testing. The sensor houses and A/D converter, computer, lamp, and fiber optic cable (Note 2).

6.1.1 The sensor must have a minimum operating range of 350 nm to 2500 nm.

6.1.2 *Analysis Software*—The computer software shall allow acquired sequences to be archived and retrieved for evaluation and allow real time display of the IR spectra signature. The software should allow viewing of the reflectance signature for specified wavelengths (350-2500 nm). Additional processing operations on each raw image sequence (for example, averaging, subtraction, noise reduction derivatives) may be performed to improve detectability of subsurface elements and nutrients.

6.1.3 Lab benchtop devices should be equipped with mounting specimen holders, or pucks specifically designed for soil analysis. These are typically borosilicate petri dishes.

**TABLE 1 Specifications for Vis-NIR Spectrometer**

Wavelength Range	350-2500 nm
Resolution	3 nm @ 700 nm 6 nm @ 1400/2100 nm
Scanning Time	100 milliseconds
Signal-to-Noise Ratio	
Visible Near Inferred	9000:1 @ 700 nm
Short Wave Inferred 1	9000:1 @ 1400 nm
Short Wave Inferred 2	4000:1 @ 2100 nm
Photometric Noise	
Visible Near Infrared	$4.8 \times 10^{-5}$ AU or 48 $\mu$ AU @ 700 nm
Short Wave Infrared 1	$4.8 \times 10^{-5}$ AU or 48 $\mu$ AU @ 1400 nm
Short Wave Infrared	$2.11 \times 10^{-4}$ AU or 110 $\mu$ AU @ 2100 nm
Visible Near Infrared Detector	(350-1000 nm) 512 element silicon array (1001-1800 nm) and (1801-2500 nm)
Short Wave Infrared 1 and 2 Detectors	Graded Index InGaAs Photodiode TE Cooled

NOTE 2—An ASD LabSpec Spectroradiometer is a commonly used device. For MIR analysis A Bruker FTIR is a commonly used device (1,5). Lower cost spectrometers with limited wavelength ranges are available but may not meet the specifications of Table 1 and may result in inaccurate estimation of soil properties. Each spectrometer comes with its own computer and data reduction programs and calibration models (7).

6.2 *White Reference Tile*—Compressed Polytetrafluoroethylene (PTFE) White reference tile to baseline the sample measurement. The tile should be enclosed in a protective container when not in use, and protective measures should be taken during cleaning to prevent personnel from direct exposure to Perfluorinated compounds (PFAs).

6.2.1 The reference panel should be large enough to cover the entire field of view of the contact probe. No exact measurement can be stated since equipment may vary.

6.3 *Wavelength Reference Calibration Puck or Tape*—Manufacturer provided reference spectra check standard. 10mm Mylar calibration sheet is used.

6.4 *A Light Source*, which could be a 50 Watt integrated light source or a lamp with a single-ended quartz halogen filament capsule 4.25V, 4.5-Watt Halogen. Preferred light source is Tungsten Quartz Halogen b/1500rs.

6.5 *Nonporous Container and Nonporous Tool* to stir and homogenize sample. Stainless steel bowl and mixing tool such as a spoon, pestle, or 2 mm hand sieve are recommended. to reduce crop residue, debris, and gravel from being included in sample.

6.6 *Lab or Hand Sieve*—Specification E11 2mm (No. 10) sieve.

6.7 *Sample Bags or Containers to be Used for Method A*—Paper bags, plastic jars, zip-top bags.

6.8 *Sample Container for Use in Method B to Scan the Sample*—The tall walled container must hold the sample and minimize exposure to outside light when scanning. White HDPE plastic jars and other tall wall containers 50 to 150 mm [2 to 6 in.] diameter, this should be a nonporous container to reduce contaminants similar to a bucket, cup, HDPE jars can

also be used. A muglight is a closed system which prevents external light from entering the field of view and reduces the loss of light from the halogen lamp. It is important that external light is controlled during the scanning process to produce replicable results.

