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META-ANALYSIS

Improvement of nutritional quality of food crops with fertilizer: a global meta-analysis

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Abstract
Providing the world's population with sufficient and nutritious food through sustainable food systems is a major challenge of the twenty-first century. Fertilizer use is a major driver of crop yield, but a comprehensive synthesis of the effect of fertilizer on the nutritional quality of food crops is lacking. Here we performed a comprehensive global meta-analysis using 7859 data pairs from 551 field experiment-based articles published between 1972 and 2022, assessing the contribution of fertilization with a wide set of plant nutrients to the nutritional quality of food crops (i.e., fruits, vegetables, cereals, pulses/oil crops, and sugar crops). On average, fertilizer application improved crop yield by 30.9% (CI: 28.2–33.7%) and nutritional quality (referring to all nutritionally relevant components assessed; carbohydrates, proteins, oil, vitamin C, representative mineral nutrients, and total soluble solids) by 11.9% (CI: 10.7–12.1%). The improvements were largely nutrient- and crop species dependent, with vegetables being the most responsive. Potassium, magnesium, and micronutrients played important roles in promoting crop nutritional quality, whereas the combined application of inorganic and organic source(s) had the greatest impact on quality. Desirable climatic conditions and soil properties (i.e., silt loam, soil organic matter 2.5–5.0%, and pH 4.5–8.5) supported further enhancements. Considering cross-continent responsiveness, the increase in the nutritional quality of food crops with fertilizer application was greatest in Africa. In a nutshell, our findings pave the way towards a quantitative understanding of nutrient management programs and responsible plant nutrition solutions that foster the sustainable production of nutritious and healthy food crops for human consumption.

Keywords Soil and environmental conditions · Soil fertility and plant nutrition · Agriculture production · Biofortification · Human health · Food security

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1 Introduction

Food security has been defined by the Food and Agriculture Organization of the United Nations as "a situation that exists when all people have physical, social and economic access to sufficient, safe and nutritious food to meet dietary needs and food preferences for an active and healthy life" (FAO 1996; FAO 2021a). It encompasses food supply, food safety, and the nutritional quality of products that deliver required amounts of proteins, energy, vitamins, and essential mineral nutrients (Global Panel 2016; Menichetti et al. 2022). The prevalence of micronutrient deficiencies, also known as the "hidden hunger," has serious health and economic consequences, especially in low- and middle-income countries (Smith and Haddad 2015; Gödecke et al. 2018; UNICEF 2019; Murray et al. 2020). Undernutrition (lack of carbohydrates and micronutrient malnutrition) remains a persistent problem despite more coordinated global efforts to overcome it in the past decades (Byerlee and Fanzo 2019; Heidkamp et al. 2021). Recent estimates suggest that globally ~ 720–811 million people are facing chronic hunger and 2.37 billion people are affected by moderate to severe nutrition insecurity, with the majority of these in Asia and Africa (Wessells and Brown 2012; FAO 2021a). On the other hand, adult obesity rates also continue to rise, with the global prevalence up to 13.1% in 2016 (FAO/IFAD/UNICEF/WFP/WHO 2020). These statistics highlight a major challenge to achieving the United Nations' zero hunger (SDG2) and good health and well-being (SDG3) Sustainable Development Goals (SDGs) by 2030 (FAO 2019; FAO/IFAD/UNICEF/WFP/WHO 2020; Heidkamp et al. 2021). Particular attention is, therefore, required to establish sustainable and equitable food security systems.

To address SDG2 and SDG3, the worldwide agriculture sector must meet the twin challenges of producing sufficient food and meeting the nutritional demands of the growing population in a sustainable manner (Ruel et al. 2018; Dobermann et al. 2022). Plant breeding, crop and soil management, and fertilizer application are acknowledged approaches for enhancing the yield and nutritional quality of agricultural products (White and Broadley 2005a; Cakmak 2008; White and Broadley 2009; Cakmak and Kutman 2018; Ishfaq et al. 2021a). Impressive progress has been made in understanding mechanisms of nutrient acquisition and their transport and functions in plants (Grotz and Guerinot 2006; Marschner 2012; Oldroyd and Leyser 2020; Assunção et al. 2022). Nevertheless, fertilizer programs implemented in the past have mainly focused on improving crop yields, and little priority has been given to nutritional outcomes for human health (Welch et al. 2013). Indeed, the nutritional value of food crops has sometimes declined due to narrower crop genetics, intensive cultivation practices, and depletion of soil nutrients (Shewry et al. 2016; Marles et al. 2017; Moreno-Jiménez et al. 2021; Ishfaq et al. 2022a). For instance, a decline in dietary potassium (K) intake and a rise in hypokalemia prevalence is reported in the US population (Sun and Weaver 2020), and low dietary intake of essential mineral elements in Western countries is widely documented (White and Broadley 2005b; Eussen et al. 2015; Ruxton et al. 2016; Vural et al. 2020). Similarly, an inverse relationship was found between the phytoavailability of mineral nutrients in the cultivated soil and related nutritional disorders in the population of sub-Saharan Africa (Cakmak et al. 2016; Kihara et al. 2020; Gashu et al. 2021). The imbalanced or excessive intake of certain minerals leads to serious health concerns; for example, a higher ratio of sodium-to-K increases the risks of cardiovascular diseases (Cook et al., 2009; Wakeel and Ishfaq 2022). Thus, a new paradigm for agriculture that considers both yield and nutritional composition is required (Poole et al. 2020; Brown et al. 2021; Dobermann 2022).

Plants require at least fourteen mineral elements in addition to carbon, hydrogen, and oxygen and more than 20 mineral elements have been identified as being essential for human health (White and Brown 2010; Marschner 2012; Brown et al. 2021). Many of these elements enter the food system through the soil, supplemented by applied fertilizers, organic amendments, and a few other sources (i.e., biological nitrogen fixation, deposition, and weathering of rocks and minerals). Depending on the local context, the biofortification of staple crops, either through genetic biofortification or agronomic biofortification, can be an effective strategy for combating malnutrition (Cakmak 2008; White and Broadley 2009; Bouis and Saltzman 2017; Ishfaq et al. 2021a). Furthermore, nutrient availability is strongly driven by soil physicochemical properties and climatic conditions, and greater insight is required to understand which growth conditions can be employed to obtain superior crop productivity and better nutritional quality. There is a need for synthesis of the available information in the literature to quantify how much different fertilization strategies contribute to the concentration of nutritionally relevant components of food crops. Such a synthesis would clarify the effectiveness of different strategies for different constituents of food and would also clarify the effects of other variables, such as soil properties and climate.

Here we performed the first comprehensive global meta-analysis to provide fundamental insights into the contribution of a wide set of plant nutrients to the nutritional value of food

Table 1 Description of specific terms used in this study.

Terminology	Description
Nutritional quality	Nutritionally relevant components such as carbohydrates, proteins, oils, vitamin C, lycopene/carotenoids, mineral nutrients, and total soluble solids (TSS) in the edible portions of food crops. Their concentration per unit weight is retrieved from reported studies, and given numbers across all crops or within individual crop types indicate grand mean values which were generated by the random effect meta-analysis model.
Mineral nutrients	A collection of nutritionally important nutrients for human health including potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), and iron (Fe)
Food crops	Classified as fruits, vegetables, cereals, pulses/oil crops, and sugar crops
Agricultural/crop produce	Edible portions of different food crops
Responsible plant nutrition	Fertilizer applications considering food production and consumption in a sustainable manner
Balanced nutrient provision	Adequate supply of essential nutrients to plants in order to minimize over or under-supply
Organic sources/amendments	Classified as organic fertilizers, farm yard manure (FYM), green manure, crop residues, poultry manure, vermicompost, sawdust, biofertilizers
Combined fertilizer application	Application of different types of fertilizers
Substitution ratios	Replacement of specific amounts of inorganic fertilizers with organic sources/amendments

crops. A detailed description of specific terms used in this study (Table 1) and a schematic illustration are provided (Fig. 1). By using 7859 data pairs from 551 field experiments-based articles of more than 90 different crop plants on six continents which were published in the last 50 years, we (i) report how fertilizer practices influence the nutritional composition of produce in a nutrient- and crop species-dependent manner; (ii) provide information on the effects of site-specific covariates such as climatic conditions and soil properties on improving the nutritional quality of plant products; and (iii) assess the relationships between yield and nutritional value of different food crops. The findings of this study provide a useful quantitative framework to assess the changes in the nutritional quality of food crops affected by fertilizer application and offer effective plant nutrition solutions to increase the production of nutritious food and contribute to the well-being of human populations.

2 Materials and methods

2.1 Data mining and validation

An extensive literature survey was conducted through the Web of Science database (http://apps.webofknowledge.com/), Google Scholar (http://scholar.google.com), and the China National Knowledge Infrastructure Database (http://www.cnki.net/) until March 2022. To retrieve articles from the databases, the following search terms were used: ("food* crop" OR "fruit" OR "vegetable" OR "cereal" OR "wheat" OR "maize" OR "rice" OR "grain" OR "legume" OR "pulses" OR "oil crop" OR "sugar crop") AND ("fertilizer*" OR "macronutrient" OR "N" OR "P" OR "K" OR "Ca" OR "Mg" OR "S" OR "NPK" OR "micronutrient" OR "Zn" OR "Fe" OR "organic source" OR "FYM" OR "compost") AND ("food* quality" OR "carbohydrate" OR "protein" OR "oil" OR "vitamin

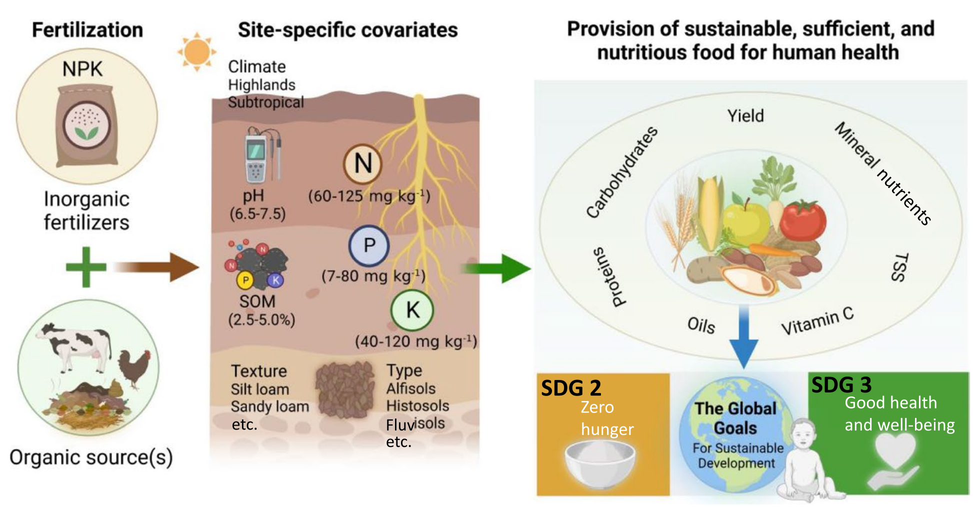

Fig. 1 A conceptual figure showing the sustainable production of nutritious food crops using fertilizers. The combination of inorganic fertilizes and organic sources for balanced nutrient provision and conditioning of desirable soil properties (indicated in the parentheses) together boosted crop yield and quality, paving the way towards the development of more sustainable agriculture and achieving food and nutritional security for a growing world population.

