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SPECIAL SECTION: DEVELOPING FODDER RESOURCES FOR SUB-SAHARAN COUNTRIES

Near-infrared reflectance spectroscopy for forage nutritive value analysis in sub-Saharan African countries

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Assigned to Associate Editor James Muir.

Abstract

Limited supply of quality feed is the most common problem limiting livestock productivity in sub-Saharan Africa (SSA). Routine feed evaluation is indispensable for formulating balanced rations, feed characterization, safety, and minimizing the environmental impact of livestock. Traditional wet chemistry has not met this demand in SSA because it is time consuming, expensive, reliant on imported reagents and equipment that requires regular maintenance. Near infrared reflectance spectroscopy (NIRS) is a rapid and accurate alternative. The NIRS can help meet the need to characterize locally available forages and feeds on the continent, thus allowing formulation of optimally balanced and safe rations, facilitating establishment of nutritive value-based pricing, and improving feed marketing and environmental stewardship. Though several NIRS systems have been purchased in many SSA countries, few are currently used. Reasons include high upfront costs, lack of requisite technical capacity, lack of access to comprehensive wet chemistry-based databases to develop and validate robust and accurate predictive equations, lack of access to or relevance of existing validated equations, and limited awareness about the value of NIRS. Recently developed portable devices can dramatically reduce cost, while providing flexibility and comparable accuracy to benchtop systems. Formation of NIRS consortia and communities of practice including public–private partnerships that link equipment, pool resources, and provide periodic training and troubleshooting, can address many of these problems. This paper elaborates the potential for using NIRS to improve feed analysis in SSA countries, the reasons for the low use of existing systems, and strategies to improve the adoption and use of NIRS.

Abbreviations: NIRS, near infrared reflectance spectroscopy; SSA, sub-Saharan Africa.

1 | THE NEED FOR FORAGE AND FEED ANALYSIS

Livestock production is widespread in low- and middle-income countries and provides livelihoods for 900 million smallholder farmers (Dolberg, 2001). Mixed crop–livestock production dominates in terms of numbers of livestock keepers and most of these livestock producers farm small areas of 1–2 ha. The majority of livestock producers are not wholly commercial in that livestock are often kept for their multiple contributions to farming operations and to farmer livelihoods and not primarily for production of milk, meat, and eggs for sale (Weiler et al., 2014). However, in many regions of sub-Saharan Africa (SSA) smallholder livestock production is intensifying and indeed will need to do so to meet the increasing demands of a growing and increasingly urbanized population. This process of intensification is leading to greater market participation by livestock keepers and requires a more systematic approach to animal management. Intensification of smallholder livestock production is constrained by a range of factors, but lack of a plentiful, year-round supply of quality feed is the most limiting constraint according to many observers (Balehegn et al., 2020; Baltenweck et al., 2020).

Most of the livestock production in low-and middle-income countries is based on a rather opportunistic feeding regime, which relies on what is available at different times of year without detailed planning and consideration of balancing different feed components and macro-nutrients (Lukuyu et al., 2011). This ad hoc approach to feeding is compounded by the strong degree of seasonality in crop growth in tropical environments with very distinct flush and lean seasons across much of the tropics (Lanyasunya et al., 2006). Most livestock feeds in SSA are by-products of arable cropping, which is prioritized because it supplies staples for family nutrition (Lanyasunya, et al., 2006). Although highly variable by region, livestock diets across much of SSA are comprised of varying proportions of crop residues, native pastures, green material from roadsides and marginal land, and leafy herbage from forest areas. These basal resources are supplemented with agro-industrial by-products of human food production including brans and husks of cereals, oil cakes, brewery waste, etc. There is relatively little dedicated land and labor for cultivation of forages for livestock (Mekasha et al., 2014). The exception is commercial operations where some improved forages and compound feeds are fed but these are sometimes of questionable quality.

An important issue for livestock producers attempting to properly feed their animals is the variable quality of feed resources. This problem is not unique to smallholder production in the tropics, but it is particularly extreme in these environments. The commercial feed sector is not well-developed, and although it is growing, there are still relatively few trusted feed brands in the countries. Rather, there is a myriad of small-scale, informal feed suppliers who often operate in an unregulated space. Feed standards exist in certain cases, but they are rarely applied and enforced (Tolera et al., 2012). This leads to insufficient emphasis on feed nutritive value and a lack of reliable information on feed labels in many cases (El-Sayed, 2014). A study of the aquaculture feed industry in Egypt highlights some of the issues typical of the livestock feed sector in low- and middle-income countries (El-Sayed, 2014). Of interviewed feed producers, 60% indicated that they had never been subject to an official quality control inspection and only about half used valid nutritional information on feed labels. Furthermore, the ad hoc nature of feed sourcing from marginal lands and roadsides, as well as reliance on forage that varies in nutritive value and quantity with various factors, leads to considerable variability in the nutritive value of diets (Coppock et al., 1986). In addition, the general lack of nutritional information for free-ranging animals constrains improvements in their performance. The result of all these factors is considerable uncertainty surrounding the nutritive value of what is fed to livestock in low- and middle-income countries. An important step towards supporting farmers in more strategic and systematic feeding regimes is to reduce this uncertainty through reliable, quick, and affordable feed analysis methods such as NIRS.

Core Ideas

- Forage nutritive value analysis is crucial for solving feed problem in sub-Saharan Africa (SSA).
- Wet chemistry is expensive, time consuming, and dependent on reagents, limiting its use in SSA.
- Near infrared reflectance spectroscopy (NIRS) provides a quick, flexible, and accurate alternative.
- The NIRS use in SSA is limited by limited knowledge, cost, lab resources, and calibration equations for local feeds.
- Low-cost, portable NIRS brands and regional NIRS consortia can solve resource limitations.

