The landscape of world research on fertilizers: a bibliometric profile

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The environmental cost of increased fertilizer application is an emerging concern, worsened by farmers' reluctance to adopt alternative fertilizer products. The right fertilizer must be applied at the correct rate and time at the right place for maximum benefit. However, empirical evidence from across the world suggests a deviation from these normative strategies. Considering the lack of a holistic overview of the knowledge structure of the growing literature on fertilizers, we conducted a bibliometric analysis using data extracted from the Web of Science Core Collection database. We identified the publication trend and the important authors, journals and countries contributing to research on fertilizers. In addition, the topics that have received research attention were also identified. We can locate that issues like nitrogen fertilizers and their effect on growth and yield will never lose relevance. Most importantly, researchers are now dealing more with topics related to the externalities of chemical fertilizer use. Our findings will help interested researchers to gain systematic insights into the knowledge structure of fertilizer research.

Keywords: Bibliometric analysis, environmental cost, fertilizer, knowledge structure, research trend.

NITROGEN fertilizers play a crucial role in ensuring global food security[1], due to which most countries promote fertilizer use through policy interventions. While fertilizers are essential for food production, excess fertilizer hampers the ecosystem. Though, in general, fertilizer policies are expected to bring changes in fertilizer use patterns and improve fertilizer use efficiency, the targets of such policies depend more on the countries' requirements. Concentrating on increasing fertilizer consumption will not benefit the countries in the long run, as the crop response to fertilizers may plateau and decline further if fertilizers are used beyond optimal quantities. Hence, the soil nutrient budgeting estimations that quantify the nutrient input and recovery from the soil become essential. If nutrient inputs are higher than the levels required and recovered by crops, the available excess nutrients cause ecosystem damage. To address this, several biofertilizers and organic fertilizer products are being developed worldwide as alternatives to chemical fertilizers. Though these fertilizer products cannot entirely replace chemical fertilizers, they can help reduce their excess consumption and hence help reduce environmental effects. Despite these benefits, the adoption of such bio-based fertilizer products is poor in most parts of the world.

Against this backdrop, we summarize the worldwide research on fertilizers using bibliometric analysis. Bibliometric analysis of fertilizer research will help map current trends, and quantify the research volume and scholarly attention gained by the topic. In addition, the most researched themes within fertilizers, and contributing authors, organizations and countries can also be identified. This comprehensive bibliometric review can contribute to a deeper understanding of fertilizer research and provide facts that could inspire scholars in this field to formulate their future research targets. Further, for readers outside this field, this article can act as a beginner's guide for navigating through different domains of fertilizer research to explore their interests.

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Data and methods

To uncover the scientific research landscape on fertilizers, we performed a trend analysis of the publications followed by science mapping. We started our bibliometric study by searching the keyword 'Fertilizer*' in the title and author keyword fields of the Web of Science (WoS) Core Collection database in October 2021. WoS has emerged as the major database used for large-scale bibliometric studies. Since research on fertilizers is being conducted worldwide, WoS can act as a unified database to extract bibliometric data on quality publications. Our search strategy targeted limiting the data for the period 2000–21. We selected articles, proceeding papers, review articles, book chapters, and other document types were excluded. Our search specification resulted in a total of 22,004 documents, and we further

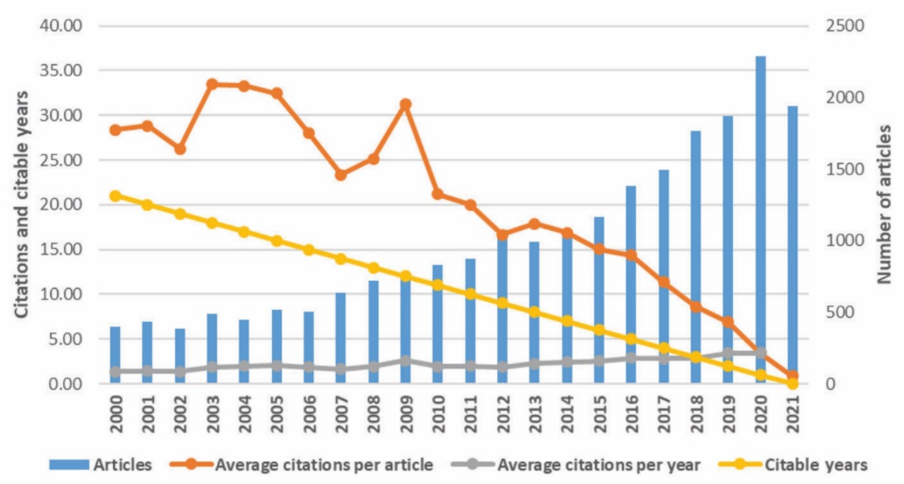

Figure 1. Scientific production of fertilizers and the citations received.

Table 1. Subject-wise publications on fertilizers

Subject area	Record count	Per cent of total
Agronomy	4956	22.52
Environmental sciences	4268	19.40
Soil science	3807	17.30
Plant sciences	3143	14.28
Agriculture multidisciplinary	2547	11.58
Horticulture	1397	6.35
Engineering environmental	1073	4.88
Ecology	891	4.05
Food science technology	854	3.88
Chemistry analytical	765	3.48
Agricultural engineering	750	3.41
Engineering chemical	747	3.40
Green sustainable science technology	739	3.36
Biotechnology applied microbiology	722	3.28
Water resources	679	3.09
Chemistry multidisciplinary	660	3.00
Multidisciplinary sciences	569	2.59
Energy fuels	458	2.08
Chemistry applied	449	2.04
Biology	407	1.85

extracted all the records related to these publications for analysis. Information was collected on authors, countries, institutions, journals, publication years, citations and cited references. We processed the collected data using the biblio-shiny package of R and the VOSviewer software.

Scientific production on fertilizers and citations received

Out of the total 22,004 documents identified, the majority (85%) were research articles, followed by proceeding papers (12%), review articles (2%) and book chapters (1%). These documents were extracted from 3109 sources (journals or books) the average number of citations per document was 15.12. A total of 54,816 authors were involved in publishing these articles. The number of published articles on fertilizers showed an increasing trend from 397 in 2000 to 2285 in 2020 (Figure 1). In 2021, a total of 1940 articles were published when we conducted the analysis. These articles have attracted citations which have increased over time, as suggested by the average number of citations per year. Though average citations per article show a decreasing trend, it only indicates that as the citable years are less over time, the articles published in recent years have not got enough time to accumulate citations. Over time, the citation numbers for articles published in recent years are expected to rise.

