



Wheat Yield Response to Chemical Nitrogen Fertilizer Application in Africa and China: A Meta-analysis

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Received: 24 January 2023 / Accepted: 27 December 2023 / Published online: 16 January 2024
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Abstract

Sustainable food production and feeding a growing population are among the main challenges in the world nowadays. Studies suggest that improving nitrogen use efficiency (NUE) is among the key strategies for sustainable crop production. However, yield response to chemical nitrogen fertilizer use (N use) and the NUE was not fully investigated both in China and Africa. The purpose of this article was, therefore, to investigate the findings of different nitrogen fertilization rate experiments and thereby identify a potential approach that could be used to improve wheat yield and NUE in Africa and China. In addition, we aimed to evaluate the effects of soil characteristics, such as pH and soil organic matter (SOM) on wheat yield responses to N uses. A meta-analysis was conducted to systematically assess the results of previous studies published in peer-reviewed journal articles. We identified and used 65 studies conducted in different African countries and 154 in different provinces of China. The articles were obtained from Tylor, Google Scholar, and Web of Science databases. The result indicated that the mean yield response to chemical nitrogen fertilizers use (N use) in Africa was far lower than that in China, implying the presence of higher wheat yield gaps in Africa than in China. In addition, the wheat yield responses to N uses showed different patterns in both regions. That is, while it was increasing with N application in Africa, it increased and reached a peak at 200 kg ha⁻¹ in China, indicating the existence of nitrogen accumulation in the provinces of China. The findings also showed significant influences of soil organic matter (SOM), pH, and precipitations on wheat yield responses to N uses. The higher yield gap in Africa can be improved by increasing nitrogen use to the optimum nitrogen fertilizer rate level, which can also increase nitrogen use efficiency and yield response. In Africa, the high yield response to N use was accompanied by N depletion, while in China it was with a high N surplus in the soil. The effects of pH, SOM, and precipitation were generally more pronounced in Africa than in China.

Keywords Africa · China · N fertilizer · Meta-analysis · Wheat yield response

1 Introduction

Nitrogen (N) is an essential nutrient for crop growth. It improves crop quality and increases productivity and production of agriculture, and thus, enormous quantities are

applied to the soil to supply the world's agricultural production every year (Belay 2014; Belete et al. 2018; Dorsey 2014; Solomon and Agena 2017). Nitrogen is also considered the most yield-limiting factor in crop production in non-fertilized agriculture (Bultosa 2012). However, despite the positive effect of N fertilizers on crops, there is an indirect negative effect on soil health in the absence of the proper use of N (Singh et al. 2015). Both excessive and underuses of nitrogen fertilizers are serious problems worldwide. In other words, resource-poor countries, for instance, African countries, have been using under-recommended rates, while resource-rich countries, including most developed countries and China, have been applying above the recommended rates leading to environmental pollution. Misuses of any type of fertilizer (organic or inorganic) pollute the environment and affect the health system. Hence, the management of N is an

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effective way of bringing about its use efficiency and boosting crop yields while reducing N-related adverse effects that have been challenging the world (Sharma and Bali 2018).

As it is with other crops, proper use of nitrogen fertilizer can significantly increase the yield of wheat—a major world's strategic food crop, rich in carbohydrates (Seleman et al. 2019; Wazir 2019), and has higher nutritional values than maize and rice (Mandic et al. 2015). Global wheat production covers 237 million hectares (about 20% of the world's arable land) annually (Oyewole 2016; Tamado et al. 2015; Zhang et al. 2017). Reports show that worldwide wheat production had increased dramatically from the 1960s to 2013 without much change in the total area grown for wheat. This considerable increase in wheat production was mainly because of the adoption of the green revolution technology packages, including fertilizers. Nevertheless, the increases in wheat production due to the green revolution were not the same everywhere. Those countries that adopted the package from the beginning have successfully boosted their yields, while those lagging for various reasons, such as the high cost of fertilizers, have obtained fewer achievements. For example, Jiao et al. (2020) pointed out that because of mineral fertilizer use and policy development in China, grain yield has increased from 1.3 tons per hectare ($t\ ha^{-1}$) in 1960 to more than $5\ t\ ha^{-1}$ in 2000, while it remained low in Africa due to less consumption of mineral fertilizer in the region. Tadesse and Assefa (2018) also reported that wheat productivity has only slightly increased, from $1.3\ t\ ha^{-1}$ in 1970 to $2.1\ t\ ha^{-1}$ in 2014, in Sub-Saharan African countries. These studies suggest that the wheat yield gap has decreased in China while remaining high in Africa. In general, yield increase was stable and insignificant in Africa, unlike the experience of other countries during the green revolution era (Abegaz 2011).

Experiences have also shown that fertilizer application and wheat yield positively correlate and that N fertilizer considerably increases wheat yield. Consequently, over-applying N fertilizers to minimize N inadequacy and increase crop yield remains common practice for farmers in many countries. Because China was among the first consumer of N fertilizer, it has also exceeded the world consumption rate by 29%, which is a heavy consumption that has led to nitrate leaching, greenhouse gas emissions, and eutrophication, in addition to N use inefficiency and economic loss (Xu et al. 2020). The negative consequences of excessive N fertilizers could be reduced by nitrification inhibitors that increase crop yield by improving NUE (Bhandari et al. 2020). The occurrence of inefficient use of N could also be due to the absence of proper N application that meets crop requirements (Haile et al. 2012). According to Eshetu (2017) and Bhandari et al. (2020), the amount of applied N fertilizer significantly affects NUE, and adjusting N fertilizer rates to the optimal level minimizes N leaching and enhances

productivity. Therefore, optimization of N use helps to balance crop yield and environmental quality (Belete et al. 2018; Daba 2017; Ma et al. 2018).

There are several studies conducted on the application rate of nitrogen fertilizer and its effect on wheat yield. Different studies have reported different results because of variations in soil type, climate, and nature of crops (varieties). These conditional findings and recommendations by various studies have challenged the farmers to understand the appropriate application rates and apply accordingly, and have led to inefficient (under or excess) uses of N fertilizers. The problem of the underuse of nitrogen fertilizer is often reported in developing countries and is associated with a high cost, unavailability, and farmers' limited knowledge about nitrogen fertilizer. In contrast, the excessive use of nitrogen fertilizer has been practiced in developed countries to achieve a higher yield, which is partly associated with a lack of knowledge.