6.9 *Soil Sampler Probe* to extract soil core with a minimum diameter of 2 cm [1 in.]. The most commonly used sampler is the hand operated soil step sample tube or hammered Veihmeyer agricultural samplers (Guide [D4700](#)). Hand bucket augers (Practice [D6907](#)) can be used. Bucket augers are slower to operate, less accurate in depth, but do mix and remold the soil during sampling.

6.10 *Drying Oven for Method A*—A thermostatically controlled drying oven, preferably of the forced-draft type, capable of maintaining a uniform temperature of  $110^{\circ}\text{C} \pm 5^{\circ}\text{C}$  throughout (see Test Methods [D2216](#)).

6.11 *Standard Soil Lab Grinder for Method A*—(110V/60Hz or 220V/50Hz) with a recommended 2mm (No. 10) perforated stainless steel plate.

6.12 *Wet/dry 600 Grit Sandpaper*.

6.13 *Portable pH and Moisture Sensors*, if required in the sampling plan.

## 7. Safety Hazards

7.1 PTFE when aerosolized can be hazardous, therefore the reference tile must be cleaned under running water with wet sandpaper to prevent aerosolized particles from entering the air.

## 8. Sampling and Test Specimens

8.1 *Sampling Plan*—All sampling and testing should be performed in accordance with a specific site sampling plan. To develop a site-specific sampling plan the following steps are taken.

8.1.1 Collect all known information about the site including but not limited to review of existing soil surveys, existing previous soil testing, aerial photography to delineate geologic features, soil pedology and taxonomy of the site.

8.1.2 Perform a site reconnaissance and look at site features such as accessibility and any limiting features.

8.1.3 Layout a sampling grid. Due to the economic and fast testing, finer grids can be used using spectral analysis. The grid may be supplemented with additional samples in areas of interest such as geologic features. Grids can range from 0.5 to 10 Hectares [1 acre to 20 acres] depending by region, size, and crop

8.1.3.1 Each regional government may have its own nutrient management requirements for minimum sample spacings, but these can easily be exceeded using spectral analysis. Local, regional, and country regulations may specify spacings and time interval requirements for sampling.

8.1.4 The sampling plan must outline specific sampling procedures to be performed. This will include.

8.1.4.1 Sampling and processing methods to obtain test specimens, including methods for sample mixing, reduction, drying, sieving, etc.

8.1.4.2 Preservation, transport, and processing samples for dry sampling (Method A).

8.1.4.3 Field testing of samples (Method B) including frequency of reference check testing.

8.1.4.4 Delineation of samples for any validation reference (wet chemistry, moisture, pH, etc.) testing based on quality control requirements.

8.1.4.5 Equipment reference check testing and cleaning requirements. Manufacturer's operations manuals should be followed. Wet scanning will require regular cleaning of the light receptor lenses.

8.1.4.6 Sample labeling, transport, and retention instructions.

8.2 Core samples are typically taken at depths intervals of 0-15 or 0-20 cm [0-6 to 0-8 in.] for most analytes. It is recommended that for nitrogen tests the depth should be greater, varying by region from 30 to 45 cm [12 to 18 in.] and even deeper based on crop type and root zones. The depth data, geolocation data, and date and time are recorded in accordance with Guide [D4700](#) or Practice [D6907](#) as required in the sampling plan. The core sample must be homogenized to eliminate the effects of the stratification of elements at different soil depths. For Method A this will be in accordance with sampling plan standard soil lab soil preparation methods, while for Method B the sample will be homogenized in a nonporous container using a nonporous solid tool (such as a clean, non-rusty spoon).

8.3 For Method A, a test specimen of only a 3 to 5 grams of soil is required for the actual bench test. The sample for the test depth in the field is a homogenized mixture of soil of 100 to 200 grams and bagged for laboratory processing. The sample can be air dried or oven dried (Test Methods [D2216](#)) depending on the sample plan requirements. Air drying is easy for sands silts and loamy soils, but heavy clay soils may require days to dry. Oven drying using Test Methods [D2216](#) is generally done overnight and is safe to preserve organics and mineralogy. The sample is then sieved through a 2 mm sieve, and a split or grab sample of screened material is used for the bench testing.

