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TOPICAL REVIEW

Evidence map of the benefits of enhanced-efficiency fertilisers for the environment, nutrient use efficiency, soil fertility, and crop production

Mathilde Chen[1,4,*], **Andrea Schievano**[2], **Simona Bosco**[2], **Ana Montero-Castaño**[2], **Giovanni Tamburini**[3], **Marta Pérez-Soba**[2,*] **and David Makowski**[4,*]

[1] Université de Paris, Inserm U1153, CRESS, Epidemiology of Ageing and Neurodegenerative diseases, 10 avenue de Verdun, Paris, France
[2] European Commission, Joint Research Centre, Via Enrico Fermi 2749, Ispra 21027, Italy
[3] University of Bari, Italy, Department of Soil, Plant and Food Sciences (DiSSPA—Entomology), Via Giovanni Amendola, 165/a, Bari, Italy
[4] INRAE AgroParisTech University Paris-Saclay, UMR MIA, 91120 Palaiseau, France
[*] Authors to whom any correspondence should be addressed.

E-mail: mathilde.chen@inrae.fr, marta.perezsoba@ec.europa.eu and david.makowski@inrae.fr

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Abstract

The identification of sustainable fertilisation practices is essential to reduce agriculture's impact on the environment while insuring sufficient crop production. The use of enhanced efficiency fertilisers (EEFs) is thought to improve nitrogen (N)-fertiliser uptake by crops while reducing nutrient losses to the environment. EEFs' performance has been assessed in several meta-analyses and systematic reviews, which are heterogeneous in content and quality of reporting. This provides fragmented information and makes it difficult to conclude about their ability to provide more sustainable fertilisation. Here we synthetise evidence from 26 meta-analyses and reviews selected by a systematic literature search to describe the separate effects of four commonly used EEFs—nitrification inhibitors, urease inhibitors, double inhibitors, or controlled-release fertilisers—on the environment, nutrient use efficiency, soil fertility, and crop production. A unique contribution of this review is the assessment of the quality of the selected papers and the synthesis of their results through a systematic framework. Results showed that compared to conventional fertilisers, EEFs generally increased soil nutrients, crop yield, and N use efficiency, and reduced N leaching, emissions of greenhouse gases and air pollutants. Some differences were found between the different EEFs; while urease inhibitors, double inhibitors, and controlled-released fertilisers decreased ammonia emission compared to conventional fertilisers, nitrification inhibitors increased these emissions or did not affect them. The results were consistent when excluding low-quality studies from the analyses. Overall, this global synthesis indicates that EEFs could maintain crop yields while reducing some of the negative environmental impacts of conventional N-fertilisers. Attention should be paid to the potential increase of ammonia emissions by nitrification inhibitors and additional evidence is needed on the potential side effects on soil health, biodiversity, and water quality.

1. Introduction

Nitrogen (N) fertilisation is essential for crop growth and soil-N replenishment, especially in intensively-farmed agricultural land. The increase in N inputs, combined with more intensive crop management and cropland extension, has boosted agricultural production in the 20th century. However, crops cannot always use efficiently N fertilisers, if supplied at excessive rates or not fully synchronized to crop growth stages, leading to substantial N losses to the environmental compartments, through a combination of different physical, chemical or microbial transformation mechanisms. This typically results in environmental damages such as water and air pollution, greenhouse gas (GHG) emission, and biodiversity loss [1, 2]. This problem is all the more worrying, as N use efficiency tends to decrease globally [3]. It is thus essential to identify fertilisation practices that improve N use efficiency, while reducing detrimental impacts of fertilisation on the environment.

Enhanced-efficiency fertilisers (EEFs) have been developed to better synchronize fertiliser N release with crop uptake [4], offering the potential to improve N-use efficiency in crops and reduce losses [4, 5]. They embrace different substances with different mechanisms. For example, urease inhibitors and nitrification inhibitors, are coupled to conventional mineral-N fertilisers to reduce N losses to the environment through the direct inhibition of enzymatic regulation of respectively urea hydrolysis or microbial nitrification in soil microbial species, respectively [6]. Combined application of urease inhibitors and nitrification inhibitors refers to as double inhibitors [6]. Finally, controlled-release fertilisers are EEFs that release N in water-soluble forms in a controlled and delayed manner, limiting fertiliser-derived-N excess in soil water and its availability to nitrifying/denitrifying soil microorganisms, when the crop N-uptake is not in place at comparable rates [7].

In the last decade, results of numerous experiments assessing EEFs' performances and environmental impacts have been synthesized in several meta-analyses and systematic reviews (MSRs). These syntheses are heterogeneous in quality and the strength of conclusions are hampered by at least one of the following limitations: focus on a single EEF type (e.g. nitrification inhibitors, urease inhibitors, double inhibitors, or controlled-release fertilisers) [8–19], emphasis on few outcomes (mostly productivity or plant N uptake) [13, 14, 18], or restrict their analysis to a specific region [8, 10, 13, 20–24].

The objective of this study is to synthesize current evidence on environmental, nutrient use efficiency, soil fertility, and crop production impacts of nitrification inhibitors, urease inhibitors, double inhibitors, and controlled-release fertilisers, using a rigorous protocol to systematically report evidence from MSRs. We retrieved, extracted and summarized results from published MSRs comparing the use of EEFs with the use of conventional fertilisers to answer the following specific questions: (a) on average, are the effects of EEFs on the environment, nutrient uptake, soil fertility, and productivity positive or negative compared to conventional fertilisers?; (b) what is the quality of the available evidence?; (c) what are the main factors influencing the effects?; (d) what are the current knowledge gaps in MSRs?; (e) do these impacts vary between the different types of EEFs?

2. Material and methods

In order to retrieve and summarize the largest possible number of MSRs published on EEFs taking into account their heterogeneity, we applied a systematic framework to report the results and quality levels of MSRs in a rigorous and transparent manner, briefly explained in figure 1 and in the following sections.