Therefore, the objectives of this meta-analysis are as follows: (1) to investigate the findings of different nitrogen fertilization rate experiments that were conducted in Africa and China, and thereby identify an appropriate potential approach that favors positive wheat yield response and (2) to analyze the effect of other factors such as SOM, pH, and precipitation on wheat yield. The study plays a significant role in summarizing different results reported by different studies and in identifying the potential approaches that need to be followed to obtain a high crop yield with a high NUE, which in turn reduces adverse environmental impacts caused by nutrient use inefficiency. The results of the study are thus helpful in better understanding wheat yield response to chemical nitrogen fertilization and in identifying nitrogen fertilization rates and other factors that favor positive responses to wheat yield in Africa and China.

The rest of this article is structured as follows. The next section describes the methods of collecting and identifying the appropriate previously published journal articles and explains bias detection, and data analysis methods. While the third section presents the findings of the meta-analysis, sections four and five, respectively, discuss the results and present the conclusion of the study.

2 Methods

2.1 Data Collection

The data for this study were collected from peer-reviewed journal articles examining the effects of nitrogen fertilizer on wheat yield in Africa and China. The articles were obtained from Tylor, Google Scholar, and Web of Science databases. The search terms used include “nitrous” OR “nitrogen fertilizer” AND “yield” AND “wheat” AND “Africa” AND

“China”. Data in graphical forms were digitalized using the Get Data v2.22 Software. To minimize biases, we screened the articles based on the following criteria. (1) The articles should be based on the data collected from field trials only; i.e., articles based on pot and greenhouse experiments were excluded. (2) The research areas should be within Africa and China. (3) The articles should contain studies on the chemical nitrogen application and no chemical nitrogen fertilizer application or control. (4) The articles were considered only if the yield data were reported. The specific range of study years was not considered as a criterion. Following these criteria, 65 articles (with a total of 665 observations) from the regions of Africa and 154 articles (2085 observations) from China were identified and used for the meta-analysis. Specifically, the articles identified were from studies conducted in nine potentially wheat-producing African countries (Ethiopia, South Africa, Morocco, Sudan, Rwanda, Egypt, Kenya, Tanzania, and Tunisia) and 14 major wheat-producing provinces of China. The distribution of experimental sites of the studies in Africa and China are shown in Fig. 1a, b.

2.2 Publication Biases Detection

In this meta-analysis, a quantile-quantile (Q-Q) plot was employed to detect the publication biases and distributions of data as it is an effective identifying tool for assessing normality in data and publication biases. It was constructed by plotting the empirical quantiles of the data against corresponding quantiles of the normal distribution of the effect size of the data. If the empirical distribution of the data is approximately normal, the points on the plot fall on a straight line defined by $Y=X$ with the slope equal to unity, where Y is the ordinate and X is the abscissa (Sileshi et al. 2009). The natural variation of effect size is usually expected to be approximately normally distributed. Hence, skewing may be an indication of publication bias. The extent of bias can be estimated by the difference between the mean and mode of the distribution (Wang and Bushman 1998).

2.3 Data Analysis

The dataset organized based on the studies from the literature review was used for the data analysis. The confidence interval at the 95% level was employed to compare the magnitude of the response ratio between fertilized and non-fertilized plots or treatments to understand the confidence interval and evaluate the result of the study. Following Gao et al. (2019), the natural log (ln) of response ratio (R) was calculated as the effect size representing the effect of chemical nitrogen use. To explain the effects of chemical nitrogen,

use on grain wheat yield, the results of R were calculated using the following equation.

$$R = \frac{Y_e}{Y_c} \quad (1)$$

$$\ln R \ln\left(\frac{Y_e}{Y_c}\right) = \ln Y_e - \ln Y_c, \quad (2)$$

where Y_e is the mean value of wheat grain yield in fertilized treatments and Y_c is the mean value of no-fertilized treatments.

Since most of the studies did not report the coefficient of variation, we adopted the unweighted method. To correct a bias at the 95% confidence interval, SPSS 20 version was used and a bootstrapping approach with 4999 iterations was applied to improve the probability that the confidence interval was calculated around the cumulative mean effect size for each categorical variable. If the 95% confidence intervals do not overlap with zero, there are significant ($p < 0.05$) positive or negative differences between fertilized and non-fertilized treatments; if not, the treatment effect is not considered statistically significant between methods. Response variables, such as yield increase (YI), partial factor productivity of nitrogen (PFPN), and agronomic efficiency of nitrogen (AEN) as indicators of nitrogen use efficiency (NUE) in wheat crop production, were quantified for both Africa and China. In this study, attainable yield (Y_e) was defined as the actual yield derived under the optimal nutrient management practices. Yield response to N fertilizer was defined as the yield gap between attainable yield and the yield from non-fertilized treatments. Percent yield response (%YI) was defined as the yield gap between attainable yield with chemical nitrogen use and the yield from non-fertilized treatments to the ratio of non-fertilized treatments. AEN and PFPN were some of the nutrient efficiency parameters and were calculated as follows:

$$AEN = \frac{Y_e - Y_c}{N} \quad (3)$$

$$YI (\%) = \frac{Y_e - Y_c}{Y_c} \times 100 \quad (4)$$

$$PFPN = \frac{Y_e}{N} \quad (5)$$

where AEN represents the agronomic efficiency of nitrogen, Y_e is the yield of fertilized treatments and Y_c is the yield of non-fertilized treatments. N represents the amount of chemical nitrogen applied on the allocated plot. The measurement unit is kilogram per hectare (kg ha^{-1}) for all response variables computed above.

