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Field trial guidelines for evaluating enhanced efficiency fertilizers

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Abstract

There are many fertilizer additives and alternatives that aim to increase plant nutrient use efficiency and reduce nutrient losses to the environment, here referred to collectively as enhanced efficiency fertilizers (EEFs). However, there is often insufficient published scientific field trial results across a variety of locations, climates, soils, cropping systems, and management scenarios to prove their efficacy and conditions

Abbreviations: 4RNS, 4R Nutrient Stewardship; EEF, enhanced efficiency fertilizer; EFC, Efficient Fertilizer Consortium; FFAR, Foundation for Food & Agriculture Research; NUE, nutrient use efficiency.

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for use. Guidelines for common minimum datasets and data stewardship in evaluating the agronomic performance and environmental impact of EEFs are needed for researchers to follow. Such guidelines will improve hypothesis testing centered on product efficacy and provide producers with guidance on how these technologies function and perform when integrated with other management practices within the 4R Nutrient Stewardship Framework. A scientific committee was formed to develop a set of protocol guidelines for evaluating EEFs in replicated, plot-based field trials on an international scale. The guidelines are composed of experimental design and core metadata, crop and soil analyses, environmental loss measurements, and data stewardship, and include both recommended and required components to allow for flexibility and adaptability depending on the trial location, objectives, infrastructure capacity, product type, and depth of understanding of the potential EEF efficacy. This approach will ensure consistency and compatibility in experimental design and data collection to support data integration, analysis, and reuse leading to large-scale impact and end-user confidence.

1 | INTRODUCTION

A proportion of fertilizer nutrients applied to agricultural land are unused by the targeted crop due to inefficient uptake, soil adsorption, losses due to leaching, runoff, erosion, and gaseous emissions, incorrect application rates, timing and placement, or other agronomic factors such as tillage, irrigation, weather, or pest damage (Yan et al., 2019; Yu et al., 2022). A crop's nutrient use efficiency (NUE), that is, the ratio of a nutrient in harvested biomass to inputs to an agricultural cropping system, is influenced by numerous factors and can be calculated in a number of ways for different purposes (Dobermann, 2007; Scientific Panel on Responsible Plant Nutrition, 2023). There are many viable solutions for increasing NUE and reducing nutrient losses from cropland, including enhanced efficiency fertilizers (EEFs) and management practices such as those discussed in the 4R Nutrient Stewardship (4RNS) framework (right source, right rate, right time, and right placement of fertilizer in nutrient management; Bruulsema et al., 2008, 2009; Fixen, 2020). Thus, producers have a variety of technologies and practices to choose from that can be tailored to fit their specific production and environmental stewardship needs. However, scientifically defensible information is needed about each of these optional tools for producers to make informed decisions about which to implement on their farms.

There are a wide variety of fertilizers, fertilizer additives, soil amendments, and plant nutrition products that claim to increase crop NUE or reduce nutrient losses to the environment, including but not limited to enzyme inhibitors, controlled and slow-release fertilizers, plant biostimulants, biofertilizers, bioformulations, and nanofertilizers (International Organization for Standardization, 2022; Maaz, 2023). In this manuscript, we are focusing on products that aim to provide crops with adequate nutrition while enhancing NUE or reducing losses to the environment. Here, we will refer to the collective group of these technologies, including biofertilizers and nanofertilizers, as EEFs. There are other types of soil additives being commercialized, including plant growth regulators and carbon sequestration products; however, these are not the primary focus of these guidelines. Nevertheless, information included in these guidelines may apply to these products as well. Additionally, while many EEFs focus on improving nitrogen (N) or phosphorus (P) efficiency, the same principles can and should apply to other nutrients. With the exception of greenhouse gas emissions, which are specific to EEFs that target N losses, the same level of methods and information present in this set of guidelines should be followed when studying any EEF.

Enhanced efficiency fertilizers have been available since the 1960s and studied extensively. Numerous meta-analyses have concluded that they are broadly effective in supporting agronomic performance by enhancing NUE, thereby lowering necessary application rates and preventing nutrient loss to the environment (Abalos et al., 2014; Burzaco et al., 2014; Grados et al., 2022; Lam et al., 2022; Li et al., 2018; Linquist et al., 2013; Qiao et al., 2015; Quemada et al., 2013; Silva et al., 2017; Thapa et al., 2016; Young et al., 2021; Zhang et al., 2019). However, these meta-analyses have limitations as they combine trials with vastly different research protocols and methodologies, often lacking proper controls and realistic treatment fertilizer rates (Maaz, 2023). While a general benefit of using EEFs has been shown, the extent to which they are beneficial and in which circumstances is often unclear and inconsistent in the literature. Despite industry claims of effectiveness, EEFs often lack sufficient published scientific field trial results in a variety of locations, climates, soils, cropping systems, and management scenarios to prove their efficacy and conditions for use. Studies evaluating these products often have conflicting results, are missing key data and metadata due to incomplete data collection or reporting, have flawed experimental designs such as improper controls, or lack sufficient statistical power to prevent Type I and II errors (Gent et al., 2018; Maaz, 2023). It has therefore proven difficult to make conclusions about many categories of EEFs because research evaluating them is often conducted in an inconsistent and incomplete manner. There is also a lack of publicly available data due to data privacy concerns, proprietary claims, or a lack of a positive treatment response, making it difficult to reach reliable conclusions when data cannot be accessed or compared directly.

Minimum datasets with common data, metadata, and reporting protocols, consistent experimental designs including control and treatment definitions, and data published in repositories regardless of the outcomes are necessary for collaborative research and assessing experimental data from a variety of trials (Brouder & Gomez-Macpherson, 2014; Doran & Parkin, 2015; Eagle et al., 2017; Gregorich et al., 1994; Kitchen et al., 2017; Slaton et al., 2022). While there are published minimum datasets that provide valuable guidelines for conducting agronomic and soils research more broadly (Doran & Parkin, 2015; Eagle et al., 2017; Slaton et al., 2022), for specific contexts (Gregorich et al., 1994; Kitchen et al., 2017), or for specific measurements such as nitrous oxide (N_2O; Charteris et al., 2020; Clough et al., 2020; de Klein et al., 2020; Dorich et al., 2020; Grace et al., 2020; Harvey et al., 2020; Venterea et al., 2020), there are no published guidelines for evaluating EEFs in field trials for both agronomic performance (i.e., crop yield) and environmental impact (reduced nutrient losses). With many EEFs being developed and brought to the market, a common protocol for evaluating EEFs in field trials is needed to ground industry claims and to provide researchers and the agricultural community with adequate guidance on how these technologies function and perform when integrated with other management practices within the 4RNS framework. Field research is challenging due to the complex interactions and sources of variability among crop, soil, climatic, and socioeconomic factors (Giller et al., 2011; Morris et al., 2018; Schut & Giller, 2020). However, progress in understanding these complicated systems can be made if consistent methodology and rigorous data stewardship are adopted and utilized throughout the scientific community.