2.1. Systematic literature search

We comprehensively searched the peer-reviewed literature for published MSRs on the effects of commonly-used EEFs compared to conventional fertilisers on the environment, nutrient use efficiency, soil fertility, and agricultural production. Two separate searches were conducted in October 2020 in Scopus and Web of Science ® data bases using the following search strings:

- *('nitr* inhibit*' OR 'controlled-release fert*' OR 'urease inhibit*' OR 'enhanced-efficiency fert*') combined with ('meta-analy*' OR 'systematic* review*' OR 'evidence map' OR 'global synthesis' OR 'evidence synthesis' OR 'research synthesis')*
- *('slow-release fert*' OR 'slow release fert*' OR 'controlled release fert*' OR 'controlled-release fert*' OR 'enhanced-efficiency fert*' OR 'enhanced efficiency fert*' OR 'improved-efficiency fert*' OR 'improved efficiency fert*' OR 'organic-mineral fert*') combined with ('meta-analy*' OR 'systematic* review*' OR 'evidence map' OR 'global synthesis' OR 'evidence synthesis' OR 'research synthesis').*

2.2. Screening and selection

After removing duplicates, publications resulting from this search were screened based on title and abstract first, and then based on full-text. Exclusion criteria were: (a) the paper was out of the scope; (b) the paper did not distinguish the effect of each EEFs; (c) the paper did not assess the impacts of EEFs in comparison to conventional fertilisers (either organic or mineral); (d) the paper was not a systematic review; (e) the paper was not a meta-analysis or did not provide any quantitative data; meta-analyses of trials results were not considered; (f) the paper was not written in English, French, or Italian.

2.3. Data extraction and quality assessment

In order to describe (a) the characteristics of included systematic review and meta-analysis and (b) the reported impacts of EEFs on the environment and crop production, we extracted from each paper the type(s) of EFF(s) studied, the control (i.e. conventional fertilisers), the metric (e.g. nitrous oxide emission, soil organic carbon content, etc), and associated

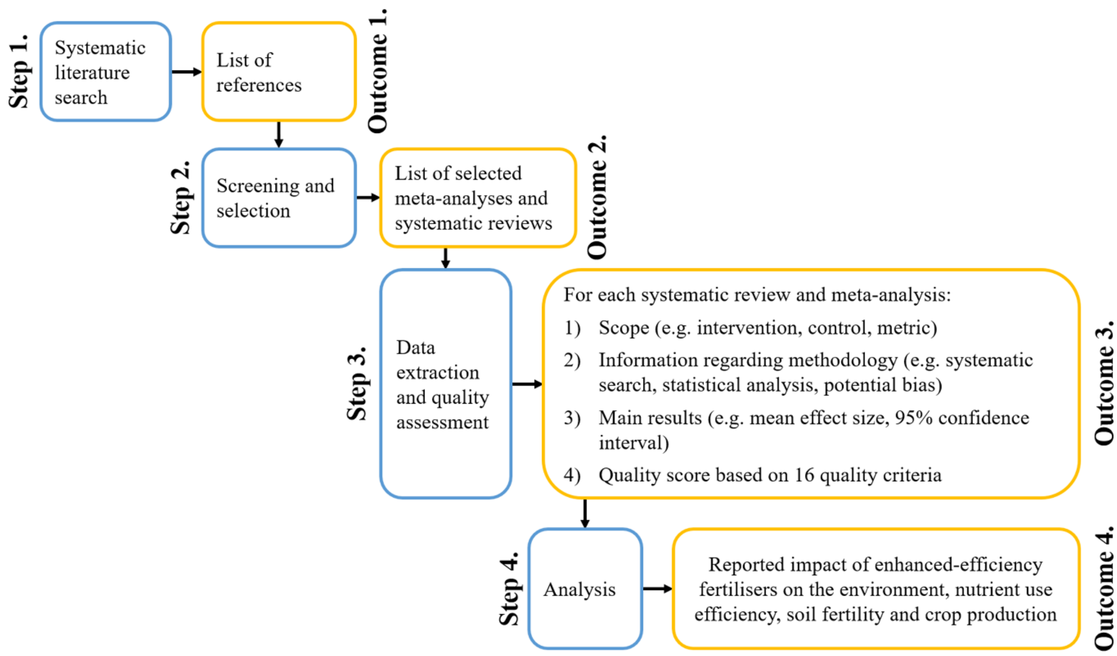


Figure 1. The four main steps (framed in blue) and corresponding outcomes (in orange) of the framework for performing a systematic review of meta-analyses and systematic reviews describing the effect of enhanced-efficiency fertilisers on the environment, nutrient use efficiency, soil fertility, and crop production.

main results. When available in the text, we reported estimated mean effect size (and corresponding 95% confidence interval), which are key quantities reported in meta-analyses to report the difference between two treatments. They are estimated from a group of individual experiments, in principle using a formal statistical method. For example, for yield, mean effect sizes were defined in the selected meta-analyses as mean (log) ratio of yield with EEF to yield without, or as mean (standardized) difference of yield with EEF and yield without. Similar effect sizes were defined by the authors of meta-analyses performed for assessing the impact of EEFs on the environment, plant nutrients uptake, soil fertility, and crop productivity. In absence of formal statistical results, we reported vote-counting or narrative results. When the estimates were not numerically reported by the authors, we extracted them using GetData Graph Digitizer software (version 2.26). Extracted meta-data were reported sticking as much as possible to the original wording of the authors.

2.4. Analysis

For each MSR and metric, the effect of application of the different EEFs types was separately assessed based on the direction and statistical significance of main results reported in each paper. A 'positive' effect corresponded to a beneficial impact based on formal statistical comparison between the application of EEFs and conventional fertilisers, while a detrimental impact was considered as 'negative' effect. Absence of significant effects, according to the statistical analysis, was reported as 'no effect'. Relevant results but without proper statistical comparison of EEF application and conventional fertilisers were rated as 'uncertain' (supplementary table 1). The numbers of selected systematic reviews and meta-analyses showing 'positive', 'negative', 'no effect', or 'uncertain' impacts of each EEF compared to conventional fertilisers were computed for each impact. For a given impact, when results were available for all types of EEFs, a Fisher's exact test was performed to compare the proportions of 'positive' effects reported for nitrification inhibitors, urease inhibitors, double inhibitors, and controlled-release fertilisers.

Additionally, we evaluated the quality of selected publications by reporting the number of satisfied criteria through a list of 16 standard quality criteria, which cover three main aspects of systematic reviews and meta-analyses: (a) the literature search strategy and studies selection; (b) the statistical analysis; (c) the potential bias [25–27]. Details on extracted meta-data and quality criteria can be found in supplementary table 2.

Main results are based on the analysis of all MSRs, that is without selection based on their quality. In order to assess the robustness of our conclusions, the counting and the comparison between the four types of EEFs was replicated considering only studies satisfying at least 50% of the quality criteria. Statistical analyses were undertaken using R version 4.1.2 (www.r-project.org) with a two-sided $p < 0.05$ considered statistically significant. The script used to analysis the data is provided in supplementary material.