C" OR "lycopene" OR "carotenoid" OR "nutrient" OR "total soluble solid"). The Boolean truncation ("*") was employed to ensure that all variants of keywords would be found. To refine the metadata search, two logical operators (AND and OR) and field tag (TI = title) were used. In addition, references to related articles were reviewed to retrieve relevant information. Peer-reviewed journal articles published from 1972 to 2022 were shortlisted following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009 and Fig. S1). We screened the retrieved articles and retained those that met the following four inclusion criteria: (i) the study was conducted under field conditions (i.e., not glasshouse, controlled environment or in vitro studies); (ii) the study included treatments of interest, including sole or combined application of fertilizer(s), and information both from a control treatment (no or very low rates of fertilizers) and a fertilized treatment at the agronomically recommended rate; (iii) yield and/or nutritional quality parameters were reported for both the treatment and control; (iv) we focused on quality parameters related to the concentration of nutritionally relevant constituents on a mass basis and did not include additional quality traits such as appearance, textural properties, aroma, size, color, cracking, and disease incidence, and treatments needed to have replicates within an experimental design allowing the calculation of the weight of individual observations.

The required data were extracted from text and tables, and to retrieve data presented graphically, the digital software Plot Digitizer (https://automeris.io/WebPlotDigitizer/) and GetData (http://www.getdata-graph-digitizer.com/) were used. The geographical coordinates of each site were recorded directly from the studies or derived by the location of the nearest city or the experimental station at which the study took place (Supplementary dataset). In our data collection, the concentration of mineral nutrients (K, Ca, Mg, Zn, and Fe) was on a dry mass basis and the concentrations of other five quality traits (carbohydrates, proteins, oils, vitamin C, and total soluble solids) were on a fresh mass basis. Besides variables related to the nutritional quality of food crops, we also collected information about site-specific covariates such as continent, plant type, climate, and original soil properties such as soil organic carbon/matter (SOM), pH, total nitrogen (N), Olsen-phosphorus (P), exchangeable potassium (Ex-K), soil texture, and soil order according to the available data. The data about soil physical properties were collected from studies or extracted from the HWSD database (Wieder et al. 2014) using geographical coordinates. When only soil organic carbon was reported, we multiplied organic carbon by a factor two to estimate the concentration of soil organic matter (Pribyl 2010). All data used for analysis is available as Supporting Information (Supplementary dataset). Normal Quantile plot (Rosenberg et al. 2000) and Jackknife technique (Mendenhall et al., 1995) were used to assess the publication bias and sensitivity of weighted mean effect sizes of improvement of nutritional quality and yield of food crops with fertilizer application, respectively. For a few fertilizer sources, the standardized effect sizes did not fully distribute evenly with the y = x line (Fig. S2 and S3), and 95% CIs (Fig. S4 and S5) were shifted when certain observations were removed. However, outliers would not skew the major results, and such evaluation generally supported our further analysis.

2.2 Data characterization

The data for site-specific covariates such as climatic conditions were classified as temperate, tropical, subtropical, and arid and semi-arid and highlands (Li et al. 2013b, a). SOM was categorized as < 0.5%, 0.5–1%, 1–2.5%, 2.5–5%, and > 5% (Chen et al. 2007). Soil pH was grouped as < 4.5%, 4.5–5.5%, 5.5–6.5%, 6.5–7.5%, 7.5–8.5%, and > 8.5% (Han et al. 2011; Chen et al. 2018a, b). Soil total N concentration was grouped as < 60 mg kg^{-1}, 60–125 mg kg^{-1}, 125–250 mg kg^{-1}, 250–500 mg kg^{-1}, and > 500 mg kg^{-1}, and soil Olsen-P as < 7 mg kg^{-1}, 7–14 mg kg^{-1}, 14–80 mg kg^{-1}, and > 80 mg kg^{-1} (Chen et al. 2007). Soil exchangeable K was categorized as < 40 mg kg^{-1}, 40–80 mg kg^{-1}, 80–120 mg kg^{-1}, 120–160 mg kg^{-1}, and > 160 mg kg^{-1} (Kirkman et al. 1994; Wakeel and Ishfaq 2022). Soil texture was classified as silt loam, sandy loam, loam and clay loam, sandy clay loam, clay, and sandy according to the USDA soil texture triangle (USDA 1999).

2.3 Statistical analysis

The response ratio was calculated by dividing the response of the treatment (fertilized) by the respective response of the control. To examine the mean effects of crop nutritional quality variations with fertilizer application, we calculated the natural logarithm response ratio (ln*RR*) of each data pair (Hedges et al. 1999) as follows:

$$\ln RR = \ln(Xt/Xc) = \ln(X\mathrm{t}) - \ln(X\mathrm{c})$$

where the subscript *Xt* and *Xc* represents the mean value of the concerned variable in the fertilized and control, respectively. Effect size is a value reflecting the magnitude of the treatment effect in comparison to a reference treatment. The ln*RR* of the response of nutritionally important mineral nutrients (K, Ca, Mg, Zn, and Fe) to fertilizer application in a given crop group was first calculated for each mineral nutrient separately, and then a single average ln*RR* was determined across all mineral nutrients. Most of the studies included in our analysis did not report standard deviations; therefore, individual observations were weighted by the number of replications in the treatment and control (Adams et al. 1997), which was then used to calculate the mean effect sizes (lnRR). The equation was:

$$Wr = ((Nt \times Nc)/(Nt + Nc))$$

where Wr is the weight associated with each lnRR, and Nt and Nc are the number of replicates for the treatment and control, respectively. As the number of observations for yield and quality differed widely in each study, we calculated the weight factors (Wr) for yield and quality separately.

A random effect meta-analysis model was utilized for data analysis (Borenstein et al. 2011; Skinner et al. 2014). The mean and grand mean effect sizes were calculated by using METAWIN 2.1 (Rosenberg et al. 2000). The 95% bootstrapped confidence intervals (CIs) were generated by utilizing 4999 iterations. Significant responses ($P < 0.05$) were recognized if the 95% CI did not overlap with zero. For convenience in interpretation of results, the weighted mean effect size was converted back into a percentage change using the formula:

$$\text{Percentage change}(\%) = (e^{\ln RR} - 1) \times 100$$

To examine the relationships between site-specific covariates and yield and nutritional quality of food crops, the scatterplot matrix and linear regression model was applied, respectively.

3 Results

3.1 Effects of fertilizers on the nutritional quality of crop products

We collected field experiment results published between 1972 and 2022 from main crop production regions across America (South America and North America), Europe, Asia, Africa, and Australia (Fig. 2a). According to data availability, a major share (4408 out of the total 7859 data pairs) was originated from China representing large variations in production situation, crop species, climatic conditions, and nutrient management.

On average across all crop species, quality traits, and fertilization treatments, fertilizer application significantly improved the concentration of diet-quality enhancing nutrients in plant produce by 11.9% (mean effect, lnRR; 95% confidence interval, CI: 10.7–12.1%; the number of observations, $n = 5363$) (Fig. 2b and Fig. S6a). Most fertilizer treatments significantly ($P < 0.05$) improved nutritional quality although the range varied among the type or combination(s) of applied nutrients. Crop nutritional quality was strongly increased in fertilization treatments with combined supply of N, P, K, and organic amendments (abbreviated as N + P + K + organic amendment(s)) (16.1%; [11.7–21.6%]), representing one of the most effective nutrient management strategies. On average, the nutritional value of produce improved by 13.7% (11.1–16.5%) with N + P + K, 13.1% (10.4–16.5%) with K, 12.8% (10.0–16.3%) with micronutrient(s), 12.1% (10.0–14.4%) with organic amendment(s), 11.1% (7.9–15.3%) with Mg, 10.6% (7.7–13.1%) with N + P, 10.5% (3.0–19.2%) with P + K, 9.4% (5.9–13.1%) with N + K, 9.1% (6.2–12.2%) with N + organic source(s), 8.1% (5.9–10.1%) with N, and 6.8% (2.9–11.1%) with S. However, application of only P (6.9%; − 1.8–15.2%) or Ca (1.3%; − 7.1–7.8%) did not significantly change the nutritional quality of crop produce.