2 | THE POTENTIAL OF NIRS FOR IMPROVING LIVESTOCK NUTRITION IN SSA

Accurate prediction and estimation of nutritive value of forages is essential from animal productivity and welfare points of view. While the best estimate of the nutritional value of any feedstuff is to feed it to an animal and observe growth and respiration in a controlled environment, this approach is impractical (Beever & Mould, 2000). For the last few decades, some less animal dependent in sacco methods of feed

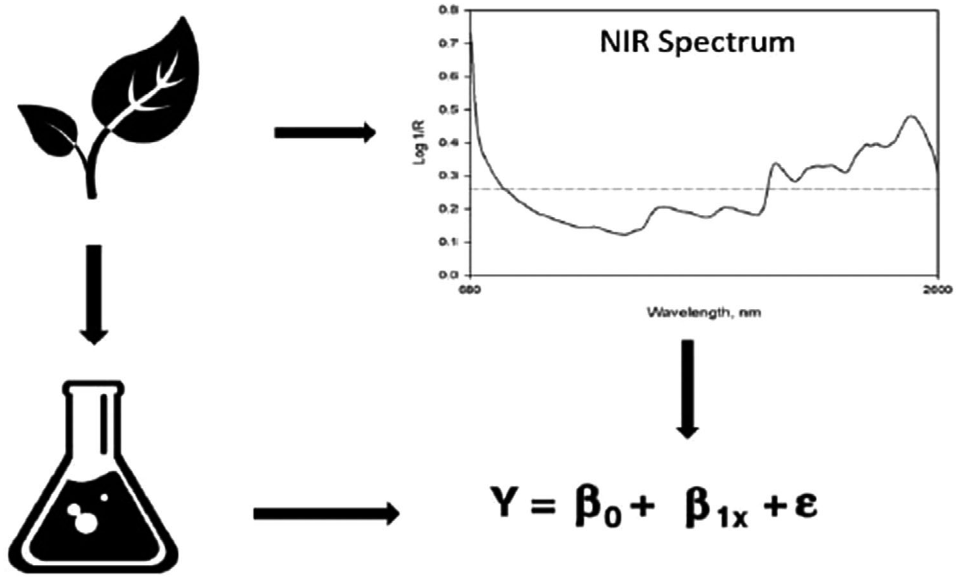

FIGURE 1 Simplified illustration of procedure used in near infrared reflectance (NIR) spectroscopy for forage nutritive analysis

evaluation have been developed to reduce dependence on animals in feed analysis and to allow more samples to be analyzed simultaneously. These include variants of the in situ degradability, in vitro fermentation, and in vitro fermentation gas production techniques. While some of these have produced relatively accurate predictions of nutritive value of certain feeds, their adoption has been limited in SSA for various reasons. Notably, these techniques rely on the use of surgically modified animals, which are challenging and prohibitively expensive to maintain (Beever & Mould, 2000). They are also tedious, time-consuming, and rely on imported expensive reagents and supplies that are often challenging to afford or access.

Various nutritive value evaluation technologies have also been developed that exploit chemistry principles to quantify nutrients, energy, and other nutrition-related attributes in feeds. These wet chemistry techniques (AOAC, 2000) are the recognized standard and most widespread methods of feed evaluation. However, they are time consuming and, more importantly, require specific, mostly imported chemical reagents and specialized instrumentation that must be run and maintained by well-trained technical staff. Due to these challenges, wet chemistry animal nutrition laboratories in many SSA countries often have a lot of dysfunctional or outdated equipment and analytical procedures that can no longer be used.

For feed characterization to become practical and relevant at a large scale in SSA, a simple, rapid, flexible, and accurate method of nutritive value estimation is required. Opportunities exist from the application of a range of spectroscopic methods such as X-ray fluorescence (XRF), near-and mid-infrared reflectance spectroscopy (NIRS/MIRS). While XRF methods are also quick, usually portable, and inexpensive, its application is limited to estimation of elemental composition of minerals and not organic compounds (Berzaghi et al., 2018). The MIRS is usually more effective for pure substances, mainly used for the identification and quantification of molecules in liquids such as milk, making it less suited for animal feeds which usually contain complex mixes of various compounds. Moreover, MIR spectra are mostly collected with methods that are impractical due to precise requirements on sample thickness (Cleland et al., 2018).

Near infrared reflectance spectroscopy is a physical method of feed nutritive value assessment based on the measurement of the reflectance of light in the near infrared range of the spectrum (1,100–2,500 nanometers [nm] region; Figure 1),which is closely related to the presence of important chemical bonds such as OH, NH, and CH (Deaville & Flinn, 2000). Since the absorption spectrum on the surface of any sample is dependent on the chemical constituents of the sample such as proteins, carbohydrates, and minerals, it is possible to reasonably accurately quantify the contents of the sample by the light reflected at wavelengths relating to those specific components, provided accurate validated calibrations of reflectance with wet chemistry exist.

Unlike traditional wet chemistry, no reagents are required, and no waste is produced, thus NIRS is an eco-friendly approach (Givens & Deaville, 1999). This is especially important for many laboratories in SSA where the procurement process for reagents is prohibitively slow and complex (Williams et al., 2020). In addition, although NIRS involves complex statistical procedures, it requires relatively little preparation of samples, it is rapid and up to 150 samples can be processed in a day by a single operator (Marten et al., 1989). It is economical, non-destructive, and can be used to simultaneously measure many nutritional attributes of a feedstuff compared with the conventional methods (Adesogan et al., 1998; Boever et al., 1995; Shenk et al., 1994). From a research methodology point of view, perhaps the greatest contribution of NIRS is that it reduces the total analytical error (sampling and laboratory) because a large number of subsamples or sequential samples can be analyzed with a limited analytical budget than is possible using the more expensive wet chemistry (Sapienza et al., 2008).