3. Results

3.1. General characteristics of the selected MSRs

The systematic search of the literature resulted in 59 publications. Out of them, 29 were excluded based on title and abstract screening, and 4 were additionally excluded after full-text assessment. In total, 26 MSRs describing the effect of nitrification inhibitors, urease inhibitors, double inhibitors, or controlled-release fertilisers were selected. The main characteristics of included studies are presented in table 1 (all references are listed in supplementary table 3). The selected papers present results at global (number of MSRs: $n = 9$), continental ($n = 3$), or national scales ($n = 9$). At the national scale, the countries considered in the selected papers are major producers of agricultural products (China, USA, Brazil, Japan, Spain, Germany) located in different continents (Asia, America, Europe). The quality scores (corresponding to the proportion of quality criteria satisfied) ranged from 25% to 75%, with 20 meta-analyses having a quality score higher than 50%.

Reported impacts include air pollutants emissions ($n = 13$), GHGs emissions ($n = 15$), N leaching and run-off ($n = 4$), plant nutrients uptake ($n = 6$), soil N content ($n = 3$), and crop yield ($n = 12$). Among the 26 selected papers, 10 reported results regarding both crop productivity and at least one environmental, nutrient uptake, or soil fertility impact while two reported results for several environmental impacts (table 1).

3.2. Effect of the different types of EEFs on the environment and crop production

Figure 2 shows the number of MSRs reporting positive, negative, no effect or uncertain effect per impact, for each EEF compared to conventional fertilisers. The length of each bar represents the total number of results reported for each impact. In addition, table 2 shows the estimated mean relative effects and corresponding 95% CI reported in the subset of studies with the highest quality scores, for each type of EEF and each type of impact, separately. Mean estimated effects of all other studies are reported in supplementary tables 4–7. Result from the sensitivity analyses considering only the high-quality MSRs are reported in supplementary figure 1.

3.2.1. Nitrification inhibitors

Overall, the effect of nitrification inhibitors was beneficial on the majority of reported outcomes (figure 2 and supplementary figure 1). Among the seven MSRs examining the effect of nitrification inhibitors on crop yield, six reported a positive effect of this EEF compared to conventional fertilisers. Positive effects on soil N_2O and NO emissions was reported in nine (out of ten) and in three (out of four) MSRs, respectively. Across MSRs, mean effect sizes for N_2O emissions reductions were found in the range of 28%–57% (supplementary table 4). The MSR with the best quality level for this metric reported that, compared to conventional fertilisers, the use of nitrification inhibitors decreased N_2O emissions by 38% (95% CI: [−44%, −31%]) (table 2). Among MSRs reporting the effects of nitrification inhibitors on CH_4 and on CO_2 emissions, positive results were found in one out of three MSRs and in one out of two MSRs, respectively (figure 2). Compared to conventional fertilisers, nitrification inhibitors were also found to improve soil NH_4^+ content and soil total-N content, as shown by two (out of two) and one (out of three) MSRs, respectively.

The results were more contrasted for crop N use efficiency, with five (out of nine) MSRs reporting a positive effect, while the four remaining MSRs reported no significant effect (figure 2). Results were also mixed for NH_3 emission, with an equal number of MSRs reporting either negative or no effect on this outcome (five out of 11 for both), while another MSR provided uncertain results. Compared to conventional fertilisers, the use of nitrification inhibitors was found to reduce N leaching and run-off, as reported by four MSRs (figure 2). The MSR showing the best quality score for this impact reported that the use of nitrification inhibitor could reduce dissolved inorganic N and NO_3^- leaching by 48% (95% CI: [38%, 56%]) and by 47% (95% CI: [32%, 59%]), respectively (table 2). However, the results were contrasted for NH_4^+ leaching, with one MSR reported a negative effect on NH_4^+ leaching, while another one reported no effect and another one reported positive effect (supplementary table 4). Finally, two MSRs found a negative effect on soil NO_3^- content (figure 2).

The numbers of studies reporting positive, negative, or no effect were similar after excluding six MSRs satisfying less than 50% of the quality criteria (see sensitivity analysis in supplementary figure 1), as compared to results extracted on the full set of MSRs (figure 2). However, no uncertain result was reported when considering only the high-quality MSRs (supplementary figure 1).

3.2.2. Urease inhibitors

The use of urease inhibitors was found to improve crop productivity, with four MSRs consistently reporting positive effects of this type of EEF on plant N uptake and crop yield (figure 2). Mean effects size for crop yield and plant N uptake improvements reported by the selected studies ranged from 1.6% to 48% and from 5.8% to 31.1%, respectively (supplementary table 5). A positive effect of urease inhibitors on soil N content (mean effect size [95% CI]: 5.8% [2.3%, 9.5%]) was also reported, although this result is based on one meta-analysis only (table 2 and supplementary table 5). Five out of seven MSRs reported a positive effect on NH_3 emission of urease inhibitors, while two other MSRs showed an uncertain effect (figure 2). Results were more contrasted for N_2O

Table 1. Characteristics of included meta-analyses and systematic reviews.

Authors, year of publication	Population	Scale	Quality score[a] (%)	Reported enhanced-efficiency fertilisers	Reported impacts: Air pollutant emissions [b]	GHG emis-sions [c]	Nitrogen leaching/ run-off[d]	Plant nitrogen uptake[e]	Soil nutri-ents[f]	Crop produc-tivity[g]
Abalos *et al* 2016	Maize systems	USA	75	CRF		x				x
Abdo *et al* 2021	Maize, wheat, and rice systems	China	69	CRF	x					
Akiyama *et al* 2012	Croplands, grasslands, paddies	Not reported	69	NI, UI, CRF	x	x				
Decock 2014	Maize systems	USA	75	DI, CRF		x				
Eagle *et al* 2017	Maize systems	North America	62	DI, CRF		x				
Fan *et al* 2018	Arable soils	Not reported	75	UI		x				
Feng *et al* 2016	Maize, wheat, and barley systems	Global	56	CRF		x		x		x
Gao *et al* 2017	Maize and wheat systems	China	69	CRF, NI		x				x
Gilsanz *et al* 2016	Grasslands, croplands, paddies, upland	Europe, Asia, North America	38	NI		x				
Hu *et al* 2013	Wheat, barley, rape-seed, potato, grain and silage maize systems	Germany	50	NI						x
Huang *et al* 2016	Annual cropping systems	China	56	UI, CRF	x					x
Jenkins *et al* 2018	Pastures	Not reported	38	UI				x		
Kim *et al* 2012	Arable lands, pastures	Global	25	NI	x					
Li *et al* 2017	Grasslands, croplands, paddies	Global	62	All	x	x	x	x		x
Linquist *et al*,2012	Paddies	Asia and USA	62	NI		x				
Liu *et al* 2017	Grasslands, croplands, paddies	Japan and Spain	75	NI	x					
Mazzetto *et al* 2020	Maize and sugar cane systems	Brazil	44	NI, CRF	x	x				
Pan *et al* 2016	Cropping systems and pastures	Global	69	NI, UI, CRF	x					
Qiao *et al* 2015	Cropping systems and pastures	Global	69	NI	x	x	x	x	x	x
Rose *et al* 2018	Cropping systems and pastures	Not reported	38	UI, DI						x
Sha *et al* 2020	Dry lands, paddies	Not reported	69	NI				x	x	
Silva *et al* 2017	Cropping systems	Global	44	UI	x					x
Thapa *et al* 2016	Maize wheat and rice systems	Global	56	All		x				x
Ti *et al* 2019	Cropping systems and pastures	Global	69	UI, CRF	x					
Xia *et al* 2017	Maize, wheat, and rice systems	China	56	NI, UI, CRF	x	x	x	x		x
Yang *et al* 2016	Cereals, forage, vegetables-industrial systems	Global	62	NI	x	x	x	x	x	x