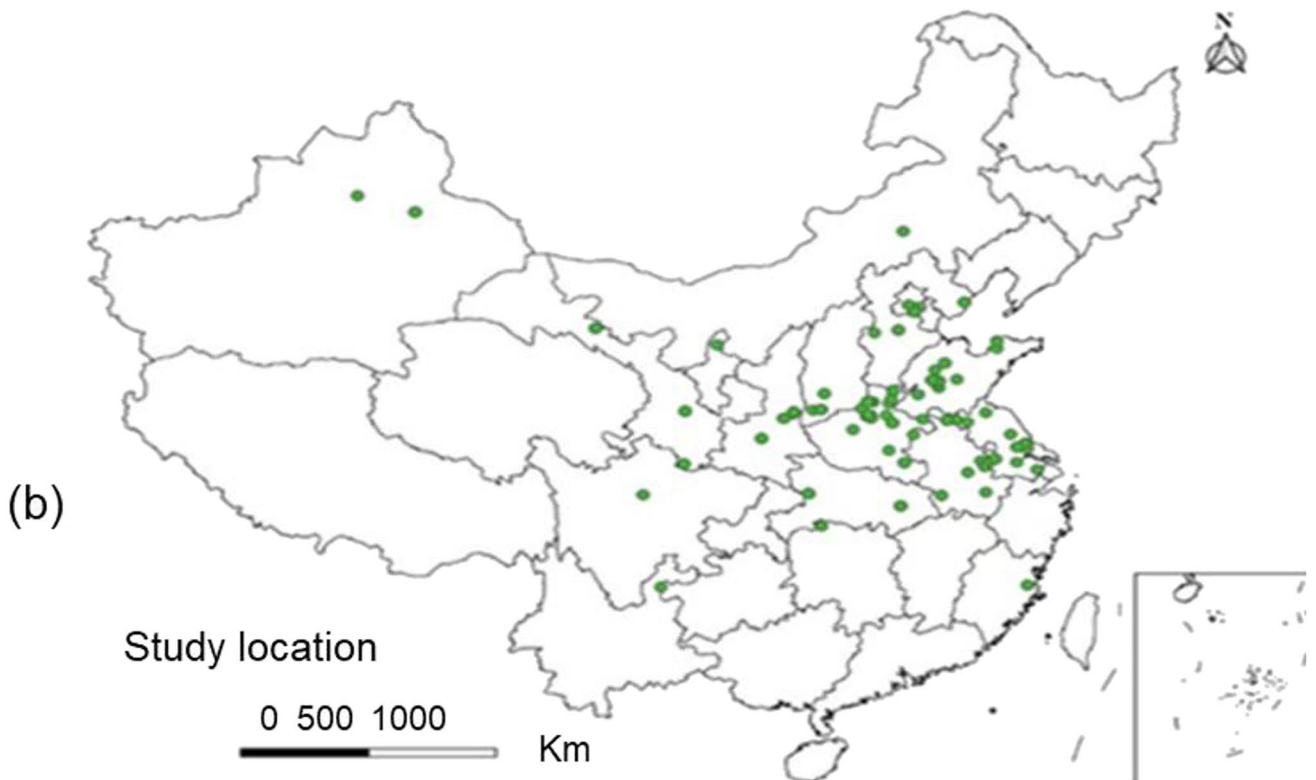
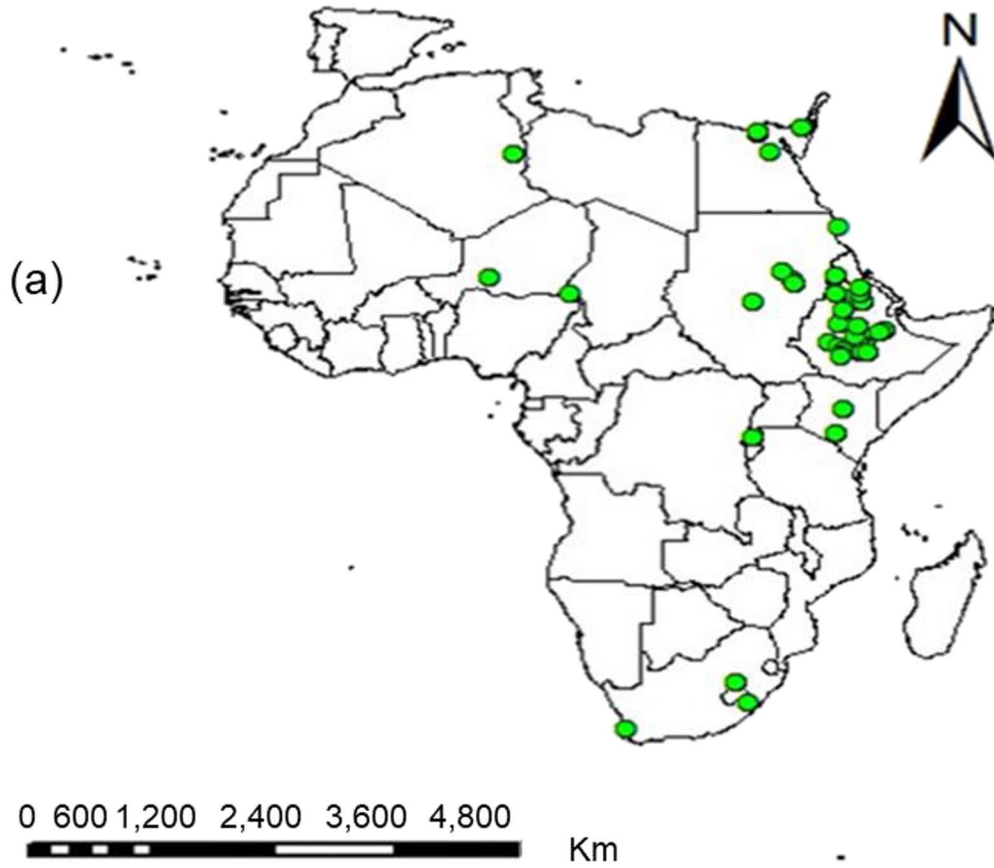


Fig. 1 Locations of N fertilizers field experiment sites on wheat crops in Africa (a) and China (b)

3 Results

3.1 Publication Bias Detection and Variability in Response Ratios of Wheat Yield in Africa and China

As mentioned earlier in the methods section, the normal Q-Q plots were applied to investigate the existence of publication bias and the distribution of normality assumptions. The results showed that the normal Q-Q plot curve in the case of Africa is slightly U-shaped, suggesting that the data are skewed to the right and publication bias exists when the population effect size differs from zero, presents (Fig. 2a). This could happen because studies with statistically significant results were more likely published than studies whose results were not statistically significant (Borenstein et al. 2009). According to Wang and Bushman (1998), if the point of observation falls on the straight line in a normal Q-Q plot and does not exceed the 95% confidence interval band, the estimated effect suggests no publication bias and is normally distributed. In our study, we made many efforts to minimize publication bias, although it cannot be eliminated in meta-analysis. For instance, we employed inclusion criteria to identify the articles that could answer the intended questions, and the articles that did not meet the aim of the study were excluded from the database.