8.4 In the case of Method B, the sample will be scanned in the field. About 100 to 200 grams at natural moisture after homogenization is required to enable the contact probe field of view to be only on the test specimen without a background material. The sampling plan may require the sample to be retained and bagged for dry lab testing or reference testing.

## 9. Preparation of Apparatus

9.1 If no power source is available at the test location, make sure that the batteries of the hyperspectral sensor and computer are fully charged upon arrival at the test location. The hyperspectral sensor should be turned on according to manufacturer's instructions and the sampling plan, typically for a minimum of 1 hour prior to starting scan analysis to allow internal system to warm up for accurate calibration.

9.2 Clean the white reference panel with wet/dry 600 grain sandpaper and water until water beads off surface.

9.3 Place probe on the white reference panel and obtain a "white reference" reading. This reading must be taken every

time the sensor is started and then repeated as required in the sampling plan, typically every 2 hours.

9.4 Clean the glass lens of the hyperspectral sensor with chemical free soft cloth as specified in the sampling plan after each scan.

## 10. Calibration

10.1 The ability to determine the elemental content from the spectral signature is also determined by the accuracy of the white reference measurements. The sampling plan will delineate reference check tests normally performed on split samples. The site model is then calibrated to validation reference check tests and other past data and data libraries. The sampling plan should ensure that this is the case the reference baseline measurements used to calibrate from traditional analysis should be within +10 percent of the “true” soil test value (8). The resulting output of the final site model should meet minimum RMSE ranges <1 for many analytes and general guidelines are recommended in Section 14.

10.2 Calibrate the sensor settings by placing clear mylar reference tape or other reference disks over white reference panel. Take reading as required in the sampling plan, typically daily, to guarantee machine efficiency.

## 11. Procedure

11.1 At the location specified in the sampling plan procure the sample. Process the sample core according to the plan. Typically, this requires mixing of soil from the required test depth interval. Remove roots and gravel particles. Record identification, location, and time data in the spectrometer computer system for moist samples in Method B. For method A bag samples to be dried and record identification, location and time data, and label them according to the sampling plan. Store and transport samples according to the sampling plan.

### 11.2 *Spectral Scanning Methods—General Requirements:*

11.2.1 The hyperspectral sensor should average a minimum of 50 scans per second to help reduce signal to noise.

11.2.2 Wavelength data must be measured to minimum  $\frac{1}{10}$  of power spectral density (PSD).

### 11.3 *Method A—Dry Specimens:*

11.3.1 Dry the sample either to air dry or oven dry conditions as required in the sampling plan and confirm equilibrium moisture content has been reached.

11.3.2 Sieve the sample through a 2 mm (No. 10) sieve and split the sample down to size are recommended in the sampling plan and according to specific manufacturer’s instructions for sample size, generally from 3 to 5 grams.

11.3.3 Place specimen in the container for scanning. Sometimes the specimen is pressed/packed into the specimen holder. If the sampling plan specifies multiple specimens pack additional specimens for scanning.

11.3.4 Be sure the spectrometer and light source and probe sources have been warmed up to manufacturer’s requirements and scan the specimens. Input sample identification and location information data into the spectral computer system.

11.3.5 Perform spectral scan of the specimen(s) according to the sampling plan. This typically consists of taking three

measurements, DN (digital number) white raw spectrum, DN dark raw spectrum, on reference pucks, and the DN soil spectrum of the soil specimen (1).

### 11.4 *Method B—Moist Specimens:*

11.4.1 Mix and homogenize the soil for the test depth interval using mixing and stirring tool. Remove roots and particles larger than 2mm.

11.4.2 Place 100 to 200 grams of moist soil into the tall-walled container with light packing into the bottom of the container.