Agronomy, Environmental Sciences, Soil Science, Plant Sciences, and Agriculture Multidisciplinary are the major WoS subject fields in which most publications on fertilizers appear (Table 1). It must be noted here that the contribution of social sciences to the subject is comparatively poor. Only 302 publications appeared in Agricultural Economics and Policy during the study period. Considering the importance of fertilizers for farming and the necessity to create field-level evidence on fertilizer adoption and use efficiency, it is high time to intensify the social science research on fertilizers.

Top contributing countries to fertilizer research

The country analysis of scientific production of fertilizers suggested that China (8913), USA (6350), Brazil (4200), India (2787) and Canada (1874) are the top contributors in terms of the number of articles published. Figure 2 depicts the scientific production of countries (144 in this analysis). The colour intensity in Figure 2 is proportional to the number of publications by the countries. When total citations are considered, USA tops the chart with 65,313 citations, followed by China (62,550), India (18,005), Canada (17,356) and Brazil (14,075) (Figure 3).

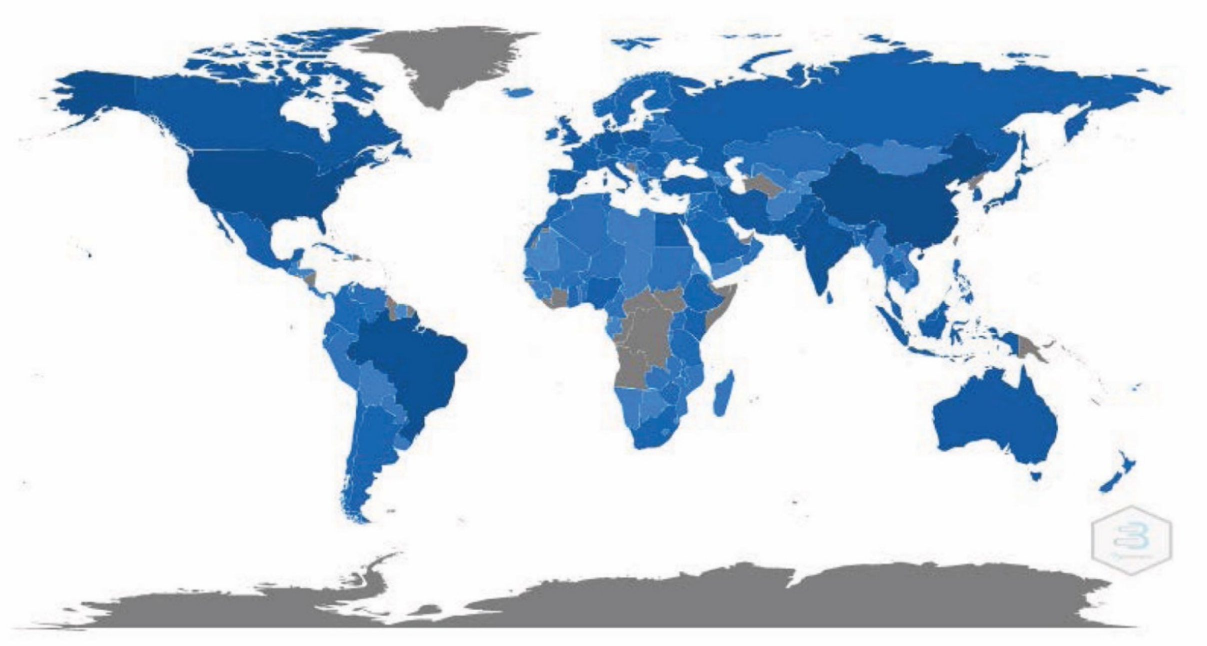

Figure 2. Country scientific production.

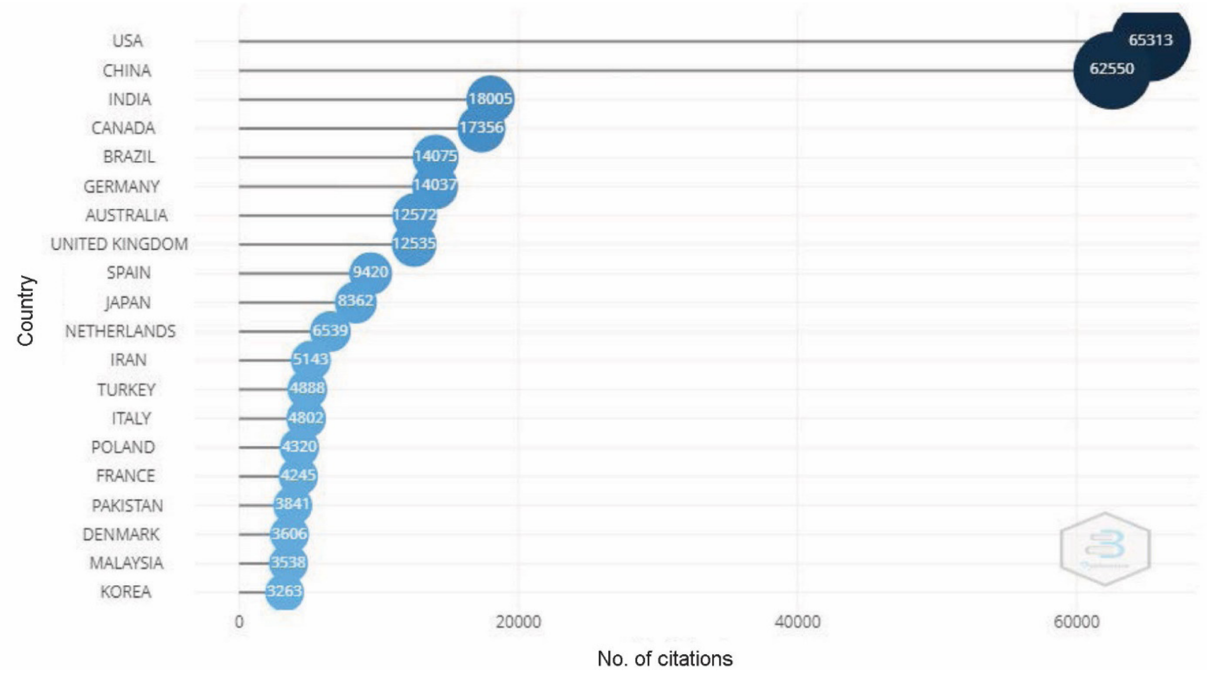

Figure 3. Most cited countries.