3.2 Effects of Nitrogen Fertilizers on Wheat Yield in Africa and China

We used regimes of N fertilizers to evaluate the effects of N rates on wheat yield in both Africa and China (Fig. 3). In the case of Africa, the mean wheat yields response at the rates of 50–100 kg ha⁻¹ and over 150 kg ha⁻¹ of N applications were, respectively, 1323 kg ha⁻¹ and 3446 kg ha⁻¹ (Fig. 3a). That is, there were statistically significant increases ($p < 0.05$) in wheat yields (by 46% for the earlier rates of N and by 63% for the latter) compared to the control (i.e., 2007 kg ha⁻¹). In contrast, the wheat yields response obtained in China were 1193 kg ha⁻¹ (i.e., 98% yield increase compared to the control) when less than 100 kg ha⁻¹ of N was applied, 1446 kg ha⁻¹ of wheat for N rates of 100–150 kg ha⁻¹, and 1886 when 150–200 kg ha⁻¹ was used. However excessive use (over 300 kg ha⁻¹) of chemical nitrogen (response mean 2086 kg ha⁻¹) significantly decreased wheat yield (by 29%) as compared to the control yield (Fig. 3b).

3.3 Effects of Soil Chemical and Physical Properties (SOM and pH) on Wheat Yield in Africa and China

We also evaluated the effects of soil chemical and physical properties, such as pH and soil organic matter (SOM) on wheat yields, besides nitrogen fertilizer in both Africa and China. The results showed that the effects of soil pH and soil organic matter on wheat yields were higher in Africa than in China. In Africa, a higher yield of wheat was obtained from alkaline soil (pH > 7) where the mean wheat yield was increased by 213%. In the meantime, a lower yield of wheat was obtained from acidic soil (pH < 7) where there was a mean yield increase of 93% (Fig. 4a, above the small dash line). Contrary to the finding from Africa, the data collected from the provinces of China indicated that a higher wheat grain yield (91% mean yield increase) was obtained from acidic soil, and a relatively lower yield of wheat grain (62% mean yield increase) was obtained from an alkaline soil. That is, the mean wheat yield in acidic soil was statistically significantly higher than the yield in alkaline soil in China (Fig. 4a, below the small dash line). The overall effects of the mean values of soil pH were 148% and 70%, respectively, in Africa and China, implying less pronounced effects of pH on wheat yield in China than in Africa.

Similarly, the effect of soil organic matter (SOM) on wheat yield was also assessed and the results demonstrated a positive yield response to SOM in Africa. However, there was no statistically significant difference between the SOM groups (< 4 and > 4 g kg⁻¹). The evidence obtained from the Africa dataset indicated that the availability of SOM in the soil was very low, indicating a high depletion of nutrients from the soil (Fig. 4b, above the small dashed line). In the case of China, the highest yield of wheat was obtained within the range of 15–20 g kg⁻¹ (mean yield increase by 63%) than within 10 g kg⁻¹ of SOM. The results indicated that the concentration of SOM fell at a very high level in China (Fig. 4b, below the small dashed line).

3.4 The Effects of Precipitation on Wheat Yield

The overall means of wheat yield to rainfall response ratio were 325, 143, and 93%, respectively, for < 600 mm, 600–900 mm, and > 900 mm of rainfall during the growing seasons in Africa. The overall means of wheat yield response ratios in China were 39 and 25% for < 600 mm and 600–900 mm of rainfall, respectively. The results illustrated that the average wheat yield response was higher in Africa than in China although the amount of rainfall in the growing season was the same; suggesting that rainfall was less important in China compared to Africa. In Africa, the maximum wheat yield response was found during the growing season of < 600 mm rainfall,

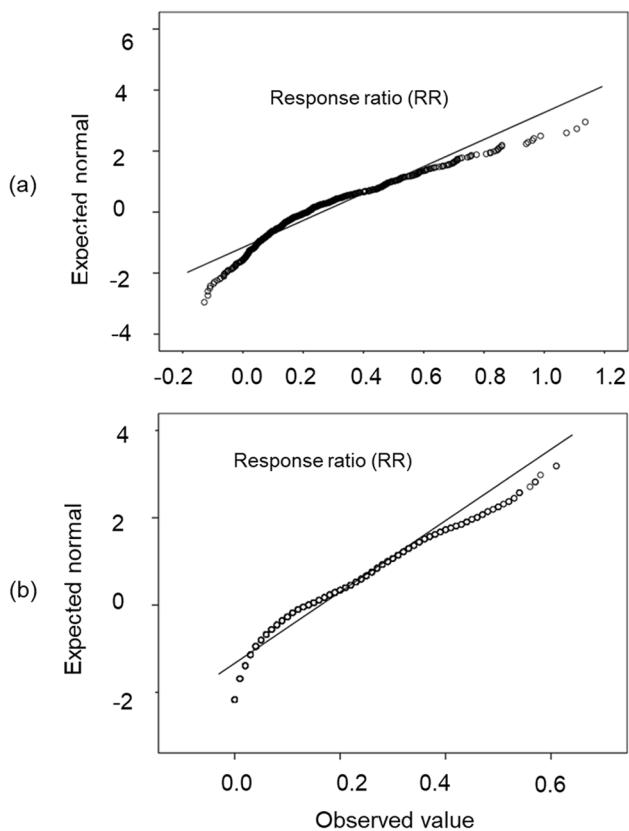


Fig. 2 Normal quantile-quantile plots of wheat yield response ratios (Log. treatments/control) in Africa (**a**) and China (**b**) for exploring the normality assumption and publication bias. The circles represent individual observations, while the solid line ($Y=X$) shows the standard normal distribution with 95% confidence interval bands

indicating that this amount of rainfall was optimal for wheat production (Fig. 5).

3.5 Measurement of N fertilizer Use Efficiency

The results showed that the mean values of partial factor productivity of nitrogen (PFPN) fertilizers were 58 for Africa and 36 for China (Fig. 6a). That is, the mean value of PFPN fertilizer for Africa was significantly higher than that of China. In other words, the overuse of N fertilizer significantly reduced the N use efficiency in the case of China. The box plot (Fig. 6a) indicated a significant and negative relationship between PFPN fertilizer and wheat yield both in Africa and China. The result also showed that a higher mean value of agronomic use efficiency of N was found in the case of Africa (Fig. 6b).