The low running costs of NIRS systems makes them particularly suited for providing rapid and economic analysis of feeds in SSA. The time, cost-savings, and flexibility of NIRS technology has been further increased with the development of handheld NIRS systems, which have shown reasonable precision and accuracy compared to the bench top NIRS instruments, but can be a fraction of the cost and are faster and more flexible (Modroño et al., 2017; Prasad et al., 2019). Such handheld instruments are, therefore, ideal for increasing feed analysis capacity in SSA.

Another important advantage of NIRS over more traditional methods is that it is easier to network multiple NIRS instruments, particularly if they are from the same manufacturer, to complement each other and function in consortia (Yakubu et al., 2020). This is an important advantage in SSA countries where laboratories are seldom self-sufficient in terms of the resources needed to function independently. A further advantage of NIRS technology over wet chemistry is that it is more suitable for on-line feed nutritive value analysis and quality control, therefore, it has potential for integration into digital systems that are increasingly becoming common in SSA countries (Chen et al., 2013). Lastly, all forms of feed samples including solid, liquid, and gases can be analyzed by NIRS (Yakubu et al., 2020).

For an acceptable prediction of nutritional value, any NIRS apparatus must first be calibrated against a set of standard reference samples analyzed by wet chemistry or another conventional method and then validated using additional samples. Many studies across all regions for various feed types have demonstrated the predictive performance of NIRS (Harris et al., 2018) and scientists continue to test various models to make further enhancements (Wajizah & Munawar, 2020). Since its development in the 1970s, NIRS has shown a lot of potential benefits for routine feedstuff analysis in laboratories all over the world. The NIRS can also be used for aiding forage plant selection, while benefiting producers through formulation of rations that are able to meet nutritional requirements of livestock, improve their productivity, and reduce greenhouse gas emissions, thus helping to reduce environmental impacts of livestock production (O'Mara et al., 2008).The use of NIRS spans diverse types of samples including forages, concentrates, feces (Decruyenaere et al., 2009), standing crops (Bell et al., 2018), and the detection of toxins such as aflatoxins (Darnell et al., 2018). In addition, it has also been used for detection, quantification, and tracing of prohibited ingredients in feed such as meat and bone meal (Chen et al., 2013; Murray et al., 2001), and analyzing nutritive value of forage from multi-species pastures (Berauer et al., 2020). In extensive grazing settings, which are common in SSA, real-time monitoring of forage nutritive value using mobile NIRS has been suggested (Bell et al., 2018). The inadequacy of previous technologies in determining the nutritional status of free-ranging livestock, due to the spatial and temporal heterogeneity of the forage nutritive value imposed by various environmental factors such as rainfall, temperature, watering point location, and by selective grazing can be overcome, at least partly, using NIRS (Awuma, 2005). Fecal NIRS, for instance, has been used to understand botanical composition of free grazing livestock (Landau et al., 2010), wildlife ecology, and support range and game land management (Tolleson, 2010). The NIRS-based nutritional prediction data can also be linked with drought early warning systems to generate a comprehensive suite of decision support tools which can be applied to a wide array of grazing, forage, and feedlot conditions (Stuth et al., 1999). Therefore, though the use of NIRS in SSA is not yet common, it can help in various ways to optimize livestock productivity and adaptation to climate change. Table 1 summarizes NIRS capability in countries and institutions where the Feed the Future Innovation Lab for Livestock Systems has established NIRS community of practice through its Strengthening Smallholder Livestock Systems for the Future (EQUIP-Feed) project.

3 | NIRS CAPABILITY FOR LIVESTOCK FEED ANALYSIS IN SELECTED COUNTRIES IN SSA

The International Livestock Research Institute (ILRI) and partners have established an extensive network of NIRS instruments across SSA with considerable sharing of equations to allow reliable analysis of feedstuffs across the region. The FOSS instruments are standardized to a master instrument based at ILRI's Feed Technology Platform at Patancheru, Hyderabad in India, using a master cell. Handheld non-FOSS instruments are standardized through a ring-test procedure, where multiple laboratories are involved in analyzing the same samples. In Addis Ababa, Ethiopia, as well as the FOSS instrument in the ILRI nutrition lab, several FOSS instruments are present in various public and private institutions. International Livestock Research Institute Ethiopia also has several hand-held instruments with standardized equations through ring-test approaches. In Burkina Faso, a FOSS instrument recently procured by the Livestock Systems Innovation Lab was standardized by ILRI and passed on to the Institut de l'Environnement et de Recherches Agricoles (Environmental Institute for Agricultural Research)-Burkina Faso. Another FOSS instrument is in use at the ILRI

TABLE 1 Near infrared reflectance spectroscopy instruments at some sub-Saharan African research institutions[a] that are or may be standardized to the ILRI Hyderabad NIRS1 master instrument in India, which is also listed

Country	Organization	Make	Model	Standarized[b]	No. of equations for dry samples
Burkina Faso	Institut de l'Environnement et de Recherches Agricoles du Burkina Faso (INERA) and International Livestock Research Institute	TellSpec	NIR-S-G1	Pending	0
		FOSS	DS2500F	Yes	1
Ethiopia	Ethiopian Institute of Agricultural Research (EIAR); Holetta Research Center	FOSS	5000	Yes	48
		BRUKER	TANGO	No	–
	EIAR; Kulumsa Research Center	FOSS	Infratec™ 1241 Grain Analyser	No	–
	EIAR; Debrezeit Research Center	FOSS	XDS near-infrared Rapid Content Analyzer	Yes	48
	EIAR; Melkassa Research Center	Perten INSTRUMENTS	IM 9500	No	–
	EIAR; Head Office, Addis Ababa	FOSS	6500	Yes	48
		FOSS	XDS near-infrared Rapid Content Analyzer	Yes	48
	Oromia Agricultural Research Institute, Sinana Research Center	Infracont	MININFRA SmartT Grain Analyzer	No	–
	Amhara Regional Agricultural Research Institute (ARARI), Bahir Dar	FOSS	Infratec 1241 Grain analyzer	No	–
	Veterinary Drug and Animal Feed Administration and Control Authority of Ethiopia	FOSS	DS2500	Pending	0
	Veterinary Drug and Animal Feed Administration and Control Authority of Ethiopia	Perten Instruments	DA 7250	No	–

