nature portfolio

Peer Review File

Plastic mulch productivity-sustainability tradeoffs and pathways toward an eco-friendly framework: insights from a global meta-analysis

Corresponding Author: Professor Gary Gan

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I am pleased to be invited to review the manuscript titled: 'Evolving Plastic-Assisted Agriculture Beyond the Productivity–Sustainability Paradox'. The paper deals with a second-order meta-analysis on the pros and cons of using plastic in agriculture at global level, and addresses in-depth agro-engineering techniques to mitigate environmental and ecological downside effects of plastic use. In addition, the study also provides wider public/social and policy indications on replacing plastic with more sustainable inputs to increase agricultural production. While I recognise the efforts made by the authors in addressing this important issue at global level and contribute to the international literature, there are some general and detailed issues the authors should address for potential consideration in publishing with Nature Communications:

General concern:

1. By looking at figure s4 (study mapping) and reading the proposed work, an overall reflection should be made: while the study refers at a global scientific evidence, there is a persistent lack of critical discussion at the 'global' level. The map on S4 clearly shows that most studies with the highest concentration of high number of experimental first-order meta-analyses are indeed in Europe.
In lines 319-323 you mention: "Although our data are largely based on studies conducted in China": how does this statement find a justification in figure s4?
and also "our findings offer scalable solutions applicable to other plastic-intensive regions beyond China". Instead, in figure 2b it is mentioned:
"In (b), study regions reflect key agricultural areas in China—the world's leading user of agricultural plastic—where side-by-side comparisons of the two systems were conducted across diverse environments.". This statement appears to me quite contradictory with the global level study of your second-order meta-analysis. Arguing that China is the largest agricultural plastic user is not enough to justify a study at global level and a discussion/comparison/scalability of results at Chinese level. Please carefully revise the above statements providing an in-depth and scientifically valid justification.

Other concerns:

Abstract.
2. Please use text rather than > or < symbols for a wider audience.

Main.
3. Line 104. "plastic-assisted farming remains favoured by many farmers and policymakers". Based on this, I would carefully revise the above sentence as there are several policy initiatives such as, for example, the Resolution of 13 September 2018 on a European Strategy for Plastics in a Circular Economy, or the Extended Producer Responsibility which have been taken into account by studies focusing on agriculture/agricultural waste and that can be considered for citation in your work:
https://doi.org/10.3390/ijerph182212042
https://doi.org/10.1016/j.jclepro.2019.119844
https://doi.org/10.1016/j.jenvman.2023.119242
https://doi.org/10.1016/j.hazadv.2025.100727
https://doi.org/10.1016/j.jenvman.2023.119242
https://doi.org/10.1016/j.resconrec.2014.03.013

https://doi.org/10.1016/j.jenvman.2019.109468
https://wm.turkmenistan.ecoline-int.org/wp-content/uploads/2021/08/EPR-and-plastics-report-IEEP-9-Nov-2017-final.pdf

4. Line 110. Why did the authors choose this period for their study? i.e. 2011-2024.

5. Line 138. “introducing a policy mechanism under the Global Plastic Treaty of the UN’s Environment Program, treating microplastic emissions as tradable carbon equivalents.”. While this is initiative is urgent and commendable, why leaving out of this discussion the integration of this mechanism with other mechanisms and tools at a more local level? Please revise.

Results.
6. fig 2. “n indicates the number of paired comparisons extracted from the reviewed literature; the blue line represents no yield difference between mulched and non-mulched systems.”. This is not clear from the figure. Where is the blue line?

8. fig 3 and fig. 5. where is n? please rephrase or explain better.

9. fig 4. too many arrows across the figure. please simplify and make it more consistent.

Discussion.
10. Lines 392-403. policy concerns are approximated here. you should extend these to a more global view. Also, life cycle assessment and critical assessment are not policy strategies nor indications.

11. Line 643-645. “Regulate international trade of agricultural products cultivated using plastic cultivation systems, and enforce quality control mechanisms to support adoption of alternative, non-plastic agricultural practices”. In light of the current geo-political situation, how would you regulate international trade policies with national/local policies? Briefly explain or provided indications.

12. Lines 466-473. ii, iii, and iv are counterintuitive. Please can you explicit into more detail ‘how’ to achieve what is mentioned in those points?