The overall nutritional quality was then broken down into seven individual traits in association with five crop species groups (Fig. 2c and Table S1), indicating an average increase of 11.6% (10.6–12.6%; $n = 5234$) across all studies. Among the five crop species groups, vegetables were comparatively more responsive to fertilizer application in terms of increasing concentrations of mineral nutrients (K, Ca, Mg, Zn, and Fe) (27.9%; [22.3–34.36%]), protein (21.3%; [16.2–26.5%]), and total soluble solids (TSS) (6.3%; [4.1–8.9%]). In cereals, the concentrations of minerals elements (21.1%; [14.9–28.4%]), carbohydrates (12.5%; [8.7–18.5%]), proteins (11.4%; [9.7–13.4%]), and oil (11.1%; [5.9–23.8%]) were significantly increased by fertilizer application. In fruits, the concentrations of vitamin C increased by 14.9% (10.5–20.5%), lycopene/carotenoids by 14.8% (10.2–20.6%), carbohydrates by 12.1% (9.4–15.2%), mineral nutrients by 9.3% (2.4–17.1%), and TSS by 5.5% (4.3–6.8%) with fertilizer application. Protein concentrations in the seeds of pulses/oil crops were increased by 10.1% (7.6–13.0%) by fertilizer application, with oil concentrations unchanged (2.6%; − 0.3–5.1%). By contrast, TSS was reduced by − 2.7% (− 4.0–1.2%) in sugar crops (comprising sugarcane and sugar beet) following fertilizer applications. Results of other nutritional quality traits in food crops were uncertain due to data limitation and were therefore not included in this study.

3.2 Individual and combinatorial effects of fertilizers on the nutritional quality of crop products

Quality crop production requires proper nutrient supplies based on soil conditions and developmental stages; N, P, K, and other fertilizers are applied separately or in various combinations accordingly (White and Broadley 2009; Marschner 2012; Dick et al. 2016). We analyzed how sole or combined fertilizer application affected individual quality traits of five crop groups (i.e., fruits, vegetables, cereals, pulses/oil crops, and sugar crops). When comparing the effect of individual nutrients on different crop groups, we found that N

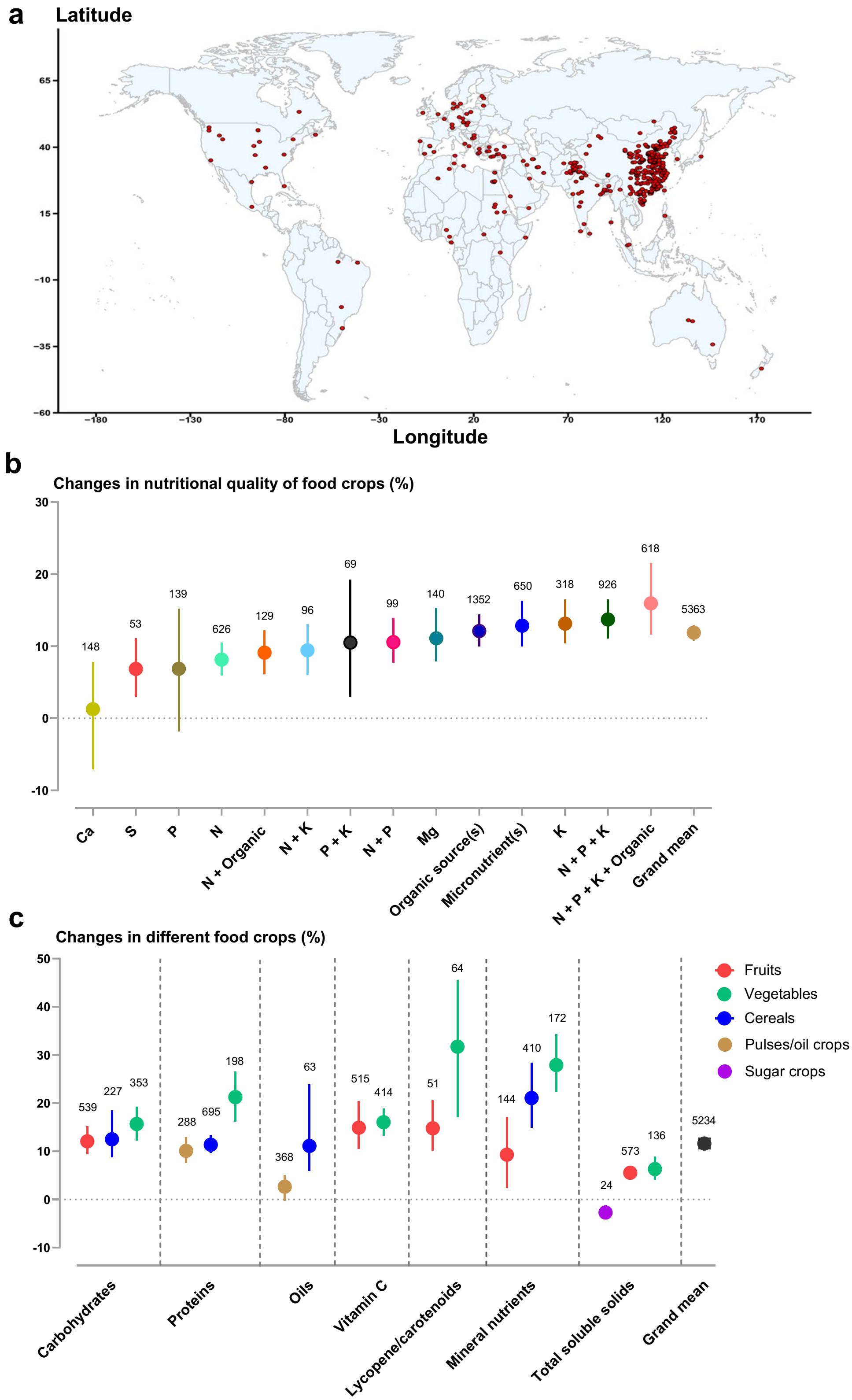

Fig. 2 Changes in the nutritional quality of food crops with fertilizer application. **a** The location of different field-based experiments used in the meta-analysis. **b** Relative contribution of type/combination(s) of plant nutrients in improving the nutritional quality of food crops, and **c** responses of different nutritional quality traits to fertilizer application in fruits, vegetables, cereals, pulses/oil crops, and sugar crops. Colored dots represent the mean effect sizes with 95% confidence intervals (CIs). Mean values < 0 indicate a negative effect, while mean values > 0 indicate a positive effect (significant effect, $P < 0.05$, if 95% CIs did not overlap 0). The numbers (n) at the upper side of the whiskers indicate the data records for each group. The mean effect size is converted into the percentage change (%).

performed well in promoting protein accumulation in cereals, pulses/oil crops, and vegetables; K increased carbohydrate and total soluble solid concentrations in fruits; Mg increased carbohydrate accumulation in vegetables and minerals in fruits; and S increased oil accumulation in pulses/oil crops. Notably, N fertilizers can also alter biological N_2

fixation in pulses/legumes depending on the type and rate of applied N, soil conditions, and plant species (Herridge et al. 2008). In general, micronutrients promoted the nutritional quality of different crop groups. Although less nutrient dense than most chemical fertilizers, the treatment with organic source(s) significantly improved most crop quality traits with the exception of accumulation of minerals in fruits and cereals and total soluble solids in sugar crops. Importantly, nearly all crops require the application of multiple nutrients (Marschner 2012; Brown et al. 2021); thus, two combined fertilizer practices N + P + K + organic amendment(s) and N + P + K frequently had greater positive effects on food nutritional quality than other, less comprehensive fertilizer treatments, such as applying only a single nutrient, e.g., P or K, except for increasing total soluble solids in sugar crops and vegetables (Fig. 3).

Carbohydrate (referring to soluble sugars and starch) concentrations were, on average, increased by 13.1% (11.2–15.4%; $n = 1119$) with fertilizer application (Fig. 3a). However, N application reduced carbohydrate concentrations in fruits, probably due to the “dilution effect” resulting from yield (fresh weight) increase, while P application had no impact. However, N supplemented with organic sources and combination of N or P with K all gave rise to increases in carbohydrate concentration. Combined application of N, P, K, and/or organic sources further increased carbohydrate concentrations in fruits as well as in cereals. Importantly, micronutrient(s) and organic source(s) had comparable impacts as N + P + K in fruits and vegetables. In vegetables, either individual N, P, or their combined application had no impact, but K addition led to positive effects. The sole application of Mg and organic source(s) had surprisingly larger impacts than N + P + K in vegetables. The larger response