Notes: details for all studies are provided in supplementary table 3. Abbreviations: GHG: greenhouse gas; CRF: controlled-release fertilisers; NI: nitrification inhibitors; UI: urease inhibitors; DI: double inhibitors.

[a] Percentage of satisfied criteria through a list of 16 criteria (see supplementary table 2).

[b] Including ammonia and nitric oxide emissions.

[c] Including carbon dioxide, methane, and nitrous oxide emissions.

[d] Including total nitrogen leaching or run-off, nitrate, ammonium, and dissolved inorganic nitrogen forms (nitrate, ammonium, and nitrite) leaching.

[e] Including plant and grain nitrogen use efficiency, plant and total aboveground nitrogen uptake, and nitrogen recovery rate.

[f] Including soil-extractable and fertiliser-derived ammonium, fertiliser-derived nitrate, dissolved inorganic nitrogen, and total soil nitrogen contents.

[g] Including crop yield and biomass.

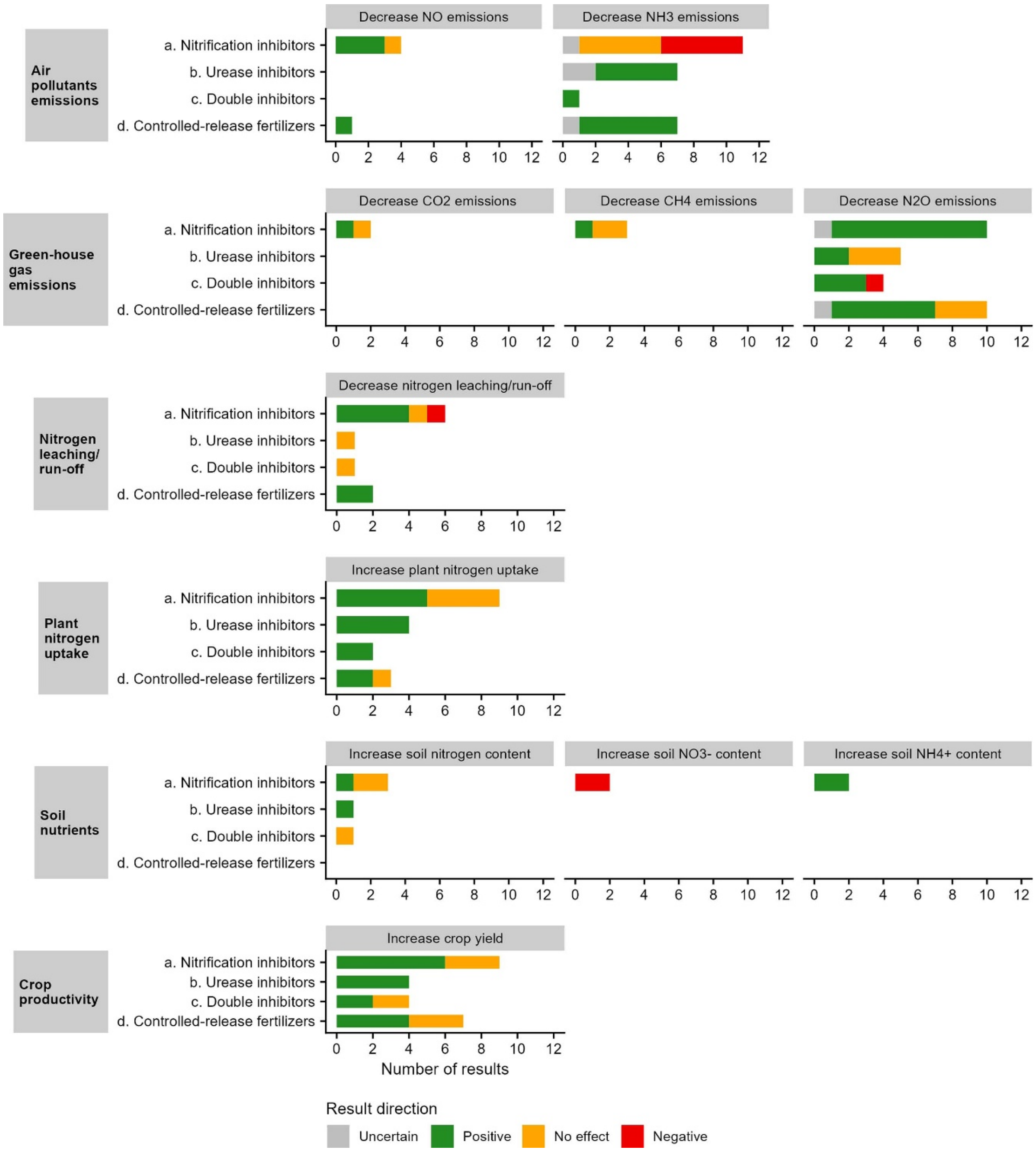


Figure 2. Number of meta-analyses and systematic reviews reporting uncertain, positive, negative, and no effect of different enhanced-efficiency fertilisers on several environmental metrics, plant nutrient uptake, soil fertility, and on crop productivity.

emission, with three (out of five) MSRs indicating no effect of urease inhibitors and two showing a positive effect. No difference was found between urease inhibitors and conventional fertilisers for NO_3^- leaching, according to one MSR. No result on the effect of urease inhibitors on soil NO_3^- and NH_4^+ content, CO_2 emission, CH_4 emission, and NO emissions was reported in the publications selected (table 1, figure 2, and supplementary table 5). Results from sensitivity analysis based on MSRs satisfying more than 50% of the quality criteria were similar, as compared to the main results (figure 2 vs. supplementary figure 1).