13. Lines 474-479. Farm managers should consider cost-effective alternatives into their decision making process. This evidence lacks here. Please revise accordingly

14. Lines 480-488. Here there is just an indication of the ‘what’ the general public and consumers should do in points i, ii, and iii. Extending these points with the ‘how’ would provide a more coherent view on the important issue of public awareness.

15. fig 6. Again there’s too much in this figure. please can you keep it simpler?

Conclusions.
16. Line 513. The ‘One health’ framework is mentioned in the introduction and in the conclusions only. The reader loses the traces of this framework in the flow of the study. Please make it clear to refer to this framework in other parts of the paper, for example the discussion section would benefit from this highlight, other than the introductory and conclusions parts.

17. Line 517. “Furthermore, we recommend creating ‘living labs’”. This is a well-known indication from the literature and widely recognised. Here are some examples:
https://www.sciencedirect.com/science/article/pii/S0195925524001756
https://doi.org/10.1016/j.jclepro.2024.141247
https://doi.org/10.1007/s11368-025-04100-z
https://doi.org/10.1186/s42055-023-00060-9
As a results it appears counterintuitive. Please revise accordingly.

Supplementary information.
18. Lines 6-8. Why did you select/choose these search engines? There is no scientific justification behind your choice. Please revise accordingly.

19. Line 73. “low quality studies”. Please explain what low quality means.

20. Fig. s3. In Line 110 of the manuscript the considered period of study is between 2011-2024 (see also my comment #4). Instead, the flow chart (fig s3) mentions the period 2017-2022. Please revise.

Prisma chart.
21. In file 629671_0_rel_ms_0_szr5cm.pdf (the PRISMA chart) it is indicated: “Records removed for other reasons”. In the supplementary information, please explain what are these reasons.

Reviewer #2

(Remarks to the Author)
The paper does not add any specific novelty to the literature, but it is a very good piece of work which helps to shape some useful reflections on the issue of plastic use in agriculture in the light of the coming work of the Intergovernmental

Negotiating Committee (INC-5). In the last decades agriculture has become an important source of plastic pollution. In countries like China and India (and many others where the pressure of the population on agricultural land for food production is particularly felt) plastic-assisted agriculture is considered a useful agronomic practice which helps to increase crop yields while saving on agricultural land expansion (so inducing to a more efficient use of agricultural land for food security purposes). Nevertheless, it happens at a significant environmental cost which particularly refers to the accumulation of microplastics in soil (deriving from polyethylene film mulches, fertilizer bags, drip irrigation pipes, industrial abrasives and agrochemical containers), reduction in soil carbon in mulched fields and the presence of nano-plastics in food chain. As the authors appropriately highlight, this latter aspect, although being the subject of controversial considerations among researchers (as some confirm and others not, due to the lack of generally accepted investigation protocols), opens the way to another relevant socio-health problem related to the food safety argument. With the aim of contributing to developing a scientifically-based framework and generate a useful discussion on the productivity-sustainability paradox (with sustainability here intended in its "environmental" sense which I suggest should always be specified as done in line 106), through a Second Order Meta Analysis (SOMA), the work synthetizes decades of research from global studies (i.e. 10,611 global works) to identify key soil and crop-related anthropogenic factors influencing the use of plastic in agriculture, as well as its merits and negative environmental impacts.
In addition, the work provides some indications for strategies aimed at reducing the use of plastic in agriculture while focusing on transformative and interdisciplinary solutions (e.g. developing bioengineered smart mulches, converting plastic waste into biochar or syngas through the creation of financial schemes for zero-waste in agriculture, combining gene-edited crops with AI-driven precision mulching techniques, introducing a policy mechanism under the Global Plastic Treaty of UNEP to treat microplastic emissions as tradable carbon equivalent. The work also promotes a reflection on a "One Health" framework for sustainable agrifood systems by integrating under the umbrella of policy science some advances in microbiology and AI-driven precision farming. All this considered, and on the basis of my research field expertise, my observations / suggestions are the following:
• line 51 – in respect of the literal form of the paper, I would avoid the use of the mathematical sign > and write "more than 170 nations" and "more than 440 organizations". The same in the rest of the paper where this aspect recurs;
• line 56 – as said above, I would specify that the term "sustainability" is here taken more in its environmental sense,
• page 236 – the section "Microplastics contaminate the soil and pollute the environment" appears too suddenly. I would suggest to better coordinate the writing of the "Results" section by dividing it into two clearly identified subsections. The first devoted to the description of the merits of plastic use in agriculture (i.e. physiochemical mechanisms driving the enhanced productivity particularly particularly related to soil moisture conservation and thermal regulation, early-season soil temperature increase, enhanced soil microenvironment and microbial activity, and weed suppression). The second subsection dedicated to the description of the environmental problems deriving from it (specifically related, as reported by the authors, to soil contamination and environmental pollution from microplastics together with food safety concerns). Here below, how I would organise it:

145 RESULTS
[…]

157 Physiochemical mechanisms driving the enhanced productivity
[…]

199 1. Moisture Conservation and Thermal Regulation. […]

210 2. Early-Season Soil Temperature Increases. […]

219 3. Enhanced Soil Microenvironment and Microbial Activity […]

229 4. Weed Suppression. […]

236 Environmental Contamination from Microplastics [I would retitle it in this way]
[…]

242 1. Soil Pollution […]

265 2. Other Forms of Environmental Impacts […] [I would retitle it in this way]

277 3. Food Safety Concerns […] [I would retitle it in this way]

• lines 310-311 – and especially in the previous parts where the work uses the terms of food security and food safety, I would give a very brief description of their actual meanings by explicating the first is referred to food supply and food shortages while the second to the human or animals' health conditions;
• lines 328-329 – with a clear focus on the short/long term impact of mulches biodegradation, some further confirmative considerations, can be found in the work by (which I suggest to recall) Campanale C. et Al., 2024, A critical review of biodegradable plastic mulch films in agriculture: Definitions, scientific background and potential impacts, TrAC Trends in Analytical Chemistry, Vol. 170, doi: 10.1016/j.trac.2023.117391;
• lines 344-345 – it is stated that, in achieving certain desirable conditions, bioengineered smart mulches can perform well or even better than traditional polyethylene films. I feel that, similarly to what is done in lines 357-358, when talking about ticker film production, a brief comment should be made on the economic aspect of smart mulches adoption. Production costs and, as a consequence, the price at which such an innovation can be offered on the market, plays an essential role for its actual

implementation (e.g. see Golberger J.R. et Al., 2015, Barriers and bridges to the adoption of biodegradable plastic mulches for US speciality crop production, Renewable Agriculture and Food Systems, Vol. 30(2): 143-153, doi: 10.1017/S1742170513000276. Furthermore, see Yang W. et Al., 2023, Factors affecting farmers' adoption of and willingness to pay for biodegradable mulch films in China, Sustainability Analytics and Modelling, Vol. 3, doi: 10.1016/j.samod.2023.100016). From this, a further brief reflection can be developed by highlighting how the probable higher price paid to adopt smart mulches in substitution of traditional ones can be justified by the need of internalising the external cost of the plastic pollution. This line of discussion would also open the way to further reflect on some policy considerations on what policy makers can do to accompany this transformative process of mulches use (e.g. see Hao A. et Al., 2024, Cost–Benefit Analysis of Mulch Film Management and Its Policy Implications in Northern China, Agriculture 2024, 14, 1081, doi: 10.3390/agriculture14071081);
• line 373 – in the subsection title, the term of blockchain is recalled. However, no explicit mention of it is made in the following text. Although something is said in the concluding section (lines 498-500), as a reader, already in this subsection, I feel a brief link to where, why and how blockchain enters into the game is necessary (i.e. mulch life cycle traceability, smart contracts, tokenised incentives, etc.);
• lines 461-462 – when talking about the promotion of higher recovery rates of waste films (and also investment on recycling infrastructure to improve the efficiency, effectiveness and economic viability of handling reusable plastics), the consideration of some specific market tools (e.g. tax and subsidies) cannot be avoided. In this sense, some works may be orientation (e.g. Pazienza P., De Lucia C., 2020, for a new plastics economy in agriculture: Policy reflections on the EU strategy from a local perspective, Journal of Cleaner Production, Vol. 253, doi: 10.1016/j.jclepro.2019.119844; De Lucia C., Pazienza P., 2019, Market-based tools for a plastic waste reduction policy in agriculture: A case study in the south of Italy, Journal of Environmental Management, Vol. 15, doi: 10.1016/j.jenvman.2019.109468).

Having said this, and in the hope that the above observations / suggestions may be useful for the authors to improve their work, I believe that the work is a useful addition to the scientific community and policy makers and can be accepted for publication.

