Alliance

Bioversity International

CIAT
International Center for Tropical Agriculture
Since 1967 Science to cultivate change

german cooperation
DEUTSCHE ZUSAMMENARBEIT

Implemented by
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

EIAR
Ethiopian Institute of Agricultural Research

CGIAR
RESEARCH PROGRAM ON
Water, Land and Ecosystems

A guide to standardized methods of analysis for soil, water, plant, and fertilizer resources for data documentation and knowledge sharing in Ethiopia

The **Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT)** delivers research-based solutions that address the global crises of malnutrition, climate change, biodiversity loss and environmental degradation.

The **Alliance** focuses on the nexus of agriculture, nutrition and environment. We work with local, national and multinational partners across Africa, Asia, Latin America and the Caribbean, and with the public and private sectors and civil society. With novel partnerships, the Alliance generates evidence and mainstreams innovations to transform food systems and landscapes so that they sustain the planet, drive prosperity and nourish people.

The **Alliance** is part of **CGIAR**, the world's largest agricultural research and innovation partnership for a food-secure future dedicated to reducing poverty, enhancing food and nutrition security, and improving natural resources.

https://alliancebioversityciat.org **www.cgiar.org**

A guide to standardized methods of analysis for plant, soil, water, and fertilizer resources, for data documentation and knowledge sharing in Ethiopia

Lemma Wogi
Nigussie Dechassa
Bereket Haileselassie
Fikre Mekuria
Ayele Abebe
Lulseged Tamene

October 2021

Alianza
Bioversity International
CIAT
Centro Internacional de Agricultura Tropical
Desde 1967 Ciencia para cultivar el cambio
german cooperation
DEUTSCHE ZUSAMMENARBEIT
implemented by giz
EIAR
Ethiopian Institute of Agricultural Research
CGIAR
RESEARCH PROGRAM ON
Water, Land and Ecosystems

Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT)
Africa Hub
c/o icipe (International Centre of Insect Physiology and Ecology)
Duduville Campus Off Kasarani Road
P.O. Box 823-00621
Nairobi, Kenya
Telephone: (+254) 0709134000
Website: https://alliancebioversityciat.org/

Citation

Wogi L; Dechassa N; Haileselassie B; Mekuria F; Abebe A; Tamene L. 2021. A guide to standardized methods of analysis for soil, water, plant, and fertilizer resources for data documentation and sharing in Ethiopia. CIAT Publication No. 519. International Center for Tropical Agriculture (CIAT). Addis Ababa, Ethiopia. 41 p.

About the authors

Lemma Wogi, School of Natural Resources Management and Environmental Sciences, College of Agriculture and Environmental Sciences, Haramaya University, Dire Dawa, Ethiopia.

Nigussie Dechassa, School of Plant Sciences, College of Agriculture and Environmental Sciences, Haramaya University, Dire Dawa, Ethiopia.

Bereket Haileselassie, Mekelle Soil Research Center, Tigray, Ethiopia.

Fikre Mekuria, National Soil Testing Center (NSTC), Addis Ababa, Ethiopia.

Ayele Abebe, National Soil Testing Center (NSTC), Addis Ababa, Ethiopia.

Lulseged Tamene, Senior scientist, Multifunctional Landscapes research area, Alliance of Bioversity International and CIAT, Ethiopia.

Version I (October 2021)

Acknowledgements

We wish to acknowledge the technical and financial support provided by the International Center for Tropical Agriculture (CIAT) (now part of the Alliance of Bioversity International and CIAT). This work received financial support from the German Federal Ministry for Economic Cooperation and Development (BMZ) commissioned by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) through the Fund International Agricultural Research (FIA), grant number: 81226032.

Research undertaken in the preparation of this guide was implemented as part of the CGIAR Research Program on Water, Land and Ecosystems (WLE) and Climate Change, Agriculture and Food Security (CCAFS), which are carried out with support from CGIAR Trust Fund and through bilateral funding agreements (see http://wle.cgiar.org/donors and https://ccafs.cgiar.org/donors). The views expressed in this document cannot be taken to reflect the official opinions of these organisations.

We thank Dr Teklu Erkossa (GIZ) for supporting the guideline development process. We appreciate the engagement and contributions of members of the Coalition of the Willing (CoW)[1] for soil and agronomy data access, management and sharing in the efforts to support national agricultural transformation through digital solutions who identified this work to be given priority and providing inputs, comments and suggestion at different levels. We thank Prof. Mitiku Haile (Mekelle University) for playing an important role in providing technical support and coordinating the key activities of the process. We thank Olga Spellman (Alliance of Bioversity International and CIAT) for copy-editing and support in structuring this Guide.

1 CoW website is under construction. More information about CoW is currently available at:
https://www.youtube.com/watch?v=oT-V2JMsSp8&list=PLRvSieEExwOrlzrR7M05GfKybKMvn0T7O&index=7&t=621s
https://blog.ciat.cgiar.org/ethiopia-holds-workshop-to-enhance-open-access-data-among-scientists/

Acronyms and abbreviations

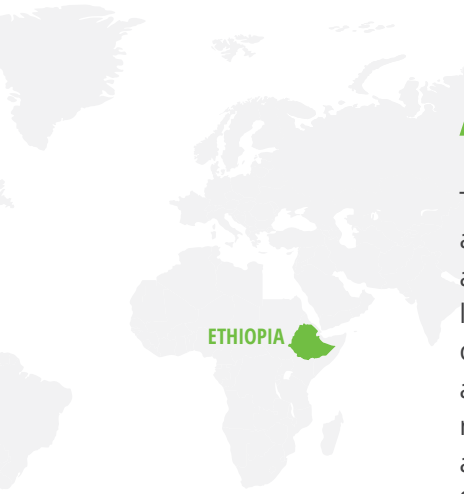
AAS	Atomic absorption spectrophotometer
AOAC	Association of Official Analytical Chemists
BD	Bulk density
DTPA	Diethyltriaminepenta acetic acid
ECw	Electrical conductivity of water
EDTA	Ethylenediaminetetraacetic acid
EIAR	Ethiopian Institute of Agricultural Research
ESP	Exchangeable sodium percentage
EthioSIS	Ethiopian Soil Information System
GDP	Gross domestic product
ICP	Inductively coupled plasma
ICP-OES	Inductively coupled plasma optical emission spectrophotometry
MAC	Maximum acceptable concentration
MAL	Maximum application limit
MIR	Mid-infrared
MoA	Ministry of Agriculture
NIR	Near infra-red
OM	Organic matter
PD	Particle density
PWP	Permanent wilting point
RARIs	Regional Agricultural Research Institutes
SAR	Sodium adsorption ratio
SSP	Single superphosphate
TTS	Total soluble solids
WHC	Water-holding capacity

List of chemical elements and compounds

Al	Aluminum
As	Arsenic
B	Boron
Ca	Calcium
$CaCL_2$	Calcium chloride
$CaCO_3$	Calcite
$CaMg(CO_3)_2$	Dolomite
$CaSO_4.2H_2O$	Gypsum
$CaSO_4$	Calcium sulphate dihydrate
H_2O	Water
Cd	Cadmium
Cl	Chlorine
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
$FeCO_3$	Siderite
Fe_2S	Pyrite
Hg	Mercury
K	Potassium
K_2O	Potassium oxide
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Na	Sodium
Ni	Nickel
Na_2CO_3	Sodium carbonate
NH_4^+	Ammonium
P	Phosphorus
Pb	Phosphorus pentaoxide
P_2O_5	Lead
S	Sulfur
Si	Silicon
Zn	Zinc

Contents

Tables



About this Guide

This guide is intended to serve as standard reference source for collecting, analyzing, interpreting, documenting, and sharing data on soil, plant, water, and fertilizer resources. It has been prepared by considering and adopting limited numbers of simple but effective methods and procedures for collecting, analyzing, documenting, and sharing data on soil, plant, water, and fertilizer resources in Ethiopia and has been specifically developed by reviewing standard methods and procedures of analyzing soil, plant, water, and fertilizer from the literature (Sertsu and Bekele, 2000; Bashour and Sayegh, 2007; FAO, 2008; Singh et al., 2010; Benton Jones, 2012; Estefan et al., 2013). The Guide is also intended to enable national collation, verification, and publication of hitherto collected and future data on soil, plant, water, and fertilizers that can be acquired from research institutes, universities, colleges, CGIAR Research Centers, and researchers.

The aim of this guide is to:

- highlight the need for well-defined and agreed standardized soil, plant, water, and fertilizer data for documentation and sharing, as well as for tracing the sites and/regions where the data have originated
- provide a standardized system for documenting and sharing soil, plant, water, and fertilizer data, so as to avoid or minimize duplication of efforts
- stimulate research on the calibration and use of analyzing soil, plant, water, and fertilizers and generate data on these resources
- draw individuals and groups from industry, public institutions, and independent laboratories together to share information
- promote and support sustainable and timely formulations of recommendations for crop and agroecology-based fertilizer, irrigation, and lime in Ethiopia
- encourage the revision of existing soil, plant, water, and fertilizer analytical procedures in Ethiopia and the production of standard manuals for future use.

Preface

In Ethiopia, since the establishment of research centres and science laboratories, most of the data related to soil parameters, plants, water, and fertilizer use have been generated, documented, and shared in various ways. Different methods and procedures of sample collection and laboratory analyses are invariably used across Ethiopia for determining the same soil, plant, water, and fertilizer parameters. For example, a method designed for extracting certain soil nutrients, such as phosphate (P), from soil with specific physical and chemical characteristics, may also be/is also used to extract the nutrient from the soil with a different physical and chemical make-up, for which a method has not yet been developed. This often leads to the use of sub-optimal and/or ill-suited laboratory methods and procedures for characterizing, extracting and determining soil, plant nutrient status, water, and fertilizer quality indicators.

Consequently, interpretation of data obtained through one method of analysis for various soils types, plants, water, and fertilizers could lead to erroneous conclusions and recommendations for their management. Similarly, data on the same soil, plant, water, and fertilizer parameters are often documented and shared in differing units of measurement, making it difficult to compare datasets. This also undermines the validity of data to be used for evidence-based decisions for the sustainable use of land and water resources. It could also cause confusion for researchers, policy makers, practitioners, and other stakeholders involved in land use planning, environmental protection, soil fertility, and crop production management practices.

Furthermore, among other factors, the lack of reliable and consistent soil, plant, water, and fertilizer data as a result of not using standardized methods has contributed to the absence of sound, evidence-based crop and agroecology-tested fertilizer and irrigation recommendations in Ethiopia. Consequently, farmers across the country are compelled to use blanket fertilizer recommendations, formulated decades ago, based on data generated through one or two methods of soil analysis and crop-fertilizer response studies conducted at a few locations under similar climatic and edaphic conditions, which have been unwisely extrapolated and recommended for use across heterogenous agroecological zones.

Collecting samples, analyzing, documenting, and sharing soil, plant, water, and fertilizer data obtained through unstandardized methods and procedures can lead to erroneous generation, interpretation, conclusions, recommendations, and implementation based on such data. Erroneous data may in turn lead to costly mistakes, for example, in terms of crop yields, project implementation, and lost livelihoods, and also hamper technology transfer. Such data would also lead to flawed policy formulations, which would undermine the national efforts to develop Ethiopia's agriculture sector.

Therefore, the Ethiopian scientific community and policy makers often seek the use of standard methods and procedures in collecting samples, analyzing, interpreting, documenting, and sharing data on soil, plant, water, and fertilizer. The use of standardized methods pave the way for (i) uniform and consistent interpretation of analytical results, and the formulation of sound fertilizer and irrigation recommendations, appropriate agricultural policy, and technology transfer.

Against this background, the team of the Coalition of the Willing (CoW) – experts and/or institutions who are wiling to share data and/or support its process – have engaged its relevant members to develop a standardization guideline for various themes. One of the key components identified at the CoW assembly and followed up by the CoW task force was standardization associated with laboratory analysis.

This reference document/guide, entitled "A guide to standardized methods of analysis for soil, water, plant, and fertilizer resources for data documentation and sharing in Ethiopia" has been developed to provide researchers, students, agricultural practitioners, policy makers and implementers at local level, etc. with a useful reference on standardized systems of soil, plant, water, and fertilizer data collection, analysis, interpretation, documentation, and sharing. The guide is not intended as a standard manual describing detailed procedures for soil, plant, water and fertilizer analyses in the country. Rather, we hope it can bridge information gaps and promote standardized laboratory methods and procedures for soil, plant, water and fertilizer analyses, thereby facilitating standardized data documentation and sharing to inform policy formulation and implementation.