Analysis of journals on fertilizers

To find the important journals publishing on fertilizers, we identified the top 20 journals in terms of the number of publications, number of citations and *h*-index (Table 2). While *Communication in Soil Science and Plant Analysis*, *Journal of Plant Nutrition* and *Nutrient Cycling in Agroecosystems* topped the list for the number of publications, the maximum number of citations was received by *Plant and Soil*, and *Soil Biology and Biochemistry*. *Agriculture, Ecosystems and Environment* had the highest *h*-index, followed by *Field Crops Research*.

Identifying core journals is helpful for further analysis of articles published in them. Using Bradford's law, we identified the core journals publishing on fertilizers. Due to the large number of publications on the topic, 41 of the 3109

Table 2. Key journals publishing on fertilizers

Source	Articles	Source	Citations	Source	*h*-index
Communications in Soil Science and Plant Analysis	547	*Plant and Soil*	16,136	*Agriculture, Ecosystems & Environment*	55
Journal of Plant Nutrition	479	*Soil Biology and Biochemistry*	15,728	*Field Crops Research*	51
Nutrient Cycling in Agroecosystems	345	*Soil Science Society of America Journal*	14,223	*Soil Biology and Biochemistry*	51
Science of the Total Environment	330	*Agronomy Journal*	13,402	*Plant and Soil*	50
Agronomy Journal	278	*Agriculture, Ecosystems & Environment*	9938	*Science of the Total Environment*	48
Agronomy – Basel	257	*Field Crops Research*	9683	*Nutrient Cycling in Agroecosystems*	46
Agriculture, Ecosystems & Environment	253	*Journal of Environmental Quality*	9589	*Biology and Fertility of Soils*	44
Field Crops Research	235	*Bioresource Technology*	8560	*Soil and Tillage Research*	43
Hortscience	230	*Science of the Total Environment*	7337	*Bioresource Technology*	40
Plant and Soil	216	*Nutrient Cycling in Agroecosystems*	7317	*Journal of Agricultural and Food Chemistry*	40
Indian Journal of Agricultural Sciences	202	*Biology and Fertility of Soils*	7309	*Global Change Biology*	38
Sustainability	188	*Communications in Soil Science and Plant Analysis*	6730	*Agronomy Journal*	37
Journal of Cleaner Production	176	*Soil and Tillage Research*	6035	*Journal of Environmental Quality*	37
Environmental Science and Pollution Research	171	*Journal of Plant Nutrition*	5059	*Applied Soil Ecology*	35
Journal of Agricultural and Food Chemistry	164	*Geoderma*	5055	*Soil Science Society of America Journal*	34
Soil Science and Plant Nutrition	157	*Environmental Science and Technology*	4888	*European Journal of Agronomy*	33
Przemysl Chemiczny	153	*Chemosphere*	4382	*Geoderma*	33
Journal of Plant Nutrition and Soil Science	150	*Journal of Agricultural and Food Chemistry*	4370	*Agricultural Water Management*	32
Archives of Agronomy and Soil Science	149	*Nature*	4127	*Soil Use and Management*	32
Biology and Fertility of Soils	141	*Soil Science*	3912	*Canadian Journal of Soil Science*	30

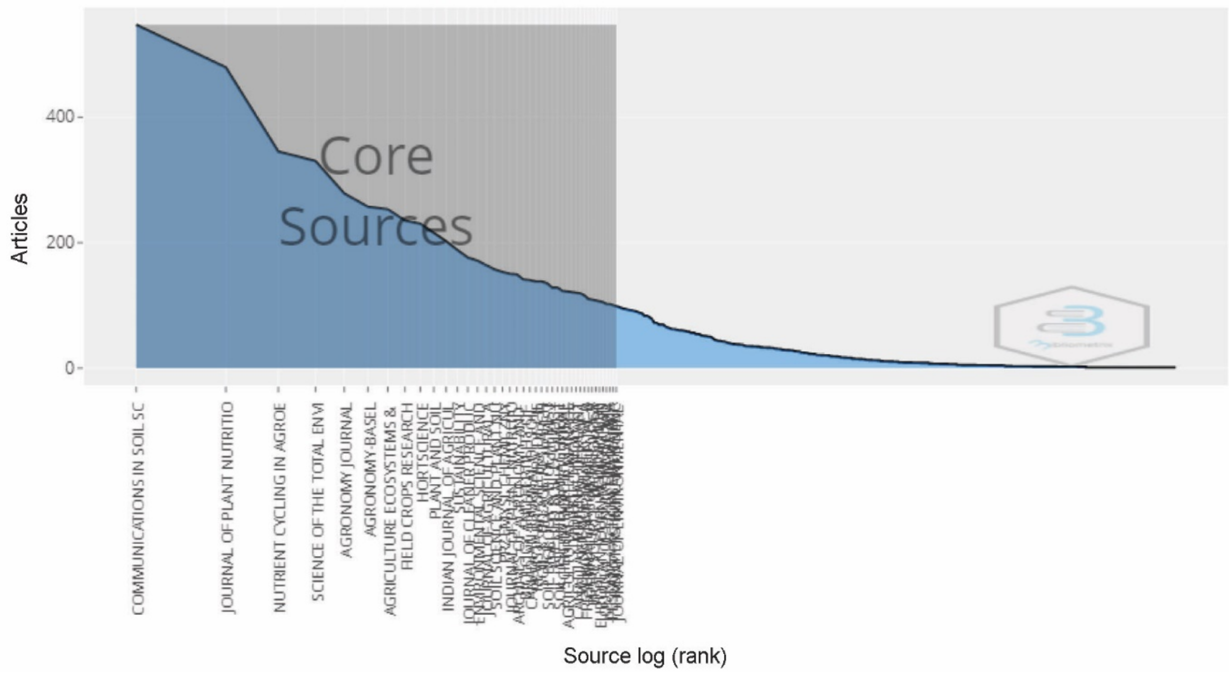

Figure 4. Core journals.