Reviewer #3

(Remarks to the Author)
The paper by Leona Wang et al. “Evolving Plastic-Assisted Agriculture Beyond the Productivity-Sustainability Paradox” presents a large-scale second-order meta-analysis (SOMA) summarizing over 70 published meta-analyses with more than 10,000 paired comparisons and over 100,000 observations. The study addresses the “plastic paradox” in agriculture, namely the tension between significant short-term productivity gains from the use of plastics and the long-term risks to soil health, environmental sustainability, and food security. The framework is timely and highly relevant given the ongoing international negotiations (which failed last week in Geneva, maybe to be addresses in the revised version?) on the regulation of plastics, and the scope of the quantitative synthesis represents a significant advance in this area.

The authors quantify robust yield increases and report a 28.7% increase across all crops with additional benefits for water use efficiency, particularly for corn and diversified cropping systems. The extrapolation to system-level benefits is convincing: between 2010 and 2021, plastic-supported systems are estimated to produce an additional 95.1 million tons of wheat and maize and save 23.2 million hectares of land. These are highly policy-relevant results that underscore the importance of this practice for global food production. The mechanistic explanations for these benefits are also convincing, with evidence of increased soil moisture, higher soil temperatures during the growing season, changes in microbial activity and diversity, and a reduction in weed emergence. The integration of mitigation options ranging from bioengineered “smart” mulch films and strategies for the efficient use of precision plastics to circular economy concepts and agroecological alternatives provides a valuable roadmap for the transition. The policy discussion is well linked to international treaty processes and provides clear starting points for negotiators, policymakers, and practitioners.

The manuscript requires some important clarifications and corrections before it can be accepted, specifically potentially misleading reporting of sample sizes. In several places, extremely high “n” values are given in culture-specific tables, for example for wheat with n = 10,103 and potatoes with n = 8,952 (lines 161 to 166). These figures are referred to as “studies,” but clearly cannot represent the number of studies and must instead refer to pairwise comparisons or experimental contrasts. This labeling occurs in both the main text and the figure captions. It must be corrected throughout to avoid confusion and an overestimation of the evidence base.
The authors state that plastic-supported agriculture avoids “201.4 Mt N_2O emissions” (lines 186 to 187). This figure appears unrealistically high when interpreted as direct N_2O emissions. It is possible that the figure is given in CO_2 equivalents. In this case, the basis for the calculation (GWP, AR6 values) must be explicitly stated. A similar problem arises in Figure 1, where the film thickness is given in both millimeters and mils (lines 144 to 154). For clarity, the manuscript should use a consistent system.

The statistical transparency of the SOMA framework needs to be improved. The Methods section (lines 525 to 581) clearly describes the conversion of effect sizes, random effects modeling, and weighting, but the manuscript does not include heterogeneity statistics or an assessment of publication bias. These are standard in meta-analyses and essential for assessing robustness. Heterogeneity measures should be reported for each important outcome category, and publication bias should be addressed using funnel plots or Egger's regression. A PRISMA-like flow diagram showing the identification, screening, and inclusion of studies would also contribute to the much-needed transparency of the synthesis.

Some claims appear exaggerated or speculative. The text claims that CRISPR-AI techniques could reduce plastic consumption by 70% (lines 362 to 367), while elsewhere a potential reduction of 50% is stated (lines 503 to 507). These

figures are presented as facts, but without references or clear methodological justification. Such claims should be explicitly labeled as prospective or ambitious, supported by available modeling or pilot data to avoid overestimating the current state of the art. The analysis of thresholds and mechanisms also needs clarification.

The authors emphasize that with a residual plastic content of more than 480 kg per hectare, yields decline by about 28% (lines 260 to 262). This is an important finding with clear implications for management, but the methods used to derive this threshold are not explained. It is essential to specify whether this effect was determined using piecewise regression, binning, or another approach, and to provide confidence intervals for the estimate.

The section on food safety is appropriately cautious and balanced, highlighting the current uncertainties regarding exposure pathways and health risks. However, it could be made even more useful for policymakers by including a summary table of the detection methods, analytical limits, and food matrices examined to date. Such a table would help negotiators and regulators understand both the progress made and the gaps in monitoring methods.