For effective utilization of the guide, regular follow-up and support will be conducted by EIAR, together with the provision of standard manuals for soil, plant, irrigation water, and fertilizers analyses that include detailed descriptions of all required facilities, field and laboratory protocols and procedures with personnel and environmental safety of each and every method documented in this guide. The guide will be updated to ensure it integrates scientific advancements in the methods of soil, plant, water, and fertilizer analyses.

1. Introduction

Sustainable agricultural production depends mainly on effective management and efficient utilization of soil and water resources. Degradation of soil and water resources as a result of poor management and inefficient use is often a major cause of declining agricultural productivity and persistent food insecurity in many developing countries.

Ethiopia's economy is heavily dependent on the agriculture sector, which accounts for 46.3 percent of the nation's gross domestic product (GDP), 83.9 percent of exports, and 80% of the labor force. However, the country is still struggling to attain food and nutrition security through sectoral transformation. This is despite the fact that it is endowed with ample soil and water resources for agricultural production. It is widely believed that the country will only manage to transform its agriculture sector, as stipulated in its various development policy documents, if it utilizes its potentially rich soil, plant, water, and organic fertilizer resources systematically for the production of food, fodder, fiber, and industrial raw materials, by ensuring environmental sustainability.

While soil and water resources are the basis for developing Ethiopia's agricultural sector, several problems constrain the productivity and sustainability of these resources—for example, dwindling soil fertility, as a result of physical and chemical land degradation, loss of irrigation water quality (salinity), and inefficient use of fertilizers. Therefore, to achieve sustained enhancement of agricultural production and improved household and national food security, these resources need to be managed systematically.

Ethiopia possesses tremendous amounts of data on soil, plant, water, and agricultural inputs, which have been collected since the early 1960s. The data have been collected by about 32 laboratories operating under the Ministry of Agriculture (MoA), Ethiopian Institute of Agricultural Research (EIAR) and Regional Agricultural Research Institutes (RARIs), universities and colleges, public water works and construction, as well as private companies. Some of the data are archived as reports within the respective institutions/organizations or published in journals, proceedings, books, etc. However, the use of most of the data emanating from the various Ethiopian institutions is constrained by several problems, which include:

A data stored across institutions in remote or isolated locations and/or held by individual researchers and academics across Ethiopia

B not all of the data have been collected using standardized methods and procedures (plant, soil, and water samples—meant for the analysis of the same quality parameters)

C lack of uniformity and consistency in analytical data reporting formats, units, methods, etc. across the institutions

D data sets could include erroneous data, which could potentially lead to costly mistakes—for example, in terms of crop yields, project implementation, and lost livelihoods—by researchers, administrators, policy makers, and other authorities, and hamper technology transfer. Such data could also lead to flawed policy formulations, which would undermine the national efforts to develop Ethiopia's agriculture sector.

Thus, the variability and inaccuracy in available soil, plant, water, and fertilizer data across the country is essentially attributable to a lack of standardization of laboratory analytical procedures and high imprecision (scattering) caused by lack of within-laboratory consistency. Consequently, it is difficult to effectively and systematically ensure data procurement for quality assurance, implementation, and sharing (FAO, 1998).

These problems have largely undermined data quality and jeopardized the prospect of sharing data to be used for similar purposes to draw dependable conclusions in Ethiopia. Moreover, the authors contend that constraints have led to a

waste of resources and duplication of efforts in collecting data on these resources for similar purposes. To allow correct and evidence-based policy decisions and the implementation of effective agriculture sector development programs, data on these primary resources need to be interpreted, documented, and shared through the use of standardized methods and laboratory procedures.

The government of Ethiopia has been promoting the use of mineral fertilizers, lime, and irrigation for several decades in an effort to increase crop yields. Accordingly, smallholder farmers have been applying mineral fertilizers widely and irrigation to a certain extent to increase crop yields. However, the application rates of mineral (inorganic), as well as organic fertilizers, in particular, is a concern. One of the issues is the lack of optimal evidence-based fertilizer recommendations for the crop, soil type, and weather conditions of the land under cultivation. The second issue is low fertilizer efficiency that varies across soil types (Bado and Bationo, 2018), weather, method, and timing of application. There is also a problem related to ensuring fertilizer quality (physical and chemical characteristics). There are also considerable gaps in the knowledge and skills in soil, plant tissue, water, and fertilizer analyses to support the formulation of recommendations for the appropriate use of fertilizer, lime, and irrigation water. These issues are partly attributable to the lack of standardized soil, plant, water, and fertilizer quality testing methods and procedures.

Some efforts have been made to formulate crop and agroecology-based fertilizer and irrigation recommendations, as well as to ensure the quality of fertilizers to increase yields and environmental sustainability. For example, EthioSIS—the Ethiopian Soil Information System launched by the Ethiopian government in 2012— as tried to map Ethiopian soils in terms of physical and chemical properties and recommended blended fertilizers for different agroecological zones of the country. Although the extent to which the research procedure and protocol used by EthioSIS to collect the soil samples and interpret the results of the analyses leaves much to be desired, good attempts have been made to characterize and map Ethiopia's soil fertility status. Multi-year experiments need to be conducted on crop responses to fertilizers and plant tissue analysis at each agroecological setting using appropriate methods and protocols to formulate evidence-based fertilizer, irrigation, and lime recommendations.

To tackle the challenges faced in collecting standardized and reliable data on soil, plant, water, and fertilizer resources, and conduct analysis for scientific applications, it is necessary to develop a guide that would lead researchers, academics, laboratory technicians, and others to follow agreed methods and procedures.

2. Sampling: soil, plant, water, and fertilizers

2.1. Soil sampling

Soil is not homogeneous, and its constituents can vary widely within the landscape of a location. Therefore, the major challenge in soil sampling is to obtain a sample that is representative of the entire field under investigation. The common procedure is to take several individual cores to form a composite; the number of cores required to make one composite sample can range from as few as four to as many as 16 (Benton Jones, 2001).

There are three commonly used soil sampling strategies. These are:

i. **simple random sampling,**
ii. **stratified random sampling, and**
iii. **systematic or grid sampling.**

A soil auger should always be used for taking soil samples so that the depth of sampling is the same for each sample. A representative composite sample should be prepared for each field by mixing several individual auger samples taken from different positions at the same depth in the respective field (Fairhurst, 2012).

Soil samples can be taken at any time, but sampling directly after fertilizer application or other amendment practices should be avoided. Samples should be taken at specific times of the year to allow comparison of analysis results at regular time intervals (Estefan et al., 2013). Taking samples during periods of crop growth enables us to ascertain the nutrient status of the soil in which plants are actively taking up nutrients; soil sampling at the time the crop begins to flower or set fruit/bulbs/tubers is recommended. Sampling before establishing a crop is only recommended when previous soil test information is not available (Benton Jones, 2001).

Samples should be taken from the upper 0–20 cm of soil depth since this is the layer that is normally tilled and contains the largest portion of the crop's root and is where most crops' feeder roots are found (Benton Jones, 2012). A composite sample of about 0.5 kg should be taken from a field representing not more than 0.5 hectares (Fairhurst, 2012).

A 20 cm sampling depth should normally be used for cereals, vegetables, and other seasonal crops. For deep-rooted crops and long-duration crops, sub-samples should be collected from different depths depending on the situation. For plantation crops or fruit trees, composite samples may be collected from depths of 0–30, 30–60, and 60–90 cm, from 4–5 pits dug in a field of about 0.5 ha. For saline or saline-alkali soils, surface (0–20 cm) and sub-surface samples (>20 cm) should be collected by reordering the sampling depth. Deep soil profile samples are required for tests such as profile NO_3–N (Griffin et al., 1995).

Depth-wise soil samples should also be taken where there is a concern about B toxicity (Estefan et al., 2013). For soil characterization and classification, profile sampling should comply with the procedure of a world reference base for soil resources (WRB, 2006).

ICARDA recommends that eight sub-samples be taken per hectare (ha) in a diagonal pattern to obtain one composite sample (Estefan et al., 2013). Fewer sub-samples are needed where little or no fertilizer has been used. Correspondingly, more sub-samples are needed where fertility is variable due to the fertilizer broadcasting and/or other soil management practices.

When sampling soils, coring with the auger should be done randomly, avoiding areas in the field that are markedly different in elevation and soil type. Coring should not be done near roads, fences, buildings, or tree lines. In fields being treated as a single unit but differing in soil type, cores from the differing soil types should not be mixed, but composites should be made from each major soil type for separate laboratory analyses.

2.2. Plant sampling

The process of plant analysis includes the collection of the plant samples, preparation of the samples for analysis, interpretation of analytical results, and recommendations. Plant species, plant age, plant part, date, and time of sampling

are variables that affect the interpretation of the results of plant analysis (Benton Jones, 2012).

Concentrations of nutrients in plant tissues can vary between species, as well as between plant parts. The concentrations may also vary between crop variety, month of the year, day, and even between hours (Benton Jones, 2001; Mengel et al., 2001).

A plant part at a specific location on the plant obtained at a definite stage of growth (based on physiological age) constitutes the sampling parameters. In general, tissues that are either physiologically young and undergoing rapid change in elemental content or those past full maturity should not be sampled. The plant part selected, and the time of sampling must correspond to the best relationship that exists between its elemental content and yield, or the physical appearance of the plant (Kalra, 1998).

As a general rule, taking a sample of mature leaves, exposed to full sunlight, just below the growing tip on main branches or stems, just before or at the time the plant begins its reproductive stage of growth, is the preferred technique. In some situations, sampling may be necessary at earlier periods in the plant's growth cycle, collecting leaf tissue of the same maturity (Benton Jones, 2012).

Therefore, when to take a plant tissue sample will vary according to plant species and the objective of the plant analysis. When to sample is determined by what interpretative data is available that will have a sampling time designation. For example, for evaluating the elemental status of a plant and taking corrective measures with supplemental fertilization, taking a tissue sample of a recently-matured leaf during the vegetative period is normally advised.

In general, the time of sampling or age of the plant at sampling is determined by the purpose of the tissue analysis. A sampling of plant parts could be done at the growth stage of the seedlings, at the mid-stage of growth, just before or at flowering or seeding/tuber initiation, and maturity (Mengel et al., 2001; Fageria et al., 2011). A sampling at both seedling and mid-stage of growth and/or at maturity may be required to do mechanistic simulation modeling of nutrient uptake by plants during growth (Dechassa et al., 2003). Sampling the plant, at or just before flowering and/or the initiation of tubers, among other practices, is often done to diagnose the deficiency, sufficiency, or toxicity of a nutrient during the plant's growth period, as well as for estimating the physiological or uptake efficiency of the nutrient (Fageria and Baligar, 2003). Sampling the plant (straw/stover) as well as the seed or tubers separately is recommended to estimate the total uptake of a nutrient by plants (nutrient accumulation) from the total area of the land on which the crop was grown. This is obtained by multiplying concentrations of the nutrient in the straw and seed or tubers by the total dry biomass of the straw and seed/tuber yields (Fageria et al., 2011).

It is also necessary to collect soil samples when taking plant samples for analysis. Soil samples should be taken at the time and in the same vicinity where plant tissue samples are collected, and the soil assay results included with the plant analysis data (Benton Jones, 2012). See Table 1 for suggested growth stage, plant parts, and number of plants for sampling field and vegetable crops, fruits and nuts, and ornamental plants. Note that if a mature leaf has to be sampled, only one mature leaf should be taken from one plant. Therefore, the number of plants to be sampled indicated in the last column of Table 1 indicates the total number of leaves to be sampled.