Our objective is to develop a set of field trial protocols and data guidelines for evaluating the agronomic performance and environmental impact of EEFs. By leveraging existing, peer-reviewed protocols and minimum datasets developed and vetted by the scientific community, we will enable consistency and compatibility in experimental design, data collection, and data analysis to support large-scale impact and end-user confidence. These guidelines can be used by researchers to generate a body of data to inform nutrient management recommendations within the 4RNS framework and to provide producers with accurate information about how, when, where, why, and in which management contexts EEFs could be beneficial.

Core Ideas

- Many enhanced efficiency fertilizers lack published field trial data to support efficacy claims.
- Common field trial protocols were developed for evaluating enhanced efficiency fertilizers.
- Proper experimental design and minimum datasets support large-scale impact and end-user confidence.
- Appropriate agronomic and environmental measures should support product efficacy claims and recommendations.

2 | METHODS

This effort originated as part of the Efficient Fertilizer Consortium (EFC), a multi-stakeholder initiative organized by the Foundation for Food & Agriculture Research (FFAR) with initial seed funding from the United States Department of Agriculture (USDA) and United States Department of State as part of the Global Fertilizer Challenge (The White House, 2022) to support innovative research to help countries with high fertilizer nutrient loss adopt efficient nutrient management solutions, including EEFs with proven performance. To determine initial pre-competitive research priorities for the EFC, FFAR supported the development of a white paper (Maaz, 2023) and organized a task force that included ten international fertilizer companies and related organizations. The top recommendation was that common protocols for evaluating the agronomic performance and environmental impact of EEFs in field trials should be developed to support consistency in data collection and more robust results. The development of guidelines was supported by current EFC funding partners (Agriculture and Agri-Food Canada; Azotic Technologies Ltd.; Cotton Incorporated; ICL Group; the Ministries of Innovation, Science, and Technology and Agriculture and Food Security of the State of Israel; Novo Nordisk Foundation; OCP Group; the Platform for Agriculture and Climate Transformation; Pivot Bio; United Soybean Board; and USDA) and will be followed by EFC-funded field trials.

Similar existing protocol frameworks developed and vetted by the scientific community (Clough et al., 2020; Eagle et al., 2017; Slaton et al., 2022) were leveraged to build a set of guidelines specific to evaluating EEFs in field trials on an international scale. After the guidelines were drafted, FFAR held an in-person convening event to further discuss and refine the protocol and data guidelines. A steering committee made up of FFAR representatives and two expert scientists, Dr. Deanna Osmond with North Carolina State University and Dr. Achim Dobermann with the International Fertilizer Association, developed the agenda, identified attendees, and selected speakers. Attendees were made up of 14 external scientists with expertise in soil fertility, data science, and greenhouse gas and water quality evaluation, 10 external stakeholders from industry, government, and not-for-profit organizations, and 17 representatives from EFC member organizations. The agenda consisted of presentations, a panel discussion, and discussion-based, topic-focused breakout groups for the scientists to share their experiences and recommendations as well as actively work on the protocol and data guidelines (Foundation for Food & Agriculture Research, 2024). A selection of convening event attendees was invited to participate on a committee to finalize and co-author the guidelines as a manuscript. The committee participated in a series of eight virtual meetings to discuss and revise the manuscript based on their current and past research experience conducting field trials internationally. The manuscript received additional reviews by scientists not on the committee, including modeling experts Dr. Bruno Basso, Dr. Kaiyu Guan, and William Salas, Danish researchers Dr. Sander Bruun and Dr. Klaus Butterbach-Bahl, and scientists from the African Plant Nutrition Institute and the International Fertilizer Development Center. Committee participants and external reviewers were identified to provide a diversity of both subject matter expertise and experience conducting research in a variety of geographic locations.

Expert feedback during the convening event and committee meetings identified what these guidelines are, and are not, intended for. While components of these guidelines represent best practices and can be used for other purposes, these protocol and data guidelines were specifically developed for the following:

1. Replicated, plot-based field experiments. While omission plot and on-farm demonstration trials can lead to greater adoption of tools and technologies by producers (Puntel et al., 2024), to ensure sufficient metadata and proper implementation of controls and treatments, this framework is not intended for omission or on-farm demonstrative trials.
2. Experiments evaluating EEFs developed to provide crops with nutrition while enhancing NUE or reducing losses to the environment.
3. Experiments evaluating EEFs that have already undergone proof of concept testing in the laboratory, greenhouse, or field and have clearly defined theoretical mechanisms. Field trials are an important part of the product evaluation process but are cost- and labor-intensive, and so should only be invested in if the identified product or combination of products first show potential in the laboratory or greenhouse.
4. International research. These guidelines are intended to be broadly accessible and to ensure the collection of essential information while allowing flexibility to account for variations in location, climate, space availability, or infrastructure limitations.

The authors recognize that these guidelines, while comprehensive, do not cover every possible detail one may encounter in some studies. Instead, these guidelines were developed to capture the minimum information needed to evaluate EEFs and associated management practices in a field setting while also allowing the researcher to maintain autonomy and flexibility in experimental design and identification of appropriate products, practices, and additional measurements to include. Nor are these guidelines prescriptive in terms of experimental design or selecting treatment products and practices; the authors recognize that there are ways in which the efficacy of products can be further enhanced, but that is not the focus of this paper.

3 | RESULTS AND DISCUSSION

A tiered approach was developed to guide experiments in a wide range of contexts to account for varying product modes of action, climates, geographies, management scenarios, and resource or equipment limitations (Figure 1). The tiers include (1) experimental design details and core metadata, which includes the minimum information that should be collected from all field trials regardless of experiment objectives; (2) crop performance and soil fertility measurements; and (3) environmental nutrient losses, including surface and subsurface water losses and gaseous emissions. Data stewardship principles must be applied across all tiers. The tiers allow for flexibility and accessibility, considering that in some production systems, particularly in locations where access to and use of fertilizer is limited, measurements of agronomic performance are prioritized over water or emissions measurements. This approach is intended to maintain researcher autonomy in experimental design and allows for various measurement intensities depending on the focus of the experiment, equipment accessibility, and depth of understanding and potential efficacy of the EEF(s) in question. Products and practices that are situation-specific and relevant to producers are key to developing the experimental design, including treatment levels and controls appropriate for the products and practices investigated.