(Continues)

TABLE 1 (Continued)

Country	Organization	Make	Model	Standarized[b]	No. of equations for dry samples
	International Livestock Research Institute	FOSS	5000	Yes	48
		Brimrose	Luminor 5030	Yes	2
		TellSpec	NIR-S-G1	Yes	2
	Bless Agri Food Laboratory Services PLC	FOSS	DS2500	Yes	48
	Ethio Chicks Private Limited Company	FOSS		No	–
		FOSS		No	–
	Mekelle University	Perten Instruments	DA 7250	No	–
Nigeria	International Livestock Research Institute	FOSS	DS2500	Yes	48
India[c]	International Livestock Research Institute	FOSS	XDS RCA	Yes	48
		FOSS	6500	Yes	48
		FOSS	5000	Yes	48
		Phazir	Thermo	Yes	4
		TellSpec	NIR-S-G1	Yes	2
		SCiO	PMS	Yes	2

[a]The institutions and organizations included are mainly those that have been involved or will be invited to join the NIRS Community of Practice established by the EQUIP-Feed project of the Feed the Future Innovation Lab for Livestock Systems in its target countries of Ethiopia and Burkina Faso.
[b]Standardized to ILRI Hyderabad NIRS master instrument (FOSS 5000/6500 and XDS RCA) for sharing the calibrations.
[c]The reason India is included is because most of the other NIRS systems are networked to the one in Hyderabad, India.

nutrition lab in Ibadan, Nigeria. Several of these instruments have equations that have been standardized to the Hyderabad NIRS master instrument in ILRI's Feed Technology Platform in India (Table 1), which provides technical support and updated equations. This careful checking and recalibration of results avoids the situation in which results from laboratories become unreliable. This is important because there are also several other instruments across SSA which have equations that have not been standardized. Besides the capabilities listed in Table 1, other institutions in Africa have at least one NIRS machine. These include Kenya Agricultural and Livestock Research Organization (KALRO), Eritrean National Agricultural Research Institute (ENARI), and National Livestock Resource Research Institute (NaLIRRI), Uganda.

4 | CHALLENGES WITH USE AND ADOPTION OF USE OF NIRS IN AFRICA

Though it is potentially a cheaper and simpler option for forage and feed analysis, the use of NIRS in SSA is limited because of various drawbacks. Traditionally, this has been due to the expense of purchasing the equipment, limited skilled technical capacity, and robust wet chemistry databases for developing and standardizing equations, and absence of rugged, low cost NIRS instruments (Shepherd & Walsh, 2007). Due to the high cost, most bench top NIRS equipment available in African laboratories are purchased through donor funding, which often does not include funds for maintenance or repairs. With the advent of much more affordable and precise mobile NIRS systems, the high initial cost is becoming less of an issue.

It is pertinent to note that NIRS is a comparative or secondary, or indirect analytical method based on regression against a primary or reference method (da Paz et al., 2019). Therefore, it should only be used where there is established confidence in data, which means that there should be well established wet chemistry laboratories, which is not the case in many SSA countries (Beever & Mould, 2000).This is because the validity of data produced using NIRS for chemical entities such as crude protein and metabolizable energy will never be better than the databases used to establish the calibration curves. There have been many instances where NIRS predictions have been inaccurate, often because they were used for forages and feeds that were not in the calibration and validation populations. Currently, there are very few equations in the functional NIRS labs in Africa. Those labs must either decline to analyze uncommon feeds (e.g., for a variety of browse and local grass species in Africa) or provide inaccurate nutritional estimates. With the absence of effectively functioning wet chemistry, NIRS calibration must still depend on "reference" samples analyzed elsewhere.

Further problems limiting NIRS adoption include inconsistent power supply, lack of conducive and dedicated space for the analysis, and lack of technicians with the capacity to annually service the equipment. Calibrating NIRS equipment is also very time-consuming and it is a highly esoteric practice requiring specialized skills in chemometrics, data analysis, and management (da Paz et al., 2019; Givens & Deaville, 1999), which are usually lacking in many laboratories in Africa. Data acquisition using NIRS is easy, but large volumes of data and lack of skills in data management and statistical analysis are always constraints (Shepherd & Walsh, 2007). In Africa and Asia, NIRS equations are usually developed using "average or typical" forage samples that are then used to develop "universal" calibration equations. If they are subsequently used for samples originating from different agroclimatic and soil conditions from the original samples, a considerable error may be introduced (Andueza et al., 2011). This is particularly important when calibrations developed in temperate areas are used for forages in tropical and subtropical conditions in SSA. Moreover, for pasture animals, multispecies forage samples are frequently submitted for analysis and NIRS may not always provide acceptable accuracy in such cases, though techniques such as Fourier transform near-infrared (FT-NIR) spectroscopy coupled with multivariate analysis has been used to effectively solve such problems (Liu et al., 2010). Robust equation development requires inclusion of a broad spectrum of plant species representing temporal, spatial, species, climatic, environmental, particle size, analytical and landscape variability (Shenk et al., 2001; Stuth et al., 2003; Undersander, 2006). Due to capacity and skill limitations, the requisite robust continuously updated databases (Dardenne et al., 2000) are usually not available in laboratories across Africa (Landau et al, 20006). However, lack of representative samples can be addressed with the LOCAL algorithm, which optimizes the prediction power by using multi-product databases in a non-linear approach (Berzaghi et al., 2000). The LOCAL algorithm is said to show better predictability compared to species-specific algorithms that depend on prediction of nutritive value for a species based on a database of samples for the same species and the global algorithms (Andueza et al., 2011). Such machine-learning algorithms are helpful in developing robust NIRS models for predicting forage nutritive value, especially when the number of samples is very small (Baath et al., 2020).