Table 3. Most important authors working on fertilizers

Author	Articles	Author	Local citations	Author	h-index
Shen, Q. R.	91	Liu, M. Z.	1133	Shen, Q. R.	38
Wang, Y.	82	Zhang, F. S.	953	Zhang, F. S.	28
Li, Y.	70	Shen, Q. R.	894	Li, M. Z.	27
Li, J.	66	Zhu, Z. L.	671	Ding, W. X.	22
Kumar, A.	63	Christie, P.	655	Vanlauwe, B.	22
Malhi, S. S.	63	Wu, L.	590	Christie, P.	21
Wang, J.	61	Chen, X. P.	555	Grant, C. A.	21
Zhang, F. S.	61	Ju, X. T.	555	Hejcman, M.	21
Balik, J.	58	Six, J.	505	Malhi, S. S.	21
Kumar, S.	57	Vanlauwe, B.	505	Li, Y.	20
Zhang, M.	55	Lu, S. Y.	491	Yang, X. M.	20
Zhang, J.	53	Liu, X. J.	484	Mclaughlin, M. J.	19
Liu, J.	52	Van Kessel, C.	430	Zhanj, J. B.	19
Trivelin, P. C. O.	52	Yan, X. Y.	430	Giller, K. E.	18
Liu, Y.	50	Yagi, K.	424	Six, J.	18
Mclaughlin, M. J.	49	Ni, B. L.	415	Trivelin, P. C. O.	18
Vanlauwe, B.	48	Shaviv, A.	415	Yagi, K.	18
Cerny, J.	47	Cantarella, H.	408	Yan, X. Y.	18
Zhang, X.	47	Robertson, G. P.	405	Ziadi, N.	18
Wang, H. Y.	46	Cui, Z. L.	404	Huang, Q. W.	17

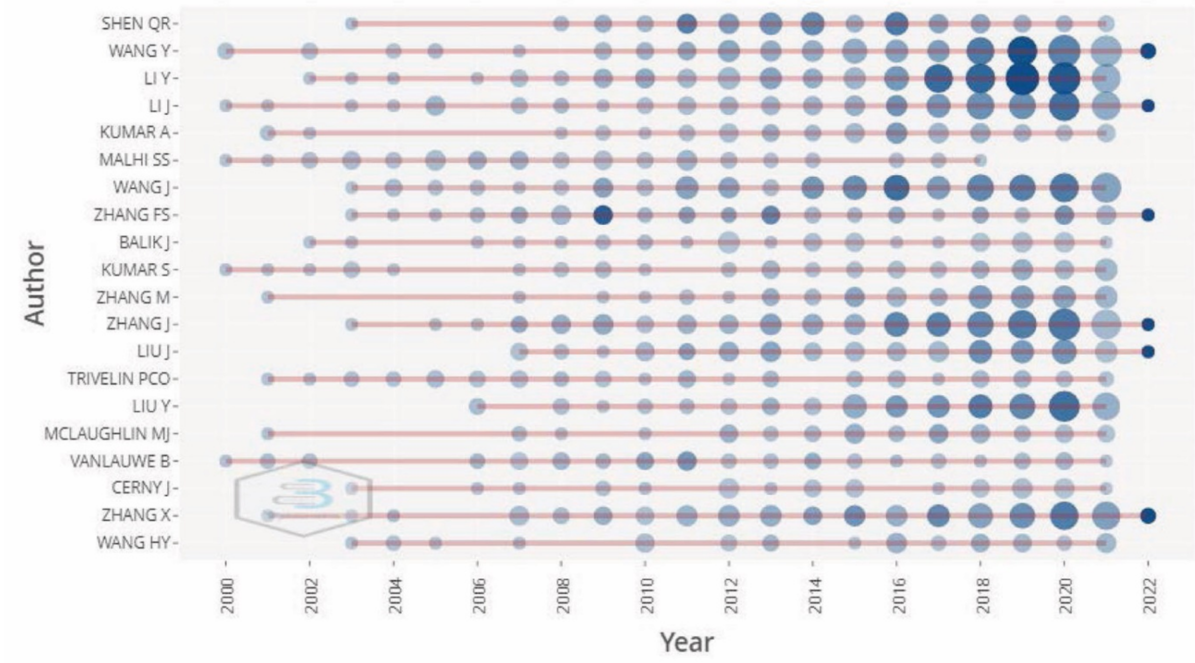

Figure 5. Top authors' production over time.

sources were identified as core journals (Figure 4). These journals contributed 33.12% (7289 articles) to the total publications on fertilizers.

Prolific authors and articles

The top authors identified in terms of the number of publications were Shen, Q. R. (91), Wang, Y. (82) and Li, Y. (70) (Table 3). While Liu, M. Z. (1133), Zhang, F. S. (953) and Shen, Q. R. (894) topped the list of authors with the highest local citations, Shen, Q. R. (38), Zhang, F. S. (28) and Li, M. Z. (27) had the highest h-index. Local citations are based on the WoS-indexed journals; hence, the actual citations received by the authors will be much higher than what is presented in Table 3. The top authors' production over time is presented in Figure 5, wherein the line represents the timeline of authors, the bubble size is proportional to the number of documents, and the colour intensity is proportional to the total citations per year. Wan, Y. and Li, J.

Figure 6. Most relevant organizations working on fertilizers.

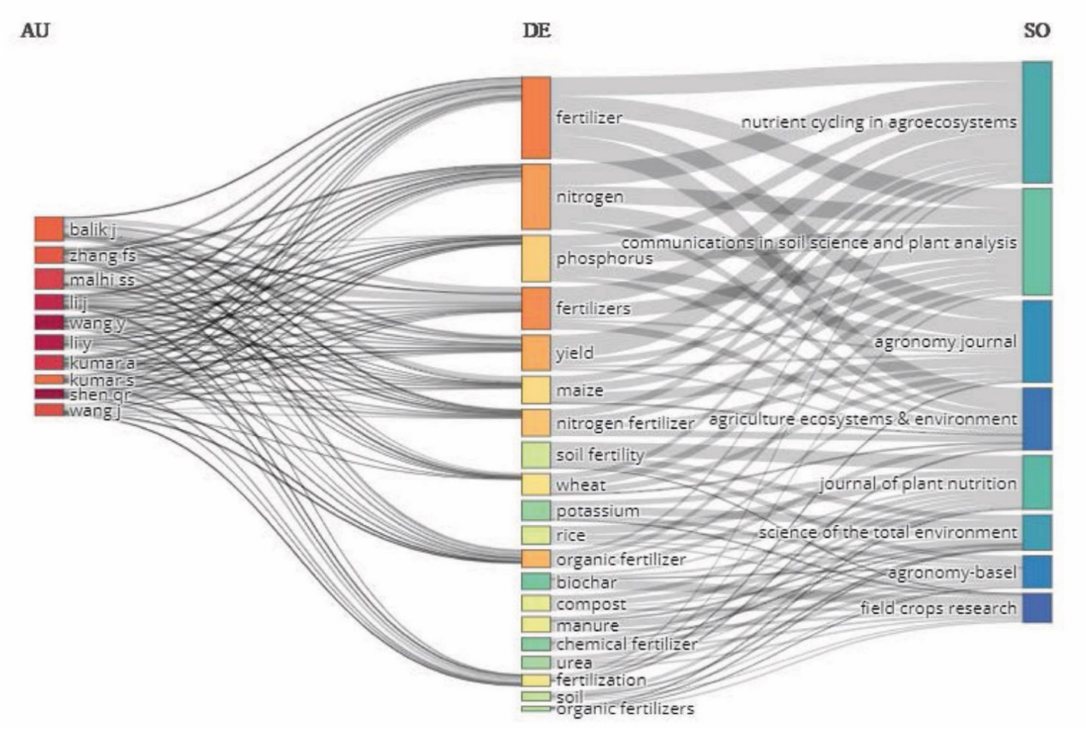

Figure 7. Three-fields plot showing the most influential authors, their critical topics of research and journals selected for publication.

are the authors with the most prolonged timeline, indicating that they have actively published articles on fertilizers throughout the study period. The number of articles by most authors peaked between 2015 and 2020, as visible from the bubble size.