3.2.3. Double inhibitors

Compared to conventional fertilisers, the application of double inhibitors showed positive effect plant N uptake according to two MSRs (out of two) (figure 2). The increase in plant nutrient uptake induced by the use of double inhibitors compared to conventional fertilisers reached 22.1% (95% CI: [15.3%, 29.6%]) in the MSR showing the best quality score (table 2). Contrasting effects on crop yield was reported, with an equal number of MSRs ($n = 2$) reporting either positive or no effect (figure 2). The use of double inhibitors showed a positive effect on N_2O emission, according to three MSRs out of four. A positive effect on NH_3 emission was also reported by one MSR (mean effect size [95% CI] reported: −52.7% [−40.4%, −64.1%], table 2). Finally, the application of double inhibitors had no effect on N leaching, according to one MSR, and on soil N content, according to another MSR. Similar to urease inhibitors, we

Table 2. Estimated mean relative effects (%) and their confidence intervals at 95%. Data were extracted for the meta-analysis showing the highest quality score for a given type of EEF and a given type of impact. When several meta-analyses had the same quality scores, all the corresponding mean effect sizes were extracted.

Impact	Metric	Mean relative effect size (%)	Confidence interval	Direction of the effect	ID reference[a]
Nitrification inhibitors					
Air pollutants emissions	Decrease NO emissions	−94.4	(−96.9, −91)	Positive	16
	Decrease NH_3 emissions*	38.0	(14.5, 64.8)	Negative	18
		20.0	(33, 67)	Negative	19
		42.6	(15.6, 76)	Negative	24
GHG gas emissions	Decrease CO_2 emissions	−6.8	(−24.8, 6.7)	No effect	26
	Decrease CO_2 emissions	−8.9	(−18.4, −2)	Positive	26
	Decrease CH_4 emissions	−2.0	(−8.0, 3.0)	No effect	19
	Decrease N_2O emissions*	−38.0	(−44.0, −31.0)	Positive	3
		−34.2	(−38.5, −29.4)	Positive	8
		−41.7	(−46.3, −37.5)	Positive	8
		−44.0	(−48.0, −39.0)	Positive	19
N leaching/run-off	Decrease N leaching/run-off*	−48.0	(−56.0, −38.0)	Positive	19
		19.0	(−10.0, 61.0)	No effect	19
		−47.0	(−59.0, −32.0)	Positive	19
Plant N uptake	Increase plant nitrogen uptake	58.0	(34.0, 93.0)	Positive	19
Soil nutrients	Increase soil NH_4^+ content*	25.3	(16.5, 32.7)	Positive	26
		41.0	(25.9, 62.4)	Positive	26
	Increase soil NO_3^- content*	−17.0	(−29.2, −8.2)	Negative	26
		−20.6	(−32, −13.5)	Negative	26
	Increase soil nitrogen content	15.0	(7.2, 23.7)	Positive	21
Crop productivity	Increase crop yield	12.9	(8.6, 17.6)	Positive	8
Urease inhibitors					
Air pollutants emissions	Decrease NH_3 emissions*	−53.7	(−58.3, −48.3)	Positive	18
		−57.7	(−63.8, −49.1)	Positive	24
GHG emissions	Decrease N_2O emissions	−24.0	(−14.0, −33.0)	Positive	6
N leaching/run-off	Decrease N leaching/run-off	−38.9	(−83.4, 45.1)	No effect	14
Plant N uptake	Increase plant N uptake	20.1	(13.1, 28.1)	Positive	14
Soil nutrients	Increase soil N content	5.8	(2.3, 9.5)	Positive	21
Crop productivity	Increase crop yield	6.2	(4.5, 7.7)	Positive	14
Double inhibitors					
Air pollutants emissions	Decrease NH_3 emissions	−52.7	(−40.4, −64.1)	Positive	14
GHG emissions	Decrease N_2O emissions	36.0	(17.0, 56.0)	Negative	4
N leaching/run-off	Decrease N leaching/run-off	−29.3	(−53.9, 4.2)	No effect	14
Plant N uptake	Increase plant N uptake	22.1	(15.3, 29.6)	Positive	14
Soil nutrients	Increase soil nitrogen content	6.7	(−7.8, 20.1)	No effect	21
Crop productivity	Increase crop yield	4.9	(3.5, 8.2)	Positive	14
Controlled-release fertilisers					
Air pollutants emissions	Decrease NO emissions	−40.0	(−76.0, −10.0)	Positive	3
	Decrease NH_3 emissions*	−21.8	(−23.2, −20.4)	Positive	2
		−14.7	(−15.7, −13.6)	Positive	2
		−33.2	(−35.6, −30.9)	Positive	2
		−68.0	(−78.5, −54.2)	Positive	18
		−50.8	(−55.2, −45.9)	Positive	24
GHG emissions	Decrease N_2O emissions*	−8.6	(−22.5, 7.4)	No effect	1
		4.0	(−8.0, 20.0)	No effect	4
N leaching/run-off	Decrease N leaching/run-off	−65.9	(−41.8, −81.3)	Positive	14
Plant N uptake	Increase plant N uptake	8.7	(3.7, 13.9)	Positive	14
Crop productivity	Increase crop yield	−0.3	(−7.9, 7.8)	No effect	1

Note: quality score is computed as the number of satisfied criteria through a list of 16 standard quality criteria, which cover three main aspects of systematic reviews and meta-analyses. Details on extracted meta-data and quality criteria can be found in supplementary table 2. Estimates extracted from all included studies are presented in supplementary tables 4–7.

Abbreviations: CH_4: methane; CO_2: carbon dioxide; GHG: greenhouse gas; N: nitrogen; N_2O: nitrous oxide; NH_3: ammonia; NH_4^+: ammonium; NO: nitric oxide.

[a] refers to the reference identification in supplementary table 3.