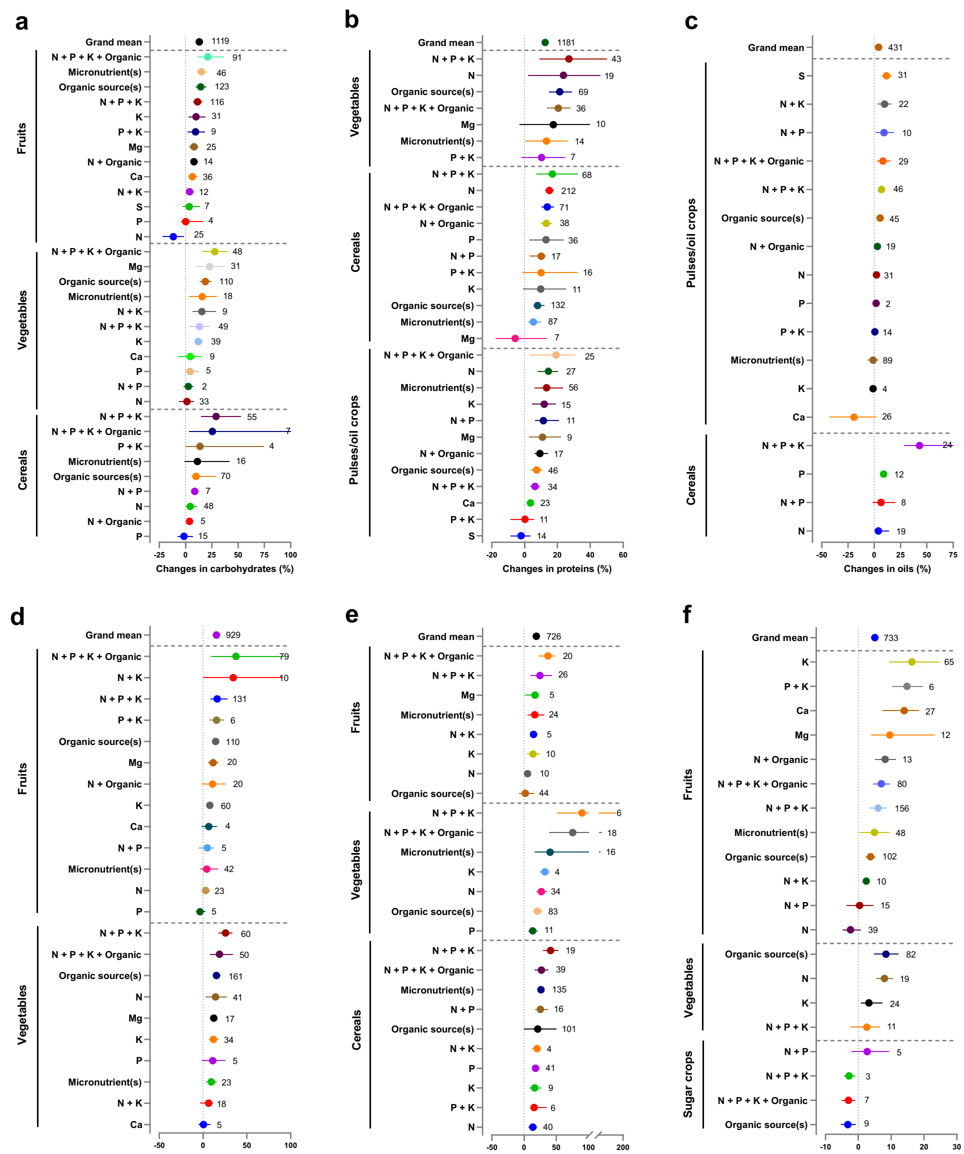

Fig. 3 Possible interactions of type/combination(s) of fertilizer inputs in increasing the nutritional quality of food crops. Changes in concentrations of **a** carbohydrates, **b** proteins, **c** oils, **d** vitamin C, **e** mineral nutrients, and **f** total soluble solids in the edible portions of different plant groups with different type/combination(s) of fertilizer application. Colored dots represent the mean effect sizes with 95% confidence intervals (CIs). Mean values < 0 indicate a negative effect, while mean values > 0 indicate a positive effect (significant effect, $P < 0.05$, if 95% CIs did not overlap 0). The numbers (n) on the right side of the whiskers indicate the data records for each group.

to Mg application can be because Mg is often a latently deficient nutrient in the soil (Ishfaq et al. 2022a). In cereals, carbohydrate concentrations did not change significantly with P application; however, combined application of P with N or K promoted carbohydrate concentration.

Protein concentrations were significantly ($P < 0.05$) increased by 12.5% (11.0–14.2%; $n = 1181$) across all crop plants in response to fertilizer application (Fig. 3b). The largest increase in protein concentrations was found with the application of N + P + K to vegetables and cereals, and with N + P + K + organic source(s) to pulses/oil crops. The next most efficient treatment was N in these three plant groups, comparable in effect to the most effective fertilization treatment. On the other hand, the P + K treatment did not have effects on protein concentration in any crop group. Mg (for vegetables and cereals), K (for cereals), and S (for pulses/oil crops) did not, either.

Oil concentrations were increased by fertilization to a lesser extent than carbohydrate and protein concentrations. The average increase was 4.1% (1.5–6.4%; $n = 431$) in pulses/oil crops and cereals (Fig. 3c). Oil concentrations increased by 11.6% in pulses/oil crops with the application of S, which might be due to the contribution of S to oil formation, especially on S-poor soils (Malhi et al. 2007; Egesel et al. 2009; Raza et al. 2018; Geng et al. 2021). However, individual application of N, P, K, or Ca had no impact on oil concentration in pulses/oil crops. Combined application of N with other nutrients enabled positive results. In cereals (mainly maize), separate application of N or P increased oil concentration; however, combined application of N and P did not, possibly due to improper ratios, complicated interactions, or insufficient number of data. The N + P + K treatment was significantly more efficient than N or P treatments.

Vitamin C concentrations were increased with fertilizer application by 15.3% (12.5–19.0%; $n = 929$) on average across all crop species (Fig. 3d). The treatments of sole K, Mg, or organic source(s) and various combinations with K significantly increased vitamin C concentration ($P < 0.05$) in fruits although N, P, Ca, or micronutrient(s) did not. In vegetables, the largest increase in vitamin C concentration was found with the application of N + P + K, followed by N + P + K + organic source(s), organic source(s), N, Mg, K, and micronutrient(s) application. Linear regression analyses indicated that higher levels of sole N application (> 400 kg ha^{-1}) negatively influenced vitamin C concentrations (Fig. 4a). However, the higher application of organic sources increased vitamin C concentrations (Fig. 4d). There was no significant increase with Ca application, although positive effects of Ca on vitamin C concentrations have been observed in some studies (Marschner 2012; Islam et al. 2016).

Crops provide large amounts of various mineral nutrients essential for human health (Welch et al. 2013; Dobermann et al. 2022; Assunção et al. 2022), among which K, Ca, Mg, Zn and Fe in the edible part of plant were grouped as single quality trait "mineral nutrients" in this study. Fertilizer application increased the concentration of these mineral nutrients, on average, by 18.9% (14.7–23.8%; $n = 726$) (Fig. 3e). Most treatments showed positive impacts, with the largest increase with the application of N + P + K + organic source(s) or N + P + K in fruits, vegetables, and cereals. The treatment of sole N, P, K, micronutrients, and combinations of N with K or P increased mineral concentration in all crops studied. We interpret the comparatively smaller concentration increase of mineral nutrients with sole N application as a "dilution effect" whereby an increase in mineral accumulation in produce is partly offset by total yield increase, as exemplified for vegetables (Fig. 4a).

The analysis showed that TSS concentration was increased, on average, by 5.0% (3.9–6.2%; $n = 733$) in fruits, vegetables, and sugar crops, although increases in TSS concentration varied widely among fertilizer types and crop species groups (Fig. 3f). In fruits, the TSS concentration was increased significantly to a larger extent by the application of K, P + K, Ca, and Mg. Combined application of N with K, P, or organic source(s) also led to significant positive results but N and N + P had no effect. The N + P + K treatment caused no change in contrast to positive effects by application of N or organic source(s) in vegetables. N + P + K, N + P + K + organic source(s), and organic source(s) even reduced TSS accumulation in sugar crops based on the limited data sets.

As noted above, N + P + K and particularly, N + P + K + organic amendment(s) frequently improved the quality traits to the greatest extent (on average by 16.1%; 11.7–21.6%). To better assess the contribution of organic amendments to quality improvement, we further classified the available data based on the type of organic amendments and specific substitution ratios (replacement of inorganic NPK with organic amendments). The nutritional quality of food crops was increased by 22.8% when inorganic N + P + K was applied with organic fertilizers, 21.9% with farmyard manure (FYM) + green manuring, 15.1% with crop residues, 14.7% with poultry manure, 13.8% with vermicompost, 11.6% with FYM, 7.2% with sawdust, and 7.0% with biofertilizer application, compared to control treatments (Fig. 5a). Notably, sawdust or biofertilizer application showed smaller quality improvement than sole NPK application (Fig. 2b). We set four categories on the basis of the substitution of inorganic NPK by organic sources as low (< 25% organic sources), moderate (25–50% organic sources), high (> 50% organic sources), and additional (recommended doses of inorganic fertilizers + additional organic sources). As shown in Fig. 5b, the low and high substitution of inorganic NPK by organic source(s) contributed moderately to the nutritional quality of crops while moderate substitution and applying

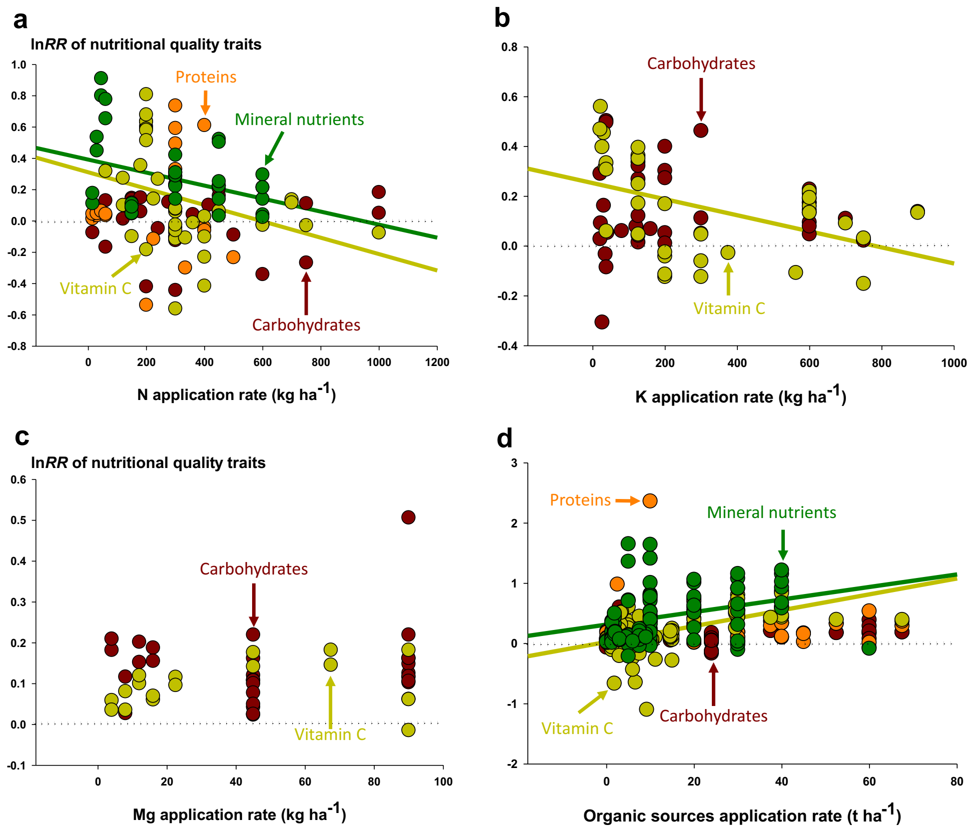

Fig. 4 Changes in the nutritional quality of vegetables with fertilizer application rates. **a** The relationship between the ln*RRs* of carbohydrates (y = 1.411e-005x + 0.01; *P* = 0.920), proteins (y = 0.000144x + 0.056; *P* = 0.730), vitamin C (y = − 0.00052x + 0.311; *P* = 0.025), and mineral nutrients (y = − 0.00041x + 0.391; *P* = 0.040) in the edible portions of vegetables with sole N application rates. **b** The relationship between the ln*RRs* of carbohydrates (y = − 1.411e-005x + 0.151; *P* = 0.894) and vitamin C (y = − 0.0003227x + 0.252; *P* = 0.008) in vegetables with K application rates. **c** The relationship between the ln*RRs* of carbohydrates (y = 0.0003360x + 0.119; *P* = 0.507) and vitamin C (y = 0.0004621x + 0.079; *P* = 0.303) in vegetables with Mg application rates. **d** The relationship between carbohydrates (y = 0.0008028x + 0.085; *P* = 0.191), proteins (y = 0.0009593x + 0.216; *P* = 0.667), vitamin C (y = 0.01318x + 0.02665; *P* = 0.001), and mineral nutrients (y = 0.01040x + 0.3155; *P* = 0.005) ln*RRs* in the edible portions of vegetables with varying application rates of organic sources. Where ln*RR* refers to the log of the response ratio (calculated in Section 2.3).

organic source(s) in addition to the recommended doses of inorganic fertilizer contributed greater.