Photo: Georgina Smith/CIAT

Table 1. Suggested growth stage, plant parts, and number of plants for sampling field and vegetable crops, fruits and nuts, and ornamental plants

Crop	Stage of growth	Plant part to sample	Number of plants to be sampled*
Field crops			
Maize	Seedling stage (< 30 cm)	All the above-ground portion	20–30
	Before tasseling	The entire leaf, fully developed below the whorl	15–25
	From tasseling and shooting to silking	The entire leaf at the ear node (immediately above or below it)	15–25
Soybean or	Seeding stage (< 30 cm)	All the above-ground portion	20–30
another bean	Before or during flowering	Two or three fully developed leaves at the top of the plant	20–30
Small grains (including rice, wheat, barley)	Seeding stage (< 30 cm)	All the above-ground portion	50–100
	Prior to heading	The fourth upper most leaves	50–100
Teff	Seedling stage	All the above-ground portion	-
	Before heading	All the above-ground portion	-
Hay, pasture or forage	Before seed head emergence or at the optimum stage for best quality forage	The fourth uppermost leaf blades	40–50
Clover and other legumes	Before bloom	Mature leaf blades taken about one-third of the way down the plant	40–50
Tobacco	Before bloom	Uppermost fully developed leaf	40–50
Sorghum-milo	Before or at heading	Second leaf from the top of the plant	15–25
Sugar beets	Mid-season	Fully expanded and mature leaves midway between the younger center leaves and the oldest leaf whorl on the outside	40–50
Groundnut	Before or at the bloom stage	Mature leaves from both the main stem and either cotyledon lateral branch	30–40
Vegetable crops			
Potato	Before or during early bloom	Third to the sixth leaf from growing tip	20–30
Head crops (cabbage, etc.)	Before heading	First mature leaves from the center of the whorl	20–30
Tomato (field)	Before or during early fruit set	Third or fourth leaf from the growing tip	20–25
Bean	Seedling stage (< 30 cm)	All the above-ground portion	20–30
	Before or during initial flowering	Two or three fully-developed leaves at the top of the plant	
Root crops			
Carrots, onions, beets, etc.	Before root or bud enlargement	Two or three fully developed leaves at the top of the plant center mature leaves	20–30
Leaf crops			
Peas	Before or during initial flowering	Leaves from the third node down	30–60

Crop	Stage of growth	Plant part to sample	Number of plants to be sampled*
Fruits and nuts			
Lemon, lime	Mid-season	Mature leaves from last flush or growth on non-fruiting terminals	20–30
Orange	Mid-season	Spring cycle leaves, 4–7 months old from non-bearing terminals	20–30
Banana	Before maturity	Petiole of 3rd open leaf from the apex, four months after planting	20–30
Coffee	Before blooming	3rd or 4th part of leaf from the apex of lateral shoot, at bloom	20–30
Avocado	Before blooming	4–7 month-old leaf from petiole. from the middle of the shoot	20–30
Mango	Before blooming	4–7 month-old leaf from petiole. from the middle of the shoot	20–30
Papaya	6th petiole from the apex, six months after planting		20–30
Pineapple	Middle one-third portion of the white basal portion of 4th leaf from the apex, at 4–6 months		20–30

* Note only one mature leaf per plant should be sampled. Source: Kalra (1998) and Singh et al. (2010).

2.3. Water sampling

A water sampling program starts with the collection of samples that accurately represent the characteristics of the bulk material and can be handled without deteriorating or contamination in the laboratory, while still providing test results (Estefan et al., 2013).

Water samples meant for irrigation quality assessment should be collected in glass or plastic bottles. Containers for water sampling should be decontaminated. Decontamination is usually done by thoroughly washing and rinsing 3–4 times with the water to be tested. The minimum water to be sampled should be 500 ml. Tube well or hand pump water samples should be collected after draining for 15–20 minutes. New tube well water samples should be collected at a depth of 3–4m. Samples from dam/micro-dam should be collected from 0–5 cm of the water surface at the center of the main flow. Collecting floating dust, oil, etc. should be avoided.

2.4. Fertilizer sampling

Fertilizer samples should be representative of bulk fertilizers (DAP, Urea, TPS, NPS, NPSB, NPSZn, NPK, NPSBZn, etc.) that are distributed within the different regions or available on the Ethiopian fertilizer market. Fertilizers should be sampled from bags/sacks with the help of a sampling probe/tube. Three identical samples of about 450−500 g each should be taken for analysis. Of the three samples, one should be submitted to the designated laboratory for analysis; another goes to the owner of the fertilizer (supplier/importer) and the third sample should be kept for further reference by the sample collector. Fertilizers from stocks of importers and/or wholesalers should be sampled following the same procedure (FAO, 2008). Samples should be labeled appropriately with the detailed information required at analysis.

Photo: Nigussie Dechassa

3. Description of sampling area and sample preparation

3.1. Area description

Data to be documented and shared for big data sets on soil, plant, irrigation water, and fertilizer should comply with all sampling area descriptions. In collecting soil, plant, and water samples there is a need to describe the sites from which the samples are taken. The specific descriptions should include sampling information, administrative location, reference and geographic locations, information on climate, soil, topography, land use management, farm size, farm ownership, and others (Tables 2 and 3). In addition, in collecting data on fertilizer, there is a need to provide information on the date of sampling, type and source of fertilizer, as well as type and source of feedstock (organic fertilizers) or name of fertilizer, grade and labeling information, and source of sample (inorganic fertilizer) (Table 4).

Table 2. Sample form to capture area description for soil and irrigation water data documentation and sharing

General information

1. Sampled/reported by: _____

2. Institution: _____

3. E-mail: _____Tel:_____P.O. Box:_____

4. For published data: Journal name: _____ Volume: _____Issue No._____

Author/s name: _____

Title of the article:_____

5. Purpose of the study_____

S No.	Sampling information			Administrative location						
	Date of sampling	Sampling depth (m/cm)	Method of sampling	Region	Zone	Woreda (District)	Kebele	Watershed/ Village	Farmer name	Farm size
1										
2										

S. No	Reference location		Geographical location			Climate		
	Nearest city/town	Nearest river, if any	Altitude (m.a.s.l.)	Latitude (N)	Longitude (E)	Mean annual RF (mm)	Mean annual Temp (°C)	
							Max.	Min.
1								
2								

S. No.	Soil and topography		Land use and management							
	Soil type	Topography	Vegetation cover	Previous crop	Fertilizer Use		Irrigation			Remarks, if any
					Type	Rate (kg ha^{-1})	Method	Source of water	Water quality	
1										
2										

Table 3. Sample form for capturing area description for plant data documentation and sharing

General information

1. Sampled/reported by: _____

2. Institution: _____

3. E-mail: _____Tel:_____P.O. Box:_____

4. For published data: Journal name: _____ Volume: _____Issue No._____

   Author/s name: _____

   Title of the article:_____

5. Purpose of the study_____

S. No.	Sampling information			Administrative location						
	Date of sampling	Plant part	Growth stage	Region	Zone	Woreda	Kebele	Village	Farmer name	Farm size
1										
2										

S. No.	Reference location		Geographical location			Climate		
	Nearest city/ town	Nearest river, if any	Altitude (m.a.s.l.)	Latitude (N)	Longitude (E)	Mean annual RF (mm)	Mean annual Temp (°C)	
							Max.	Min.
1								
2								

S. No.	Soil and topography		Land use and management							
	Soil type	Topography	Vegetation cover	Previous crop	Fertilizer Used		Irrigation			Remarks, if any
							Irrigation method	Source of water	Water quality	
					Type	Rate (kg ha^{-1})				
1										
2										

Table 4. Sample form for capturing area description for fertilizer data documentation and sharing

General information

1. Reported/Sampled by: _____

2. Institution: _____

3. E-mail: _____Tel:_____P.O. Box:_____

4. For published data: Journal name: _____ Volume: _____Issue No._____

Author/s name: _____

Title of the article:_____

5. Purpose of the study_____

Organic fertilizer									
S. No.	Sampling information			Administrative location					
	Date of sampling	Type of organic fertilizer	Type and source of feed stock	Region	Zone	Woreda	Village	Farmer name	Farm size
1									
2									
3									

S. No.	Reference location		Geographical location			Climate		
	Nearest city/town	Nearest river, if any	Altitude (m.a.s.l.)	Latitude (N)	Longitude (E)	Mean annual RF (mm)	Mean annual Temp (°C)	
							Max.	Min.
1								
2								
3								

Inorganic fertilizer					
S. No.	Date of sampling	Type of fertilizer	Grade and other labeling information	Source of sample	Remarks
1					
2					

3.2. Sample preparation and processing

3.2.1. Soil

The conventional first procedure for preparing soils for analysis is to air-dry field soil samples at ambient temperature (21-27°C) before crushing and sieving (Benton Jones, 2001). The drying process should be completed as rapidly as possible to minimize microbial activity (mineralization). The time required to bring a soil sample to an air-dried condition is determined by its moisture, organic matter content, and texture. Soils high in clay and/or organic matter content require a considerably longer time to bring to an air-dried condition than do sandy-textured soils. Drying can be facilitated by exposing as much of the soil's surface as possible to circulating air and by elevating the drying temperature, but not exceeding 38°C because significant changes in the physiochemical properties of the soil can occur at elevated drying temperatures.

Following drying, the soil sample is crushed, either using a porcelain mortar and pestle or using a mechanical device, and then passed through a 10-mesh (2 mm) screen. For determining organic carbon and total nitrogen, a 0.5 mm sieve should be used. Sieving removes stones and other extraneous substances, yielding a uniform sample that can be easily handled in the laboratory and stored indefinitely. This preparation procedure can contaminate a soil sample, either from the composition of the contacting surfaces or from the deposition of dust and/or previous sample residue. The crushing and sieving devices must be free of elements that might be determined in the analysis. For example, brass sieves should not be used if copper (Cu) and zinc (Zn) are elements to be determined.

In general, once the soil sample has been air-dried, crushed, and screened, it can be stored indefinitely in a dry environment without significant changes in soil test values (Houba and Novozamsky, 1998; Houba et al., 2000).

To prepare and process soils for Laser Diffraction analysis, samples should be air-dried, then ground gently, and sieved through a 2 mm sieve. Fine soil sub-samples should be prepared via coning and quartering method and eventually subjected to both wet and dry mode of analysis on a Laser Diffraction Particle Size analyzer. To prepare and process soils for near infra-red (NIR) and mid-infrared (MIR) analysis, the soil samples should be ground and sieved through a 2-mm sieve. Sub-samples should be prepared by coning and quartering method and ground to less than 0.5 mm (fine powder particle size between 20–53 µm).

3.2.2. Plant

After sampling plants for tissue analysis, care is required to ensure that the tissue retains its original condition, preventing loss of dry weight and keeping the tissue from being contaminated with external substances and dust. Placing fresh plant tissue in an closed container for any length of time requires refrigeration, with the sample container being free from any substances that can contaminate the sample.

An elemental concentration interpretation is based on tissue dry weight; thus, any condition that affects dry weight will in turn negatively affect the elemental concentration. When collected, plant tissue begins to decay; a significant reduction in dry weight will occur, as well as the loss of some elements by volatilization, particularly nitrogen (N) and sulfur (S). To preserve tissue dry weight, it is important to make sure that fresh plant tissue is not placed in plastic bags unless the temperature is kept below 5°C. In addition, air-drying tissue before transporting it to the plant analysis laboratory will minimize loss in dry weight. Plant tissue should be delivered to the laboratory within 24 hours of collection if storage below 5°C is not possible.

Sources of contamination include soil, dust, and foliar-applied chemicals which, if not removed, can result in a misinterpretation of an analytical result. Contamination can also occur as the result of careless handling of the collected tissue samples. Elements found as major constituents in soil and dust will alter the analytical result for those elements, the elements being aluminum (Al), iron (Fe), and silicon (Si). If all three of these elements appear in high concentration in the assay result, soil/dust contamination is likely to be the source; but if only one element appears at high concentration, soil/dust contamination is not likely to be the source. Under some circumstances, assay results for other elements may be affected, depending on the nature and degree of presence of the soil/dust.

Decontamination to remove foreign substances from the tissue surface may be necessary, particularly it contains elements that are essential for the interpretation of the result of the analysis. If Fe is an element of primary interest, the plant tissue must be decontaminated, otherwise the Fe analysis result will be highly suspect. If Fe is not an element of primary interest, rainfall or the application of overhead irrigation will normally keep just-maturing leaf tissue relatively free from a significant accumulation of dust and soil particles; therefore, decontamination may not be necessary. However, if plants are not regularly bathed with either rainfall or overhead irrigation, dust and soil particles will begin to accumulate on leaf tissue, requiring decontamination to remove the accumulated particles. After sampling, plant parts should be cleaned for any contamination by washing with deionized water or appropriate detergent, oven-dried at 70°C for 24 hours to a constant weight. Samples should be ground with a stainless steel grinder and stored in airtight plastic bags (Benton Jones, 2001).