Nearly 40 sources of error have been identified by Williams and Norris (1987) all of which could affect the results of NIRS analysis. These errors are categorized as factors associated with the instrument (e.g., instrument noise, stray light, wavelength selection, static electricity, instrument temperature control, power supply); those associated with the samples (e.g., chemical composition, including absorbing groups present, influence of chemical constituents on physical

TABLE 2 A summary of potentials and limitations of near infrared reflectance spectroscopy (NIRS) technology for sub-Saharan African (SSA) countries[a]

Potentials	Limitations
Low cost of analysis: Makes it more affordable to researchers and other users in SSA	High initial cost: With some bench top models costing up to US$40,000 making them unaffordable for many laboratories in SSA
No need for reagents: Making it suitable in most sub-Saharan African countries where importation of reagents is lengthy and complex process	Specificity of calibration: With large diversity of feed types and forage species in SSA, some of the universal calibrations developed may not be accurate. (Species-specific calibrations are yet to be developed for majority of feed types in SSA.)
Speedy: Enabling results to be obtained within seconds. Up to 150 samples can be processed in a day by a single operator with relatively little sample preparation	Technicality of calibration: Calibrating NIRS equipment is highly technical practice requiring specialized skills in chemometrics, data analysis, and management, which are usually limited in laboratories across Africa
Accuracy: Generally comparable with conventional wet chemistry, but also improving with improved instrumentation and development of algorithms	Technicality of standardization: Processes like transfer of equations, response upgrading, model upgrading required to run NIRS units are very technical and require specific training.
Nondestructive: Samples can be used for multiple analysis, reducing the need to resample	Multiple sources of errors: Such as those associated with the samples, those associated with the operator and those associated with the instrument
Easy to handle, install, and operate: Making it suitable for African labs where there is always limited trained staff	
Durability: Many labs in SSA have malfunctioning and outdated machinery due to limited access to servicing and spare parts. The NIRS is relatively durable.	
Networkable: Making it easier for many labs, which have their own resource limitations, to share resources such as spectra data, samples, equations etc.	
Versatility: Available NIRS instrument ranges from bench top to small mobile ones making them suitable to diverse livestock production settings in SSA. Advancement in the miniaturization may one day produce smart phone-based systems which are accessible and affordable to smallholder farmers in Africa.	

[a]Source: Modified from Yakubu et al. (2020).

condition, moisture status of sample before and after grinding, bulk density of ground sample, physical texture of sample, sample temperature); and those associated with the operator (e.g., calibration practice, number of samples used in wavelength selection or calibration, sample preparation, sampling and subsampling procedure, grinder type, mean particle size, particle size distribution, blending after grinding, sample storage, sample cell loading, packing, cleanup). Generally, therefore, for developing robust NIRS prediction models, laboratories should minimize sources of error, use results for reference samples prepared using proper wet chemistry methods, standardize sample preparation and process, standardize NIRS equipment, use advanced regression models like partial least square (PLS) or artificial neural network (ANN), perform routine instrument maintenance, analyze only representative samples, and undergo yearly prediction model updates (Sapienza et al., 2008). Significant capacity development in these areas is needed to facilitate greater use of NIRS for feed analysis in SSA. Table 2 summarizes the potentials and limitations of the NIRS system with regard to its use in SSA.

5 | STRATEGIES FOR IMPROVING USE AND ADOPTION OF NIRS TECHNOLOGY IN AFRICA

5.1 | Increasing awareness about the importance of forage nutritive value

Smallholder farmers in SSA produce most of the meat and milk from livestock, but few understand the concept of forage nutritive value. Several studies in different parts of the continent such as Ethiopia (Blummel, 2019), Burkina Faso (Ayantunde, 2020), Niger (Jarial et al., 2017), have shown little to no relationship between the cost and nutritional value of livestock feeds, though a few exceptions exist. Feed quality standards are either nonexistent or hardly used and most forages are sold based on their bulk or organoleptic characteristics. Therefore, there is a concerted need to improve awareness about the importance of forage nutritive value, the myriad of factors influencing nutritive value, and how improved nutritive value can drive improved performance and reduce feed waste and adverse environmental impacts of livestock production. These awareness campaigns need to target market-oriented farmers rather than those who keep livestock for reasons such as status or insurance, as such farmers are less interested in optimizing the performance of their livestock.

5.2 | Using portable and mobile NIRS instruments

Traditional NIRS machines require a significant initial investment, however, most NIRS models are portable among instruments from the same manufacturer and have low long-term maintenance costs (Stuth et al., 2003). Mobile NIRS systems are a fraction of the cost of bench top systems, with some costing as low as US$2,000. This greatly increases the affordability of NIRS instruments by SSA laboratories as high upfront costs of bench top systems were perhaps the greatest limitation to their widespread adoption. Recent research shows that such mobile systems can be as precise and accurate (Prasad et al., 2019; Shepherd & Walsh, 2007), more flexible (O'Brien et al., 2012), and can be networked (Modroño et al., 2017) to bench top systems. Due to their simplicity, they can help increase subsampling making analysis easier, more effective, and cheaper (Modroño et al., 2017). Greater use of portable and mobile NIRS in SSA will probably improve the capacity for feed analysis in SSA, as it will allow frequent nutrient analysis enabling timely decision making, feeding of balanced rations, less feed waste and environmental pollution, and greater animal productivity. In addition, the timely decision making will be very helpful for extensive grazing systems where frequent decisions have to be made on migration and grazing patterns (Bell et al., 2018). Moreover, in most sub-Saharan African countries where extensive grazing across vast areas of range and pasturelands is common, in situ analysis will be a far more cost effective and feasible means than bringing samples to the laboratory. Several recent studies have demonstrated the potential of handheld/mobile NIRS compared to more expensive bench top NIRS. Prasad et al. (2019) for instance indicated that a few handheld NIRS brands provide comparable accuracy to the common bench-top brand (FOSS XDS), with the Tellspec costing <3% the price of the bench top instrument. Similarly, expensive quartz cups that are used during scanning can also be replaced with much cheaper plastic bags to give comparable accuracies of prediction (Figures 2 and 3). In more advanced settings where automatic feeders are used, portable NIRS have been used to monitor, in real time, feed ingredients and optimize nutritive value and animal productivity (Mostafa et al., 2021). Handheld NIRS instrumentation has also been suggested for use in detection of fraud and adulteration of soya-based products used as animal feed ingredients, with very high degree of accuracy (R^2 = .94–.99) (Haughey et al., 2015). More and more prototypes are being tested as quick portable safety tools used to prevent feed contamination at farm levels (Fernández et al., 2019).