4 Discussion

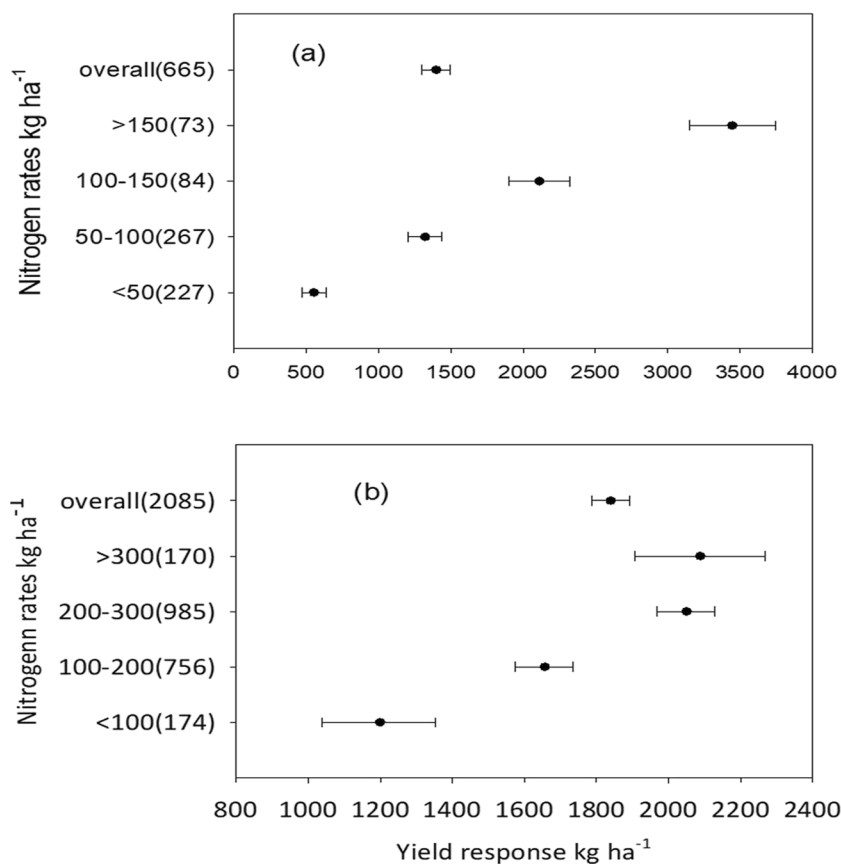
4.1 Wheat Yield Response to Chemical N Rates in Africa and China

In this meta-analysis, chemical nitrogen application rates and other related information were collected from different literature, a dataset was developed, and the data were then organized into different regimes of fertilizer application rates. The findings indicated that different application rates of N fertilizer significantly affected the mean yield of wheat grain both in Africa and China. There were also variations in the magnitude of effects among the rates of N fertilizers applied in the two regions. In the case of Africa, there was a positive and linear correlation between the N rate(s) and the yield of wheat. These findings comply with the findings of Abebe (2016), Dugassa et al. (2019), and Tilahun and Tamado (2019). In particular, Abebe (2016) reported that wheat grain yield was highly influenced by the N fertilizer rate and that the proper rate and time of application are critical for meeting crop needs and attaining higher grain yields.

A high grain yield production has been achieved with increased usage of N fertilizer in developed countries even though it remains a concern in low-income countries because of fertilizers' high prices (Bhandari et al. 2020). As of the present meta-analysis, the regime of N fertilizer that resulted in the highest wheat yield increase has partially agreed with the N fertilizer rates (30 to 138 kg ha⁻¹) recommended by Yohalashet et al. (2017). However, these N rates could be lower than developed countries' N consumption levels. In African countries, particularly in Ethiopia, the consumption level of fertilizer is considerably below the recommended rates because of its high prices, and less than 40% of farmers use fertilizers in the region (Agbahey et al. 2015). In nutshell, the amount of fertilizers used in low-income countries is minimal and inadequate to compensate for the nutrients removed by harvested crops.

Nutrient use efficiency is a critically important concept in the evaluation of crop production systems. Nutrient use efficiency, which affects the performance of the cropping system, is in turn greatly affected by fertilizer management. Nitrogen fertilizer management, in terms of using the right source, the right rate, in the right place, and at the right time, is reported to be poor in the cases of African countries. This poor management of fertilizers has led to poor nitrogen use efficiency and has caused a low crop yield response. Underrated consumption of chemical fertilizer is found to be the primary factor that leads to a significant reduction in yield response in Africa. Farmers are using a small amount of fertilizer that does not meet crop requirements. This may result in poor nitrogen use

Fig. 3 Yield response of grain wheat (yield of wheat fertilized treatments – yield of wheat not fertilized treatments, for four levels of chemical nitrogen fertilizer rates) in Africa (a) and China (b). Box circles indicate means, and the horizontal lines on the left and right sides represent the upper and lower limits of the 95% confidence interval. Means (circles) are not significantly different from one another if their 95% confidence intervals (error bars) overlap. The means and 95% confidence intervals of the response ratios are in the bootstrapping method. Each group of data was determined with an F-test ($p < 0.05$). The numbers in the bracket show the number of observations



efficiency and wheat production performance. To address this challenge, nitrogen management should receive due attention in addition to the cropping system. Hence, maximizing the usage of N fertilizers to the level of crop requirements is one of the ways to enhance NUE and wheat productivity in Africa. Because Africa is a resource-poor country and farmers are unable to afford and apply sufficient fertilizers that can meet the crops' requirements, the governments of African countries should explore the appropriate approach that subsidizes the smallholder farmers to increase the consumption level of fertilizers that improve nitrogen use efficiency, thereby increase yield response. Increasing nitrogen usage up to an optimum nitrogen fertilizer rate increases nitrogen use efficiency and yield response.

The result found in the case of China was different from that of Africa. The pattern showed that the wheat yield was increasing with the N fertilizer rate up to a certain level, and then started decreasing. This implies that there was excessive usage of N fertilizer that led to a reduction in wheat yield. The use of N fertilizer in the case of China was more than the crop requirement. A similar finding was also reported by Habbib et al. (2017) that the overuse of fertilizers has been practiced to achieve a high wheat yield in many countries. However, the unreasonable application of

fertilizers has led to N accumulation in soil and later would result in yield reduction as well as environmental pollution. Similarly, our study witnessed N accumulation in many provinces of China. A related study (Wang et al. 2012) also discussed that an increase in application rates of N fertilizer can increase the accumulation of N in the soil, especially when over 221 kg ha⁻¹ of N fertilizer is used. This could result in severe adverse effects on soil properties (Liu et al. 2020). Some other studies conducted on the effect of N fertilizer rates also reported that grain yield had significantly influenced by the rates of N application (Adnan 2016; Ayadi et al. 2016; Eshetu 2017; Lakew 2019; Roman et al. 2018; Ullah et al. 2018). The studies, generally, concluded that the right amount of N fertilizer rates and time of application had a positive correlation with crop production, particularly with wheat grain.