Several minor points should be addressed: The maximum concentration of microplastics in soil (up to 690,000 particles per kilogram) should be put into context by specifying the soil type, depth, and analysis method, and mass, if possible. Particle numbers alone are not indicative. This would enable readers to assess whether this value represents an extreme hotspot or a more general risk. Typing and formatting errors must be corrected, including “obhectives” instead of ‘objectives’ (line 369), “Sci Hurt” instead of “Sci Hortic.” in the references (lines 679 and 722) and inconsistent punctuation in the affiliation details.

Figures are generally informative, some adjustments are necessary. In Figures 2 and 3, “n” should be labeled as paired comparisons rather than studies. Confidence intervals should be provided for important moderator effects, e.g., for the +47% increase in water use efficiency in diversified systems (lines 191 to 194) and the +54% yield gain at <200 kg nitrogen per hectare (lines 174 to 177). Figure 5 requires consistent units and base values for greenhouse gas and nutrient flows, and Figure 6 could be improved with clearer legends or symbols to make it more understandable for interdisciplinary readers.

In summary, this manuscript represents an ambitious and important contribution. It synthesizes an enormous amount of evidence, demonstrates the dual benefits and risks of plastic-supported agriculture with unusual clarity, and provides a well-structured roadmap for mitigation measures and policy decisions. I recommend publication after major revisions. The sample sizes need to be corrected, unit inconsistencies need to be resolved, uncertainties and heterogeneity statistics need to be reported, and speculative claims need to be toned down or put into context. Improved methodological transparency and minor editorial improvements would significantly improve the quality of the article.

Reviewer #4

(Remarks to the Author)
Manuscript Number: NCOMMS-25-51950
Title: Evolving Plastic-Assisted Agriculture Beyond the Productivity Sustainability Paradox

Comments

Plastic pollution is a global issue. This comprehensive meta-analysis examines the dual role of plastic film mulching in agriculture—enhancing crop yields while posing significant environmental risks. The study synthesizes global data to quantify the yield benefits and environmental costs under plastic mulching. The authors propose mitigation strategies, including bioengineered mulches, circular economy approaches, and policy reforms. This notwithstanding, there are some concerns that make me preclude it from being considered further for publication in the Nature Communications Journal.

1. The study retrieved plastic mulching data rather than micro/nanoplastics data. I do not understand how they used the data to analyze and discuss microplastic contamination. I do not think the aim of the study related to micro/nanoplastic pollution and the section “Microplastics Contaminate the Soil and Pollute the Environment” makes sense.

2. While SOMA mitigates bias, the inclusion of studies with varying experimental designs (e.g., film thickness, crop types, climatic zones, etc.) may introduce residual variability. A sensitivity analysis should be conducted to address the data heterogeneity.

3. The Discussion section did not discuss the results from SOMA. In addition, the discussion on nanoplastics in food chains relies heavily on indirect evidence. More empirical data on translocation mechanisms and human health risks are needed.

4. The SOC loss mechanism is oversimplified. Please incorporate evidence on soil aggregate stability, carbon mineralization (e.g., qCO2), and microbial functional genes to strengthen causal reasoning. Nanoplastic uptake pathways also require clarification, particularly size- and material-specific differences and rhizosphere interactions.

5. The feasibility of bioengineered mulches and AI-driven alternatives is underexplored. Cost-benefit analyses should be included to strengthen practical adoption arguments.

6. Most data derive from China. However, in Figure S4, China is not a major study site but Europe is the most studied sites included in the 71 original meta-analyses. Expanding to other plastic-intensive regions would enhance generalizability. Long-term (> 10 years) mulching impacts on soil ecosystems are also underrepresented and should be discussed.

7. Abstract: Too much background introduction before bringing up what the study addressed.

Correct “>170 nations and >440” to “> 170 nations and > 440”.

Please add “and” before “(f) Integrating policies…”.

8. Please capitalize the first letter of each keyword.

9. Any reference to support “However, nitrogen use efficiency (NUE)—the crop yield per unit of applied nitrogen (N) under specific soil and climatic conditions—declined from 21.3 to 11.1 kg of grain per kg of N, representing a 48% decrease.”?

10. Forest plots should report heterogeneity statistics (I2, P). Terminology (e.g., PUE, nano/microplastic size definitions) must be standardized.

11. The ' intelligent ' plastic film can be degraded during the crop growth season. Can it have the same effects as traditional plastic film such as inhibiting weeds, heat preservation and moisture conservation?