3.3 Effects of site-specific covariates on quality improvement by fertilizer application

Climate and soil conditions affect fertilizer use efficiency (Dobermann et al. 2022; Ishfaq et al. 2022b). According to collected data about climatic zones, the nutritional quality of crop products was improved by 11.4% (10.3–12.6%; n = 5363) by fertilizer application, without significant differentiation across highlands, subtropical, arid and semi-arid, temperate, and tropical regions (Fig. 5c). The response of the nutritional quality of crops to fertilizer application varied with soil texture; silt loam (19.1%) and sandy loam (15.9%) allowed significantly greater quality improvement from fertilizer application than sandy soils (6.6%) (Fig. 5d). Fertilizer did not significantly affect crop quality on oxisols and anthrosols, but fertilizer effects were significantly positive on all other soil orders, with the greatest response of fertilizers on alfisols and histosols (Fig. S7a). Crop nutritional quality was increased by 11.7% (10.3–13.2%; n = 3946) by fertilizer application across studies with soil organic matter (SOM) reported, with the largest increase of 16.6% at SOM 2.5–5%. Fertilizer effects on crop produce quality were greater at SOM 2.5–5% and 1–2.5% (12.1%) than at SOM < 0.5% (6.1%). The remaining two effective ranges were SOM 0.5–1% (11.1%) and > 5% (8.3%) (Fig. 5e). Soil pH is an important predictor of the availability of applied nutrients to plants (Marschner 2012; Husson 2013). In studies reporting soil pH, the nutritional quality of crops was increased by 12.2% (10.8–13.6%; n = 4040) by fertilizer application, and the positive effect was found at pH 4.5–8.5 with no effect in highly acidic (pH < 4.5) or alkaline (pH > 8.5) soils (Fig. 5f). Crops responded positively to fertilizer

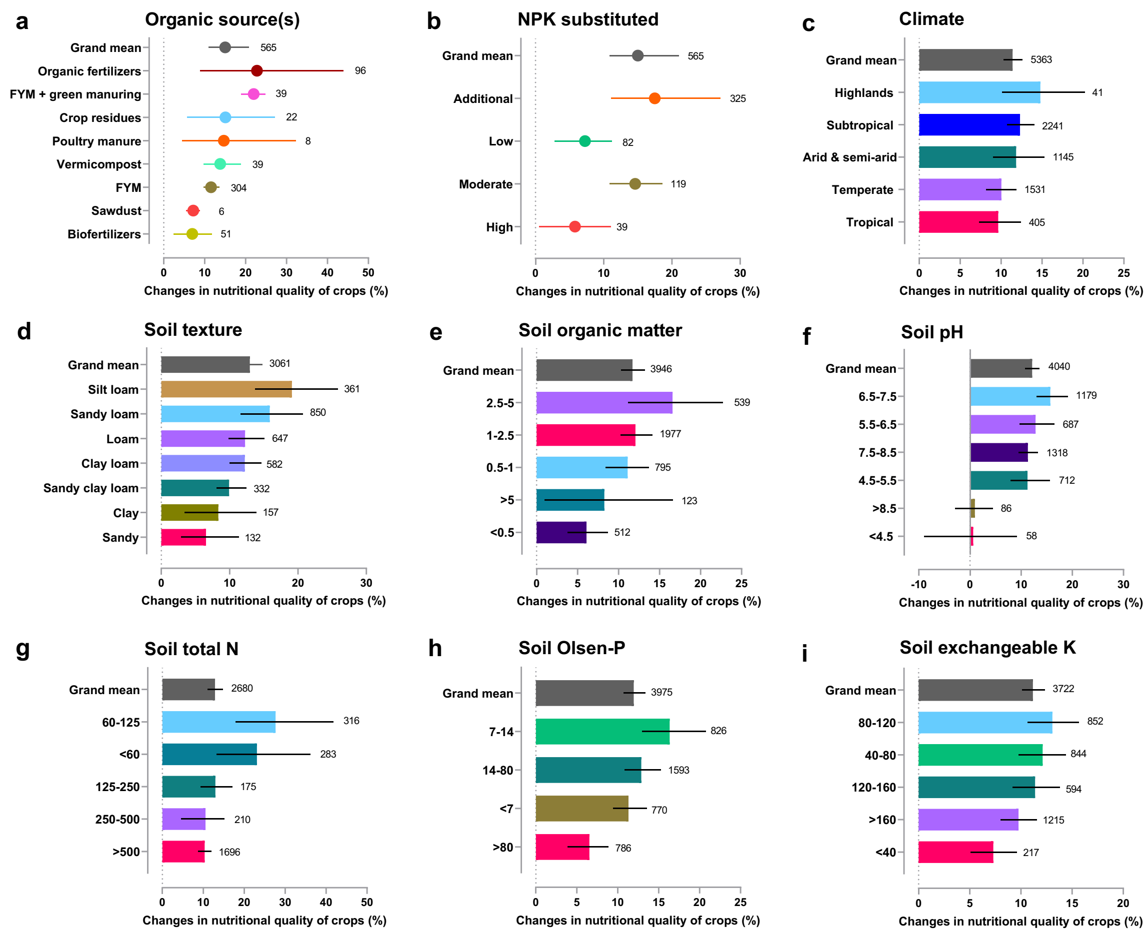

Fig. 5 Effects of site-specific covariates on the increase in the nutritional quality of food crops with fertilizer application. Variations in the nutritional quality of food crops with **a** the type of organic sources applied with mineral fertilizers and **b** the amount of inorganic fertilizers (NPK) substituted with organic source(s). Variations in the increase in crop nutritional quality with fertilizer application among various **c** climatic conditions, and different types/levels of soil **d** texture, **e** organic matter (%), **f** pH, **g** total nitrogen (mg kg^{-1}), **h** Olsen-phosphorus (mg kg^{-1}), and **i** exchangeable potassium (mg kg^{-1}). Colored dots/bar graphs represent the mean effect sizes with 95% confidence intervals (CIs). Mean values < 0 indicate a negative effect, while mean values > 0 indicate a positive effect (significant effect, $P < 0.05$, if 95% CIs did not overlap 0). The numbers (n) on the right side of the whiskers indicate the data records for each group.

application at different levels of soil total N, Olsen-P, and Ex-K (Fig. 5g–i). Soils containing 60–125 mg N kg^{-1} total N had greater quality improvement (27.7%) upon fertilizer application than those with more than 500 mg N kg^{-1} total N (10.3%) (Fig. 5g). Soils with 7–14 mg P kg^{-1} showed greater quality improvement (16.4%) by fertilizer application than those with more than 80 mg P kg^{-1} (6.5%) (Fig. 5h). In the case of Ex-K, the largest effect was derived from soils with 80–120 mg Ex-K kg^{-1}, with the lowest and significant effect when Ex-K was less than 40 mg kg^{-1} (Fig. 5i).

The scatter plot matrix indicated significant relationship in most of the site-specific covariates in increasing the nutritional quality of food crops by fertilizer application (Fig. S8). We ranked these site-specific covariates according to their relative importance for predicting quality improvement. Results showed that soil pH and Ex-K were the most important variables while texture and total N were the least important variables in improving the nutritional quality of food crops with fertilizer application (Fig. S9).

Different continents have distinct natural, agricultural, and economic conditions affecting crop breeding, soil fertility, fertilizer consumption, and crop yields (Welch et al. 2013; Muthayya et al. 2013; Bouis and Saltzman 2017). In a continent-wise comparison ($n = 5353$), we found that the increase in the nutritional quality of crops with applied fertilizers was greatest in Africa (29.8%; [19.7–43.1%]), and significantly lower in Asia (12.8%; [10.6–15.4%]; excluding China) and Europe (12.3%; [9.3–15.6%]). As a particular country that contributes significantly to