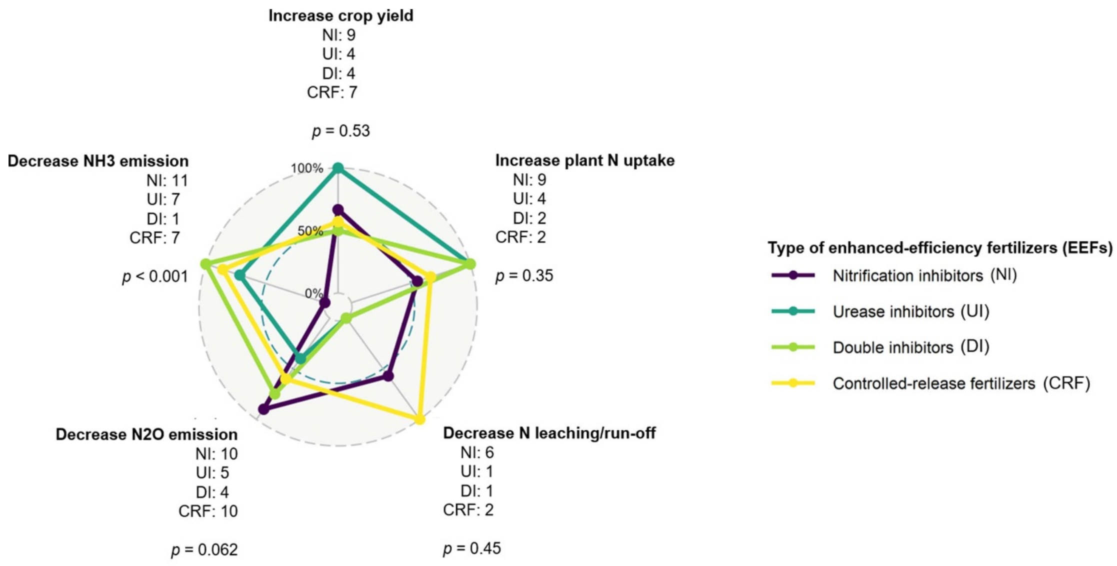
NA indicates missing values.

*indicates situations where multiple mean effect sizes were extracted, either because several meta-analyses had the same level of quality or because several results were provided by one meta-analysis for the same impact.

report no results of the effect of double inhibitors on soil NO_3^- and NH_4^+ content, CO_2 emission, CH_4 emission, and NO emissions (table 1, figure 2, and supplementary table 6). Excluding MSRs satisfying less than 50% of the quality criteria lead to similar conclusions (supplementary figure 1).

3.2.4. Controlled-release fertilizers

Positive results of using controlled-release fertilisers, as compared to conventional fertilisers, were reported for plant N uptake by two MSRs out of three (figure 2). The MSR with the highest quality score reported a 8.7% (95% CI: [3.7%, 13.9%]) increase



Note: Total number of results from meta-analyses and systematic reviews for each type of EEFs are reported for each impact. p-value for Fisher test assessing for each impact whether the distribution of scores is significantly different between the four types of EEFs.

Figure 3. Proportion of positive results and total number of results on ammonia (NH_3) emissions, nitrous oxide (N_2O) emissions, nitrogen (N) leaching/run-off, plant nitrogen uptake and crop yield extracted from meta-analyses and systematic reviews for different enhanced-efficiency fertilisers (EEFs).

in plant nutrient uptake induced by the use of controlled-release fertilisers (table 2). Compared to conventional fertilisers, controlled-release fertilisers application showed a positive effect on crop yield in four MSRs, but no effect in the remaining three. The application of controlled-release fertilisers had also a beneficial effect on N leaching/run-off (two MSRs) and NO emission (one MSR). Controlled-release fertilisers were reported to decrease NH_3 emissions in six (out of seven) MSRs. Results were more contrasting for N_2O emissions, with six (out of ten) MSRs reporting positive results, three indicating no effect, and another providing uncertain result in absence of formal statistical analysis. Among selected MSRs, none examined the effect of controlled-release fertilisers on the content of any form of N in the soil, CO_2 emission, and CH_4 emission (table 1, figure 2, and supplementary table 7). Similar results were obtained when excluding low-quality studies (supplementary figure 1).

3.3. Differences between the EEFs types

Figure 3 shows the proportion of positive results among the selected studies for nitrification inhibitors, urease inhibitors, double inhibitors, and controlled-release fertilisers, separately. We were able to compare these proportions for NH_3 emission, N_2O emission, N leaching/run-off, plant N uptake, and crop yield, because several high-quality studies were available for these impacts for the different EEFs considered.

Compared to other EEFs, the proportion of positive results for NH_3 emissions was significantly lower for nitrification inhibitors ($p < 0.001$). Among the different EEFs, the proportion of positive results for plant N uptake ranged from 51% for nitrification inhibitors to 100% for the other EEFs. Results from the Fisher test indicate that these differences were not significant between EEFs types ($p = 0.35$), due to a lower number of meta-analyses. A marginally significant difference was found for N_2O emissions among EEFs ($p = 0.062$), with nitrification and double inhibitors showing higher proportion of positive results (90 and 100%, respectively) than urease inhibitors and controlled-release fertilisers (40 and 60%, respectively). All types of EEFs presented a similar proportion of beneficial results for crop yield ($p = 0.53$) and N leaching/run-off ($p = 0.45$) (figure 3).

Sensitivity analyses conducted among high-quality MSRs showed that nitrification inhibitors and double inhibitors reported a higher number of positive results on N_2O emissions as compared to urease and double inhibitors ($p = 0.020$). Conclusions remained similar for NH_3 emissions ($p < 0.001$), plant N uptake, crop yield, and N leaching/run-off results ($p > 0.05$ for all).

3.4. Key factors influencing the impact of EEFs on the environment, crop production, and nutrient use efficiency

Among selected MSRs, 17 report that the impact of EEFs on air pollutant emissions, GHG emissions, N leaching/run-off, plant nutrients uptake, soil N content, and crop yield varied according to several factors (table 3). Factors related to N fertilisation practices influenced EEFs' effects in eight MSRs out of 17,

Table 3. Key factors influencing size of the effect in selected meta-analyses and reviews.