5.3 | Adherence to guidelines and standard methods

The NIRS users in African laboratories will need to adhere to some standard operational guidelines to ensure the sustainable functioning and use of NIRS instruments. If prediction models are shared among laboratories, methods for preparing and processing samples for scanning or developing equations must be fully described and strictly followed (Sapienza et al., 2008). Extrapolation outside the range of the reference samples must be avoided since accuracy of prediction becomes less reliable (Sapienza et al., 2008). Where finding enough reference samples is a challenge, for example, when novel plant species are involved (Baath et al., 2020), instead of species-based calibrations, global models (R^2 = .92–.99, for CP of legumes [n = 20]) developed from samples of different forage categories, warm season legumes, may provide a solution, provided that such calibrations give sufficiently accurate predictions (Baath et al., 2020).

5.4 | Using partnerships to overcome barriers to adoption of NIRS

The main limitations for the adoption of NIRS technologies in Africa include the lack of robust databases of equations containing adequate diversity to represent future samples, lack of skilled scientists to calibrate, validate, and regularly

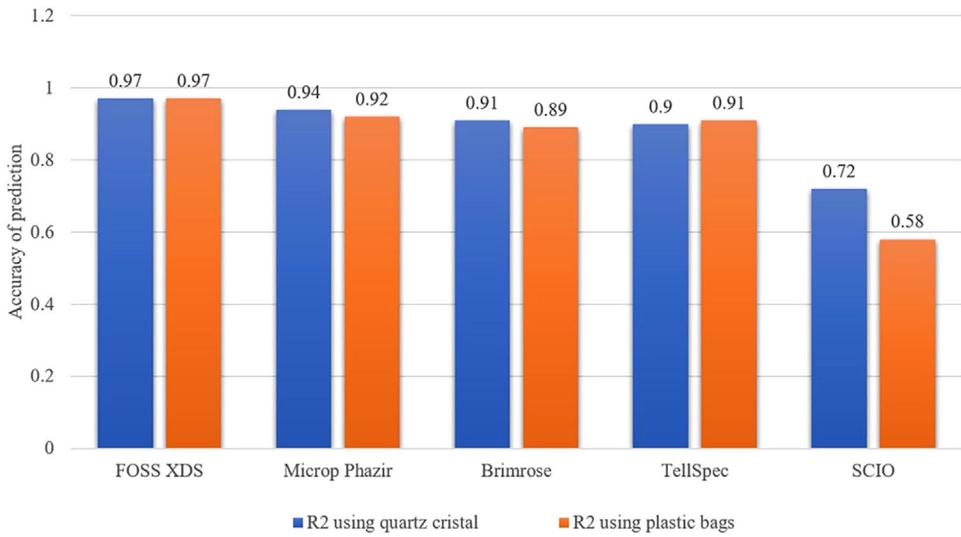

FIGURE 2 Comparison of accuracy of prediction between FOSS XDS bench top near infrared reflectance spectroscopy (NIRS) brand and other mobile or handheld NIRS brands (Source: Modified from Prasad et al., 2019)

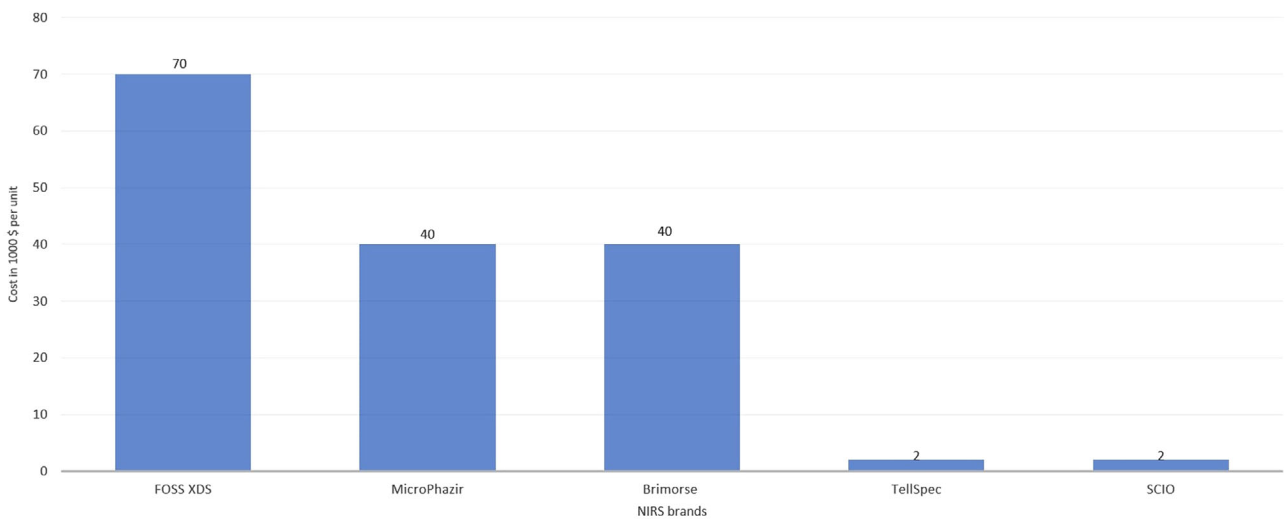

FIGURE 3 Comparison of per unit cost of bench top near infrared reflectance spectroscopy (NIRS) brand (FOSS XDS) with handheld or mobile brands (Source: Modified from Prasad et al., 2019)