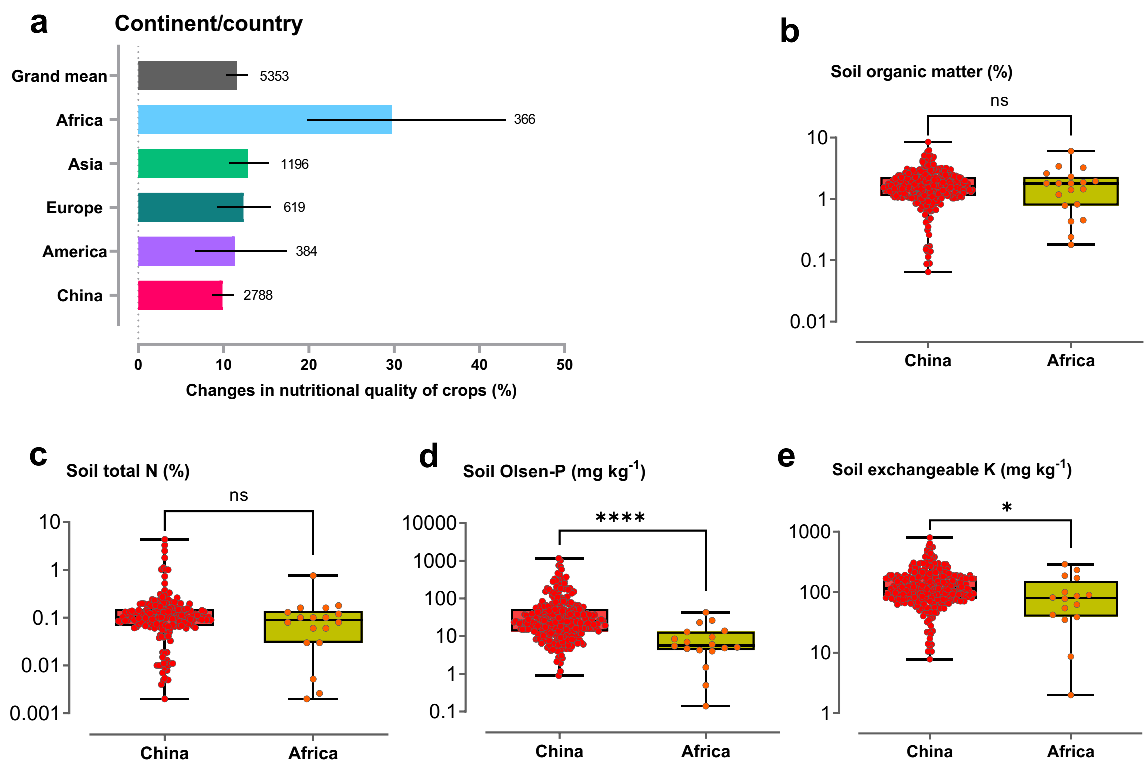

Fig. 6 Variations in the nutritional quality of food crops with fertilizer application among different continents. **a** Cross-continent responsiveness in the increase in the nutritional quality of food crops with fertilizer application. A comparison of China and sub-Saharan Africa in terms of soil **b** organic matter, **c** total nitrogen, **d** Olsen-phosphorus, and **e** exchangeable potassium concentrations. In panel **a**, colored bar graphs represent the mean effect sizes with 95% confidence intervals (CIs) and the numbers (n) on the right side of the whiskers indicate the data records for each group. In panels **b**–**e**, box graphs show the geometric mean while the whiskers represent the maximal/minimal values. Asterisks indicate significant differences at $*P < 0.05$ and $***P < 0.001$, according to the Mann-Whitney test. Where ns refers to non-significant.

fertilizer consumption and crop production worldwide, China had the least increase in crop nutritional quality in response to fertilizer (9.9%; [8.5–11.2%]) (Fig. 6a). We next analyzed potential soil factors influencing fertilizer responses in Africa and China, two regions where future crop production is of paramount importance to ensure food and nutritional security. There was no clear difference in the SOM (Fig. 6b) and soil total N (Fig. 6c); however, soils contained significantly lower concentrations of available P ($P < 0.0001$) and K ($P < 0.05$) in Africa. The comparatively higher responsiveness of fertilizer in Africa as compared to China is most likely due to the high prevalence of nutrient-poor soils in Africa and the low prevalence in China (Fig. 6d and e).

3.4 Differential effects of fertilizer application on crop yield

Quality traits are closely associated with crop yield due to internal biological and physiological crosstalk during crop development (Scheelbeek et al. 2018; Lu and Zhu 2022; Assunção et al. 2022). Overall, yield significantly ($P < 0.05$) increased, by 30.9% (28.2–33.7%; $n = 2496$), with fertilizer application (Fig. 7 and Fig. S6b). The yield increase varied with fertilizer types and crop species groups. Sole application of N, P, K, or Mg significantly increased yields of the five different groups of crops, and micronutrients and organic amendments did so, too. Thereby, N application led to a larger effect than application of P, K, Mg, Ca, or S. Application of micronutrients in fruits led to an increase in yield similar to that of N + P + K application. Out of various combined fertilizer applications, the largest increase in yield was obtained with the application of N + P + K + organic amendment(s) or N + P + K across crop groups. Notably, N + P + K (102.4%; [69.7–144.3%) and N + P + K + organic amendment(s) (94.7%; 64.5–133.2%) showed significantly greater impact on vegetable yield than other treatments. No effect was found for N + organic amendments in vegetables and Ca or S in pulses/oil crops.

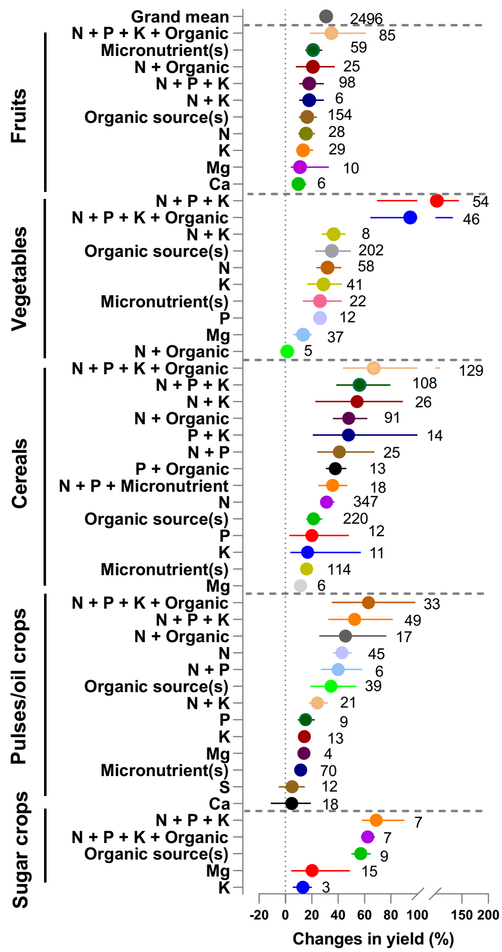

Fig. 7 The contribution of the sole and combined application of fertilizers in increasing the yield of fruits, vegetables, cereals, pulses/oil crops, and sugar crops. Colored dots represent the mean effect sizes with 95% confidence intervals (CIs). Mean values < 0 indicate a negative effect, while mean values > 0 indicate a positive effect (significant effect, $P < 0.05$, if 95% CIs did not overlap 0). The numbers (n) on the right side of the whiskers indicate the data records for each group.

Fertilizer application improved crop yield significantly by 34.7% (31.5–38.3%; $n = 2220$) across different climatic conditions (Fig. 8a). The mean effect was largest (40.7%) under subtropical conditions, and significantly lower (27.1%) under temperate conditions, with the response in other climate zones intermediate. In studies recording soil texture, fertilizer application increased yield by 31.4% (27.9–35.0%; $n = 1737$). The increases in yield with fertilizer application were greatest (60.9%) when crops were grown in silt loam, and clay (18.4%) and sandy (15.9%) soils gave rise to significantly less impact than silt loam (Fig. 8b). Fertilizer effects decreased in the order alfisols (66.6%), ultisols (58.6%), histosols (48.5%), and inceptisols (45.0%), but were significantly greater than on soil with weak response, such as fluvisols (12.0%), mollisols (10.2%), and vertisols (4.2%) (Fig. S7b). In studies reporting SOM, yield increase of all crops upon fertilizer application was 30.4% (27.2–33.9%; $n = 1916$), with larger increases at SOM 2.5–5% and lower increases at SOM < 0.5% and > 5% (Fig. 8c). In studies reporting soil pH, fertilizer additions increased yield by 32.7% (29.7–35.9%; $n = 2026$) across all crops, and crops were more responsive on neutral soils (pH 6.5–7.5) in comparison with alkaline (pH > 8.5) soils (Fig. 8d). In studies reporting total soil N concentration, on average, yield was increased by 37.5% (33.5–42.0%; $n = 1577$) by fertilizer application. The increase in yield upon fertilizer application was greater at medium soil N concentrations such as 250–500 mg kg^{-1}, 125–250 mg kg^{-1}, and 60–125 mg kg^{-1}, and least at higher and lower soil N concentrations (Fig. 8e). In studies reporting available P in soils, the increase in yield with fertilizer application at available P concentration of 7–14 mg kg^{-1} (49.2%) and < 7 mg kg^{-1} (37.9%) was significantly greater than at 14–80 kg^{-1} (21.9%) and > 80 mg kg^{-1} (15.2%) (Fig. 8f). In P-depleted soils, P fertilizer application can be less effective due to the strong P binding capacity (Lambers 2022). In studies reporting soil Ex-K, the increase in yield following the application of fertilizers was 20.1% at > 160 mg kg^{-1} soil Ex-K, significantly higher than zero, but it was significantly lower than the grand mean (29.9%), while responses greater than the grand mean were recorded at 40–80 mg kg^{-1} (40.6%) and 80–120 mg kg^{-1} (36.0%) soil Ex-K (Fig. 8g). The scatterplot matrix indicated significant relationship in most of these site-specific covariates in increasing the yield of food crops by fertilizer application (Fig. S10). The relative importance of the site-specific covariates is shown in Fig. S11, suggesting that soil total N was one of the most important variables while soil pH and Ex-K were the least important variables in improving the yield of food crops with fertilizer application.