12. Please do not stretch the Figures vertically.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I have carefully read the revised manuscript and the authors have diligently addressed all points raised. I, therefore, suggest that the manuscript can be further processed to publication on Nature Communications.
My best wishes to the authors.

Reviewer #2

(Remarks to the Author)

Reviewer #3

(Remarks to the Author)
The authors have addressed most of the concerns raised in my initial review. However, in the revised version there remain several issues that should be carefully revised before publication.

Abstract:
The statement “Despite global negotiations in 2024 and 2025, a binding UN treaty stalled due to insufficient scientific input” is factually incorrect. The negotiations did not stall because of a lack of scientific input—there was, in fact, substantial scientific engagement. The negotiations stalled largely for political reasons, as several major (oil-producing) countries questioned the sufficiency of scientific evidence to delay action—similar to patterns observed in climate change negotiations. Please revise this statement to reflect the actual political context and ensure accuracy. The cited reference (Spring et al., your citation 13) called for greater attention to science (and published before the negotiations!), but does not support your causal claim that insufficient input caused the stalemate. Please correct this carefully.

Further, the phrase “developing AI-driven biodegradable smart mulches” appears primarily as a buzzword. While the idea is innovative, the manuscript does not provide any substantive discussion or analysis of AI applications in this context—nor does it reference relevant literature. Moreover, the ecological and energy costs of AI systems should at least be acknowledged. Recent studies (e.g., Nature, 2025) predict that AI-related energy consumption may reach the scale of entire regions like India by 2035. Please either remove the AI reference from the abstract or add a properly balanced and referenced discussion in the main text. In its current form, this reference is misleading and not supported by the manuscript content.

Similarly, the mention of “CRISPR-edited films” in the abstract is inconsistent with the main text, where you discuss CRISPR-edited crops (line 479) as part of next-generation farming systems. This is a conceptual mismatch and should be clarified. Please ensure the terminology in the abstract aligns with the actual content and focus of the paper.

Overall, while the paper is significantly improved and contains valuable work, the abstract does not accurately represent its core findings. It overemphasizes contemporary buzzwords (AI, CRISPR) without providing corresponding depth or evidence in the manuscript. I strongly recommend a full revision of the abstract to ensure it reflects the actual scientific contributions and focus of the study.

Reviewer #4

(Remarks to the Author)
My primary criticism is a fundamental mismatch between the data presented and the discussion/conclusions drawn. The meta-analysis rigorously re-evaluated agricultural performance using data on plastic mulching films. It contended that prevailing policy and environmental discourse frequently extrapolates beyond the scope of the available data, resulting in overstated claims regarding its effects. Besides, the manuscript devoted more than 2 pages to discussing the environmental impacts of microplastics and nanoplastics. This is a critical over-extension, as the study does not retrieve or analyze data on the formation, fate, or toxicity of these fragmented particles.

The extensive speculation on the topic beyond mulching film data, spanning multiple pages, is not supported by the evidence presented and severely undermines the manuscript's focus and validity.

For a journal with the broad audience and impact of Nature Communications, it is essential that the discussion is tightly constrained by the data. The policy implications and environmental discourse must be directly and robustly supported by the study's own findings. In its current form, the manuscript does not meet this standard.

Response to Referees

Dear Reviewers,

Thank you for the opportunity to revise the manuscript. We sincerely appreciate the constructive comments and suggestions you provided. Your feedback has been invaluable, and we have carefully addressed each point. All changes in the manuscript are highlighted in red, and our point-by-point responses are provided below each of your comments.

We have ensured that all citations and the bibliography comply with journal formatting and policies. The Abstract has been shortened to meet the 150-word limit, and citations have been consolidated to keep the total references within 70, the maximal limit.

We trust that all concerns raised by each of you have been adequately addressed. However, should you have any further concerns about the revision, please let us know.

A note of sharing: The Intergovernmental Negotiating Committee of delegates from more than 170 nations and 440 organizations met in Busan, November 2024, and again in August 2025 in Geneva for a legally binding instrument to end global plastic pollution, but concluded without an agreed text, due to insufficient scientific evidence. In this paper, with your help, we identify priorities to address the productivity–sustainability paradox and provide actionable strategies to end terrestrial plastic pollution. We think this timely publication will be instrumental to the ongoing intergovernmental negotiations!