update equations, and poorly equipped and managed laboratories, which produce inadequate wet chemistry data for the development of prediction equations. These problems can be solved by networking (Figure 4) to provide mutual collaboration among scientists and laboratories who share resources (Landau et al., 2006). The collaboration will involve generally three categories of members such as: (a) NIRS equipment companies, which provide the equipment, software, maintenance services and training, while benefiting from the market that is created; (b) Research organizations, which use the technology while sharing resources (spectral data and calibration equations); and (c) Private sector partners (farmers, feed processors etc.) who provide the market for NIRS services with researchers, while benefiting from the service created. Such collaborations should involve partners from well-equipped and resourced laboratories, such as in the case of instruments standardized and networked to the ILRI NIRS laboratory, who can help develop and share equations and databases developed under rigorous standards and for which extensive chemical composition and NIRS spectra are known (Coleman & Moore, 2003).

For successful utilization of the potential of NIRS technology in sub-Saharan African countries, regional centers of scientific and technological excellence, organized in networks and consortia, will be required to: (a) support high quality laboratory wet-chemistry analysis; (b) develop NIRS calibra-

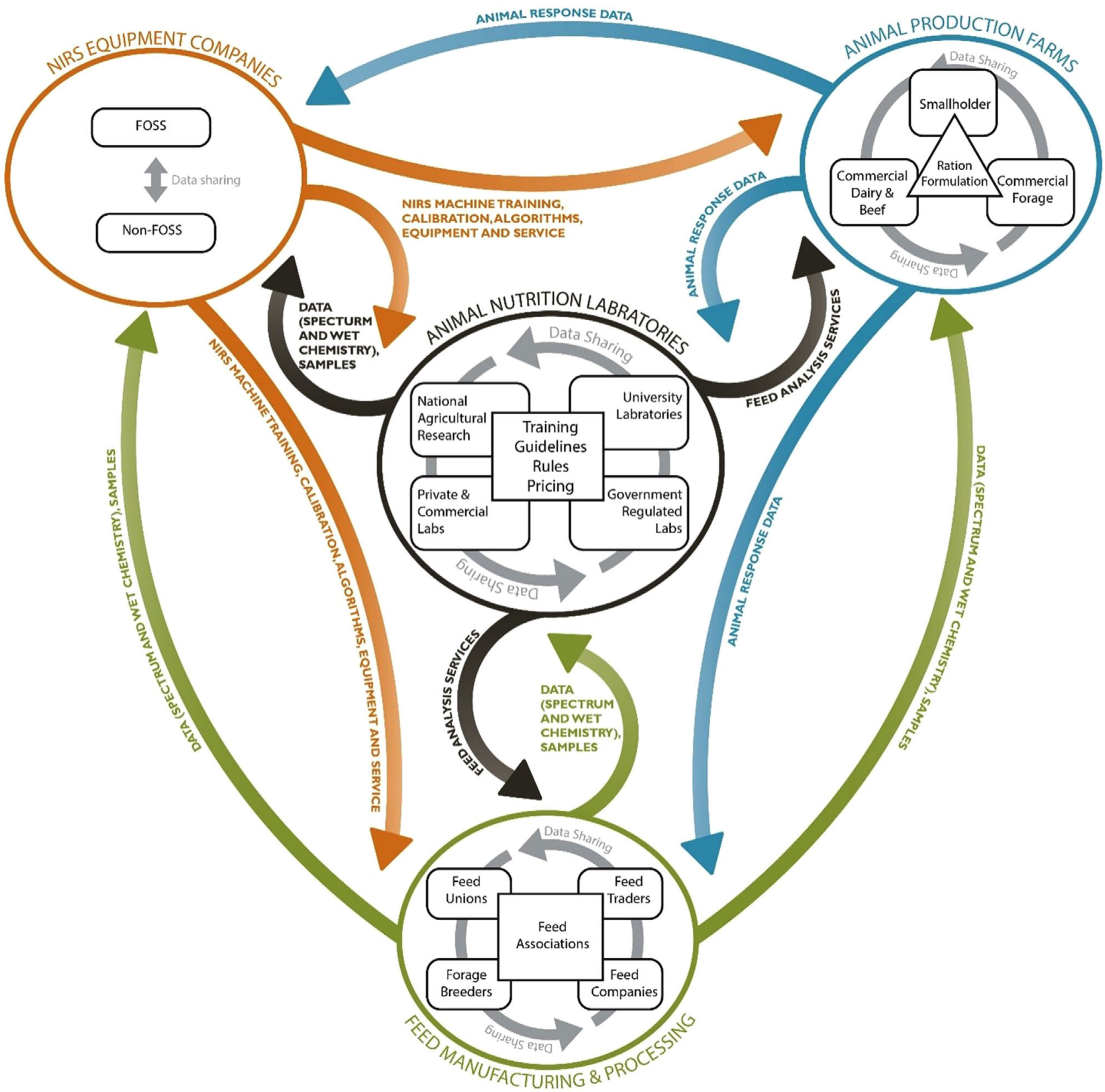

FIGURE 4 An outline of relationships between members of near infrared reflectance spectroscopy (NIRS) consortia

tion databases and interpretation systems; and (c) regularly upgrade scientific and technical skills and knowledge through training and education (Shepherd & Walsh, 2007).This will allow the NIRS service to be provided through decentralized or mobile NIRS units and results provided back to farmers and researchers (Shepherd & Walsh, 2007). National or regional laboratories could play a supporting role such as through provision of high-quality reference data using conventional methods, maintenance of decentralized units and databases, and provision of calibration and interpretive guidelines (Shepherd & Walsh, 2007). The experience and structure of the NIRS forage and feed consortium (NIRSC) (http://www.nirsconsortium.com/) can be adopted to establish similar consortia in Africa. The aim of such consortia will be to promote and standardize the use of NIRS through the development of robust, accurate prediction calibrations. Members of the consortium can include commercial laboratories, universities, National Agricultural Research Institutes/Centers (NARs), crop production research entities, and instrument companies (Consortium, 2012). The consortia should share knowledge with members and train students to develop the next generation of users. Well-functioning consortia will also enhance trust in feed labeling, which will further improve adoption of NIRS, provided there is increased awareness of and price premium for, feed quality. Possible members of NIRS consortia in Africa and their functions are outlined in Table 3.