3.5 Correlative effects of fertilizer application on crop yield and nutritional quality

Linear regressions were performed to evaluate correlative properties of crop yield increase and nutritional quality increase due to fertilization. There were strong positive correlations between the fertilizer responses of carbohydrate concentrations and yield in cereals, vegetables, and fruits (Fig. 9a); protein concentrations and yield in cereals and pulses/oil crops (Fig. 9b); oil concentrations and yield in cereals and pulses/oil crops (Fig. 9c); vitamin C concentrations and yield in fruits (Fig. 9d); and mineral nutrients concentrations and yield in fruits, vegetables, and cereals (Fig. 9e). There was negative correlation between protein concentrations and yield in vegetables (Fig. 9b), no relationship was found between vitamin C concentrations and yield in vegetables (Fig. 9d), and TSS and yield in fruits, vegetables, and sugar crops (Fig. 9f). General positive relationships

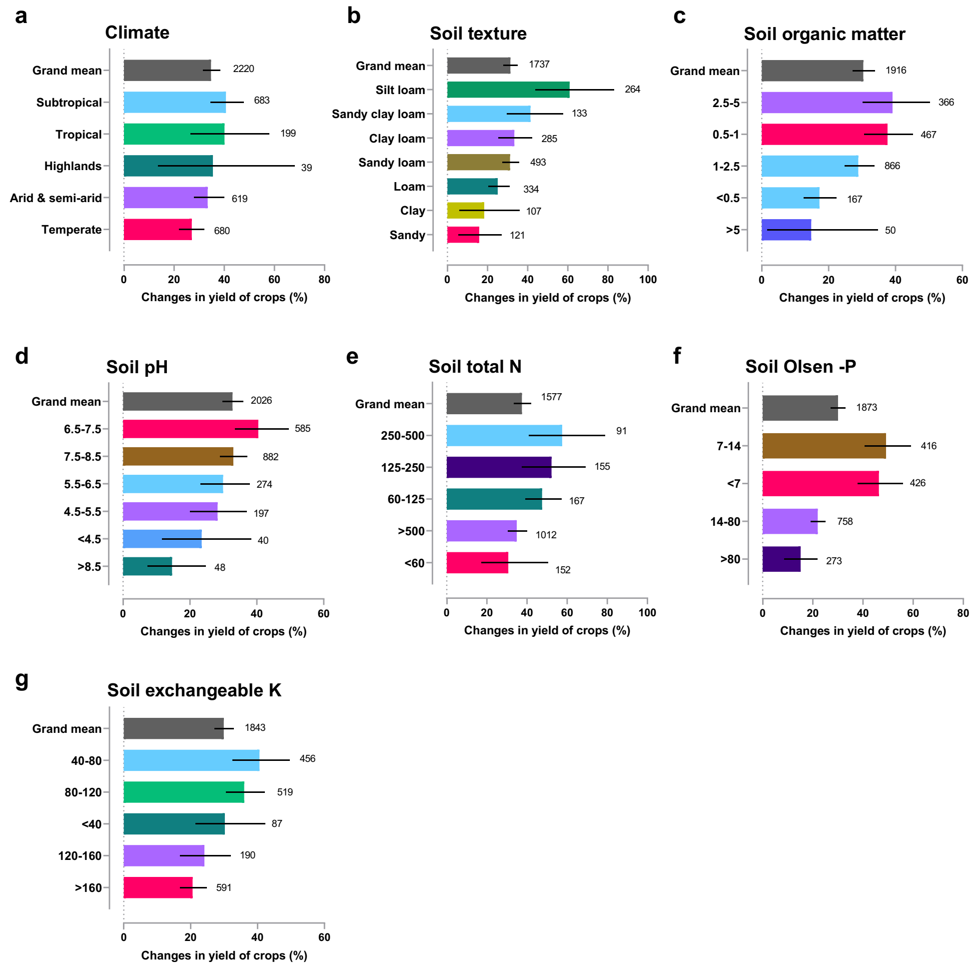

Fig. 8 Effects of site-specific covariates on the increase in yield of food crops with fertilizer application. Effects of **a** climatic conditions, and soil **b** texture, **c** organic matter (%), **d** pH, **e** total nitrogen (mg kg^{-1}), **f** Olsen-phosphorus (mg kg^{-1}), and **g** exchangeable potassium (mg kg^{-1}) on the increase in yield of crops with fertilizer application. Colored bar graphs represent the mean effect sizes with 95% confidence intervals (CIs). Mean values < 0 indicate a negative effect, while mean values > 0 indicate a positive effect (significant effect, $P <$ 0.05, if 95% CIs did not overlap 0). The numbers (n) on the right side of the whiskers indicate the data records for each group.

between the fertilizer responses of nutritional quality and yield of food crops suggested that nutritional quality and yield can be improved in tandem with appropriate fertilizer applications (Fig. 9 and Table S2).

4 Discussion

This meta-analysis synthesizes information from 551 field experiment-based articles and highlights that fertilizer application increases the yield and nutritional quality of crop plants in a nutrient- and crop-dependent manner. The results provide insights into the effects of site-specific covariates related to soils and climate on the increase in yield and nutritional value of food crops by fertilizer application, thereby informing on the likely effectiveness of fertilizer management practices in a given production environment, supporting the development of strategies to obtain higher yields and better quality products.

The findings show that nutrient interactions make important contributions to increasing the nutritional quality of produce. Sole application of N or P fertilizers fails to increase the concentration of carbohydrates, oil, vitamin C, or TSS in many crop groups; however, combined application of K with N, P, or both has the greatest positive effects on the nutritional quality of crops (Fig. 3). N + P + K and N + P + K + organic amendments are the most effective nutrient management solution for increasing the concentrations of key quality components (i.e., carbohydrates, proteins, oil, vitamin C, lycopene/carotenoids, mineral nutrients, and TSS) of food crops (Figs. 2 and 3). We speculate that the greater increases in yield and nutritional quality obtained by combined application of inorganic fertilizers and organic amendment(s) are due to four main reasons. Firstly, the application of organic amendment(s) in fertilizer programs can improve the physicochemical properties, microbiome diversity, and eco-functionality of the soil, thus favoring root growth and enhancing the availability of nutrients for plant roots (Tiessen et al. 1994; Bonanomi et al. 2020; Hofland et al. 2020; Kravchenko et al. 2021; Ling et al. 2022). Secondly, the additional supply of multiple nutrients, i.e., Ca, Mg, Zn, and Fe from organic sources may contribute to improving the nutritional quality of agricultural produce (Gil

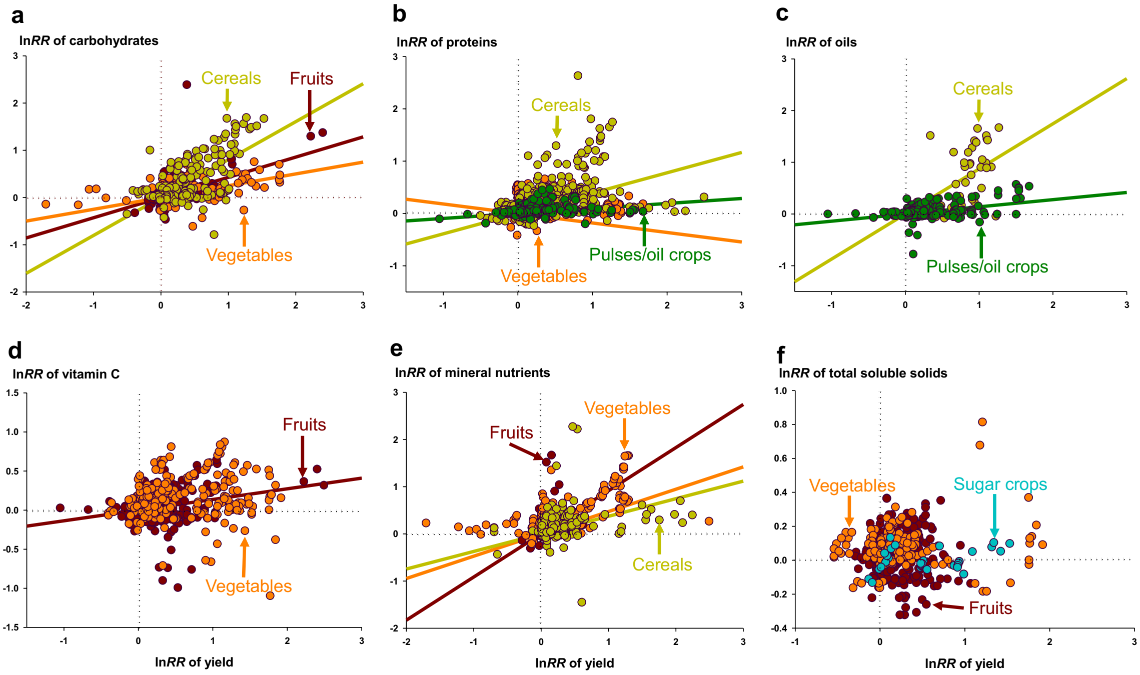

Fig. 9 Relationships between yield and nutritional quality of different crop groups driven by fertilizer application. Linear regressions indicate positive relationships between yield and quality traits **a** carbohydrates in fruits (R^2 = 0.4317; P < 0.001), vegetables (R^2 = 0.3967; P < 0.001) and cereals (R^2 = 0.6492; P < 0.001), **b** proteins in vegetables (R^2 = 0.1473; P < 0.001), cereals (R^2 = 0.3728; P < 0.001), pulses/oil crops (R^2 = 0.6413; P < 0.001), and **c** oil concentrations in pulses/oil crops (R^2 = 0.3281; P < 0.001) and cereals (R^2 = 0.6926; P < 0.001). Positive correlations between yield and **d** vitamin C in fruits (R^2 = 0.4695; P < 0.001) and vegetables (R^2 = 0.3108; P < 0.001), **e** mineral nutrients in fruits (R^2 = 0.2127; P < 0.001), vegetables (R^2 = 0.5627; P < 0.001) and cereals (R^2 = 0.1288; P < 0.001), and **f** total soluble solids in fruits (R^2 = 0.1315; P < 0.001), vegetables (R^2 = 0.4766; P < 0.001), and sugar crops (R^2 = 0.1364; P < 0.045). Where ln*RR* refers to the log of the response ratio (calculated in Section 2.3).

et al. 2008; Singh et al. 2019; Henneron et al. 2020). Thirdly, the nutrient releasing capacity of the organic amendment(s) is usually slow and long-lasting and nutrients become available only after mineralization, thus ensuring continuous supply of nutrients throughout the growing season (Torn et al. 1997; Kan et al. 2022). Fourthly, at any given site, any nutrient can be the limiting nutrient for either yield or quality as indicated by Liebig's law of the minimum. Thus, the larger number of nutrients applied by combined fertilizers increases the odds of fulfilling the need for the most limiting nutrient (Tiessen et al. 1994; Singh et al. 2019).

The replacement of 25–50% of the inorganic NPK fertilizers by organic amendment(s) could attain maximum nutritional quality of food crops. The substitution of 25% mineral N fertilizers by organic amendment(s) would circumvent approximately 26.93 million tonnes of global dependence on synthetic N inputs (FAOSTAT 2022), and in addition benefit soil eco-functionality (Tiessen et al. 1994; Ling et al. 2022). High replacement of inorganic NPK fertilizers by organic sources (> 50%), however, generally results in a decrease in the nutritional quality of food crops (Fig. 5b), which might be due to the lower immediate availability of mineral nutrients in organic sources than inorganic fertilizers and a short-term decline in soil fertility (Zhang et al. 2019a, b, c, d).