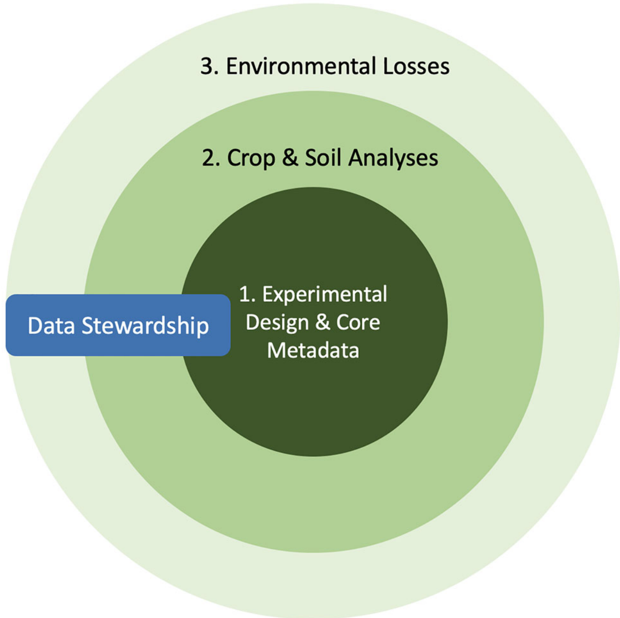

FIGURE 1 Tiered framework for field trials evaluating enhanced efficiency fertilizers. Tier 1: Experimental design details and core metadata that must be universally reported regardless of experimental objective; Tier 2: Crop and soil measurements; and Tier 3: Environmental losses, including nutrient loss through runoff and leachate and gaseous losses through nitrous oxide emissions and ammonia volatilization. Data stewardship principles must be followed across all tiers.

For EEFs that target nutrient losses and have shown potential in field settings, it is recommended to measure the full scope of loss pathways through water and, for N-based EEFs, gaseous emissions, to support efficacy claims and capture any trade-offs that may occur. For example, the use of nitrification inhibitors on their own may decrease N_2O emissions and nitrate leaching while increasing ammonia (NH_3) volatilization (Lam et al., 2017; T. Li et al., 2018; Pan et al., 2016; Qiao et al., 2015), and combining N-fixing microbes or urease inhibitors with nitrification inhibitors may decrease direct N_2O emissions but increase NO_3^- leaching and indirect N_2O emissions (Souza et al., 2023). On the other hand, for some locations, particularly those with limited fertilizer accessibility, affordability, and use, measuring the full scope of nutrient loss pathways may be excessive and cost- and infrastructure-prohibitive. Experimental design and product selection should reflect the appropriate measurements and desired outcomes specific to a location, climate zone, soil characteristics, and cropping system.

3.1 | Experimental design

There are several key components that should be included when conducting field trials for EEF research (Table 1). Justification for conducting the trial must be reported, including a rationale for conducting the study describing the data or knowledge gap addressed, clearly defined hypotheses and objectives, and an explanation of location selection including the probability of crop response to fertilization. Study objectives, trial space available, and the types of measurements taken (e.g., water quality or emissions) will dictate the number of possible treatments, replicates or blocks, and plot size. These parameters must be representative of the targeted production system and described clearly.

Single-year trials can generate useful information and can often lead to data collected from a greater number and variety of locations if resources are limited. However, annual variation in weather conditions can impact fertilizer effectiveness, agronomic response, and the fate and scale of nutrient loss (Morris et al., 2018; Schut & Giller, 2020), so we recommend multi-year trials.

Some EEFs, or experiments conducted on fields with certain soil properties or slopes, may require adequate buffers between plots to avoid cross-contamination or carryover effects. We recommend a minimum distance of 1 m between plots, which can be adjusted depending on the crop, treatments, plot size, and slope. Buffer size can be reduced if sampling avoids plot edges and subsurface horizontal flow is not anticipated. Buffer management is up to researcher discretion and should be appropriate to the EEF type, location, soil properties, and cropping system.

3.1.1 | Treatments

Identifying EEFs and associated practices to evaluate with field trials is not a simple or straightforward task. The selected EEF(s) should target improved NUE and nutrient loss pathways relevant to the specific field trial location. The risk and pathway(s) of nutrient loss, and the most appropriate measurements to quantify those nutrient losses, for a particular site must be identified and defined. The mode of action must be clearly described both with detailed product label information from the manufacturer and sufficient proof-of-concept from laboratory, greenhouse, or field experiments, all of which should be reported with the trial results. Particularly for new products, researchers are encouraged to discuss product details with the manufacturer when designing an experiment. Proper product handling, and the necessary infrastructure to do so (such as refrigeration for live materials), must also be considered, implemented, and recorded with results.

Nutrient management is inextricably linked with the nutrient source and can greatly impact how EEFs perform in field settings. All treatment components of 4RNS should be thoroughly described and included with trial results, including the rate, source, placement, and application timing (Fixen, 2020; Slaton et al., 2022).

TABLE 1 Experimental design and treatment information, controls, rates, and replications guidelines for evaluating enhanced efficiency fertilizers (EEFs) in field trials.

Parameter	Category
General	
Clearly stated hypothesis	Required
Field selection justification and likelihood of crop response to fertilization	Required
Plot dimensions (report length and width)	Required
Treatment design description (e.g., randomized complete block)	Required
Report number of site-years or seasons included in study	Required
Multi-year trials	Recommended
Between-plot buffers (1 m minimum)	Recommended
Treatment EEF information	
Justification for product(s) selected, including proof of concept, location-specific needs, targeted nutrient loss pathway(s), and socioeconomic considerations	Required
Product label information, including purchase date and source (company or retailer), manufacture date and production lot number, characteristics and composition, timeframe of effectiveness, lifespan and half-life, ideal conditions for effectiveness (soil, water, and weather), expected release pattern and duration, estimate amounts of nutrients provided, targeted efficacy[a], and recommended application/placement method, rate, timing, and depth	Required
Description of materials that may negatively impact product effectiveness if mixed, especially for live strains	Required
Experimental controls	
A treatment without any nutrient of interest added (true control) following the same management practices as all other treatment plots	Required
A treatment with the conventional product applied at equivalent nutritional levels as the EEF	Required
Additional treatment controls for each 4RNS practice that varies among nutrient sources (timing, placement, and application method)	Recommended
For trials with many treatments or that have a large footprint, multiple plots of the same control within a replication or block	Recommended
Treatment rates	
Description and number of treatment rates	Required
Elemental nutrient rates applied (i.e., kg N ha^{-1}, if applicable)	Required
Treatment application date(s)	Required
Treatment application method(s)	Required
The following treatments for each nutrient source or product type: (1) optimum rate for non-limiting yield, (2) rate expected to exceed crop requirements, and (3) two or more suboptimum nutrient rates	Recommended
Replications and blocks	
Report number of replications (four minimum recommended, three or less requires justification).	Required
For smaller expected effect size or greater variance, additional replications determined by power analysis[b]	Recommended
Blocking guidelines: Each block should include at least one full set of experimental units and be placed in an area as homogeneous as possible to minimize variability due to field conditions (i.e., soil properties, slope, and drainage). If the treatment area is very uniform, blocking may not be necessary	Recommended

Abbreviation: 4RNS, 4R Nutrient Stewardship.