The University of Florida, China Agricultural University, University of Sao Paulo, Nanjing Agricultural University, and the International Union of Soil Sciences were the leading research organizations working on fertilizers based on the number of publications (Figure 6). The three-field plot in Figure 7 shows the predominant authors, the research topics in which they work and the journals they publish. *Nutrient Cycling in Agroecosystems*, *Communications in Soil Science and Plant Analysis*, *Agronomy Journal*, etc. are among the key journals. Interestingly, in addition to the performance of nitrogen, phosphorus and potash fertilizers, researchers

Table 4. Most valuable documents

Articles	Total citations (TC)	Citations per year	Normalized TC
Galloway, J. N., 2004, *Biogeochemistry*	3116	173.11	93.57
Cordell, D., 2009, *Global Environ. Change*	2525	194.23	80.93
Galloway, J. N., 2003, *Bioscience*	1760	92.63	52.60
Kuzyakov, Y., 2000, *Soil Biol. Biochem.*	1619	73.59	57.09
Ju, X. T., 2009, *Proc. Natl. Acad. Sci. USA*	1488	114.46	47.69
Lehmann, J., 2003, *Plant Soil*	1082	56.95	32.34
Cakmak, I., 2008, *Plant Soil*	987	70.50	39.23
De-Bashan, L. E., 2004, *Water Res.*	955	53.06	28.68
Bouwman, A. F., 2002, *Global Biogeochem. Cycles*	929	46.45	35.37
Snyder, C. S., 2009, *Agrric. Ecosyst. Environ.*	771	59.31	24.71
Zhu, Z. L., 2002, *Nutr. Cycling Agroecosyst.*	679	33.95	25.85
Stehfest, E., 2006, *Nutr. Cycling Agroecosyst.*	666	41.63	23.74
Smil, V., 2000, *Annu. Rev. Energ. Environ.*	642	29.18	22.64
Marschner, P., 2003, *Soil Biol. Biochem.*	610	32.11	18.23
Hodson, M. J., 2005, *Ann. Bot., London*	596	35.06	18.36
Davidson, E. A., 2009, *Nature Geosci.*	577	44.38	18.49
Asai, H., 2009, *Field Crops Res.*	577	44.38	18.49
Robertson, G. P., 2009, *Annu. Rev. Environ. Resour.*	570	43.85	18.27
Ladha, J. K., 2005, *Adv. Agron.*	568	33.41	17.50
Hu, Y. C., 2005, *J. Plant Nutr. Soil Sci.*	547	32.18	16.85

also concentrated on the yield of crops like rice, wheat and maize, as well as on organic fertilizers and associated products like manure and compost.

Next, we identified the most impactful articles based on the total number of citations and citations per year (Table 4). The article by Galloway *et al.*, titled 'Nitrogen cycles: past, present, and future', published in *Biogeochemistry* in 2004, received the highest citations (3116). Authors have constructed global N cycles for the 1860 and early 1990s using appropriate data. In addition, they have made projections for the year 2050 as well. They have reported that human activities dominate the N budget at global and regional scales. In terms of citations received per year, the article by Cordell *et al.*, titled 'The story of phosphorus: Global food security and food for thought' published in *Global Environmental Change* tops the list. In this article, the authors have highlighted the vital issue of phosphorus shortage in the future for fertilizer production. They have pointed out that phosphorous production will peak around 2030, after which the world is expected to deal with decreasing stock of this critical raw material for fertilizer production. Thus, it is high time to include this issue in the long-term strategy formulation for future food security. The other articles in the list deal with topics like nitrogen cascade, priming effect, reducing risk due to intensive N fertilization practices, nutrient availability and leaching, agronomic biofortification of cereals using fertilizers, greenhouse gas emissions from crop production and fertilizer management practices, etc.

Most researched topics

The treemap in Figure 8 shows the author keywords that occur most often in the list of keywords of all the articles extracted for analysis. Nitrogen, growth, soil, yield, management and phosphorus are the keywords that appear most times. These six keywords together contribute 40% to the total, suggesting these as the topics that gained the most attention from researchers.

We also developed a keyword co-occurrence network to study the relationship between the keywords and the most researched topics (Figure 9). The network was developed by keeping a threshold value of 50 (a keyword must appear at least 50 times to be included in the network). Thus, out of 35,459 keywords, 201 were included in the network diagram. The network provided five different clusters, each addressing different research themes. The first and the largest cluster was formed around the keyword 'organic fertilizer'. The cluster comprised 54 keywords and dealt with topics related to organic farming, biofertilizer, manure, compost, integrated nutrient management, organic farming, sustainable agriculture, etc. One can infer that academia is well aware of the externalities of excess chemical fertilizer use, and hence attempts are being made to develop and assess the utility of alternate and greener fertilizer options. The next cluster is formed around the topic 'nitrogen', closely connected with growth, biomass, yield, nutrition, fertigation, irrigation, etc. This cluster mainly presents research on the performance of nitrogen fertilizers and improvizations on the methods of nitrogen fertilizer application. The third is a general cluster with fertilizer as the main topic. The other topics studied in relation to fertilizers include slow release, controlled release, nutrient recovery, heavy metal, phytoremediation, wastewater, etc. The fourth cluster is again formed around 'nitrogen fertilizer' as the central theme, but research under this cluster deals mainly with emissions, greenhouse gas, volatilization, food security, life cycle assessment, etc. The fifth and final cluster is formed around crops like wheat, maize, barley and soybean, and their fertilization practices.