3.2.3. Irrigation water

The optimum time frame between sample collection and analysis of irrigation water should generally not exceed 6 hours; 24 hours is considered the absolute maximum. Samples should be placed immediately in a lightproof (no sunlight) insulated box containing ice packs to ensure rapid cooling. The irrigation water samples should be kept out of direct sunlight; there should be no air space in the sample containers and the samples should be kept cool because sunlight and warm temperature can influence microbial activities in the water and change its composition. Thus, if the analysis is to be done in the future, after analysis of turbidity, the water samples should be filtered and stored at 4°C.

3.2.4. Fertilizer

Each sample of inorganic fertilizer is halved into two sub-samples. One half of each sample should be ground, sieved through a 1 mm sieve, and stored in a sample bottle for analysis. The remaining half of the samples should be kept unground for particle size estimation. The samples should be stored in an airtight glass bottle or taken for analysis in a moisture-free room (fitted with a dehumidifier) as most fertilizers are hygroscopic. The sample size should be 1.0 g (to be weighed exactly).

Samples of organic fertilizer should be air-dried at room temperature, ground with a porcelain mortar and pestle, and passed through a 0.5 mm sieve for the determination of physical and chemical properties. The samples of the organic fertilizer always need to be prepared using the wet-digestion method[2].

2 Details and explanations of this and other procedures are provided in a supporting manual.

Photo: CIAT/Georgina Smith

4. Standard methods for soil, plant, water, and fertilizer analyses

4.1. Soil

Soils have different properties that affect plant growth, the hydrological cycle, carbon sequestration, ecosystem services, land use, etc. Soil properties are determined in laboratories using different methods and are expressed in various units of measurement. However, it is important to have standardized methods to determine the properties, as well as the units of measurement for expressing, interpreting, documenting, and sharing the data.

4.1.1. Physical characteristics

Soil physical properties are related to how liquid and gas movements through the soil pores are affected by the particles. Both soil mineral particles and soil organic matter influence the physical properties of soils. Soil physical properties should be determined using standard methods and expressed in commonly used units (Table 5).

Table 5. Methods and units of measurement of soil physical parameters for data documentation and sharing

Soil parameter	Unit	Method	Purpose
Coarse fraction	%	Gravimetric	Irrigation and soil characterization and classification
Soil moisture content	%	Gravimetric	Moisture factor
Particle size distribution	%	Hydrometer	Agronomy and soil fertility
		Pipette	Soil characterization and classification
Bulk density	g cm^{-3}	Core sampling	All
Particle density	g cm^{-3}	Pycnometer	All
Soil moisture release characteristic	mm $(mm)^{-1}$	Sand box	Soil and water management
Field capacity	mm $(mm)^{-1}$	Pressure plate	
Permanent wilting point (PWP)	mm $(mm)^{-1}$	Pressure plate	
Soil permeability	mm $(min)^{-1}$	Hydraulic head/parametric	Soil hydraulic conductivity
Mineralogical analysis		X-ray diffraction	Clay mineralogy analysis

Note that "%" in the Table is on a mass basis.

Soil moisture content

Soil moisture influences crop growth not only by affecting nutrient availability, but also nutrient transformations and soil biological behavior. Although it can be assessed in the field by the neutron probe, the gravimetric approach is more flexible, as samples can be readily taken from any soil situation. All analyses in the laboratory are related to an air- or oven-dry basis, and therefore must consider the actual soil moisture content. Over-heating of the soil sample should be avoided by maintaining the oven temperature at 105–110°C.

Particle size distribution (texture)

Soil texture is an important physical property of soil. It influences soil fertility, drainage, water-holding capacity, aeration, tillage, and bearing strength.

Soil texture or particle size analysis, also referred to as mechanical analysis, is used to determine the proportion of different-sized particles in the soil and hence its textural class. The measurements are also used as basic indicators of soil physical and chemical properties, and as a standard check on the finger texturing of surveyors in the field. A standard method must be used because results are greatly affected by pre-treatment and by the method itself (Dewis and Freitas, 1970).

For standard particle size measurement, the soil fraction that passes a 2-mm sieve is considered. Laboratory procedures normally estimate the percentage of sand (0.05–2.0 mm), silt (0.002–0.05 mm), and clay (< 0.002 mm) fractions in soils.

Primary soil particles are usually cemented together by organic matter, which has to be removed by treatment with hydroxide peroxide (H_2O_2). However, if substantial amounts of calcium carbonate ($CaCO_3$) are present, actual percentages of sand, silt, or clay can only be determined by the prior dissolution of the $CaCO_3$. For highly saline soils, some modification is necessary to allow for the weight of soluble salts removed during the pre-treatment. Soils with high gypsum content need washing to remove sufficient gypsum to prevent flocculation of the clay. The two common procedures used for particle size analysis or mechanical analysis are the hydrometer method and the pipette-gravimetric method. The pipette method is accurate compared to other procedures, whereby an aliquot is pipetted from a given depth at given times and the oven-dry soil contents determined by weighing after evaporation of the water. The hydrometer (or Bouyoucos) method of

silt and clay measurement relies on the effect of particle size on the differential settling velocities within a water column. For most agricultural purposes, however, the Bouyoucos method is sufficiently precise.

The results of particle size analyses are usually quoted as percentages by weight of the whole soil or of the 'fine earth' fraction of < 2 mm diameter. The proportions of sand, silt and clay are used with the familiar triangular texture diagram to determine the textural class of the soil (Landon, 1991).

Bulk density

Bulk density is the overall density of soil (i.e. the mass of mineral soil divided by the overall volume occupied by the soil, water, and air), and it should be distinguished from the density of the solid soil constituents, usually called the particle density, which is conventionally taken as 2.65 g cm^{-3}. The weight of soil solids in bulk density measurements is taken as the oven-dry constant weight at 105°C (Benton Jones, 2012; Estefan et al., 2013).

The results are used as indicators of problems of root penetration and soil aeration in different soil horizons. Bulk density (BD) values vary considerably with moisture content, particularly those of fine-textured soils; samples should therefore be taken at or near to field capacity (Landon, 1991). Two methods are commonly used to determine soil BD. One method deals with samples of disturbed soil, and the other method deals with samples of undisturbed soil. The second method uses consolidated soil masses, e.g. clods and cores.

The BD of fine-textured mineral soils usually ranges from about 1.0 to 1.5 g cm^{-3}, and that of sandy soils from 1.3 to 1.7 g cm^{-3}. The bulk density of organic soils is usually much less than that of mineral soils and may be as low as 0.4 g cm^{-3}. Bulk density and total pore space are readily altered by tillage operations. The bulk density of mineral soils may vary considerably, implying the need to find soils with appropriate bulk densities for the cultivation of farmlands.

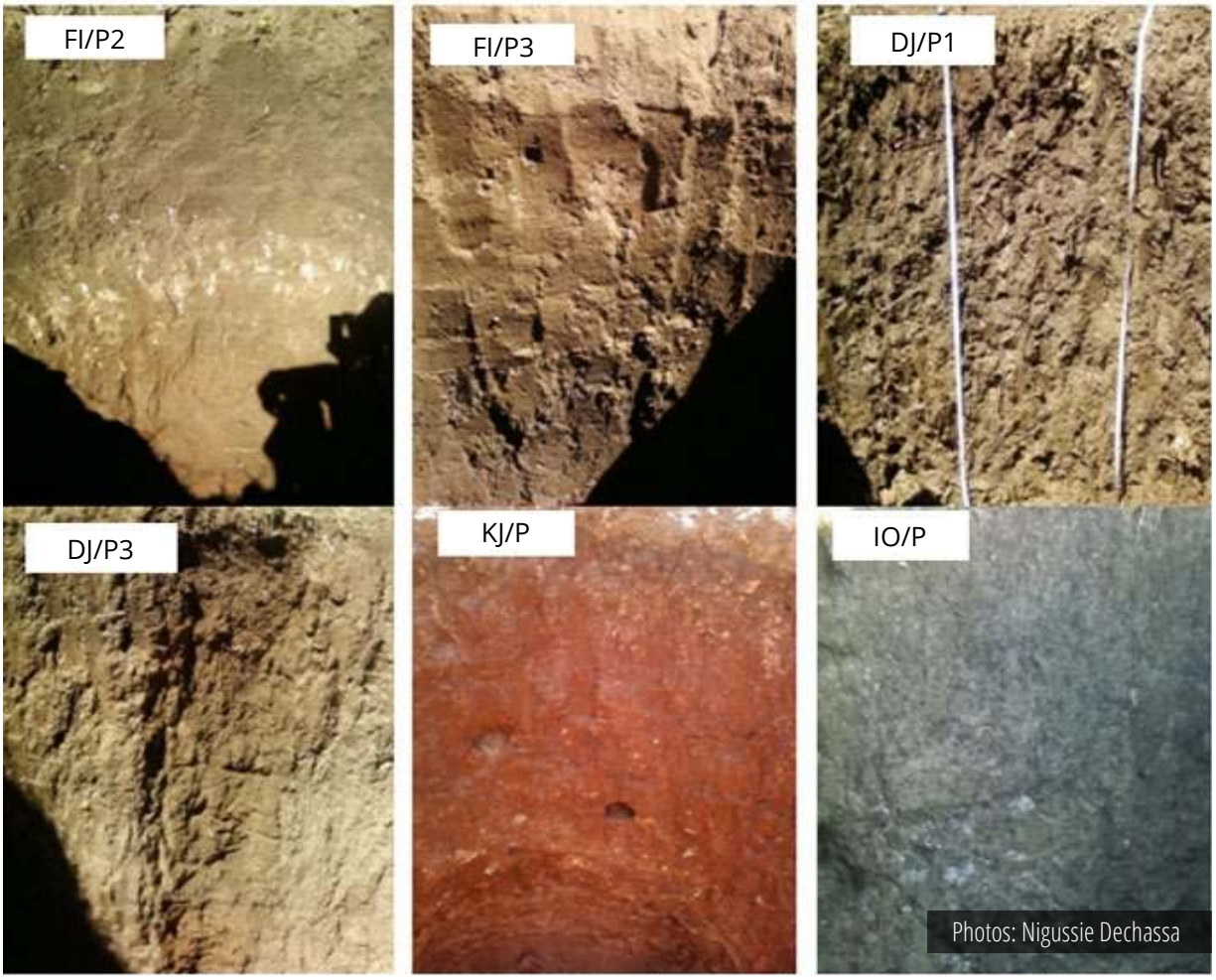
Table 6. Typical bulk density ranges of mineral soils

Material	Bulk density (g cm^{-3})
Recently-cultivated soils	0.9–1.2
Surface mineral soils, not recently cultivated, but not compacted	1.1–1.4
Soils showing root restriction:	
- Sands and loams	1.6–1.8
- Silts	1.4–1.6
- Clays	Extremely variable

Source: Landon (1991).

Particle density

Soil particle density (PD) is defined as the ratio of the mass (oven-dry mass) of the soil particles to the particle volume expressed in grams per cubic centimeter (only solid, no pore space). The volume of soil is determined by measuring the volume of water displaced by the particles. The magnitude of PD depends on the type of minerals in the particles and the content of organic matter (OM) in the soil. The particle density of most soils varies from 2.60 to 2.75 g cm^{-3}. Organic soils have a lower PD since OM has a density of 1.2–1.5 g cm^{-3}. The result of PD is used with BD to calculate soil porosity.



Water-holding capacity

Water-holding capacity (WHC) is defined as the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially ceased. The stage of field capacity—the point at which the soil WHC has reached its maximum for the entire field—is attained in the field after 24 to 72 hours of saturation; this is the upper limit of plant-available soil moisture. One has to distinguish between soil water content, (the percentage of water on an oven-dry weight basis), and the soil water potential (the energy status of water in the soil), which is usually expressed in pressure units (Pascal or bar).

Soil water-holding capacity is mostly determined at field capacity (–33 kPa) and at permanent wilting point (–1500 kPa) using a pressure plate apparatus. Available water is calculated as the difference between water retained at field capacity and permanent wilting points.

4.1.2. Chemical properties

Soil chemical properties have an important bearing on agricultural productivity, soil health, ecosystem services, environmental sustainability, etc. Therefore, determining the different soil chemical properties through standard methods and expressing the values in commonly used scientific units is a vital prelude for sound interpretation, documentation, and sharing of the data. The main use of soil chemical analysis is usually to indicate potential excess or deficiency problems in soils (Landon, 1991) as well as for characterizing and classifying soils as a natural resource. The standard methods of soil chemical analysis and interpretation for data documentation and sharing are shown in Table 7.