[a]Targeted efficacy could include reduction in application rate, emissions, cost, and so forth. Communication with the manufacturing company is encouraged.

[b]See Johnson et al. (2015).

3.1.2 | Experimental controls

Defining proper controls is necessary for generating defensible results. Eagle et al. (2017) recommended that for soil fertility research, at least two categories of controls should be considered: (1) a treatment without any fertilizer or EEF added (true control), and (2) a treatment with a conventional fertilizer product applied at equivalent nutritional levels as the EEF. A true control is important for determining crop responsiveness to fertilization, which can impact conclusions made about an EEF and its effect on yield or NUE. If timing, placement, or application differ between nutrient sources, additional controls for each variable should be considered. For trials with a large number of treatments or large footprint, multiple plots of the same control within a replication or block should also be considered. Adjustments may be needed for sources that contain more than one plant nutrient, such as diammonium phosphate, monoammonium phosphate, ammonium sulfate, potassium nitrate, and so forth, to prevent confounding effects.

3.1.3 | Treatment rates

Determining the optimum nutrient rate is often the most challenging component of 4RNS as there are countless location-specific variables, such as soil properties, climate, drainage, and crop cultivar, that could impact crop response as well as the behavior of nutrients in the soil and nutrient loss risk. The same challenge holds true for conducting EEF trials, which is why implementing a range of nutrient rates, including optimum, suboptimum, and above-optimum rates, is ideal for comparing EEF behavior and crop response in unpredictable conditions, especially for products that call for lower nutrient rate needs either by substitution or enhanced efficiency. It is important to know what the optimum rate of an elemental nutrient is at the same time and place as an alternative source when comparing the two and determining whether the alternative source is effective. Rose et al. (2018) found that the greatest differences in yield between fertilizers treated and untreated with nitrification inhibitors were observed at suboptimum fertilizer rates, supporting our recommendation to have a range of both suboptimum and optimum fertilizer rates rather than simply comparing two nutrient sources at the optimum rate. Additionally, it can be challenging to identify what the true agronomic optimum rate of fertilizer is for a given field as recommended rates may not always be accurate, and optimum N rates in particular can change seasonally (White et al., 2021). We recommend the following treatments for each nutrient source or product type (or combination of sources) compared: (1) proper controls, (2) optimum rate for non-limiting yield, (3) rate expected to exceed crop requirements, and (4) two or more suboptimum nutrient rates.

While “producer fertilizer rates” are often included in experimental trials to capture realistic production scenarios, we do not recommend producer rates for comparing treatment nutrient sources in this framework. Producers may apply more than what is needed for crop removal to ensure yields are not limited by insufficient nutrients. In many cases, and particularly for N, recommended or optimum rates produce yields similar to above-optimum rates (Austin et al., 2019; Helmers et al., 2012; Osmond et al., 2015; Pittelkow et al., 2017). Comparing two nutrient sources at greater than optimum rates where the nutrient of interest is not limiting may result in a lack of response or lead to incorrect conclusions about the effectiveness or full potential of a product. The potential benefit of an EEF to reduce nutrient rates while maintaining yield may not be realized in situations where the nutrient of interest is not limiting.

3.1.4 | Replications and blocks

We recommend a minimum of four replications. If three replications or less are used, a justification is required. This could include cost or space limitations for large-scale plots. All available EEF information should be reviewed, and the potential or expected effect size should be carefully considered. If a smaller effect size or greater variance is expected among treatments, additional replications determined by power analysis should be considered (Johnson et al., 2015). Blocking can be used to minimize variability within replications due to field conditions such as soil properties, slope, or drainage. We recommend blocking for nonuniform trial areas. Each block should include at least one full set of experimental units and be arranged to minimize variability due to field conditions.

3.2 | Core metadata

Detailed information about the field trial location, including location details, field characteristics (soil description, drainage, slope, and weather), field history information (cropping rotation, past fertilizer or manure applications, and ideally for the previous 5 years or more), and management practices (tillage, presence of artificial drainage, irrigation, and pest management) must be reported (Table 2). Note that this information represents a minimum (additional details may be reported and are desirable, particularly for modeling purposes) and must be collected regardless of experimental design since it is crucial for interpreting results and extending their value through multi-site comparisons and meta-analyses (Eagle et al., 2017). If a trial is conducted on a research farm or public land, the latitude and longitude of the trial location are required. As this information may be sensitive for privately owned producer fields, reporting latitude and longitude for on-farm trials is not required but recommended if documented permission from the producer and landowner is given. In cases where privacy concerns prevent exact georeferencing, the postal code is required.

Minimum datasets often focus on consistency of reporting metadata, as this information is important for comparing and combining data from different experiments (Eagle et al., 2017; Kladivko et al., 2014; Slaton et al., 2022). Many metadata variables can be useful to help explain agronomic performance and response to fertilizer treatments, so Slaton et al. (2022) also recommend “a narrative explaining how crop management and production system traits may influence, interact with, or manipulate fertilizer treatments and potential crop yield.” It is also important to document assumptions made regarding field history or management practices, as this

TABLE 2 Core metadata for field trials evaluating enhanced efficiency fertilizers.

Parameter	Category
Location	
Country, state, province, county, region, or nearest city[a]; latitude and longitude[b]	Required
Slope and elevation	Recommended
Soil description	
Official soil description, series, type, classification, or map unit[c] (report information for all soils in trial area)	Required
Cropping and rotation history	
Cropping system/rotation description; previous growing season crop or cover crop	Required
Previous 2 years or more of crops or cover crops grown and associated yield/biomass	Recommended
Fertilizer and lime application history	
Current growing season non-nutrient of interest fertilizer or lime applied	Required
Previous 1–5 years or more of fertilizer and lime application history, including manure and compost	Recommended
Tillage	
Type[d] (intensive/conventional/full, reduced, and no-till), timing (pre-plant fall and pre-plant spring), and descriptive narrative (equipment and method) for current growing season.	Required
Date(s), depth, and speed of operation; percent of soil surface area disturbed; narrative of tillage used for previous 1–5 years or more	Recommended
Artificial drainage	
Type (tile, ditching, land leveling, none)	Required
Tile spacing and depth	Recommended
Irrigation	
Type (flood, furrow, flush, delayed flood, overhead, ditch, subsurface/drip, none)	Required
Irrigation amount (cm); irrigation narrative (frequency and flood depth); water quality analysis (pH, N content, etc.); timing (dates and description)	Recommended
Pest management	
Brief description of pest management and reference for local recommendations	Recommended
Weather	
Mean annual temperature and precipitation	Required
daily precipitation and minimum/maximum/mean temperature; solar radiation; humidity; description of major weather events	Recommended

Note: Parameters identified as minimum requirements are categorized as "required," while parameters that are desirable or specific to the study objectives or location are "recommended."