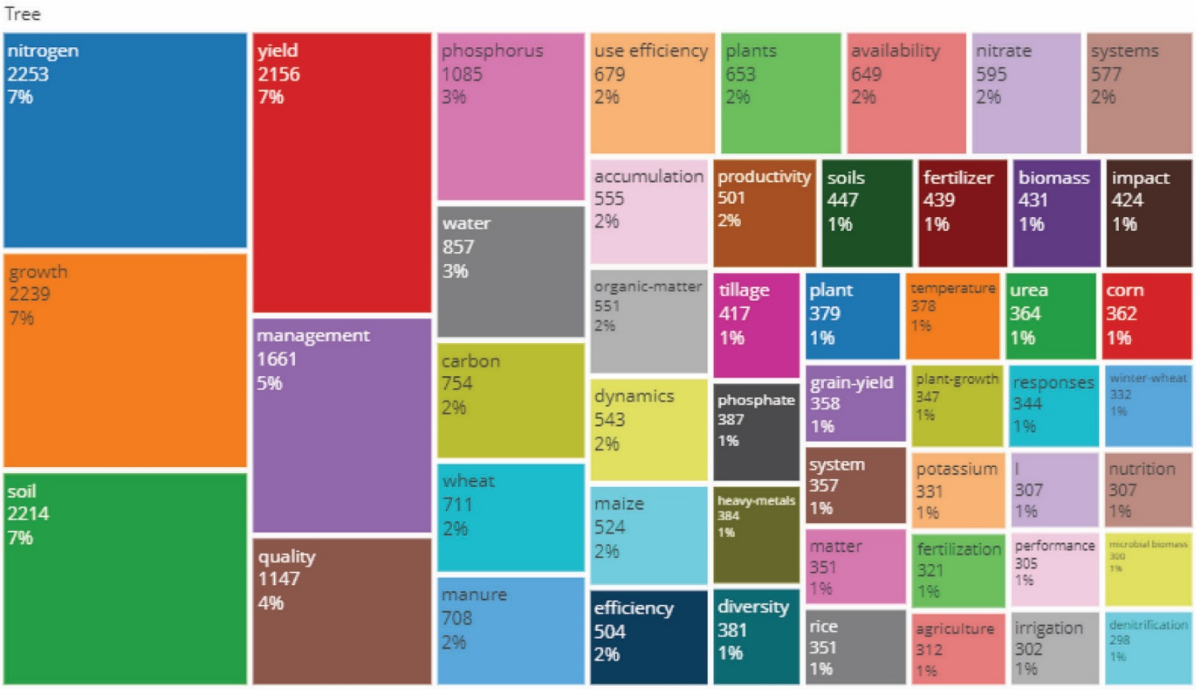

Figure 8. Tree map depicting topics that received the greatest attention from researchers.

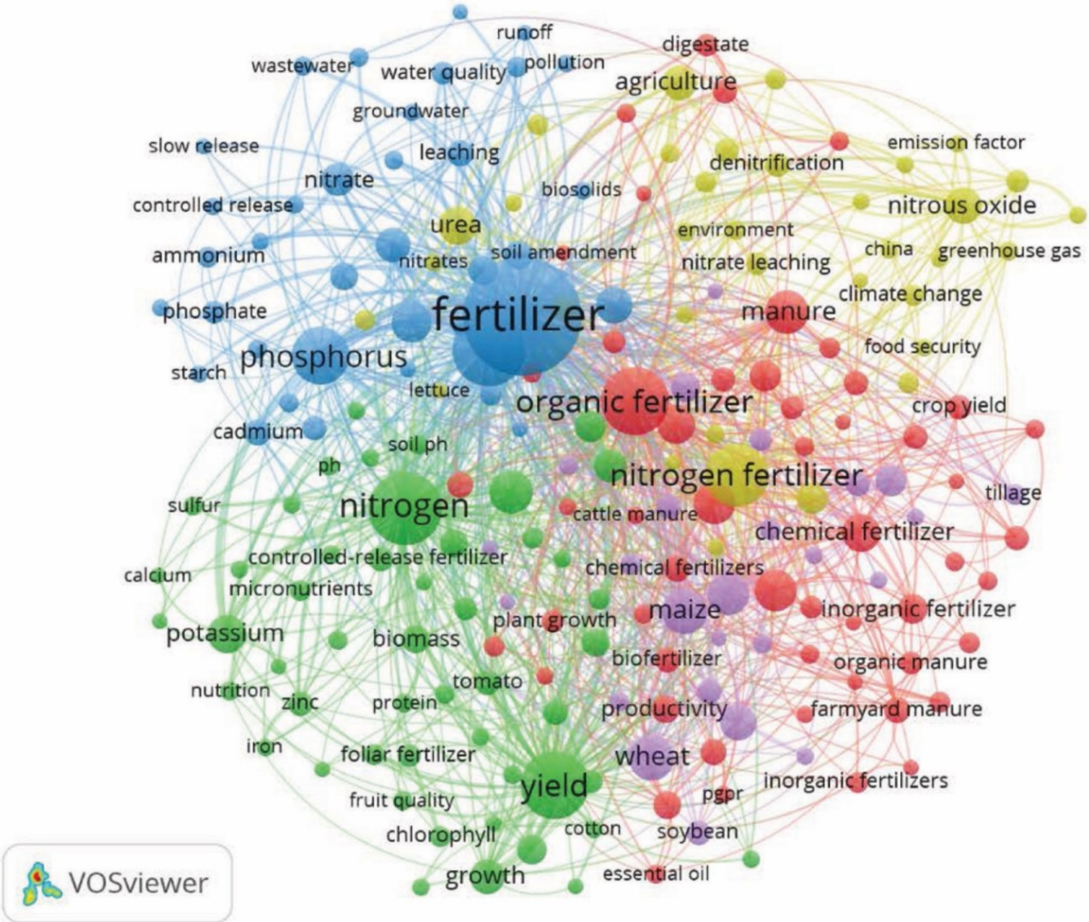

Figure 9. Co-occurrence network of author keywords.

Synopsis of fertilizer research

Now we unravel the significant themes under which research on fertilizers can be summarized. Further, we discuss some critical studies that provide meaningful insights into these themes.

Fertilizer market and policies

Right policies are crucial to establishing a competitive and efficient fertilizer market[2]. The inability of the governments in some countries to act in line with the envisaged policies is the major constraint in fertilizer uptake by farmers. The subsidy programmes successfully raise food production temporarily, but the welfare effects are modest[3]. Issues related to targeting and low fertilizer response by crops are critical impediments to the success of subsidy programmes. Envisaging good programme designs can lead to a successful implementation of subsidy schemes. The design should avoid diverting fertilizers from the programme, a significant concern in many countries worldwide. Diversion also results in an overestimation of the effects of fertilizer subsidy programmes[4].