11.4.3 Be sure the equipment is on and warmed up prior to testing. Be sure the light source and receiver lenses are clean. Take white reference measurements as required in the sampling plan.

11.4.4 Press the contact probe into the soil approximately minimum of 5 mm and assure 25 mm of soil is below the contact probe and perform the spectral scan of the soil. Perform replicate test if required in the sampling plan.

11.5 Each individual spectral scan results in a record of reflectance and absorbance as the example in Fig. 1. This data is collected in the spectrometer computer and further processed as discussed in the calculations Section 12.

11.6 Discard and dispose of the specimen or retain for retesting or storage as required in the sampling plan.

## 12. Calculations

12.1 The spectral data is stored in equipment specific proprietary formats and the calculations are performed for spectral modeling vary. There are no standard methods for these calculations. For detailed information on these procedures refer to the FAO Primer (1). Some methods below are commonly applied to data post processing and data modeling. Site data are collected in a spectral data matrix database and then subjected to model training to optimize prediction of the designated parameters of concern.

12.2 *Data Pre-Processing*—Site data may be processed to remove noise in the raw spectra, improves signal to noise ratio, and minimize foreign light scattering. The selection of pre-processing is subjective and, in some cases, may not be employed for data modeling.

12.3 *Wet Sample Normalization*—To normalize for effects of moisture, the sample spectra must be normalized (3). Techniques for normalizing may use first a piecewise polynomial fitting or derivative algorithm then a CARS-PLSR (competitive adaptive reweighted sampling- partial least square regression) model calibrated by the optimal variables. The optimal variable set of wavelengths is determined by the iterative re-weighting process of the algorithm used in the calibration model generation.

12.4 *Model Training and Testing*—The whole site data set is subjected to model training. The data set is split into a training set and one for independent testing. Common methods used in modeling employ multivariate models such as Partial Least Squares Regression (PLSR), Principal Component Regression (PCR), Machine Learning including Random Forest and Artificial Neural Network (RF, ANN), and Principal Component

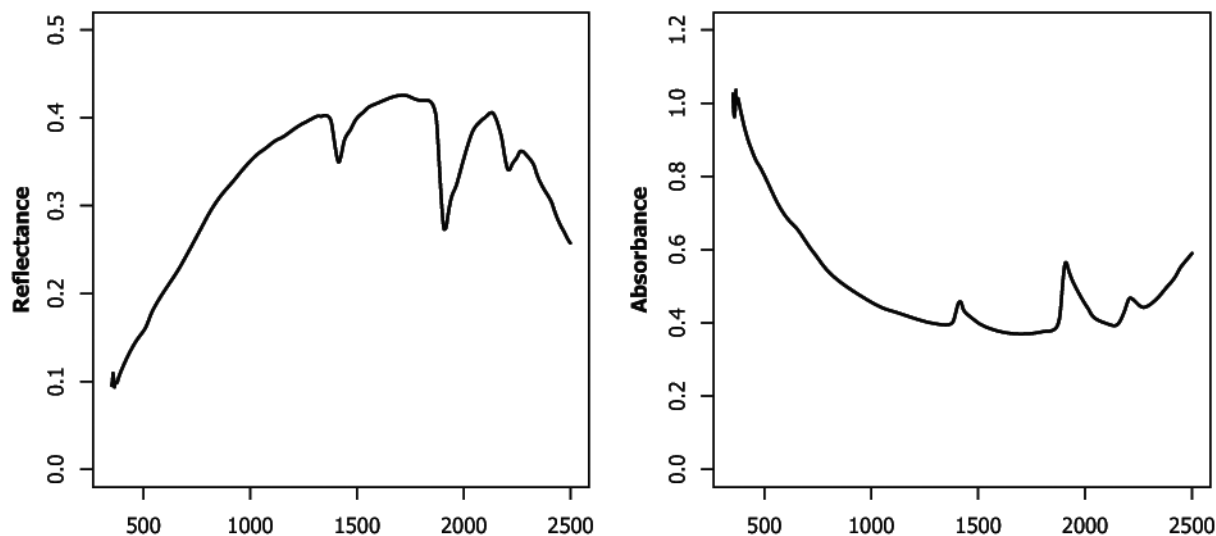


FIG. 1 Soil vis-NIR Spectrum in Reflectance (left) and Absorbance (right) (1)

Analysis (PCA) (1). The purpose of model training is to obtain a multivariate empirical model that links the spectral data to the target soil properties.