[a]The smallest unit of location available depending on location.

[b]If privacy concerns prevent the use of latitude and longitude, postal code is required.

[c]Provide all information available and appropriate to the location. See the World Reference Base for Soil Classification (IUSS Working Group WRB, 2022).

[d]Intensive/conventional/full tillage: Full-width tillage is considered to be standard for some locations and crops. It disturbs the soil to bury crop residues, reduces the size of crop residues and clods, mechanically controls emerged or emerging weeds, and leaves the soil surface bare of vegetation and residue to prepare for planting the next crop. It typically includes primary tillage (plowing) and secondary tillage (disking). It leaves <15% of crop residue on surface. Reduced tillage: Includes mulch, ridge, or strip tillage and has less intensity, less frequency, or shallower depth than conventional tillage. It leaves 15%–30% of residue on the soil surface. Reduced tillage disturbs but does not invert the soil. No-till: Absence of tillage operations from harvest of the previous crop to harvest of the current crop. No soil disturbance beyond the disturbance caused by the drill or planter (e.g., disk openers).

legacy of qualitative data provides the opportunity to use data for addressing related or new questions that have yet to be considered.

3.3 | Soil sampling and analyses

The collection and analysis of soil samples prior to treatment application is important for establishing a baseline soil nutrient availability as well as identifying any limiting factors that could impact crop yield or nutrient availability (Slaton et al., 2022). The soil nutrient status may also assist with determining treatment nutrient rates appropriate for a given field. While a uniform soil sampling depth would be ideal for cross-site comparisons, we recognize that chosen soil sample depths vary by location, cropping system, and other factors. While we do not require a specific soil sampling depth, we recommend the 0- to 15-cm depth as the most useful across a variety of situations (Lyons et al., 2023). Ultimately, soil sampling depth(s) should be appropriate to the specific

TABLE 3 Soil measurement guidelines for field trials evaluating enhanced efficiency fertilizers.

Parameter	Category
Soil sample collection time	
Prior to treatment nutrient application (within 1 month recommended); date(s) of soil sampling and associated growth stages (preplant, vegetative, reproductive, post-harvest)	Required
Additional sampling times (report dates and growth stages)	Recommended
Composite soil samples	
Number of cores per composite soil sample collected (six minimum); one composite sample per block or replication	Required
Eight to ten cores per composite soil sample (or more for large-scale trials); one composite sample per plot; diameter of core used	Recommended
Soil sample depth	
Report all depths sampled. Depths should be appropriate to the location, cropping system, and so forth.	Required
Sample depth of 0–15 cm; additional relevant sampling depths	Recommended
Soil sample collection strategy[a]	
Report which one (i.e., random or stratified) and any software used to determine soil sampling locations	Required
Soil sample preparation	
Sample handling description; soil preservation method (air-dried, oven-dried, freezing); drying or freezing temperature and length	Required
Grinding method; sieve size	Recommended
Laboratory methodologies	
Extraction/laboratory methods used for all parameters	Required
Equipment used; laboratory name and location; single laboratory to run all samples for a given experiment to reduce variation	Recommended
Soil parameters[b]	
Replication-level analyses for soil texture, pH, soil organic carbon or soil organic matter, and relevant nutrient of interest measurements; rep-level analyses	Required
Bulk density, soil profile characterization, and any additional relevant parameters; plot-level analyses	Recommended

Note: Parameters identified as minimum requirements are categorized as "required," while parameters that are desirable or specific to the study objectives or location are "recommended."

[a]Spatial distribution of soil samples (Carter & Gregorich, 2007).

[b]For multi-year trials, soil texture and soil organic carbon may be measured once at the start of the experiment. All others should be measured annually or more frequently depending on the experiment objectives.

location (e.g., standardized fixed depth and genetic horizon depth) and cropping system (e.g., depth of tillage), and they must be reported (Table 3). We recommend that soil samples be collected within 1 month prior to treatment nutrient application, though specific timing can be determined by the researcher for the target crop and nutrient. At a minimum, soil samples for all trials must be analyzed for the nutrient of interest, pH, soil organic carbon or organic matter, and soil texture prior to treatment application. If soil texture has already been analyzed and is available for a given site, those values can be used. Additional soil parameters will depend on the objectives of the trial and are up to researcher discretion. Note that additional soil measurements may be required for water quality analyses or gas emissions measurements. One composite soil sample per replicate or block is required, though we recommend one composite sample per plot. Six soil cores per composite soil sample are required as a minimum, though 8–10 are recommended to address fine-scale spatial variation (James & Wells, 1990) and even more may be necessary (15–20) for large-scale experiments or highly variable fields. Other sampling times, depths, and parameters are dependent on the nutrient of interest, experimental design, and objectives. For example, hypotheses on mode of action for novel inhibitors or stabilizers may require intensive temporal sampling to document efficacy, nutrient release patterns and behavior over time, and trends of nutrient transformation (i.e., ammonium to nitrate) compared to conventional nutrient sources.

While specific methodologies are up to the discretion of the researcher and are largely dependent on the size and variability of the trial area as well as the experimental design details, soil sampling, handling, and processing methodologies must be reported as they can impact the results, are required for accurate interpretation and evaluation, and enable accuracy of future meta-analyses. For example, we recommend that sieve size is reported as more finely ground soils will have greater extractable nutrients and biological assay values.

TABLE 4 Crop management, yield, and tissue measurement guidelines for field trials evaluating enhanced efficiency fertilizers.

Parameter	Category
Planting	
Planting date, row spacing, seeding rate, crop variety, or hybrid	Required
Estimated residue cover at planting (%); weed pressure description; cover crop termination status, timing, and method (chemical and mechanical)	Recommended
Harvest	
Crop yield, harvest date, growth stage at time of harvest, area harvested (length × width), harvest method (hand harvest, plot combine, and full-scale combine), plant fraction harvested, number of harvests; specify raw or calculated yield values	Required
Plant population and spacing; total aboveground biomass	Recommended
Crop moisture concentration	
Crop moisture concentration associated with yield values (g kg^{-1}), indicate actual or corrected; standard moisture concentration if used; drying method	Required
Crop damage	
Description of damage to the crop due to weather, lodging, disease, pests, and so forth.	Recommended
Tissue nutrient concentration	
Plant tissue nutrient concentration (nutrients of interest) and description of analyses methods; plant components sampled; sampling timing	Recommended

Note: Parameters identified as minimum requirements are categorized as "required," while parameters that are desirable or specific to the study objectives or location are "recommended".