Nevertheless, different studies conducted in different locations suggested different rates of N fertilizer application. For instance, studies conducted by Michael and Nigussie (2017) and Abebe (2016) suggested 69 kg ha⁻¹ of N fertilizer use achieved a high wheat grain yield, while Belete et al. (2018) suggested 120 kg ha⁻¹ with the split application. In addition, Belay (2014) and Dugassa et al. (2019), respectively, suggested 46 kg ha⁻¹ and 96 kg ha⁻¹ of N as the right nitrogen fertilizer rates to obtain a high yield of

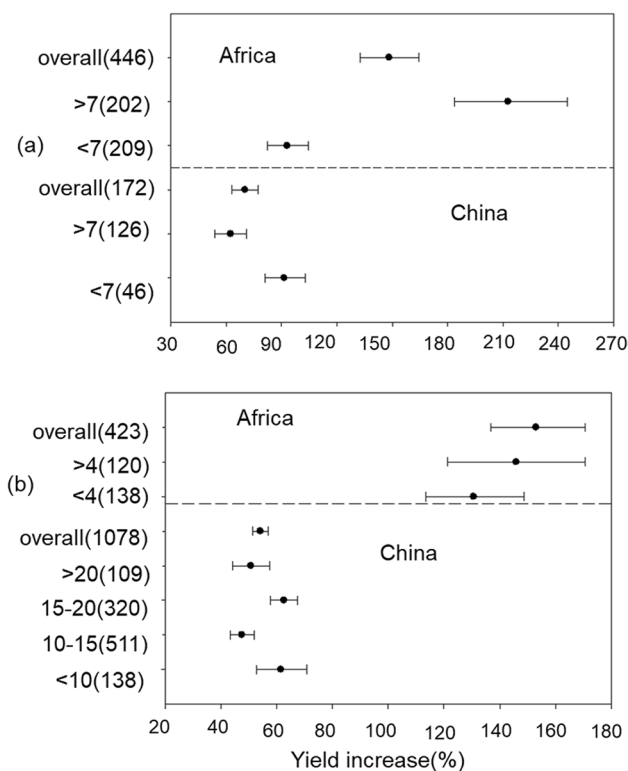


Fig. 4 Yield response to the power of pH (a) and soil organic matter in Africa and China. Box circles indicate means. Error bars represent 95% confidence intervals. Means (circles) are not significantly different from one another if their 95% confidence intervals (error bars) overlap. The means and 95% confidence intervals of the response ratios are in the bootstrapping method. The numbers in brackets indicate the number of observations

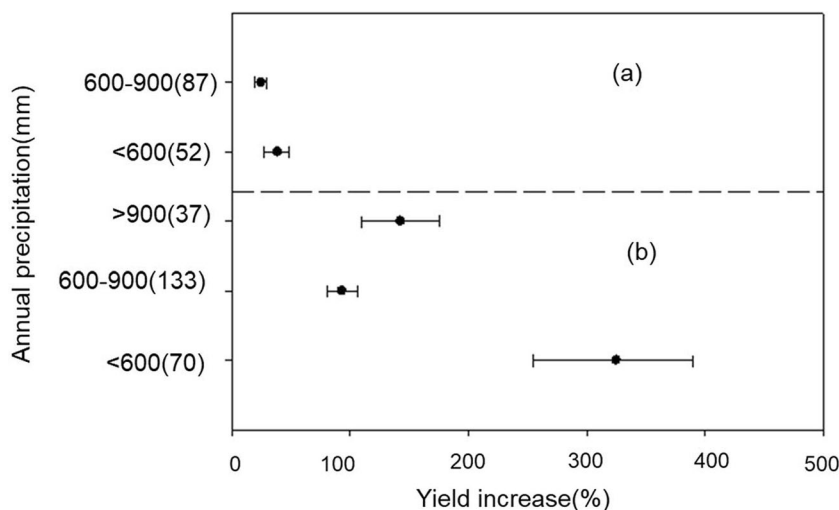
wheat. These different recommendations indicate that the right application rate of N fertilizer for high wheat production is conditional. These different regimes of N fertilizer suggested by different authors agreed with the results we

found in our meta-analysis where positive and significant correlations were indicated in the case of Africa. According to Rekaby and Eissa (2016) and Ma et al. (2019), due to a lack of knowledge, farmers apply an excessive amount of N assuming that increases in N fertilizers significantly result in high potential wheat yield regardless of the reality that excessive use of N fertilizer does not significantly increase crop yield, instead decreases NUE and led to environmental pollutions. Our findings in the case of China regarding the excessive use of N fertilizers appear to be in line with the above findings. As we described earlier, over 300 kg ha⁻¹ N fertilizer application resulted in a yield reduction of 29% in China. Therefore, optimization of N use is critically needed, and reducing the current N fertilizers application rate is necessary to minimize negative environmental impacts caused by the overuse of chemical N fertilizers in China.

4.2 Effect of Soil Chemical and Physical Properties on Wheat Yield

Nitrogen is not the only limiting factor that affects the grain yield of wheat; soil characteristic factors such as pH, organic matter, and other nutrients found in the soils have contributed to the production of particular crops (Dorsey 2014). Our study indicated that these factors have a significant effect on wheat yield responses. The overall contribution of these soil properties such as pH and soil organic matters was more pronounced in Africa than in China. In the case of Africa, wheat was more productive in alkaline soils than in acidic soils. That is, a high yield of wheat was found in alkaline soils, while a low yield was obtained from acidic soils. This result reassures the findings of Berhe (2017) that strong acidic soil has significantly affected wheat yield and yield components. Gebremedhin (2019) has also reported that acid soil infertility is a serious problem to crop production, which is consistent with our findings in the case of Africa. Boko

Fig. 5 Effects of precipitation on wheat yield in China (a) and Africa (b). The box circle indicates means. Error bars represent 95% confidence intervals. Means (circles) are not significantly different from one another if their 95% confidence intervals (error bars) overlap. The means and 95% confidence intervals of the response ratios are in the bootstrapping method. The numbers in brackets indicate the number of observations