Table 7. Methods and units of measurement of major soil chemical properties for data documentation and sharing

Soil parameter	Unit	Method		Purpose
		Extraction/Digestion	Estimation/Analysis	
Soil pH		Soil: Water ratio 1: 2.5	Potentiometric	Agronomy and soil fertility
		Soil: KCl solution ratio 1: 2.5	Potentiometric	Soil characterization and classification
Electrical conductivity	dSm^{-1}	Soil: water ratio 1: 2.5	Conductivity meter	Agronomy and soil fertility
Organic carbon	%	Wet oxidation (Walkley-Black)	Titration	All
Total nitrogen	%	Kjeldahal method	Titration	All
Mineralizable-N	$mg\ kg^{-1}$	Alkaline $KMnO_4$	Distillation-Titration	Agronomy and soil fertility
NO_3-Nitrogen	$mg\ kg^{-1}$	Phenoldisulphonic acid	Spectro-photometric	
NH_4-Nitrogen	$mg\ kg^{-1}$	Copper sulphate	Indophenol blue (colorimetric) or Distillation-Titration	
Available phosphorus	$mg\ kg^{-1}$	Bray's method II for acid soils	Spectro-photometric	
		Olsen's method for neutral and alkaline soils		
Exchangeable potassium	$mg\ kg^{-1}$	Neutral ammonium acetate	Flame photometric	
Available sulphur	$mg\ kg^{-1}$	Monocalcium phosphate	Turbidimetrically using spectrophotometer	
Exchangeable bases (Na, Ca, Mg and K)	$cmol_{(+)}\ kg^{-1}$	Ammonium acetate (pH = 7)	Flame photometric (Na and K) and AAS/ ICP-OES (Ca and Mg)	All
Micronutrient cations (Zn, Cu, Fe and Mn)	$mg\ kg^{-1}$	DTPA extraction	AAS/ ICP-OES	Agronomy and soil fertility
Boron	$mg\ kg^{-1}$	Hot water	Azomethine-H colorimetric	Agronomy and soil fertility
Molybdenum	$mg\ kg^{-1}$	Ammonium acetate	AAS/ICP-OES	
P, K, S, Na, Ca, Mg, Zn, Cu, Fe, Mn, B and Mo	$mg\ kg^{-1}$	Mehlich-III for acidic soils	ICP-OES/Estimation method for the respective element	Agronomy and soil fertility
Cation exchange capacity	$cmol_{(+)}\ kg^{-1}$	Ammonium acetate (pH = 7)	Distillation-Titration	All
Exchangeable acidity (Al^+ and H^+)	$cmol_{(+)}\ kg^{-1}$	KCl	Titration	Agronomy and soil fertility
Calcium carbonate	%	HCl	Titration/Calcimetric	Soil characterization and classification
Gypsum	%	Acetone precipitation	Conductivity meter	
Free Fe, Al and Mn	%	Dithionite-citrate solution	AAS/ ICP-OES	
Active Fe, Al and Si	%	Acid oxalate solution	AAS/ ICP-OES	
Organically-bound Fe and Al	%	Sodium pyrophosphate	AAS/ ICP-OES	
Total nutrient analysis (P, K, S, Zn, Cu, B and Mo)	% or $mg\ kg^{-1}$	Mixed acid or dry ashing (P, K, Zn, Cu, B, and Mo)	Estimation method for the respective element	Soil fertility
Hazardous heavy metal analysis in soil (As, Cd, Hg, Pb, Cr, Co, Ni)	$mg\ kg^{-1}$	EDTA	AAS/ ICP-OES	Environmental soil chemistry

Note the % indicated in the table is on a mass basis

EDTA= Ethylenediaminetetraacetic acid; AAS = Atomic Absorption Spectrophotometer; ICP-OES = Inductively Coupled Plasma Optical Emission Spectrophotometry; DTPA = Diethyltriaminepenta acetic acid

Soil pH

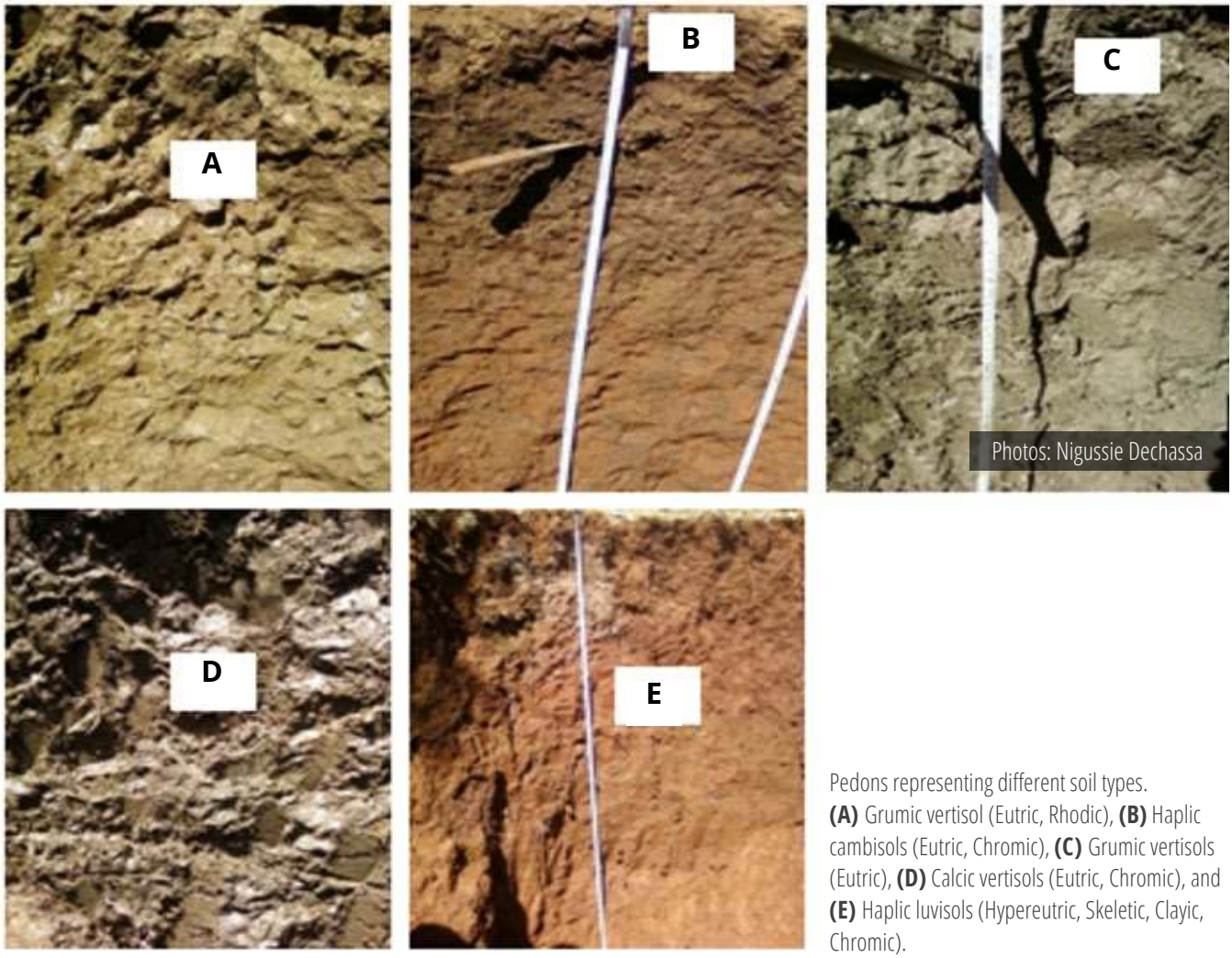
Soil pH is a measure of the acidity or basicity on a scale from 0 to 14, with a pH of 7.0 indicating the neutral point that is neither acidic nor basic (Tan, 2011). Determination of soil pH in a soil/water suspension normally provides adequate information and has the merit of simplicity (Landon, 1991). Soil pH can also be determined using neutral salt solutions, namely, 0.01 M calcium chloride ($CaCl_2 \cdot 2H_2O$) (Schofield and Taylor, 1955) or 1 M potassium chloride (KCl). Therefore, the pH-water method should be used as a standard method for measuring active acidity whereas soil pH-KCl or pH-$CaCl_2$ method should be used for measuring potential acidity.

Soil pH values vary considerably across soil types and environmental condition, entailing different management systems for agronomic as well as environmental purposes. Standardized soil pH ranges with varying degrees of acidity and basicity are shown in Table 8.

Table 8. Ranges of common soil pH values and interpretation

Category	pH (1:2.5 H_2O)
Very strongly acid	< 5.0
Strongly acid	5.1–5.5
Moderately acid	5.6–6.0
Slightly acid	6.1–6.5
Neutral	6.6–7.3
Mildly alkaline	7.4–7.8
Moderately alkaline	7.9–8.4
Strongly alkaline	8.5–9.0
Very strongly alkaline	> 9.0

Source: Murphy (1968)



Pedons representing different soil types. **(A)** Grumic vertisol (Eutric, Rhodic), **(B)** Haplic cambisols (Eutric, Chromic), **(C)** Grumic vertisols (Eutric), **(D)** Calcic vertisols (Eutric, Chromic), and **(E)** Haplic luvisols (Hypereutric, Skeletic, Clayic, Chromic).

Electrical conductivity

Electrical conductivity is an indicator of soil health as it affects crop growth and yields through its influence on plant nutrient and water availability, activities of soil microorganisms, etc. It is measured in the soil-water suspension ratio of 1:2.5.

Soil organic carbon

Soil organic carbon is routinely determined by the Walkley-Black dichromate method (Hesse, 1971) as cited by Landon (1991). The results are usually quoted as the percentage by weight of organic C in the soil. Published organic C to total organic matter conversion factors for surface soils vary from 1.724 to 2.0. In the soils of arid and semi-arid regions, a value of 1.724 is an acceptable factor and is commonly used, although, whenever possible, the appropriate factor must be determined experimentally for each type of soil (Bashour and Sayegh, 2007). Categories for rating soil organic carbon content are shown in Table 9.

Table 9. Rating of soil organic carbon

Rating	Soil organic carbon (OC, %)
Very low	< 0. 5
Low	0.5–1.5
Medium	1.5–3.0
High	>3.0
Very high	Not given

Source: Debele (1980) as cited by Tekalign et al. (1991)

Soil nitrogen

Nitrogen (N) occurs in soils in several forms: organic compounds, nitrate and nitrite anions, and ammonium ions, which can occur as exchangeable cations; nitrates are the main forms of N used by plants. Apart from the application of N fertilizers, the main source of N in soils is the breakdown and humification of organic matter; slow decomposition of humus releases NH_4 ions, which are subsequently oxidized to nitrite and nitrate (Landon, 1991).

Different measurements of soil N give divergent results because varying proportions of the different types of N are extracted (Mengel et al., 1982). The most common and standard method for determining the total nitrogen content in the soil is the micro Kjeldahl digestion and distillation system, which involves the catalytic oxidation of organic and chemically combined N and subsequent alteration to NH_4, then to NH_3 (Hesse, 1971). This method also extracts some of the interstitial NH_4 held in clay lattices, but in most tropical soils the error thus introduced is probably very small (Landon, 1991).

Except in detailed management studies, N measurements are difficult to interpret, since the types of N present and their relevance to plant nutrition and environmental effect are not usually known. Even within specific environments, there seems to be no general agreement on ratings of N values measured by the same method (Landon, 1991). The ratings of total nitrogen are given in Table 10, as a very general reference to total N content for Ethiopian soils.

Table 10. Total nitrogen rating for some Ethiopian soils

Rating	Total nitrogen (TN, %)
Low	< 0.01
Medium	0.01–0.12
High	0.12–0.25
Very high	>0.25

Source: Debele (1980) as cited by Tekalign et al. (1991)

Available phosphorus

Phosphorus (P) exists in various forms in mineral soils in the forms of soil organic matter, as well as in other various inorganic forms. The inorganic P forms are primarily mixtures of aluminum (Al-P), iron (Fe-P), and calcium (Ca-P) phosphates. The relative proportions of these forms are a function of soil pH, with higher percentages of Al-P and Fe-P occurring in acid soils, and a higher percentage as Ca-P occurring in neutral to alkaline soils (Mengel et al., 2001). Therefore, the extraction procedure for the measurement of plant-available P is governed to a large degree by soil pH (Benton Jones, 2012).