Obtaining higher yield and better quality while maintaining long-term soil fertility is a key target of crop production although the relationships between yield and quality remain unclear. Some previous studies have reported that aspects of nutritional quality were negatively related to yield due to the "dilution effect," variety/genotypic variations, or other management practices (Correndo et al. 2021; Si et al. 2022; Miner et al. 2022), but this is not always observed (White et al. 2009; Assefa et al. 2018; Pan et al. 2020; Guangxin et al. 2022). Our meta-analysis is based on a wide set of nutrient management practices, and overall, positive relationships between yield and most of the quality traits were observed when the yield was increased through fertilizer application (Fig. 9 and Table S2).

Vegetables showed the greatest increase in yield and nutritional quality in response to fertilizer application (Fig. 2c and Fig. 7). This might be due to greater fertilizer requirements of many vegetable crops in comparison to other crops (Ficiciyan et al. 2021; Sánchez et al. 2021). Another possible reason is that vegetables are often short duration crops with a larger harvest index than many other crops, suggesting that fertilizer applications are more likely to contribute to the development of their edible organs and related quality traits (Shi et al. 2010; Ficiciyan et al. 2021). Finally, vegetables like leguminous plants can be very efficient in nutrient acquisition due to their root system architecture (Shi et al. 2010; Ishfaq et al. 2021b). These interpretations suggest directions for future research to understand the physiological mechanisms behind the variation in responses of yield and nutritional quality to fertilizers among different plant groups.

Environmental conditions change the physicochemical properties of soil and plant performance substantially (Lesk et al. 2021; Ishfaq et al. 2022b). The effects of site-specific climatic conditions and seven important edaphic factors, namely, soil texture and order, SOM, pH, total N, Olsen-P, and Ex-K, on the yield and nutritional quality of food crops were evaluated to identify the environmental conditions influencing the impact of fertilizer addition on improving yield and nutritional quality of food crops. In general, our results show that crops cultivated in regions with higher temperatures, poor SOM, extremes in pH, and predominantly in sandy soils might be prone to smaller increases in yield and nutritional quality with fertilizer applications (Figs. 5 and 8). Highlands contained a higher level of SOM (Fig. 10), which may improve the soil eco-functionality and availability of mineral nutrients for crops and, thereby, lead to larger response to applied fertilizers (Solomon et al. 2002; Lal 2004; Lichter et al. 2008). Among soil properties, optimal levels of SOM, N, P, and K can precondition the improvement of yield and nutritional quality of food crops, and the application of fertilizers has larger effects on the yield and nutritional quality of crops grown in these soils (Figs. 5 and 8). Under extreme conditions, the limited increase in yield and nutritional quality of crops grown on soils with low SOM ($< 0.5\%$) underscores the consequences of the low

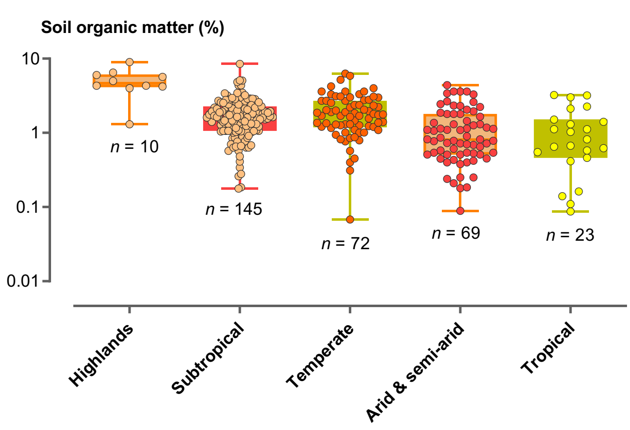

Fig. 10 Changes in soil organic matter under different climatic conditions. The numbers (*n*) at the lower side of the whiskers indicate the data records for each group.

nutrient buffering capacity of these soils (Torn et al. 1997; Mäder et al. 2002; Schmidt et al. 2011). The improvement in crop quality was lowest at the lowest level of soil Ex-K (< 40 mg kg^{-1}) (Fig. 5i), possibly because the depleted clay mineral needs to be replenished before a plant response occurs (Wakeel and Ishfaq 2022). The non-significant responses of nutritional quality to fertilizer applications in highly acidic ($pH < 4.5$) and alkaline soils ($pH > 8.5$) is possibly due to the effects of exchangeable cations: H^+, Fe^{3+}, and Al^{3+} in acidic soils and Na^+ and Ca^{2+} in alkaline soils, which can inhibit root growth, compete with nutrient cations applied in fertilizers, and alter the availability of certain nutrients by forming sparingly soluble oxides, phosphates, or carbonates (Guo et al. 2010; Marchner 2012; Husson 2013). Globally, approximately 950 million hectares of ice-free land are acidic (Uexküll and Mutert, 1995), and more than 833 million hectares are salt affected (FAO 2021b). Both conditions are potentially limiting agricultural productivity, and a larger dataset derived from these types of soils is required to more precisely quantify the contribution of fertilizers and other management practices (i.e., liming, manure, and gypsum application) to world food production.

The increase in the nutritional quality of food crops with fertilizer application was greatest in Africa, compared to other regions of the world such as Asia (excluding China), Europe, America, and China (Fig. 6a). This underscores the importance of fertilizers to boost food and nutritional security in Africa. A closer look at the data shows no clear difference in SOM (Fig. 6b) and total N (Fig. 6c) between Africa and China, but the soils of Africa had significantly less phytoavailable P and K (Fig. 6d and e). Nutrient deficiency is widespread in the soils of sub-Saharan Africa (van Ittersum et al. 2016; Kihara et al. 2017; Ten Berge et al. 2019; Manzeke et al. 2019; Gashu et al. 2021; Kihara et al. 2020), and crop production on nutrient-poor soils is generally more responsive to the application of fertilizers. By contrast, as Chinese farmers have developed intensive cultivation systems, increasing amounts of fertilizers have been applied in recent decades and this enrichment of the soil may have contributed to a lower responsiveness to fertilizer (Zhang et al. 2015a, b, c, d, e; Cui et al. 2018; FAOSTAT 2022; Ishfaq et al. 2022a; Chen et al. 2022a, b).

The increase in the nutritional quality of food crops with fertilizer application can minimize nutrition-related risks, especially in the regions where staple food is produced and consumed locally with little applied fertilizers (Cakmak 2008; Manzeke et al. 2012; Ishfaq et al. 2021a; Assunção et al. 2022). Although combined nutrient management practices (organic and inorganic) have been well practiced by some smallholder farmers (Zhang et al. 2019a, b, c, d), the availability of organic fertilizers/amendments needs to be ensured particularly in nutrient-deficient regions, to produce nutritious food. Providing incentives to farmers to adopt better soil and crop management practices (i.e., organic fertilizers or other organic amendments, legume-based rotation, and liming) might ensure the production of nutritious food and contribute to the availability of sustainable, healthy diets.

Currently, fertilizer application improves crop nutritional quality by 11.9% and yield by 30.9% on average; combined application of NPK and organic amendments can further boost crop nutritional quality and yield in the future when optimal soil conditions become more prevalent, such as pH 6.5–7.5, SOM 2.5–5.0%, soil total N 60–125 mg kg^{-1}, Olsen-P 7-80 mg kg^{-1}, and Ex-K 40-120 mg kg^{-1}. In our analysis, we did not assess the effects of other important management practices such as liming, legume-based rotation, and irrigation which can also affect the availability of mineral nutrients and nutritional quality of food (Navarro et al. 2010; Zhao et al. 2022; Mudare et al. 2022), and systematic literature review is suggested to quantify their contribution. Predicted effects of climate change and extreme weather events may also influence some of these results (Scheelbeek et al. 2018; Jägermeyr et al. 2021; Lesk et al. 2021; Ishfaq et al. 2022b), requiring in-depth investigations. In future studies, it will be important to assess the complex interactions of fertilization × genotypes × environmental stresses on yield and nutritional quality of food crops holistically to ensure a more sustainable global food system.

5 Conclusions

Fertilizer programs implemented in the past have mainly focused on improving crop yields, with little priority given to the nutritional outcomes for human health. There was a need to comprehensively quantify how different fertilization strategies contribute to accumulation of nutritionally relevant components in food crops. By analyzing 7859 data pairs from 551 field experiments, we concluded that (i) on average, fertilizer application improves crop yield by 30.9% (CI: 28.2–33.7%) and nutritional quality by 11.9% (CI: 10.7–12.1%); (ii) over all sites, N + P + K or N + P + K + organic amendment(s) is the most effective nutrient management solution for increasing the concentrations of key quality components (i.e., carbohydrates, proteins, oil, vitamin C, lycopene/carotenoids, mineral nutrients, and TSS) of food crops; (iii) vegetables are the most responsive to fertilizer application in terms of improving nutritional quality; (iv) in general, crops cultivated in regions with higher temperatures, poor SOM, extreme pH, and predominantly in sandy soils might be prone to smaller increase in nutritional quality with fertilizer applications; (v) the increase in the nutritional quality of food crops with fertilizer application is greatest in Africa, compared to other regions of the world such as Asia (excluding China), Europe, America, and China; (vi) the nutritional quality and yield of food crops can be improved in tandem with appropriate fertilizer applications. In a nutshell, our global meta-analysis offers a useful quantitative framework to better understand the effectiveness of fertilizer management practices in a given production environment (i.e., soil properties and climatic conditions), fostering the sustainable production of nutritious and healthy diets for human consumption.

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Authors' contributions M. I. and X. L. were involved in conceptualization, data curation and analysis, and manuscript writing. Y. W., J. X., M. U. H., H. Y., L. L., B. H., and I. E. were involved in data collection. P. J. W., I. C., W. S. C., J. W., W. V. D. W., C. L., and F. Z. were involved in writing, review, and editing the manuscript.

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