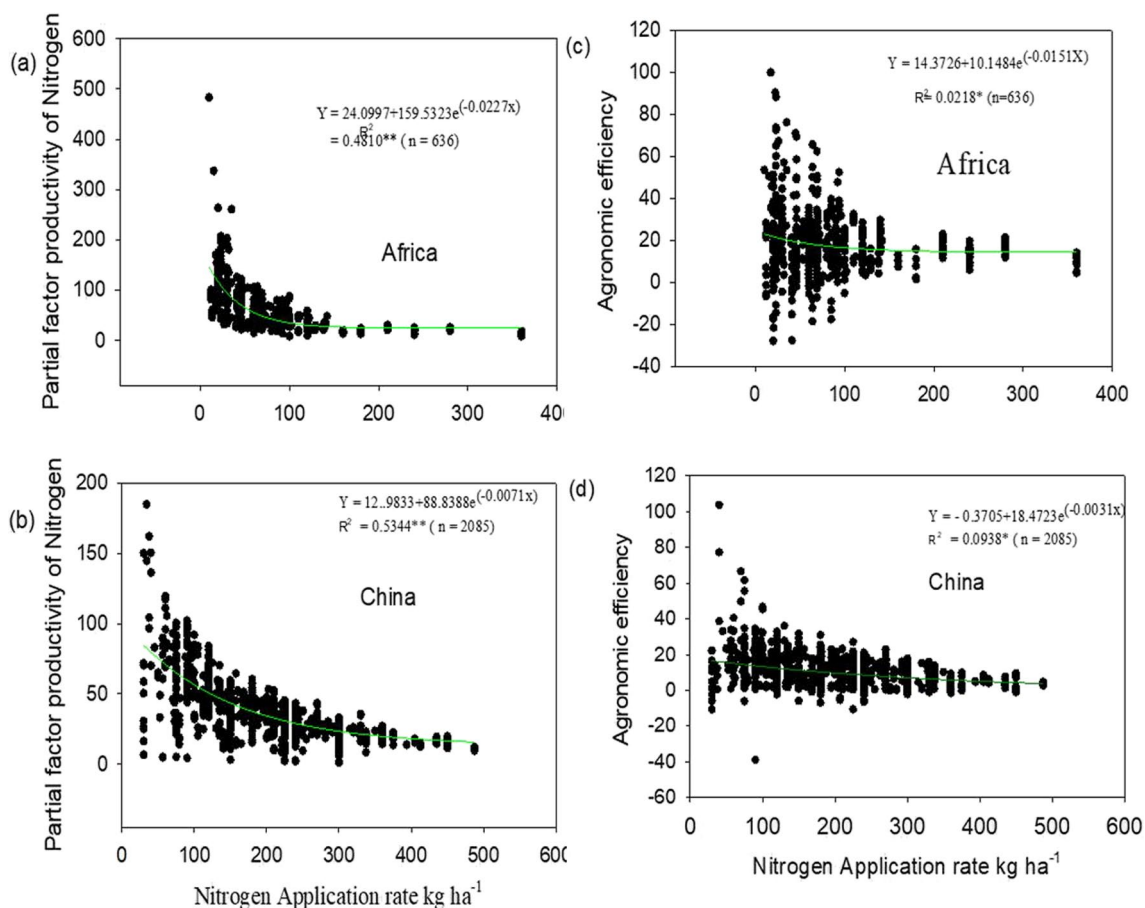


Fig. 6 Relationships between fertilizer application of nitrogen fertilizer (N) and its partial factor productivity of nitrogen (**a** and **b**) and Agronomic use efficiency in kg ha^{-1} (**c** and **d**) for wheat crop in China and Africa. In the regression model, Y is partial factor produc-

tivity of nitrogen (**a** and **b**) and agronomic use efficiency (**c** and **d**), X is application rates of N . Significance of regression coefficients and intercepts was determined with a F -test ($p < 0.05$). The number of data points was given in each equation

and Haile (2017) asserts that an acid soil with a pH below 5 affects root development, resulting in decreased nutrient and water uptake and decreased crop growth and yield. This finding supports the result we found in the case of Africa that the level of soil acidity indicated in the literature was very low and has led to a low yield increase relative to alkaline soil. Another study conducted by Tadele and Legese (2018) summarized that the suitable level of soil pH of 6.25–7.55 is a normal range and appropriate for most wheat varieties.

On the contrary, the highest wheat yield was obtained from acidic soil in the case of China. This could happen if factors that would influence productivity were at optimal conditions. That happens when factors such as the application of the right amount of nitrogen fertilizer (based on soil test), the use of acidic soil tolerant varieties, and other factors that increase wheat production were optimal at a time. In our cases, the acidity level of the soil was also not too low; its pH ranges from 6.28 to 6.8 and on average 6.49—a slightly acidic soil, which is a desirable condition for wheat production. Killian et al. (2011) witnessed that a pH of 6.5 is the

favorable range for winter wheat production, which is nearly in agreement with the outcome we discovered. According to FAO (2008), the suitable pH range for the majority of crops is between 6.5 and 7.5, which confirms the availability of optimum N . In summary, the study depicts that wheat is more productive in alkaline soil in the case of Africa, while in acidic soil in China.

The amount of soil organic matter (SOM) indicates whether soil quality is improving or degrading in an area. As SOM increases, cation exchange capacity (CEC), soil N contents, water holding capacity, and microbiological activities increase (Horneck et al. 2011). As mentioned earlier, the overall effect of SOM is stronger in Africa than in China. The findings indicated that soil organic matter had no significant effect on wheat grain yield among the classification though there is a positive correlation with wheat production. However, Oldfield et al. (2019) reported a positive and considerable effect of SOM concentration on wheat and maize yields. Increases in SOM concentration to a defined target can help to achieve a potential yield increase. A high

concentration of SOM was observed in China, while it was relatively less in Africa. Nevertheless, the effect of SOM on wheat yield to N use was higher in Africa than in China. As pointed out by Haile et al. (2012), soil with low organic matter has a low capability of making N available to plants, as organic matter determines the availability of N. Soil organic matter improves soil fertility, increases crop yields, and positively affects food production, water storage, the retention of xenobiotics, the development of soil microorganisms, and nutrient cycling (Ukalska-Jaruga et al. 2020).

In China, the overall effect of SOM on wheat production was assessed and a positive relationship was found. The soils of the provinces of China contained high SOMs and resulted in a high wheat yield. This is in line with Tahir et al. (2011) who found out that the practice of using organic matter along with chemical fertilizer could help to obtain a better grain yield than the gains with chemical fertilizer solely. Though the density of SOM is low, unlike in China, the contribution of SOM to wheat yield response was higher in Africa than that in China, suggesting that improving soil fertility is one of the effective approaches to maximize wheat yield.