Impacts	Factors explicitly reported in the reviewed synthesis papers
Decrease of air pollutant emissions	Aridity [14]; Crop type [24, 25]; Baseline emission [14]; EEFs product [14, 18, 19, 25]; N fertiliser rate [22, 25]; Soil N content [25]; Soil organic carbon content [25]; Soil pH [14, 25]; Soil texture [14]; Soil type [19]; Type of land use [14, 19]; Type of fertiliser [14, 19];
Decrease greenhouse gas emissions	Aridity [7]; Baseline emission [3, 14]; Crop type [14, 23, 25]; EEFs product [3, 25]; Fertiliser application timing [7, 23]; Nitrogen fertiliser placement [7, 23]; Nitrogen fertiliser rate [7]; Soil pH [6, 7, 14, 23, 25]; Soil organic carbon content [14]; Soil texture [7, 14]; Soil type [3, 9, 17]; Temperature [14]; Tillage [7]; Type of land use [3, 9, 14]; Type of fertiliser [9]; Water management [7, 23];
Decrease of nitrogen leaching/run-off	Nitrogen fertiliser rate [25, 26]; Soil nitrogen content [25]; Soil organic carbon content [14]; Soil texture [19]; Type of fertiliser [19, 26]; Type of land use [14, 19];
Increase plant nutrients uptake	Crop type [16, 21]; EEFs product [14, 21]; Nitrogen fertiliser placement [14]; Nitrogen fertiliser rate [21, 24]; Rainfall [14]; Soil organic carbon content [14, 25]; Soil organic matter [21]; Soil pH [14, 25]; Soil texture [14, 21]; Temperature [14]; Type of fertiliser [14, 21]; Type of land use [14]; Water management [14];
Increase soil nitrogen content	EEFs product [19, 21, 26]; Fertiliser application timing [21]; Nitrogen application rate [21, 26]; Type of land use [19, 21]; Type of fertiliser [19]; Soil pH [21, 26]; Soil texture [19, 21];
Increase crop yield	Crop type [10, 14]; EEFs product [13–15, 25]; Nitrogen application rate [20, 25]; Nitrogen fertiliser placement [14]; Rainfall [14]; Soil N content [25]; Soil organic carbon content [14, 25]; Soil pH [14]; Soil texture [14, 22]; Temperature [14]; Type of fertiliser [13, 14]; Type of land use [14];

(Continued.)

Table 3. (Continued.)

Note: numbers in brackets refer to the reference identification in supplementary table 3. Abbreviations: EEFs: enhanced-efficiency fertilisers.

with generally stronger benefits of EEFs under high N application rates and multiple applications. Evidence for other N-fertilisation factors (type of fertilisers used, N placement) depended on the considered impact and EEFs. For example, one meta-analysis reports higher impact on nitrification inhibitors on NO_3^- leaching when applied with manure but lower impact on NH_4^+ and NO_3^- content when applied with mixture [28]. Soil type, texture, pH and N and organic carbon contents also influenced EEFs' impact according to eight MSRs. Six MSRs found that EEFs' impact on crop yield, plant nutrients uptake, air pollutants, and GHG emissions varied between crop types. The effect on these impacts were also influenced by abiotic conditions, such as rainfall, aridity/soil moisture, and temperature according to two MSRs. Three MSRs found that other farming practices such as water management and tillage influenced the effect of EEFs on GHG emissions and plant N uptake.

4. Discussion

This study, based on the results of 26 MSRs, provides a systematic and global synthesis of the current evidence on the effect of EEFs, namely nitrification inhibitors, urease inhibitors, double inhibitors, and controlled-release fertilisers on a wide range of environmental impacts, plant nutrients uptake, soil fertility, and crop productivity. EEFs were found to have beneficial effects on several environmental metrics; in particular, EEFs were reported to reduce NH_3 and N_2O emissions. Additionally, EEFs application was also reported to potentially enhance plant N uptake and crop yield compared to conventional fertilisers. Results were consistent when considering the quality of extracted meta-analyses and reviews. Taken together, these findings suggest that the use of EEFs has the potential to provide environmental and productivity benefits compared to conventional fertilisers.

With few exceptions [5, 6, 29], most published meta-analyses assessed the effect of specific types of EEFs on a restricted list of productivity and/or environmental outcomes. The second-order meta-analysis of Young, Ros, and de Vries [29] describes the effect of nitrification inhibitors, urease inhibitors, and controlled released fertilisers on several indicators related to crop productivity, soil quality, environmental losses, cropping management, and soil management. Consistent with our findings, they found that the use of these EEFs was associated with increased crop yield and N use efficiency, reduced CO_2, N_2O, and NH_3 emissions, and reduced N surplus, leaching, or runoff. Two meta-analyses [5, 6] examined the effect of all types of EEFs, separately, on crop productivity (i.e. yield and/or plant N use efficiency) and NO_3^- losses, NH_3 and/or N_2O emissions and reported similar conclusions. These corroborate findings from meta-analyses that report the impact of few EEFs on a restricted list of outcomes, showing that the effect of EEFs was generally positive on yield [6, 13, 21, 28, 30], plant N uptake [28, 30, 31], N losses, GHG emissions [10], air pollutants emissions [32], and soil N content [28, 30, 31].

Not all types of EEFs have the same effects, as expected according to their target function. For example, nitrification inhibitors and double inhibitors were more frequently reported to reduce N_2O emissions compared to urease inhibitors and controlled-release fertilisers, the latter being more effective in reducing NH_3 emissions and risks of N-losses to water bodies through leaching or runoff. These findings are in line with previous findings [29] and confirm the expected outcomes of the different EEFs products, which act through different chemical/biochemical mechanisms. For instance, nitrification inhibitors target the inhibition of microbial nitrification activity. Specifically, nitrification is retarded over a relatively long time period (20–28 d), when ammonium ions can be efficiently uptaken by crops, before nitrification processes could occur [4]. Less N would then be found in the form of nitrates, which are prone to either denitrification (to N_2O) or to leaching. However, higher NH_4^+ ion concentrations in soil increase the risk evaporation as gaseous NH_3. This potential trade-off effect of nitrification inhibitors is confirmed by the majority of the meta-analyses (figure 2). Regarding leaching or run-off of mineral N forms into ground/superficial water courses, all meta-analyses confirmed positive effect of nitrification inhibitors on dissolved inorganic N and on NO_3^- N leaching, while the results were more contrasted for NH_4^+–N leaching. One meta-analysis conducted in China reported a variable effect of nitrification inhibitors on NH_4^+ according to the type of product used (i.e. dicyandiamide or 3,4-dimethylpyrazole phosphate) [28]. This was confirmed by another meta-analysis conducted at global scale [30]. NH_4^+ ions, despite their high water-solubility, are less prone to leaching, as compared to NO_3^-, because of their positive charge which determines higher chances for adsorption on negatively-charged soil aggregates [19]. However, the higher soil NH_4^+–N concentrations determined by nitrification inhibitors can relatively increase the possibility of direct N losses not only as gaseous NH_3 but also as soluble form along with precipitations.