There are six major soil testing or extraction methods (procedures) commonly used for determining soil P (Table 11). Each method was designed for a specific soil situation.

Extraction reagents vary in their composition depending on their application for extracting a particular form of P found in soil as well as other soil properties (mainly pH). Dilute acids solubilize Ca-P, Al-P, and, to a lesser degree, Fe-P and Fe, are included in complex Al and prevent re-adsorption of P by Fe oxides. The bicarbonate HCO_3-based extraction reagents apply particularly to alkaline soils in which the major portion of P exists as Ca-P.

Table 11. Major soil P extraction methods based on specific soil characteristics

Test methods	Date	Adapted range of soil
Morgan	1941	Acid soils with CEC < 10 $cmol_{(+)}$ $kg\ soil^{-1}$
Bray P1	1945	Acid soils (pHw < 6.8) of moderate texture
Bray P2	1945	Acid soils in which rock phosphate has been the primary P fertilizer source or the major portion of P exists in the soil as various forms of calcium phosphate
Mehlich No. 1	1953	Acid (pHw < 6.5) coastal plain soils of low CEC (< 10 $cmol(_+)$ $kg\ soil^{-1}$) and low organic matter content (< 5%)
Olsen	1954	Calcareous, alkaline, or neutral pH soils where soil P is mostly in various forms of calcium phosphate
Mehlich No. 3	1984	For a wide range of acid soils with extracted P correlating well with Bray P1 P for acid soils, and with Olsen P for calcareous, alkaline, or neutral pH soils

The most widely applicable method of determining soil P is Olsen's method of bicarbonate extraction (Black, 1965). The method is preferred for soils of pH >7. For acid soils, the Bray, Truog or Morgan methods may be used (Dewis and Freitas, 1970; Hesse, 1971). Therefore, these methods should be used in Ethiopia depending on the specific soil physical and chemical characteristics.

The Mehlich 3 P extraction procedure has been put to use in recent years in Ethiopia for extracting P from all soil types. Caution should be exercised particularly in using it for extracting the nutrient from calcareous soils since it extracts considerably higher amounts of P than the Olsen method and the results of its extraction correlate poorly with the results of the Bray P1 on the same type of soil (Benton Jones, 2001).

However, as a general rule, in Ethiopia, the Olsen method should be used for neutral to alkaline soils and the Bray II method should be used for acidic soils as a standard.

Because of the variety of methods used, no one general interpretation of available P can be given (Landon, 1991). The values for Olsen's method (Olsen et al., 1954) according to the rating of Cottenie (1980) and the values for Bray II according to the ratings of Bray and Kurtz (1945) are presented in Table 12.

Table 12. Rating of Olsen and Bray II extractable soil phosphorus

Rating	Olsen P (mg kg $soil^{-1}$)[a]	Bray II P (mg kg $soil^{-1}$)[b]
Very low	< 5	< 20
Low	5–9	20–40
Medium	10–17	40–100
High	18–25	> 100
Very high	> 25	-

Source: [a]Cottenie (1980); [b]Bray and Kurtz (1945)

Exchangeable bases

Exchangeable bases, namely, potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) are extracted from the soil usually by the use of neutral normal ammonium acetate (Schollenberger and Simon, 1945), in which NH_4+ cation is used as the exchange cation for extracting basic cations (Table 13).

Table 13. Rating of soil exchangeable bases (cmol $_{(+)}$ kg soil^{-1})

Rating	Potassium	Calcium	Magnesium	Sodium
Very low	< 0.2	< 2	< 0.3	< 0.10
Low	0.2–0.3	2–5	0.3–1.0	0.1–0.3
Medium	0.3–0.6	5–10	1.0–3.0	0.3–0.7
High	0.6–1.2	10–20	3.0–8,0	0.7–2.0
Very high	>1.2	>20	>8.0	>2.0

Source: FAO (2006)

Cation exchange capacity

Cation exchange capacity (CEC) is the ability of a soil to attract and retain cations such as potassium (K), sodium (Na), calcium (Ca), magnesium (M), ammonium (NH_4), etc. Cation exchange capacity is influenced mainly by pH for soils dominated by variable charge colloids. Neutral ammonium acetate (1 N $NH_4C_2H_3O_2$, pH 7.0) is most commonly used to estimate soil cation exchange capacity through exchanging all cations by NH4$^+$ ions.

Cation exchange capacity is reported as centimoles of positively charged ions retained per kg of soil (cmol$_{(+)}$ kg soil^{-1}). Values of CEC are in the range of 1.0 to 100 cmol$_{(+)}$ kg soil^{-1}, least for sandy soils and most for clay soils (FAO, 1990; Landon, 1991) (see Table 14).

Table 14. Rating of soil cation exchange capacity

Rating	CEC (cmol $_{(+)}$) kg soil^{-1})
Very low	< 5
Low	5–15
Medium	15–25
High	25–40
Very high	> 40

Source: Landon (1991)

Sulphur

Sulphur (S) exists in soil and soil solution mainly as the sulphate (SO_4-S) anion in combination with the cations Ca, Mg, K, Na or NH_4. Sulphur in the form of SO_4^{2-} anion is easily adsorbed by clay, iron, and aluminum oxides. Sulphur exists both in inorganic and organic forms. The major inorganic sources of

S include gypsum ($CaSO_4$), and pyrite (Fe_2S). Phosphate ions (as monocalcium phosphate) are used to extract adsorbed SO_4^{2-} ions. The extraction is also carried out using $CaCl_2$ solution. However, monocalcium phosphate is considered to be better for the more efficient replacement of SO_4^{2-} ions (see Table 15 for the rating of the availability).

Table 15. Rating of soil sulphate content

Rating	Sulphur (mg kg soil^{-1})
Very low	< 0–10
Low	10–20
Medium	20–35
High	35–45
Very high	> 45

Source: Bashour and Sayegh (2007)

Micronutrients

The micronutrients boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molibdenum (Mo), and zinc (Zn) are the seven essential elements for plant growth/life (Römheld and Marschner, 1991) at requirement levels of less than 0.10% in the plant's dry matter (Epstein, 1965; Glass, 1989). Plant-available Fe, Zn, Cu and Mn in soils are extracted using a chelating agent DTPA (diethylenetriaminepentaacetic acid) (Lindsay and Norvell, 1978) (see Table 16 for critical levels).

Table 16. DTPA-extractable critical levels of soil cationic micronutrients for plant uptake and growth (mg kg soil^{-1}).

Rating	Zn	Mn	Fe	Cu
Very Low	0–0.5	0–0.5	0–2.0	0–0.1
Low	0.6–1.0	0.5–1.2	2.0– 4.0	0.1–0.3
Medium	1.0–3.0	1.2–3.5	4.0–6.0	0.3–0.8
High	3.0–6.0	3.5–6.0	6.0–10.0	0.8–3.0
Very high	> 6.0	> 6.0	> 10.0	> 3.0

Source: Lindsay and Norvell (1978)

Boron

Boron (B) is a non-metal, in contrast to the other micronutrients. The hot-water extraction method is the most popular one for measuring extractable soil B or the fraction of B related to plant growth in alkaline soils. Water-soluble B, which is the available form of B, is extracted from the soil by water suspension. Boron in soil extracts is measured calorimetrically using the reagent Azomethine-H (Bingham, 1982). Also, B can be analyzed by colorimetric methods using reagents such as Carmine and, most recently, by Inductively Coupled Plasma (ICP) and Atomic Emission Spectrometry (Estefan et al., 2013).

Where soil B levels are less than 0.5 mg kg soil^{-1}, deficiency is likely to occur for most crops. However, where levels are greater than about 5.0 mg kg soil^{-1}, toxicity may occur. Thus, there is a narrow range between sufficiency and toxicity levels.

Molybdenum

Molybdenum (Mo) is present in the soil in very small amounts. The total Mo content in soils is perhaps the lowest of all the micronutrient elements. Molybdenum exists mainly as $HMoO_4^-$ ion under acidic condition, and as MoO_4^{2-} ion under neutral to alkaline conditions. Determination of available Mo is done by extraction with ammonium acetate. Critical values of Mo ranging from 0.2 to 0.5 mg kg^{-1} plant dry matter have been reported for most crops. Thus, there is a narrow range between sufficiency and toxicity ranges of Mo in plant tissue.

Exchangeable acidity

Exchangeable acidity is primarily associated with the exchangeable aluminum and hydrogen ions present in very acid soils. These ions can be released into the soil solution by unbuffered salts such as KCl. In moderately acid soils, the quantity of easily exchangeable aluminum and hydrogen is quite limited.

Carbonates

Various primary and secondary carbonates are found in soils. The most common types are calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$]. Less common soil carbonates are sodium carbonate (Na_2CO_3) and siderite ($FeCO_3$). Carbonates buffer soil pH and are an indication of the relative abundance of bases. Besides pedogenic implications, carbonate minerals play an important role in soil management (Doner and Lynn, 1989). The distribution and amount of carbonates influence soil fertility, erodibility, and available water capacity.

Calcimetric and titration methods have been used as standard methods for estimation of carbonates in soils. Both methods are equally applicable for determining carbonates in the soil. However, the calcimetric method is rapid and does not need more chemicals, whereas the titration method is slow and labor intensive.

Gypsum

Gypsum is present in soils in the form of calcium sulphate dihydrate ($CaSO_4.2H_2O$). The presence of gypsum and calcium carbonates interferes with some laboratory measurements including cation exchange capacity and particle-size distribution. This impedes interpretation of soil analytical data for land evaluation and mapping, land utilization, reclamation, and recommendation of fertilizer.

The laboratory methods used for the analysis of gypsiferous soils are the same as those used for non-gypsiferous soils. Acetone precipitation of gypsum, which involves redissolving of the gypsum precipitate using distilled water and measurement of the electrical conductivity, is a common method for estimation of gypsum in soils (Sayegh et al., 1978).

Heavy metals

The micronutrients Cu, Fe, Mn, nickel (Ni), Zn, as well as cobalt (Co) are heavy metals. From an environmental aspect, the elements cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), and lead (Pb) are heavy metals that are beginning to be found in ever-increasing concentrations in soils.

Zinc toxicity can occur with the use of some sources of sewage sludge. In addition, Cd, Cr, Hg, Cu, Pb, and Ni are elements commonly found in sewage sludge, their presence and concentration depending on their source and sewage treatment procedures. These heavy metals can be absorbed by plants and then introduced into the food chain by consumed plant products. Therefore, having these substances analyzed for their elemental content is important, in order to determine what elements and at what concentrations they are being applied to the soil. Some regulations define the load limits that apply to the use of these substances based on their heavy metal content [maximum acceptable concentration (MAC)], specifying rates [maximum application limit (MAL)], and frequency of application required to prevent plant effects, as well as avoiding the movement of these elements into the food chain.

Heavy metals are extracted from the soil using Ethylenediaminetetraacetic acid (EDTA) and measured by Atomic Absorption Spectrophotometer (AAS) or Inductively Coupled Plasma Optical Emission Spectrophotometry (ICP-OES).

Soil salinity

Salinity is a major problem in many areas of the world. Accumulation of excessive salt in soils can reduce crop yields, reduce the effectiveness of irrigation, ruin soil structure, and affect other soil

properties. Salinity is mostly a result of the continued use of poor quality irrigation water. Soil salinity is usually measured in saturated paste extracts as the electrical conductivity of soil solution and expressed as total soluble solids (TSS) (Table 17).

Table 17. Methods and units for soil salinity parameters to be considered for data documentation and sharing

Soil parameter	Unit	Method
Extraction		Saturated paste
pH		Potentiometric
ECe	dS m^{-1}	Conductivity Meter
Carbonate and Bi-carbonate	me L^{-1}	Titration
Soluble cations (Na, Ca, Mg and K)	me L^{-1}	Flame photometric (Na and K) and AAS(Ca and Mg)/ICP-ES
Soluble anions		
Chloride	me L^{-1}	Silver nitrate titration
Sulphate	me L^{-1}	Turbidimetrically using spectrophotometer
Boron	me L^{-1}	Azomethine-H colorimetric
Nitrate	me L^{-1}	Spectro-photometric

Generally, salt-affected soils are categorized into saline, sodic, and saline-sodic soils. Table 18 shows classes of salt-affected soils based on pH of the saturated paste, electrolytic conductivity of the saturated paste extract (ECe), and exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR) and soil physical conditions.