Narratives with sufficient detail to support reproducibility and a thorough understanding of what was done are essential for accurate interpretation and defensibility of the results (Slaton et al., 2022). It is also recommended to use a single laboratory for all analyses within a study for consistency, as data produced by different laboratories could impact results given inter-lab variability (Jacobsen et al., 2007). Soil samples should be retained until results are published, but ideally would be properly stored and archived beyond the date of publication.

3.4 | Agronomic performance

To evaluate whether EEFs are effective at supporting crop yield and enhancing nutrient uptake, it is necessary to measure harvestable yield or biomass. While the specific details will depend on the cropping system and study objectives, this framework includes the general information that should be included with trial results, including planting information (date, row spacing, seeding rate, crop variety or hybrid, residue cover, weed pressure, and cover crop termination information), harvest information (date, growth stage, area, method, plant component sampled, and number of harvests), crop moisture concentration associated with yield values (actual or corrected), crop damage or yield impact due to weather, lodging, disease, or pests, and individual site-year yields (Table 4).

Total biomass, plant tissue nutrient concentration, and moisture concentration may be required depending on the NUE calculation method (Dobermann, 2007; Scientific Panel on Responsible Plant Nutrition, 2023). We do not have specific requirements for proper plant sample handling; however, researchers are expected to follow best practices to ensure tissues do not degrade during handling or storage prior to analysis (Johnson & Morgan, 2010). Plant samples should be retained until results are published, but ideally would be properly stored and archived beyond the date of publication.

3.5 | Environmental losses: Water

Measuring off-field nutrient losses through surface runoff or subsurface leaching can give an estimate of how effective an EEF is at keeping nutrients in the soil profile and usable by the crop (Vetsch et al., 2019), with direct implications for water quality. Nitrate leaching is also important to quantify for estimates of indirect N_2O emissions, that is, emissions originating from N that have been moved off-site by other loss mechanisms (Hergoualc'h et al., 2019; Souza et al., 2021, 2023). While there are a variety of ways to measure water nutrient concentrations and flow, it is recognized that specialized infrastructure is needed and comprehensive measurements cannot be conducted for all products. However, claims of reduced environmental nutrient losses need to be supported by a minimum set of measurements to allow for multi-site comparisons (Abendroth et al., 2022; Kladivko et al., 2014; Wellen et al., 2020). If appropriate for the objectives of the study and the trial location is equipped to collect and measure nutrient loss via water, use the guidelines

TABLE 5 Guidelines for measurement of nutrient loss via water for field trials evaluating enhanced efficiency fertilizers according to method (tile drainage, suction lysimeter, and edge of field runoff).

Parameter	Category
Subsurface losses: tile drainage	
Methodology	
Description of plot setup, including plot size, depth of plot isolation, tile drain spacing, tile drain depth, equipment and materials used, and relevant methodology	Required
Water quality samples	
Minimum of one flow-proportional composite sample per week (based off of flow-weighted or time; collection duration dependent on location and equipment)	Required
Nitrate-N and dissolved P concentration in tile drainage sample	Required
Sediment, total N, total P, and other nutrient(s) of interest (concentration in tile drainage sample)	Recommended
Measure of flow volume	
Continuous measurement of drainage flow volume; descriptions of calculations used[a]	Required
Subsurface losses: suction lysimeters[b]	
Methodology	
Suction lysimeters or other validated methodologies described in detail	Required
Water quality samples	
Nitrate-N concentration in soil solution sample	Required
Concentration of soluble P and other nutrient(s) of interest in soil solution sample	Recommended
Surface losses: edge of field runoff	
Methodology	
Description of plot setup, including plot size, equipment and materials used, and relevant methodology	Required
Water quality samples	
Minimum of one flow composite sample per precipitation event for dissolved N and P, particulate N and P, and sediment concentration analysis	Required
Multiple discrete samples per precipitation event to develop a pollutograph of the constituent over time	Recommended
Additional information	
Description of any calculations or equations used for determining nutrient loss	Required
Soil moisture, infiltration rate, and field water capacity	Recommended

Note: Parameters identified as minimum requirements are categorized as "required," while parameters that are desirable or specific to the study objectives or location are "recommended".

[a]To calculate average flow-weighted NO_3-N: NO_3-N load/total flow volume for a given period. To calculate NO_3-N load: Measured NO_3-N concentration × flow for a given period.

[b]If a site is not equipped with tile drains, nutrient concentration can be measured via suction lysimeters.

outlined in Table 5 (in addition to core metadata, soil, and crop measurements in Tables 2–4; Figure 1).

Nitrate-N and phosphate-P loss measurements should be considered for N and P EEF trials in irrigated systems (Follett et al., 1991; Quemada et al., 2013) as well as in tile-drained systems. For sites not equipped with tile drains monitored for each experimental replicate or plot, it is worthwhile to measure the concentration of nutrients leaching through the soil profile for treatment comparison by sampling the soil solution using suction lysimeters (Sawyer et al., 2019; Zhou et al., 2010). It is to be noted that there is a large amount of variability in water quality data with time and space, and multiple site-years are needed to make reliable conclusions about treatment differences. These guidelines support consistent and rigorous data collection to allow for more reliable comparisons across locations.

3.6 | Environmental losses: Gaseous emissions

EEFs with claims of reduced N losses to gaseous emissions should be supported by results showing changes in losses due to the use of the product. Field trials assessing EEFs for their N_2O emission or NH_3 volatilization reduction ability should follow the guidelines set forth in Tables 6 and 7. The methodology, gas species measured, and frequency of sampling will ultimately depend on the experimental design

TABLE 6 Guidelines for nitrous oxide (N_2O) measurements in field trials evaluating enhanced efficiency fertilizers (EEFs).

Parameter	Category
Method description	
Detailed methodology description, including references	Required
Chamber design, anchors, and deployment	
Chamber materials, insulation, sealing, venting, and anchor placement depth: Clough et al. (2020)	Recommended
Chamber anchors: Parkin and Venterea (2020)	Recommended
Chamber deployment: Charteris et al. (2020)	Recommended
Chamber placement and number	
Minimum one chamber per plot or replicate	Required
If there is large spatial variability in applied nutrients due to application method (i.e., banding), chambers must cover the entire inter-row area. If chambers are not large enough to cover this area, multiple chambers should be used	Required
Gas sampling (nonsteady state, non-flow through chambers)	
Samples per chamber: three (four or more recommended)	Required
Sampling frequency: two samplings per week for the first 3 weeks after treatment application (two samplings or more per week for the first four or more weeks after treatment application recommended, depending on expected release pattern of the EEF)	Required
Sample collection, storage, and analysis: Harvey et al. (2020)	Recommended
Gas sampling (nonsteady state, flow-through or air recirculating chambers)	
Automated chamber guidelines: Grace et al. (2020)	Recommended
Standards and gas analysis	
Standards and gas analysis: Harvey et al. (2020)	Recommended
Flux calculations and gap filling	
Flux calculations: Venterea et al. (2020)	Recommended
Gap filling guidelines: Dorich et al. (2020)	Recommended
Ancillary measurements	
Air temperature, soil temperature and depth sampled, soil water content and depth sampled; these must be collected at time of sampling (at a minimum) for manual chamber deployment; for automated chambers, sensors and data loggers should be installed to collect these data remotely	Required
Soil nitrate-N and ammonium-N sampled prior to treatment application (baseline measurements), within 1 week after treatment application, and 2 weeks after treatment application; soil sample depth should be appropriate to method of application	Recommended
Other methodologies	
Additional methodologies, such as flux tower measurements, are not ruled out and can be useful for large-scale testing of products that have shown high potential in replicated plot-based field trials, however they are not within the scope of this set of guidelines	
Flux tower measurement guidelines: Brown et al. (2024) and Nemitz et al. (2018)	