Subsidies have made fertilizers available and affordable to farmers[5]. Fertilizer subsidy programmes have long-term effects on the demand of smallholder farm households for commercial fertilizers and crop production[6]. Another aspect of the subsidy is that it usually benefits the larger farmers, and environmental pollution caused by subsidies is also significant[7]. Identifying the factors preventing the policies from evolving as more pro-poor and environment-friendly is essential. The share of fertilizer subsidies received by farmers and industry was estimated for India[8]. The farmers receive about 66% of the subsidies; the remaining share goes to the industry. Policies should stress balancing fertilizer use and subsidy provided to fertilizers[9]. This is because, though subsidies are responsible to some extent for the soil nutrient imbalance in India, if removed, they will drastically affect the country's food production. Thus, the policymakers need to conceptualize other strategies to reduce the subsidy burden of the Central Government.

Direct benefit transfer (DBT) for fertilizer subsidy distribution is a new policy implemented in India that targets to reduce the diversion of subsidized fertilizers and the Government's subsidy burden. A dipstick evaluation in six districts (Rangareddy, Pali, Una, Hoshangabad, Krishna and West Godavari) where the DBT pilot was running live indicated a positive response from the different stakeholders[10]. However, there are several hurdles that the DBT scheme may have to face when implemented fully[11].

Fertilizer use pattern

The trends in fertilizer consumption and the role of the Green Revolution in food security are discussed extensively in the literature[12]. Further, several studies have tracked the evolution of chemical fertilizer consumption in India[5,13,14]. In recent years, Asian countries, including China and India, have been criticized for the overuse of chemical fertilizers. Among the factors responsible for the drastic rise in chemical fertilizer use, the fertilizer application rate is the most important[15]. Studies have also examined whether adopting fertilizer types like complex fertilizers affects nutrient overuse[16]. Overuse of chemical fertilizers has environmental consequences due to the surplus nutrients released[17]. Though seeking the environmental benefits of a possible shift in agricultural technology is crucial, we must consider sustaining crop yield levels and protecting farmers' income. Among the alternatives to chemical fertilizers, organic fertilizers like manure and biofertilizers are prominent. Since manure is relatively less productive in the short run, there is fear that technological shift from chemical fertilizers towards organic manure may compromise production or hurt farmers' income (Ghosh)[18]. There has been no accelerated growth in the distribution of bio-based fertilizers with time, and the spatial diffusion is inadequate. Despite the entry of small private units into the industry, there is no clear indication of the success of privatization. Considering the social benefits promised, the Government has ample grounds to intervene to set up an effective market for the new product while encouraging private players. However, the policy and instruments of intervention need to be designed with care[18].

Yield response of crops to fertilizers

Several studies examined how the response of crop yield to fertilizers and thus the economic incentives for their use varied according to agro-ecological conditions[19]. The countries with relatively high levels of fertilizer use, e.g. China, have relatively low response rates[12]. Nevertheless, some countries, which experience low fertilizer application rates, also have low fertilizer response. In recent years, numerous analyses of maize yield response based on farm household data have been conducted in the eastern and southern regions of Africa[20–23]. The fertilizer response of maize crops to refine recommendations for different regions of Africa through meta-analysis was also studied[24]. The yield response of crops to fertilizers was found to be low in Africa, so the farmers are not willing to use higher amounts of fertilizers[25]. Studies also report the spatial variation in yield response to fertilizers[26]. Most studies assessed the variation in yield response, the ability of the soil to provide nutrients and the nutrient requirements.

Environmental effects of fertilizer use

Estimating global environmental costs due to fertilizer application is a topic that has attracted the attention of researchers in recent years[27]. Fertilizer-intensive agriculture brings with it some externalities as well. Excessive nitrogen application to the crops causes nitrogen pollution to the ecosphere. N_2O and NO_x gases pollute the atmosphere directly and indirectly, thus increasing atmospheric warming and climate change issues[28]. The available literature suggests that N-fertilizer application contributes most to N_2O emissions from India, a 49% share in 2005 compared to 40% in 1985 (ref. 29). Due to the diverse soil, land-use types and climatic conditions, there are uncertainties in the quantification of greenhouse gas emissions from agricultural soils of India[30]. Researchers have also reviewed the literature on direct N_2O emissions from agricultural systems and statistically analysed the data to arrive at a specific estimate of emission factors[31]. Studies on the fertilizer use intensity and the threat it poses to the ecological environment[32], developing greenhouse gas emission coefficients[33] and estimating the emissions from fertilizer use utilizing the coefficients are emerging themes in fertilizer research. The emission of atmospheric nitrous oxide has accelerated since the world started using chemical fertilizers, suggesting the use of manure to keep the emissions under control[34]. Estimating the social cost of nitrogen for individual countries at different levels of agricultural development is also crucial[35].

Summary

This study aimed to assess worldwide research on fertilizers. To this end, using science mapping tools like VOSviewer and biblioshiny package of R, we provide the outcomes of a comprehensive bibliometric analysis of 22,004 articles indexed in the WoS Core Collection database. Overall, some prominent trends were identified in the research on fertilizers. First, the number of publications increased consistently between 2000 and 2021, and the average citations per year remained more or less the same, indicating consistent research interest in fertilizers. Second, China, USA, Brazil and India contributed significantly to publications manifesting their strong voice in fertilizer research. Third, among the journals, *Communications in Soil Science and Plant Analysis*, *Plant and soil*, and *Agriculture, Ecosystems & Environment* formed the strongest pillars of scientific production with respect to the number of articles, citations, and *h*-index respectively. Fourth, Shen, Q. R. was the predominant among the authors with respect to the number of publications and the *h*-index. In research continuity on fertilizers, Wan, Y. and Li, J. topped the list. Fifth, we also identified the most valuable publications regarding citations received. Finally, we highlight organic fertilizer, nitrogen, crop growth, and crop yield as the prominent research themes on fertilizers using a tree map and a co-occurrence network of author keywords.

In this study, we have integrated bibliometric analysis and the traditional content review to provide meaningful insights into the research landscape regarding fertilizers. However, the limitations of such an approach must also be considered before drawing inferences. First, we solely use the data extracted from the WoS database for 2000–21. The data extracted are based on the search word 'fertilizer*' in this case. A narrower or broader search string would result in a different set of publications for analysis. However, since our target here is to map the fertilizer research as a whole, the search strategy, search duration and mapping approaches are appropriate. Hence, notwithstanding these limitations, the findings of this study provide a comprehensive picture of fertilizer research, which could help the researchers delve deeper into the narrower sub-themes within this broad domain.