Table 18. Classes of salt-affected soils

Class	Electrical conductivity (EC), dS m^{-1}	Soil pH	Exchangeable sodium percentage	Sodium adsorption ratio (SAR)	Soil physical condition
Non-saline	< 4	< 8.5	< 15	< 13	Flocculated
Saline	> 4	< 8.5	< 15	< 13	Flocculated
Sodic	< 4	> 8.5	> 15	> 13	Dispersed
Saline-sodic	< 4	> 8.5	> 15	> 13	Flocculated

Source: Richards (1954)

4.2. Plant tissue analysis

Plant tissue analysis is viewed primarily as a diagnostic device for determining which plant nutrient in the plant tissue assay results is below or above the optimum concentration for normal plant growth (Benton Jones, 2012). The concentration of nutrients in plant tissue can be measured in a plant extract obtained from fresh plant material (i.e. tissue analysis), as well as in whole, dried plant material. The former test is qualitative and is appropriate only for quick measurements on a growing plant (Kalra, 1998; Benton Jones, 2012).

Plant analysis has many applications, which mainly include: diagnosing nutrient deficiencies, toxicities, or imbalances; measuring the quantity of nutrients removed by a crop to replace the nutrients to maintain soil fertility (vital for sustainable land productivity); estimating overall nutritional status of the region or soil (key for increasing crop yields and environmental protection); monitoring the effectiveness of fertilizer practices adopted; predicting crop grain yields; estimating nutrient levels in diets available to livestock (Smith and Nelson, 1986); determining the internal nutrient efficiencies (output per unit of nutrient uptake) of varieties or cultivars based on the recovery of soil and/or fertilizer nutrients by different methods of application, including foliar (vital for sustainable farming systems) (Kalra, 1998; Fageria and Baligar, 2003; Fageria et al., 2011).

To implement all of the above-mentioned applications of plant analysis, it is necessary to analyze plant tissue following standard laboratory methods and procedures. The standardized methods of analysis and units of measurement for documenting and sharing data on plant nutrient concentrations are shown in Table 19.

Table 19. Standardized methods and units of measurement for plant analytical parameters, for data documentation and sharing

Plant parameter	Unit	Method		Purpose
		Method/ Digestion	Estimation/ Analysis	
Dry matter	g or kg	Oven drying	Gravimetric	
Moisture factor	%	Oven drying	Gravimetric	
Nitrogen	%	Kjeldahal method	Titration	All
Nutrient concentrations in plants	% or mg g dm^{-1} (macronutrients); or mg kg^{-1} dm (micronutrients)	Mixed acid or dry ashing (P, K, Ca, Mg, Zn, Cu, Fe, Mn, B and Mo)	Estimation method for the respective element	Soil fertility assessment
Total uptake hazardous heavy metal analysis in plants (As, Cd, Hg, Pb, Cr, Co, Ni)	kg ha^{-1}	Mixed acid or dry ashing	AAS/ICP-OES	Environmental quality assessment

Note the % indicated in the table is on mass basis; dm = dry matter

Plant tissue analysis involves destruction of organic matter that is accomplished either by high temperature thermal oxidation or by wet-acid digestion; the former method is frequently referred to as 'dry ashing', and the latter as *wet-acid digestion* or *wet digestion*. The most commonly used method for plant analysis is dry ashing (Benton Jones, 2012).

Various techniques are used to interpret plant analysis results. The sufficiency or adequate range technique is the most common (Table 20). Critical values and standard reference values are used for particular crops (Benton Jones, 2012). The concentration ranges are also termed intermediate, satisfactory, normal, or sufficient. It is usually considered that fertilizer practices need not change if nutrient concentrations fall within this classification (Fageria et al., 2011).

Table 20. General sufficiency or optimum ranges of macro- and micro-nutrient concentrations in plants

Macronutrients	Sufficiency or optimum range (%)	Micronutrients (mg kg^{-1})	Sufficiency or optimum range
N	2.0–5.0	Zn	20–100
P	0.2–0.5	Fe	50–250
K	1.0–5.0	Mn	20–300
Ca	0.1–1.0	Cu	5–20
Mg	0.1–0.4	B	10–100
S	0.1–0.3	Mo	0.1–0.5
		Cl	2000 to 20000

Source: Singh et al. (2010).

Nutrient uptake or accumulation is defined as the product of concentration and tissue dry weight. The accumulation unit is commonly kg per ha^{-1} (macronutrients) and mg per ha^{-1} (micronutrients) for field trials, and g or mg per plant for greenhouse or controlled condition experiments (Fageria et al., 2011).

However, no such ranges have been established for the various crops cultivated in Ethiopia. Ranges in the literature can be used until Ethiopia establishes its deficiency and adequacy ranges of nutrients in plant tissues for diagnostic purposes. However, the ranges found in most of the literature look somewhat too high for the low yields often harvested in Ethiopia, given that most of the established ranges come from countries with high-input agriculture and high yields. Therefore, for Ethiopia, the ranges should be used with caution, and we may rather use the lower values of the adequacy ranges given for various crops in the literature as adequate, rather than the higher values of the ranges.

4.3. Irrigation water

The concentration and composition of dissolved salts in any water determine its quality for irrigation. Mostly, the concerns with irrigation water quality relate to the possibility of high salt concentrations, sodium hazard, carbonate and bicarbonate hazard, or toxic ions (e.g., B or Cl). The analyses required for determining water quality include EC and soluble anions and cations.

Methods for determining irrigation water quality and units of expressing the values, as well as interpretations of irrigation water quality on soil, are shown in Tables 21 and 22, respectively.

Table 21. Methods and units of measurement of physical and chemical parameters of irrigation water, for data documentation and sharing

Water parameter	Unit	Method
Total dissolved solids	mg L^{-1}	Evaporation and gravimetric
Turbidity	mg L^{-1}	Turbidimetric
pH		Potentiometric
EC	dS m^{-1}	Conductivity Meter
Carbonate and bicarbonate	me L^{-1}	Titration
Soluble cations (Na, Ca, Mg and K)	me L^{-1}	Flame photometric (Na and K) and AAS (Ca and Mg)/ICP-OES
Soluble anions		
Chloride	me L^{-1}	Silver nitrate titration
Sulphate	me L^{-1}	Turbidimetrically using a spectrophotometer
Boron	me L^{-1}	Azomethine-H colorimetric
Nitrate	me L^{-1}	Spectro-photometric
Hazardous heavy metals in water (As, Cd, Hg, Pb, Cr, Co, Ni)	mg L^{-1}	AAS/ICP-OES

Table 22. Interpretative guidelines for defining irrigation water quality parameters for irrigation use

Potential problem		Degree of restriction on use			
	Units	Units	None	Slight to moderate	Severe
pH		Normal range 6.5 to 8.4			
Salinity, ECw	ds/m		< 0.7	0.7–3.0	> 3.0
TDS	mg/L		< 450	450–2,000	> 2,000
Infiltration					
SAR = 0–3 and ECw	ds/m		> 0.7	0.7–0.2	< 0.2
SAR = 3–6 and ECw	ds/m		> 1.2	1.2–0.3	< 0.3
SAR = 6–12 and ECw	ds/m		> 1.9	1.9–0.5	< 0.5
SAR = 12–20 and ECw	ds/m		> 2.9	2.9–1.3	< 1.3
SAR = 20–40 and ECw	ds/m		> 5.0	5.0–2.9	< 2.9
Specific ion effects:					
Sodium[a]					
Surface irrigation		SAR	< 3	3–9	> 9
Sprinkle irrigation		mg/L	< 3	> 3	
Chloride[b]		$cmol_{(+)}\ L^{-1}$			
Surface irrigation		$cmol_{(+)}\ L^{-1}$	< 4	4–10	> 10
Sprinkle irrigation		mg/L	< 3	> 3	
Boron		$cmol_{(+)}\ L^{-1}$	< 0.7	0.7–3.0	> 3.0
Bicarbonate[c]		$cmol_{(+)}\ L^{-1}$	< 1.5	1.5–8.5	> 8.5

ECw = electrical conductivity of the irrigation water; SAR = sodium absorption ratio.
[a]At a given sodium adsorption ratio (SAR), the infiltration rate increases as water salinity increases;
[b]For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use-values shown.
[c]Applies to overhead sprinkling only.
Source: Benton Jones (2012)

Photo: Georgina Smith/CIAT

4.4. Fertilizer

Fertilizers are manufactured chemical products of standard composition. Their qualities are stated by the manufacturers and statutorily notified in most countries. Hence, a fertilizer analysis is carried out to determine whether the stated quality meets the statutorily-notified standards. However, compositions of organic fertilizers, unlike mineral fertilizers, are quite variable and, thus, difficult to set statutory standards and regulate precisely.

Fertilizer quality is described in terms of physical and chemical characteristics. The physical parameters include moisture content and particle size. The chemical parameters are pH, amount and form of nutrients in a particular fertilizer, and various impurities that may be toxic to plants if their concentrations are above critical limits, e.g. biuret in urea.

Many fertilizers are fortified with micronutrients such as boronated single superphosphate (SSP) and zincated urea. Therefore, in a fertilizer analysis, in addition to estimating total nutrient content, it is necessary to determine the forms of nutrients and other associated compounds, and to assess their quality (FAO, 2008). For organic fertilizers, it is the content of carbon and that of total nutrients that are considered relevant and not their forms.

Fertilizer analysis is carried out primarily for quality control and statutory purposes. Even though several methods are available for fertilizer quality analyses, there are no internationally accepted methods. Each country has adopted certain methods in its fertilizer statute, and only these methods are relevant for that country. However, methods adopted, verified, and notified by the Association of Official Analytical Chemists (AOAC) are widely used for fertilizer analyses (Motsara, 1985). Because of this, the methods described in Table 23 can be used for fertilizer quality analysis in Ethiopia.

Table 23. Methods and units of measurement for fertilizer analytical parameters, for data documentation and sharing

Parameter	Unit	Method		Purpose
		Extraction/ Digestion	Estimation/ Analysis	
Organic fertilizer				
Moisture content	%	Oven drying	Gravimetric	
pH		OM: Water ratio 1: 10	Potentiometric	Agronomy and soil fertility
Electrical conductivity	dS m^{-1}	OM: Water ratio 1: 10	Conductivity Meter	Agronomy and soil fertility
Organic carbon	%	Wet oxidation (Walkley-Black)	Titration	All
Total nitrogen	%	Kjeldahal method	Titration	All
Total nutrient analysis (P, K, S, Zn, Cu, B and Mo)	% or mg kg^{-1}	Mixed acid	Estimation method for the respective element	Soil fertility
Inorganic fertilizer				
Moisture content	%	Oven drying	Gravimetric	For curiosity analysis on the content of imported fertilizer by researchers, academicians and practitioners
Particle size	mm		Sieving	
Bulk density	g cm^{-3}		Mass displacement using a measuring cylinder	
Specific gravity			Pycnometer	
pH		Fertilizer: Water ratio 1: 10	Potentiometric	
Total nitrogen	%	Kjeldahal method	Titration	
Total nutrient analysis (P, K, S, Zn, Cu, B and Mo)	%	Mixed acid	Estimation method for the respective element	

4.4.1 Fertilizer application rates

Fertilizer application rates are usually expressed in kg of the primary element in the fertilizer per unit of land (usually hectare). However, most often, fertilizer rates are expressed in either the pure form of the primary element, as well as in oxide form for phosphorus, potassium, magnesium, etc. Most of the time, the alternate use of the two forms for each element is a matter of convention rather than a scientific requirement and is at the discretion of the writer. In particular, phosphorus application rates are often expressed either in the form of the conventional oxide, namely, P_2O_5 (diphosphorus pentaoxide) or as the elemental or (pure) form of P per unit of land. Similarly, potassium fertilizer rates are expressed either as either K_2O (dipotassium oxide) per hectare or as the elemental (pure) form of K per unit of land. However, one should note that the quantities of phosphorus or potassium, in either case, are not equal. Therefore, it is necessary to convert one form into the other by doing a slight calculation based on the ratio of the atomic masses of the elements in the oxide forms. See relevant literature.