On the other hand, other types of EEFs were less prone to trade-offs effects on unwanted emissions, as compared to nitrification inhibitors. Despite the lower number of results available (figure 3), double inhibitors were found efficient for simultaneously increasing N-use efficiency, while avoiding both NH_3 and N_2O emissions. For controlled-release fertilisers, in particular, we found a consensus among meta-analyses, supporting simultaneous positive effects on N-use efficiency, NO_3 emissions, N-leaching and N_2O emissions, as well as for crop yield (figure 3). Such results confirm that acting for decreasing the rate of N release under water-soluble forms is a promising strategy to prevent losses of the mineral-N input along with soil physical, chemical and microbiological transformations [8]. In addition, some effects of EEFs were found to be context-dependent and influenced by several factors, such as fertilisation management or biophysical conditions. These findings suggest the positive impacts of EEFs can be stronger in some specific conditions [4–6, 33].

In this synthesis, several knowledge gaps on the effect of EEFs use on environmental and production aspects are identified. Selected reviews and meta-analyses found in the literature mainly focused on temperate regions, with little attention to tropical areas. Among EEFs, nitrification inhibitors were most frequently investigated, followed by urease inhibitors, controlled-release fertilisers, and double inhibitors. Future research works should focus in priority on double inhibitors because this type of EEF was underrepresented in the literature (double inhibitors were considered in six studies out of 26, only). Crop yield, plant N uptake, N_2O emissions, and NH_3 emissions were the most frequently reported outcomes for all types of EEFs. Besides, evidence for CO_2 and CH_4 emissions or for soil NO_3^- and NH_4^+ content is limited to nitrification inhibitors and absent for other types of EEFs. In particular, no meta-analyses were found to present results regarding the potential effects of EEFs on soil biodiversity, biogeochemical processes, plant growth and metabolism, water quality, human and animal health, and on their ecotoxicity on non-target organisms. Different environmental aspects could be potentially affected by the massive use of some EEFs, especially in the case of urease, nitrification and double inhibitors, which are bioactive substances [4].

Although very informative, our study suffers from several limitations. First, the primary objective of our study was not to provide a detailed analysis of the local impacts of EEFs, but rather to provide robust evidence on their impact on a variety of outcomes at large scale. For this reason, we chose to focus on meta-analyses and not on primary studies. The results reported on the selected meta-analyses are based on large sets of experimental data and thus are less dependent on local conditions than the results of individual studies. Their results are more robust than those reported in individual studies. On the other hand, the results reported in these meta-analyses cannot be easily used to investigate the factors explaining the heterogeneity of the effects of EEFs at a high level of detail, because these factors are studied in a very heterogeneous manner in published meta-analyses. In order to analyse the effect of these factors more precisely, it would be necessary to extract data from the individual studies and, even in this case, the statistical analysis of the resulting dataset will be restricted by the type of factors reported in each individual study. Still, we were able to report all the factors impacting significantly the effects of EEFs as mentioned by the authors of the selected meta-analyses, which allowed us to identify the main sources of variation in the effects of EEFs. The results extracted from included studies were presented independently, rather than being aggregated as in a second-order meta-analysis providing a single overall mean effect size across all MSRs. However, we chose this approach because we consider that it is more informative to present a range of possible outcomes instead of summarizing all results by a single value. Mean effect sizes and corresponding 95% CI reported from high-quality MSRs should be considered as illustrative examples, but may not be relevant in all situations (e.g. national scale, specific crops). Depending on the objectives targeted by the users, it is possible to choose one or other of the values reported using the summary tables (supplementary tables 4–7). Second, although some impacts have been assessed in numerous studies, others have barely been considered in the literature, revealing important knowledge gaps, particularly on the impact of EEFs on biodiversity.

5. Conclusion

This study, based on the results of 26 MSRs, provides a systematic and global synthesis of the current evidence on the effect of EEFs, namely nitrification inhibitors, urease inhibitors, double inhibitors, and controlled-release fertilisers on a wide range of environmental impacts, on nutrients use efficiency, soil fertility and crop productivity. EEFs were found to have beneficial effects on several environmental metrics; in particular, EEFs were reported to reduce NH_3 and N_2O emissions. Additionally, EEFs application was also reported to potentially enhance plant N uptake and crop yield compared to conventional fertilisers. Results were consistent when considering the quality of extracted meta-analyses and reviews. Taken together, these findings suggest that the use of EEFs has the potential to provide environmental and productivity benefits compared to conventional fertilisers.

Using a reproducible, rigorous, and transparent framework, we were able to summarize current evidence on the impacts of EEFs. By covering a wide range of environmental aspects, as well as crop yield, our study provides a holistic assessment of the benefits for the environment and crop production of a large range of EEFs, compared to earlier studies that examined a restricted list of outcomes. Our approach also allowed us to assess the quality of selected meta-analyses and reviews published on this topic. The quality of included studies was presented in a transparent manner and considered when reporting the results. A large majority of MSRs published on this topic was of a relatively high quality and we found that our conclusions were robust to quality level and were not changed when excluding MSRs of low quality. Still, we found that several quality criteria were not often satisfied, especially absence of publication bias analysis, dataset not available, and individual effect size.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request..

Code availability

The scripts used for this study is provided in supplementary materials.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

Mathilde CHEN and David MAKOWSKI conceived the idea for the study. David MAKOWSKI, Marta PÉREZ-SOBA, Andrea SCHIEVANO, Ana MONTERO-CASTAÑO, and Simona BOSCO designed the study methodology. Mathilde CHEN and Andrea SCHIEVANO extracted the data. Mathilde CHEN and David MAKOWSKI did the formal data analysis. Mathilde CHEN, Andrea SCHIEVANO, and David MAKOWSKI prepared the first draft of the manuscript. All authors reviewed and edited the manuscript. Mathilde CHEN and David MAKOWSKI were responsible for the figures. David MAKOWSKI supervised the study.

ORCID iDs

Mathilde Chen https://orcid.org/0000-0002-5982-2143
Andrea Schievano https://orcid.org/0000-0003-3458-2654
Simona Bosco https://orcid.org/0000-0002-9388-6087
Ana Montero-Castaño https://orcid.org/0000-0003-2631-0085
Giovanni Tamburini https://orcid.org/0000-0001-7546-8183
Marta Pérez-Soba https://orcid.org/0000-0002-7413-9385
David Makowski https://orcid.org/0000-0001-6385-3703

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