Note: When applicable, specific recommendations are made depending on flux measurement method. We recommend and refer to the Global Research Alliance N_2O chamber guidelines for select parameters. Parameters identified as minimum requirements are categorized as "required," whereas parameters that are desirable or specific to the study objectives or location are "recommended."
Abbreviation: EEF, enhanced efficiency fertilizer.

and study objectives; for example, if a nitrification or urease inhibitor is being evaluated, NH_3 volatilization should be measured. It is to be noted that there is a large amount of variability in emissions data, and multiple site-years are needed to make reliable conclusions about treatment differences. These guidelines support consistent and rigorous data collection to allow for more reliable comparisons across locations.

There are many ways to measure NH_3 volatilization and N_2O emissions. These guidelines provide considerations and required measurements when designing an experiment to evaluate an EEF's effectiveness of reducing N losses through gaseous emissions.

3.6.1 | Nitrous oxide emissions

Nitrous oxide emissions are sporadic in space and time, being described as occurring in "hot spots" and "hot moments"

TABLE 7 Guidelines for wind tunnel and dynamic chamber-based ammonia (NH_3) measurements for field trials evaluating enhanced efficiency fertilizers (EEF).

Parameter	Category
Method description	
A detailed description of the methodology, including references[a]	Required
Gas sampling frequency	
Multiple samplings per day for the first 0–72 h after treatment application, followed by daily sampling for the next 4 days	Required
Daily sampling for five or more days after treatment application, depending on the form of N and expected release pattern of the EEF	Recommended
Ancillary measurements	
Meteorological data including wind speed, air temperature, precipitation, and solar radiation	Required
Soil pH, moisture, and temperature, measured periodically throughout experiment; soil texture	Required

Note: Parameters identified as minimum requirements are categorized as "required," whereas parameters that are desirable or specific to the study objectives or location are "recommended."

Abbreviation: EEF, enhanced efficiency fertilizer.

[a]These guidelines can be applied to a number of different methodologies, including wind tunnels, Dräger tubes, dynamic flux chambers, and semi-open static chambers with dositubes.

(Wagner-Riddle et al., 2020). This presents measurement challenges as year-round measurements over large areas are needed for accurate assessments of annual total emissions, ensuring brief emission events are captured and fluxes are spatially and temporally integrated. Flux tower measurements using eddy covariance or flux-gradient methods are ideally suited to capture hot spots and hot moments; however, these require large fields and are not suited for agronomic field trials (Brown et al., 2024). Soil gas chambers have been widely deployed for replicated, plot-based field trials and are recommended here since they are adequate for comparative assessments between practices and EEFs. In cases where agronomic trials provide strong evidence of EEF effectiveness in reducing N_2O emissions, flux tower measurements could be valuable for large-scale evaluation of products. In particular, the flux-gradient method deployed in a multi-plot configuration with one gas analyzer (typically monitoring four large fields) is very suitable for this type of testing (Brown et al., 2024; Machado et al., 2020; Tenuta et al., 2016). In all cases, a detailed description of the methodology and references used must be included with the results.

Soil gas chambers can be deployed using manual or automatic sampling. Manual deployment is typically done with nonsteady state, non-flow through soil gas chambers. In this configuration, anchors are covered with the chamber, and gas samples are obtained over a set time (∼30 min), and vials are then taken to a laboratory for gas analysis (Rochette & Hutchinson, 2005). Outside of this short time, the chambers should be removed from the collars so that the chambers interference with weather variables such as precipitation and solar radiation is kept to a minimum. With the development of affordable fast-response analyzers, the use of manual or automatic deployment of soil chambers coupled to these analyzers for real-time gas concentration measurements is becoming more common, usually utilizing nonsteady state, flow-through chambers where gas is recirculated through the chamber for a set time while passing through the analyzer. In the manual, real-time deployment configuration (also referred to as "survey" chambers), analyzer and chamber are moved between anchors (collars) for flux measurements. In the automatic chamber deployment configuration, chambers are automatically moved over the same anchor repeatedly over set intervals within a day, and air is directed to the gas analyzer through an electronically controlled manifold. The latter, automated option, is generally more limited in terms of spatial coverage due to the need for electrical power and/or a shelter to house the instrument(s).

The suggested guidelines for N_2O flux measurements consider first general attributes applicable to any chamber configuration deployment, and then provide guidance on specific configurations (Table 6). Chamber quantity, placement, and sampling will largely depend on experimental design, nutrient source application method, and the expected release pattern of the EEF. If there is large spatial variability in nutrient placement due to application method (i.e., banding), chambers must cover the entire inter-row area. If available chambers are not large enough to cover this area, multiple chambers should be used. For manual sampling using nonsteady state, non-flow through chambers, we require a minimum of three headspace gas samples per chamber (four or more recommended) during a set deployment time (e.g., 30 min) (Venterea et al., 2020). While chamber sampling frequency will depend on when and how the treatment nutrient sources are applied, a minimum of two sampling timings per week for the first 3 weeks after application is required. Two samplings per week for the first 4 weeks or more after application or during heavy rainfall periods is recommended, depending on the expected release pattern of the EEF. Continuous monitoring with automated chambers should be considered when evaluating products with controlled- or slow-release mechanisms, as the timed release of the nutrients may shift when emissions take place. It is important to understand when the large emission episodes occur and how long they last, especially during the episodic events including freeze–thaw events in the non-growing season (Wagner-Riddle et al., 2017; Yang et al., 2022). Sampling should be optimized to generate data for comparing EEF treatments, specific to the objectives of each study.

At the time of gas sampling, air temperature, soil temperature, and soil water content measurements are required. These parameters are routinely collected with gas samples and can help explain differences in emissions. We also recommend that soil nitrate-N and ammonium-N be collected prior to, within 1 week, and 2 weeks after treatment application. These soil N measurements are valuable metrics to help explain differences in emissions; however, the authors understand that this is an added effort and cost and so concluded that it is a recommended rather than required measurement.