Thus, in the case of phosphorus and potassium fertilizers, for example, which is often expressed in oxide forms, use the following conversion factors (FAO, 2000):

– To change P_2O_5 to P, multiply P_2O_5 by 0.4364.

– To change P to P_2O_5, multiply P by 2.2914.

– To change K_2O to K, multiply K_2O by 0.8302.

– To change K to K_2O multiply K by 1.2046.

However, authors must maintain consistency in using one or the other forms throughout their documents. In other words, they should not interchangeably use the two forms in the same document.

Photo: Georgina Smith/CIAT

Photo: Stephanie Malyon/CIAT

5. Spectrum analysis

Spectrum analysis is a fast method that involves near-infrared (NIR) and mid-infrared (MIR) spectroscopy. This method can be used to analyze clay minerals, organic matter, plant nutrients, and irrigation water that strongly affect plant growth and influence plant nutrition. Laser diffraction analysis, also known as static light scattering, is the most common method for determining particle size distribution other than traditional sieve analysis. These are non-destructive techniques well-suited for analyzing some of the essential physical and chemical properties of the soil. These techniques can be used to collect soil spectra reflectance in the laboratory. They are indirect techniques. Thus, calibrations and validations are necessary to obtain reliable predictions about the properties of Ethiopian soils.

Data to be shared for a big data set on soil, plant, and irrigation water generated by spectral methods should comply with methods and units of measurements described in Tables 24–27.

Table 24. Methods and units of measurement of spectrum analysis on soil particle size distribution, for data documentation and sharing

Soil parameter	Unit	Method	Purpose
		Laser Diffraction	
Particle size distribution	%	Statistical techniques	Agronomy and soil fertility

Table 25. Methods and units of measurement for spectral analysis on soil chemical parameters, for data documentation and sharing

Soil parameter	Unit	Methods		Purpose
		NIR (12500cm^{-1} to 4000 cm^{-1})	MIR (4000 cm^{-1} to 400 cm^{-1})	
pH		Multivariate statistical techniques	Multivariate statistical techniques	Agronomy and soil fertility
Electrical conductivity	dS m^{-1}			Agronomy and soil fertility
Organic carbon	%			All
Total nitrogen	%			All
P, K, S, Na, Ca, Mg, Zn, Cu, Fe, Mn, B and Mo	mg kg^{-1}			Agronomy and soil fertility
Cation exchange capacity	cmol $_{(+)}$ kg^{-1}			All
Hazardous heavy metal in Soil (As, Cd, Hg, Pb, Cr, Co, Ni)	mg kg^{-1}			Environmental soil chemistry

Table 26. Methods and units of measurement for spectral analysis on plant analytical parameters, for data documentation and sharing

Plant parameter	Unit	Method	
		NIR (12500cm^{-1} to 4000 cm^{-1})	MIR (4000 cm^{-1} to 400 cm^{-1})
Carbon	%	Multivariate statistical techniques	Multivariate statistical techniques
Nitrogen	%		
P, K, S, Ca, Mg, Zn, Cu, Fe, Mn, B and Mo	mg kg^{-1}		
Hazardous heavy metal in Plants (As, Cd, Hg, Pb, Cr, Co, Ni)	mg kg^{-1}		

Conversion factors should be included in case data generated using one method is reported for any other method.
The number of samples used for validation of spectrum analysis should be mentioned.

Table 27. Methods and units of measurement for spectral analysis on irrigation water parameters, for data documentation and sharing

Water parameter	Unit	Methods	
		NIR (12500cm^{-1} to 4000 cm^{-1})	MIR (4000 cm^{-1} to 400 cm^{-1})
pH		Multivariate statistical techniques	Multivariate statistical techniques
Electrical conductivity	dS m^{-1}		
Soluble cations (Na, K, Ca and Mg)	me L^{-1}		
Chloride	me L^{-1}		
Sulphate	me L^{-1}		
Boron	me L^{-1}		
Hazardous heavy metal in water (As, Cd, Hg, Pb, Cr, Co, Ni)	mg L^{-1}		

Photo: Georgina Smith/CIAT

6. References

Bado VB; Bationo A. 2018. Integrated management of soil fertility and land resources in sub-Saharan Africa: involving local communities. *Advances in Agronomy* Vol. 150, pp. 1–33. Academic Press.

Bashour II; Sayegh AH. 2007. Methods of analysis for soils of arid and semi-arid regions. FAO, Rome, 119 p.

Benton Jones J. Jr. 2001. Laboratory guide for conducting soil tests and plant analysis. CRC Press, Boca Raton, FL.

Benton Jones J. Jr. 2012. Plant nutrition and soil fertility manual. Second Edition. CRC Press, New York.

Bingham FT. 1982. Boron. In: Page AL (ed.). Methods of soil analysis, Part 2: Chemical and mineralogical properties. Amer. Soc. Agron., Madison, WI, USA. pp. 431–448.

Black CA. (ed). 1965. Methods of soil analysis. Two volumes. Agronomy No. 9. Amer. Soc. of Agron., Madison, Wisconsin.

Bray RH; Kurtz LT. 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.* 59:35–45.

Cottenie A. 1980. Soil and plant testing as a basis of fertilizer recommendations (No. 38/2).

Debele B. 1980. The Physical Criteria and Their Rating Proposed for Land Evaluation in the Highland Region of Ethiopia. Land Use Planning and Regulatory Department, Ministry of Agriculture, Addis Ababa, Ethiopia.

Dechassa N; Schenk MK; Steingrobe N. 2003. Phosphorus Efficiency of Cabbage (*Brassica oleraceae* L. var. capitata), Carrot (*Daucus carota* L.), and Potato (*Solanum tuberosum* L.). Plant and Soil 250:215–224.

Dewis J; Freitas FCR. 1970. Physical and chemical methods of soil and water analysis. Soils Bull. No. 10. FAO, Rome.

Doner HE; Lynn W. 1989. Carbonate, Halide, Sulphate and Sulphide. In: Bighma JM; Dixon JB; Milford MH. American Society for Agronomy and the Soil Science Society of America, Madison, Wisconsin.

Epstein E. 1965. Mineral Nutrition. In: Bonner J; Varner JE. (eds.), Plant Biochemistry. Academic Press, Orlando, FL. pp. 438–466

Estefan G; Sommer R; Ryan J. 2013. Methods of soil, plant and water analysis. ICARDA (International Center for Agricultural Research in the Dry Areas), Beirut, Lebanon.

Fageria NK; Baligar VC. 2003. Methodology for Evaluation of Lowland Rice Genotypes for Nitrogen Use Efficiency. *Journal of Plant Nutrition* Vol. 26, No. 6, pp. 1315–1333.

Fageria NK; Baligar VC; Jones CA. 2011. Growth and Mineral Nutrition of Field Crops. 3rd Edn., Taylor & Francis Group, New York, 530 p.

Fairhurst T. 2012. Handbook for integrated soil fertility management. CTA/CABI.

Food and Agriculture Organization (FAO). 1990. Guidelines for soil description. 3rd Ed. (revised). Soil Resources, Management and Conservation Service, Land and Water Development Division. FAO, Rome. 70 pp.

Food and Agriculture Organization (FAO). 1998. Guidelines for quality management in soil and plant laboratories. Vol. 74. Food and Agriculture Organization of the United Nations, Rome, Italy.

Food and Agriculture Organization (FAO). 2000. Fertilizers and their Use: A pocket guide for extension officers. 4th Edition. International Fertilizer Industry Association Rome.

Food and Agriculture Organization (FAO). 2006. Plant nutrition for food security: A guide for integrated nutrient management. FAO, Fertilizer and Plant Nutrition Bulletin 16, Rome.

Food and Agriculture Organization (FAO). 2008. Guide to laboratory establishment for plant nutrient analysis. FAO Fertilizer and Plant Nutrition Bulletin 19, Food and Agriculture Organization of the United Nations, Rome, Italy.

Glass DM. 1989. Plant Nutrition: An introduction to Current Concepts. Jones and Barlett, Publishers, Boston, MA.

Hesse PR. 1971. A textbook of soil chemical analysis (No. 631.41 H4).

Houba VJG; Novozamsky I. 1998. Influence of storage time and temperature of air-dried soils on pH and extractable nutrients using 0.01 M $CaCl_2$. *Fresenius J. Anal. Chem.*, 360:362–365.

Houba VJG; Temminghoff EJM; Gaikhorst GA; van Vark W. 2000. Soil analysis procedures using 0.01 M calcium chloride as extraction reagent. *Commun. Soil Sci. Plant Anal.* 31:1299–1396.

Kalra Y. 1998. Handbook of reference methods for plant analysis. CRC press. Taylor & Francis Group. 287 p.

Landon JR. 1991. Booker tropical soil manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Longman UK Limited, Essex, UK, 474 p.

Lindsay WL; Norvell WA. 1978. Development of DTPA soil test for zinc, iron, manganese and copper. *Soil Sci. Soc. Am. J.*, 42:421–428.

Mengel DB; Nelson DW; Huber DM. 1982. Placement of Nitrogen Fertilizers for No-Till and Conventional Till Corn 1. *Agronomy Journal*, 74(3):515-518.

Mengel K; Kirkby EA; Kosegarten H; Appel T. 2001. Principles of Plant Nutrition. Klewer Academic publishers. 5th Edn. Klewer Academic Publishers. Dordrecht. 849 p.

Motsara MR. 1985. Influence of AOAC Fertilizer Analysis Methods Beyond North America. *Journal of Association of Official Analytical Chemists*, Volume 68, Issue 4, 1 July 1985, pp 611–617.

Murphy HF. 1968. A Report on the Fertility Status of Some Soils of Ethiopia. Experimental Bull. No. 1. Imperial College of Agriculture and Mechanical Arts; Alemaya, Ethiopia, 201 p.

Olsen SR; Cole CV; Watanabe FS; Dean CA. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US. Dep. Agric . Cir. No. 939, 19.

Richards LA. 1954. Diagnosis and improvements of saline and alkali soils. USDA. Agriculture Handbook 60. 160 p.

Römheld V; Marschner H. 1991. Functions of micronutrients in plants. In Micronutrients in Agriculture, 2nd ed. (J. J. Mordvedt, F. R. Cox, L. M. Shuman and R. M. Welch, eds.), pp. 297–328. SSSA Book Series, No. 4, Madison, WI, USA.

Sayegh AH; Khan NA; Khan P; Ryan J. 1978. Factors affecting gypsum and cation exchange capacity determinations in gypsiferous soils. *Soil Science*, 125(5):294–300.

Sertsu S; Bekele T. 2000. Procedures for soil and plant analysis, Technical Paper. National Soil Research Center, Addis Ababa, Ethiopia.

Schofield RK; Taylor AW. 1955. The Measurement of Soil pH1. *Soil Science Society of America Journal*, 19(2):164–167.

Schollenberger C; Simon R. 1945. Determination of exchange capacity and exchangeable bases in soil-ammonium acetate method. *Soil Science*, 59:13–24.

Singh D; Chhonkar PK; Pandey RN. 2010. Soil, Plant and Water Analysis—A Method Manual. IARI, New Delhi.

Smith RJ; Nelson LR. 1986. Crop Breeding, Genetics and Cytology. Selection for Seed-Filling Period in Soybean. *Journal of Crop Science* Volume 26, Issue 3.

Tan KH. 2011. Principles of soil chemistry. 4th Edn. CRC press. Taylor & Francis Group, 362 p.

Tekalign T; Haque I; Aguayi EA. 1991. Soil, plant, water, fertilizer, animal manure and compost analysis. Working Document No. 13. International Livestock Centre for Africa (ILCA), Addis Ababa.

World Reference Base for Soil Resources (WRB). 2006. World Soil Resources Reports No. 103. Food and Agriculture Organization of the United Nations, Rome, Italy.

Alliance

Implemented by

RESEARCH PROGRAM ON Water, Land and Ecosystems

CGIAR
Science for a food-secure future

Bioversity International and the International Center for Tropical Agriculture (CIAT) are part of CGIAR, a global research partnership for a food-secure future.

Bioversity International is the operating name of the International Plant Genetic Resources Institute (IPGRI).

Africa Hub

c/o icipe (International Centre of Insect Physiology and Ecology)
Duduville Campus Off Kasarani Road
P.O. Box 823-00621
Nairobi, Kenya

https://alliancebioversityciat.org
www.cgiar.org