Because soil pH and organic matter strongly affect soil functions and the availability of nutrients, paying attention to possible ways of managing soil pH is very important. The practices of fertilization, amendments, tillage practice and crop selection should all receive due consideration to overcome problems associated with soil functions. (McCauley et al. 2017). To have a good response to wheat yield, an effective method for increasing pH for Africa and lowering pH to a certain level for China is necessary. The result indicates that the content of these soil factors (pH and OM) highly influenced wheat yield responses, and their importance is higher in Africa than in China. The contribution of these soil factors was less in China compared to Africa, implying that improving soil fertility is one of the effective approaches to increase wheat yield in Africa, while in China, a more integrated approach including crop-soil fertility management will be needed. Fagerial and Baligar (2005) recommended some approaches need to be adopted. For instance, fertilizer factors (sources, methods, rates, and times of application), use of animal manure, and adoption of conservation tillage systems and water management are appropriate soil management practices. The proper use of these strategies not only maintains and improves soil quality but also improves NUE and thereby improving crop yield and minimizing production costs.

4.3 Effect of Precipitation on Wheat Yield

This study indicated that on average a higher wheat yield was found in Africa than in China although the amount of rainfall in a growing season is the same; suggesting that rainfall is less important in China compared to Africa. In

Africa, a significant yield increase was found at 600 mm rainfall growing season. This result reassures the findings of DAFF (2010), who reported that the annual precipitation needed for wheat production is 600 mm. We also found that the effect of seasonal rainfall on wheat yield was significantly different among the groups. The mean yield increase of wheat was found to be lower under medium seasonal rainfall, which was 93%. Under a high seasonal rainfall, the mean wheat yield increase was 143%, which is higher than the medium and lower than the wheat yield increase under low seasonal rainfall. This variation may be due to a high degree of fluctuation of rainfall during growing seasons with the occurrence of a period of dry weather. Our result is similar to the finding of Megersa et al. (2020). Fluctuation in precipitation and temperature throughout the year, particularly during the growing season, negatively impacts crop production and determines its success and failure (Bannayan et al. 2011). Akinniran et al. (2013) also reported that the yield of maize varies significantly with the annual distribution of rain rainfall. Similarly, Dehgahi et al. (2014) reported that rainfall has a big influence on wheat production, especially during the growing season. To avoid yield decline as a result of rainfall variability during the growing season, the onset and delay of rainfall, which is a challenge for African farmers, accessing timely climate information issued from the national meteorological agency of the respective country enable farmers to make a right decision need to be followed (Bekele et al. 2020). The finding in the case of China showed that rainfall had no significant effect on wheat yield increase and is less important for wheat production. However, although water deficit during the entire growing season is a serious problem, for instance in the north China plain (Liu et al. 2015), the grain yield of wheat has significantly increased because of a considerable increase in irrigation and N usage. The results of this meta-analysis also illustrate that wheat production is unthinkable without supplementary irrigation in the case of China, unlike in Africa.

4.4 Measurement of Nitrogen Fertilizer Use Efficiency in Africa and China

As the indicators of nutrient use efficiency (NUE), we investigated partial factor productivity of nitrogen (PFPN) and agronomic efficiency of nitrogen (AEN) in this study. The results showed relatively a higher NUE in Africa than in China. The NUE was also significantly and negatively associated with wheat yield both in Africa and China. According to the present meta-analysis, improving PFPN in wheat production to the optimum level would increase wheat yield by 65% and 68%, respectively, in Africa and China. The study showed that NUE was slightly better in Africa than that in China. This could be the result of the fewer amount of N fertilizers that were used in Africa. Other studies also indicated

that N fertilizers rate and time of application have significant effects on NUE and crop yields (Gaj and Nacer 2012).

Likewise, we found a higher AEN for Africa and relatively less for China. The observed mean values for PFPN and AEN were generally higher for Africa than for China. The occurrence of such conditions could be due to the over-application of N fertilizer, as excessive and irrational use of N strongly affects NUE. Recent studies (Wallace et al. 2020; Yadav et al. 2017; Khan et al. 2020) discussed that excessive use of nitrogen fertilizer could lead to significant costs and serious environmental problems in addition to NUE which agreed with our finding in the case of China. Indeed, the application of an appropriate N rate is not the only mechanism to improve NUE, but cropping system, soil and water management, and time of application were among the main practices that increase NUE (Dargie et al. 2018). In general, our results showed that there was a significant non-linear negative relationship between N application rates and PFPN, and AEN, indicating that PFPN and AEN decreased as an increasing amount of fertilizer was applied. Therefore, to improve NUE and maximize wheat production, environmentally friendly fertilization regimes based on soil tests are strongly recommended. Similarly, to achieve high PFPN and AEN, managing the N supply from the soil and other indigenous source is as important as maximizing nitrogen efficiency.

5 Conclusion

The study analyzed different methods that could improve wheat production and how efficiently it uses nitrogen. The research found that using N fertilizer to grow wheat resulted in better yields in China compared to Africa. This means that there is more potential to increase the productivity of wheat in Africa than in China. Our finding shows that wheat production in Africa had slightly better nitrogen use efficiency compared to China. The impact of Ph and soil organic matter on wheat production was stronger in Africa than in China. Rainfall during crop growing season has a lesser impact in China compared to Africa. This suggests that it is not possible to grow wheat in China without using irrigation. The study highlighted that a high yield response to chemical N use in Africa was accompanied by N depletion, while in China it was associated with a high N surplus. To control the use of nitrogen in the future, it is important to have guidelines that farmers can easily follow. These guidelines should be specific to nitrogen use, the type of soil, and the type of crops being grown. These guidelines would assist farmers in understating what they need to measure and where they should focus on making improvements. The guidelines will

explain why changes in management are necessary and how they will affect the performance of the system.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42729-023-01609-5>.

Acknowledgements This work was supported by the China Scholarship Council (201913043), the Bill & Melinda Gates Foundation (OPP1209192), and the “Sino-Africa Friendship” China Government Scholarship (2019- 1442).

Declarations

Ethics Approval and Consent to Participate This study is a meta-analysis review and does not contain any study with human or animal subjects performed by any of the authors.

Competing Interests The authors declare no competing interests.

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