12.5 Model Assessment—Part of the data set is linked to reference test data from the site or as taken from spectral libraries of similar texture, geologic soils. The model is then compared to the reference set to evaluate Root-Mean Square Error (RMSE) accuracy. For an acceptable model the RMSE values given in Section 14 should be met.

12.5.1 In the NIR literature (1) it is called SEP (standard error of prediction).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (1)$$

$$MSE = \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

12.5.2 Mean error (bias).

$$ME = \sum_{i=1}^n (y_i - \hat{y}_i) \quad (2)$$

### 13. Report: Test Data Sheet(s)/Form(s)

13.1 The methodology used to specify how data is recorded on the test data sheet(s)/form(s), is given below, and is covered in 1.7 and in Practice D6026.

13.2 Record as a minimum the following general information (data):

13.2.1 Date of issue of this test method.

13.2.2 Nutrient results are reported in parts per million (PPM).

13.2.3 Actual test method used.

13.2.4 The location and depth where the sample was obtained.

13.2.5 Person(s) involved in performing the test.

13.2.6 The hyperspectral sensor’s manufacturer, model, and serial number.

13.2.7 Any variations to this test method, anomalies noticed during testing, correction factors, or any equipment problems that occurred during testing.

13.2.8 Complete identification of the material tested including type, source, form, and dimensions.

13.2.9 In case of Method I, drying times and oven temperature applied for sample drying.

13.2.10 Record of wet chemistry method used for validation reference test (Mehlich, Bray, Olsen, Loss on Ignition, NH4OAc Extractable, etc.).

13.3 Report Numeric Values—Generally, after modeling, results are only accurate to two significant digits.

13.3.1 Depth of Testing nearest 2.5 cm [0.1 ft] range.

13.3.2 The spectral reflectance and absorbance signature is reported in nanometers (nm) and wavelength data must be measured to a minimum 1/10 of power spectral density (PSD).

13.3.3 OM to 0.5 %.

13.3.4 CEC meq/100gm—two significant digits.

13.3.5 Moisture Content nearest %.

13.3.6 pH nearest whole number.

13.3.7 Other analytes recorded in PPM to two significant digits.

### 14. Precision and Bias

14.1 Precision—Test data on precision is not presented due to the nature of this test method. It is either not feasible or too costly at this time to have ten or more agencies participate in an in-situ testing program at a given site.

14.1.1 Subcommittee D18 is seeking any data from the users of this test method that might be used to make a limited statement on precision.

14.1.2 Model RMSE—Model evaluation precision should meet the following: In case a precision statement is developed, the following Root Mean Square Error (RMSE) values in Table 2 should be used as a guide for most analytes. RMSE values below 1 are generally acceptable and Table 2 shows typical values achieved by good models. Further studies are being

**TABLE 2 Recommended RMSE Values for Spectral Model Predicted Accuracy**

Element	Low Wavelength (nm)	High Wavelength (nm)	RMSE Min/Good
OM	350	2500	<1 or 0.5
CEC	350	2500	<3
pHw	350	2500	<1 or 0.3
Potassium	350	2500	<1 or 0.3
Copper	350	2500	<1 or 0.9
Boron	350	2500	<1 or 0.3
Sulfur	350	2500	<1 or 0.9
Zinc	350	2500	<2

conducted for analytes with higher RMSE values since chemical wet lab validation methods have inherent errors:

14.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

## 15. Keywords

15.1 agricultural management; agriculture; hyperspectral; hyperspectral sensor; nutrient analysis; soil nutrients; soil testing

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