1. Sutton, M. A. *et al.*, Our Nutrient World: The challenge to produce more food and energy with less pollution, Centre for Ecology and Hydrology, 2013.
2. Benson, T. and Mogues, T., Constraints in the fertilizer supply chain: evidence for fertilizer policy development from three African countries. *Food Secur.*, 2018, **10**, 1479–1500.
3. Jayne, T. S., Mason, N. M., Burke, W. J. and Ariga, J., Review: taking stock of Africa's second-generation agricultural input subsidy programs. *Food Policy*, 2018, **75**, 1–14.
4. Jayne, T. S., Mather, D., Mason, N. and Ricker-Gilbert, J., How do fertilizer subsidy programs affect total fertilizer use in sub-Saharan Africa? Crowding out, diversion, and benefit/cost assessments. *Agric. Econ*., 2013, **44**, 687–703.
5. Gulati, A. and Banerjee, P., Rationalising fertiliser subsidy in India: key issues and policy options. Working Paper, Indian Council for Research on International Economic Relations, New Delhi, 2015.
6. Ricker-Gilbert, J. and Jayne, T. S., Estimating the enduring effects of fertiliser subsidies on commercial fertiliser demand and maize production: panel data evidence from Malawi. *J. Agric. Econ*., 2017, **68**, 70–97.
7. Birner, R., Gupta, S. and Sharma, N., The political economy of agricultural policy reform in India fertilizers and electricity for Irrigation. International Food Policy Research Institute, Washington, DC, 2011.
8. Gulati, A. and Narayanan, S., Demystifying fertiliser and power subsidies in India. *Econ. Polit. Wkly*., 2015, **35**, 784–794.
9. Chand, R. and Pandey, L. M., Fertilizer growth, imbalances and subsidies – trends and implication. Discussion Paper, National Centre for Agricultural Economics and Policy Research, New Delhi, 2008.
10. Aayog, N., Direct Benefit Transfer in Fertilizer: Fourth round of concurrent evaluation – A nationally representative study, 2020.
11. Kishore, A., Praveen, K. V. and Roy, D., Direct cash transfer system for fertilisers: why it might be hard to implement. *Econ. Polit. Wkly*., 2013, **48**, 54–63.
12. Hossain, M. and Singh, V. P., Fertilizer use in Asian agriculture: implications for sustaining food security and the environment. *Nutr. Cycling Agroecosyst.*, 2000, **57**, 155–169.
13. Chand, R. and Pavithra, S., Fertiliser use and imbalance in India: analysis of states. *Econ. Polit. Wkly*., 2015, **50**, 98–104.
14. Sharma, V. P. and Thaker, H., Demand for fertilisers in India: deteminants and outlook for 2020. *Indian J. Agric. Econ.*, 2011, **66**, 638–661.
15. Chen, X. *et al*., What has caused the use of fertilizers to skyrocket in China? *Nutr. Cycling Agroecosyst.*, 2018, **110**, 241–255.
16. Sun, Y., Hu, R. and Zhang, C., Does the adoption of complex fertilizers contribute to fertilizer overuse? Evidence from rice production in China. *J. Clean. Prod*., 2019, **219**, 677–685.
17. Jan, P., Calabrese, C. and Lips, M., Determinants of nitrogen surplus at farm level in Swiss agriculture. *Nutr. Cycling Agroecosyst.*, 2017, **109**, 133–148.

18. Ghosh, N., Promoting bio-fertilizers in Indian agriculture. *Econ. Polit. Wkly*., 2004, **39**, 5617–5625.
19. Theriault, V., Smale, M. and Haider, H., Economic incentives to use fertilizer on maize under differing agro-ecological conditions in Burkina Faso. *Food Secur*., 2018, **10**, 1263–1277.
20. Marenya, P. P. and Barrett, C. B., Soil quality and fertilizer use rates among smallholder farmers in western Kenya. *Agric. Econ*., 2009, **40**, 561–572.
21. Sheahan, M., Black, R. and Jayne, T. S., Are Kenyan farmers under-utilizing fertilizer? Implications for input intensification strategies and research. *Food Policy*, 2013, **41**, 39–52.
22. Xu, Z., Guan, Z., Jayne, T. S. and Black, R., Factors influencing the profitability of fertilizer use on maize in Zambia. *Agric. Econ*., 2009, **40**, 437–446.
23. Burke, W. J., Jayne, T. S. and Black, J. R., Factors explaining the low and variable profitability of fertilizer application to maize in Zambia. *Agric. Econ.*, 2017, **48**, 115–126.
24. Ichami, S. M., Shepherd, K. D., Sila, A. M., Stoorvogel, J. J. and Hoffland, E., Fertilizer response and nitrogen use efficiency in African smallholder maize farms. *Nutr. Cycling Agroecosyst.*, 2018, **113**, 1–19.
25. Liverpool-Tasie, L. S. O., Is fertiliser use inconsistent with expected profit maximization in sub-Saharan Africa? 'Evidence from Nigeria'. *J. Agric. Econ*., 2017, **68**, 22–44.
26. Xu, X., He, P., Pampolino, M. F., Qiu, S., Zhao, S. and Zhou, W., Spatial variation of yield response and fertilizer requirements on regional scale for irrigated rice in China. *Sci. Rep.*, 2019, **9**, 1–8.
27. Good, A. G. and Beatty, P. H., Fertilizing nature: a tragedy of excess in the commons. *PLoS Biol*., 2011, **9**, e1001124.
28. Kanter, D. R., Zhang, X. and Mauzerall, D. L., Reducing nitrogen pollution while decreasing farmers' costs and increasing fertilizer industry profits. *J. Environ. Qual.*, 2015, **44**, 325–335.
29. Garg, A., Shukla, P. R. and Upadhyay, J., N_2O emissions of India: an assessment of temporal, regional and sector trends. *Clim. Change*, 2012, **110**, 755–782.
30. Bhatia, A., Pathak, H. and Aggarwal, P. K., Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. *Curr. Sci.*, 2004, **87**, 317–324.
31. Albanito, F. *et al.*, Direct nitrous oxide emissions from tropical and sub-tropical agricultural systems – a review and modelling of emission factors. *Sci. Rep*., 2017, **7**, 1–12.
32. Cai, J., Xia, X., Chen, H., Wang, T. and Zhang, H., Decomposition of fertilizer use intensity and its environmental risk in China's grain production process. *Sustainability*, 2018, **10**, 498–512.
33. Kahrl, F., Li, Y., Su, Y., Tennigkeit, T., Wilkes, A. and Xu, J., Greenhouse gas emissions from nitrogen fertilizer use in China. *Environ. Sci. Policy*, 2010, **13**, 688–694.
34. Davidson, E. A., The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geosci*., 2009, **2**, 659–662.
35. Keeler, B. L. *et al*., The social costs of nitrogen. *Sci. Adv*., 2016, **2**, e1600219.

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