TABLE 3 Members of a possible near infrared reflectance spectroscopy (NIRS) consortium/community of practice and their roles and benefits

Members of consortium	Contribution to Consortia	Expectation from consortia
National Agricultural Research Institutes/Centers (NARs)	Samples, spectral data, data on animal response, machines; expertise in animal nutrition, data management, and analysis	Standardization, reference database, calibration, and technical training
Higher educational institutions (universities)	Samples, spectral data, data on animal response, machines, expertise in animal nutrition, data management, and analysis	Standardization, reference database, calibration, and technical training
National agricultural products quality standards controlling agencies	Expertise, NIRS machines, market for NIRS analysis	Standardization, reference database, calibration, and technical training
Private laboratories	Market for NIRS analysis, NIRS machines, spectral data	Standardization, reference database, calibration, technical training, market for analysis
NIRS instrument companies	Provide equipment, at reduced price or credit, provide periodic maintenance services and technical training	Market for equipment (hardware and software), user feedback data
Private feed processing companies	Samples, market for NIRS analysis	Standardization, reference database, calibration, and technical training
Livestock feed traders	Samples, demand for NIRS analysis	Feed nutritive value classification and nutritive value-based pricing
Commercial dairy, beef producers	Samples, market for NIRS analysis, data on animal response	NIRS analysis service
Farmers unions, for example, Feed Cooperative Unions	Samples, market for NIRS analysis, feedback on animal response	NIRS analysis service
Small holder farmers	Feed samples, data on animal response, market for NIRS analysis	NIRS analysis service

For consortia to function effectively, specific guidelines such as NIRS consortia internal and external monitoring measures, will be needed on sample handling, optimizing accuracy and consistency across members of NIRS consortia. It will be critical to improve each member‘s ability to monitor internal performance by providing resources to assist with quality assurance and control (Consortium, 2012). Moreover, external monitoring measures such as instrument standardization and monitoring programs need to be implemented.

5.5 | Development of NIRS community of practice or public–private partnership

In areas where the status of the use of NIRS is not common, which is typical of much of SSA, before formation of consortia, the potential and actual NIRS capacity should first be mapped. This will require undertaking an inventory of public (central and regional research institutes, universities, national research organizations) and private (service laboratory, feed industry) NIRS analysis providers. Actual and potential users of the technology such as farmer organizations, researchers, feed-processing factories or unions should be identified and invited to join the community of practice. Institutions with NIRS instruments should then be linked to form a community of practice (CoP), which may be more localized than a regional or national NIRS consortium. This should be followed by checking the compatibility of equipment, implementation of spectra standardization procedures where required, and sharing extensive calibration equations. This will, therefore, involve revisiting existing NIRS equations and identifying missing equations to allow upgrading to meet specific analytical needs, either because of new samples or entirely new provenances or traits. In addition, new equations should be developed for feeds that are not well represented by the existing calibrations or that have inaccurate global calibrations. All newly developed or updated equations should then be made accessible to all stakeholders through a platform developed by the community of practice. Provisions for proper attribution of the origin of equations or spectral data by users should be made to encourage continuous development of calibration equations for more forage types. The community of practice should support the capacity of members to ensure both accuracy and consistency of results, through the implementation of standard sample handling and processing techniques and internal monitoring, across the participating laboratories.

6 | CONCLUSIONS

This review has described the lack of forage and feed testing in most of SSA, the underlying reasons for the dysfunctional state of most wet chemistry laboratories, and the potential of

NIRS to solve the problem. The most important limitation to adoption of NIRS in SSA has been the high cost, but the advent of precise and accurate, flexible, robust, low cost mobile or portable NIRS systems provides an opportunity to greatly increase feed and forage testing capacity across the continent. This can improve ration formulation and feed labeling, which can greatly increase livestock production and reduce adverse environmental effects and feed waste. However, significant capacity building will be needed to ensure the technical skills for running and maintaining the equipment and developing and updating equations. In addition, there is a great need to raise awareness about the importance of forage nutritive value among producers to foster greater adoption and use of NIRS across the continent. Critical to success of NIRS adoption across the continent will be creation of consortia that develop, update, and share equations and best practices for ensuring representative sampling, improving analytical precision and accuracy.

AUTHOR CONTRIBUTIONS

Mulubrhan Balehegn: Conceptualization; Data curation; Investigation; Methodology; Writing-original draft; Writing-review & editing. Padmakumar Varijakshapanicker: Data curation; Resources; Writing-original draft; Writing-review & editing. Michael Blummel: Conceptualization; Resources. Augustine Ayantunde: Conceptualization; Data curation; Formal analysis; Methodology; Resources; Writing-original draft; Writing-review & editing. Kodukula Venkata Subrahamanya Vara Prasad: Conceptualization; Data curation; Resources. Alan Duncan: Data curation; Conceptualization; Drafting, and editing. Mesfin Dejene: Date curation and resources. Adegbola T. Adesogan: Conceptualization; Data curation; Formal analysis; Funding acquisition; Resources; Writing-original draft; Writing-review & editing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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