We recommend following the Global Research Alliance N_2O chamber guidelines for chamber design (Clough et al., 2020), chamber deployment and accounting for sources of variability (Charteris et al., 2020), air sample collection, storage, and analysis (Harvey et al., 2020), automated flux measurements (Grace et al., 2020), flux calculations (Venterea et al., 2020), statistical considerations (de Klein et al., 2020), and gap-filling missing measurements (Dorich et al., 2020).

3.6.2 | Ammonia volatilization

Ammonia volatilization losses from fertilizer application can be as high as 60% of applied N (Sommer et al., 2004) and are dependent on several factors, including climate conditions, soil type, management, and fertilizer type. There are different methodologies for measuring NH_3 concentrations, including closed- and open-path laser spectrometers and photoacoustic spectrometers (Twigg et al., 2022), that can be used on flux towers, however, similar to N_2O, these techniques are generally used for measuring losses over a large area (>1 ha) and are less relevant for comparative studies. There are several methodologies that are appropriate for comparative studies on replicated, plot-based field trials, including wind tunnels (Woodley et al., 2018), Dräger tubes (Roelcke et al., 2002), dynamic flux chambers (de Ruijter et al., 2010), and semi-open static chambers with dositubes (Van Andel et al., 2017). For wind tunnels and dynamic flux chambers, NH_3 concentrations can be measured using one of the spectrometers mentioned above or by using acid traps. In all cases, a detailed description of the methodology and references used must be included with results (Table 7).

Unlike N_2O, NH_3 losses generally occur within the first 3 weeks after fertilization and so multiple NH_3 measurements must be taken per day for the first 0–72 h after N fertilizer application and daily for the next 4 or more days, depending on the form of N applied, expected release pattern of the EEF, and the soil moisture content. Ammonia losses are also strongly affected by soil pH as the ratio of ammonium to NH_3 changes dramatically as pH increases above 7.0. Depending on fertilizer type, and particularly for urea-based fertilizers, soil pH can change dramatically over the experimental period and so should be measured periodically throughout the experiment. Soil moisture, temperature, and meteorological measurements should also be collected frequently and included with results.

3.7 | Data stewardship

Proper data planning, handling, preparation, and publishing are essential for meaningful, broadly impactful results (Table 8). A data management plan should be developed at the outset of a project, and we recommend that at least 10% of the project budget should be devoted to full data stewardship efforts including a timeline for publishing data in an appropriate data repository. Datasets with raw, plot-level data that have been prepared for statistical analysis should be published in data repositories or as data papers regardless of whether results are significant. We carefully discussed whether summarized data would be sufficient for publication, and while summarized or treatment-level data are acceptable for journal publications, raw data must be published to avoid errors, understand how the data was collected and differences between replications or blocks, allow for future meta-analyses and modeling activities, and ensure that data are not misused or misinterpreted.

The International System of Units (SI Units) is required, and SI Units must be specified for all numerical values. Elemental units must be used for all nutrients (i.e., kg P ha^{-1}). Meaningful precision and significant digits, scientific notation, unit conversions, including between percentages and decimals, and date formatting should be treated with care and caution, carefully checked for errors prior to publication and described when appropriate. It is the responsibility of the researcher to use common statistical procedures for outlier identification, and if outliers are removed, the method and justification for removal must be clearly described.

Clear and broadly accepted terminology must be used and defined in a data dictionary. Examples include the USDA National Agriculture Library Thesaurus Concept Space (NALT, 2024) and the Thesaurus and the Global Agricultural Concepts Space (Baker et al., 2019). Data files should

TABLE 8 Data stewardship guidelines for field trials evaluating enhanced efficiency fertilizers.

Data Stewardship Guideline	Category
Data management plan	
At least 10% of the project budget devoted to data stewardship efforts, including a data management plan that includes a timeline for publishing data	Recommended
Data and units	
Raw, plot-level data prepared for statistical analysis and submitted to a data repository or data publication	Required
SI Units specified with all numerical values	Required
Elemental units for all nutrients (i.e., kg N ha^{-1})	Required
Clear description of meaningful precision (significant digits), proper scientific notation, correct unit conversions, number formats, and missing values	Required
Data files and QA/QC	
Data files should include a data dictionary with clear definitions for all terms in dataset, broadly accepted terminology[a], clearly defined dates, quality control features, explanations for missing data, plot-level information, recorded variance for any consolidated data, and how to note values below detection limits	Required
Criteria and considerations for selecting a data repository	
(1) Generated digital object identifier (DOI); (2) anonymized and secure PII (personal and proprietary); (3) curation policy; (4) ability to link or upload supporting documents and code; (5) conditions for access (is payment required?); (6) ability to download tracking information; (7) mechanism for users to provide feedback or query; (8) security measures; (9) cataloging; (10) transparent functionality; (11) code of ethics for proper use of data; (12) licensing agreement	Recommended
FAIR principles	
Findable: Described with a DOI and rich metadata indexed in a searchable resource Accessible: Retrieved using a standardized communication protocol (free, open and universally implementable) Interoperable: Represented with a formal, shared, and broadly applicable language with FAIR vocabularies Re-usable: Richly described by a plurality of attributes (clear provenance, usage license and meets domain standards)	Required

Note: Parameters identified as minimum requirements are categorized as "required," whereas parameters that are desirable or specific to the study objectives or location are "recommended."

Abbreviation: SI Units, International System of Units; QA, quality assurance; QC, quality control.

[a]Examples include the United States Department of Agriculture National Agriculture Library Thesaurus (NALT, 2024) and the Thesaurus and the Global Agricultural Concepts Space (Baker et al., 2019).

include a data dictionary, clearly defined dates, quality control features, explanations for missing data and how it is reported, plot-level information, and how values below detection limits are entered. Care should be given to selecting a data repository. While some funding agencies require specific repositories for publishing results, we include a list of criteria and considerations for selecting reliable and accessible data repositories (Table 8).

4 | CONCLUSIONS

With existing and novel developments of EEFs, it is essential that quality data from field trials evaluating these technologies become available. Here, we provide a set of protocol and data stewardship guidelines in a tiered framework that includes both required and recommended information for use by a variety of research objectives and infrastructure capacities. While experimental design details and investigated products and practices will be site-, situation-, and research question-specific, this set of guidelines aims to ensure consistency in data collection to generate interoperable and defensible results. By supporting common data standards, this effort will catalyze a more consistent and impactful body of results and a greater understanding of EEFs. Regulatory organizations can utilize this framework for updating and refining EEF regulations, particularly with regard to demonstrating efficacy in increasing NUE and reducing environmental losses. Results generated using these guidelines can provide producers with accurate, trustworthy information about which EEFs could be used in their production systems to achieve production and environmental stewardship goals.

AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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