Thank you for your support of this publication.

Below are point-by-point responses (in blue):

Reviewer #1 (Remarks to the Author):

I am pleased to be invited to review the manuscript titled: ‘Evolving Plastic-Assisted Agriculture Beyond the Productivity–Sustainability Paradox’. The paper deals with a second-order meta-analysis on the pros and cons of using plastic in agriculture at global level, and addresses in-depth agro-engineering techniques to mitigate environmental and ecological downside effects of plastic use. In addition, the study also provides wider public/social and policy indications on replacing plastic with more sustainable inputs to increase agricultural production. While I recognise the efforts made by the authors in addressing this important issue at global level and contribute to the international literature, there are some general and detailed issues the authors should address for potential consideration in publishing with Nature Communications:

RESPONSE: Thank you for your detailed assessment of the manuscript. We highly appreciate your comments and suggestions, which have substantially helped us improve the manuscript.

General concern:

1. By looking at figure s4 (study mapping) and reading the proposed work, an overall reflection should be made: while the study refers at a global scientific evidence, there is a persistent lack of critical discussion at the 'global' level. The map on S4 clearly shows that most studies with the highest concentration of high number of experimental first-order meta-analyses are indeed in Europe.
In lines 319-323 you mention: "Although our data are largely based on studies conducted in China": how does this statement find a justification in figure s4?
and also "our findings offer scalable solutions applicable to other plastic-intensive regions beyond China". Instead, in figure 2b it is mentioned:
"In (b), study regions reflect key agricultural areas in China—the world's leading user of agricultural plastic—where side-by-side comparisons of the two systems were conducted across diverse environments.". This statement appears to me quite contradictory with the global level study of your second-order meta-analysis. Arguing that China is the largest agricultural plastic user is not enough to justify a study at global level and a discussion/comparison/scalability of results at Chinese level. Please carefully revise the above statements providing an in-depth and scientifically valid justification.

RESPONSE: First, thank you for your detailed reviews of the manuscript and the supplementary files. Your detailed comments/suggestions have helped us enhance the revision.

Second, we apologize that the global map in the previous version had some errors, and the map has been redrawn with the errors corrected. The Chinese study sites were many, so we simply drew the largest dot to indicate them in the previous version; we realize now that was not the best way to show the study sites. Thus, in the revision, we have redrawn the global map by adding all the individual Chinese sites instead of one large dot. The map looks quite different from the previous one, but it is now accurate.

Third, we declare that the study site dots on the map are approximate because some first-order meta-analysis articles did not report the latitude or longitude information in their articles. In that case, we did not locate their study sites, so we still missed some of the study sites on the global map, which is why we called the approximate sites.

Fourth, we would like to clarify to reviewers that most studies with the highest concentration of a high number of first-order meta-analyses are indeed in China, not in Europe. Based on the revised global map and the reviewer's comments, we have modified the relevant statements to clarify this. The redrawn map is presented as Figure S3 in the revision.

Other concerns:

Abstract.
2. Please use text rather than > or < symbols for a wider audience.

RESPONSE: Corrected.

Main.
3. Line 104. “plastic-assisted farming remains favored by many farmers and policymakers”. Based on this, I would carefully revise the above sentence as there are several policy initiatives such as, for example, the Resolution of 13 September 2018 on a European Strategy for Plastics in a Circular Economy, or the Extended Producer Responsibility which have been taken into account by studies focusing on agriculture/agricultural waste and that can be considered for citation in your work:
https://doi.org/10.3390/ijerph182212042
https://doi.org/10.1016/j.jclepro.2019.119844
https://doi.org/10.1016/j.jenvman.2023.119242
https://doi.org/10.1016/j.hazadv.2025.100727
https://doi.org/10.1016/j.jenvman.2023.119242
https://doi.org/10.1016/j.resconrec.2014.03.013
https://doi.org/10.1016/j.jenvman.2019.109468
https://wm.turkmenistan.ecoline-int.org/wp-content/uploads/2021/08/EPR-and-plastics-report-IEEP-9-Nov-2017-final.pdf

RESPONSE: We have modified the statement. Following the reviewer’s suggested references (links above), we have added several statements about relevant policy initiatives targeting the issue (**Lines 89-92**). More on the topic is discussed in the Discussion section (**Lines 403-416**). These modifications and additions have strengthened the points that the paper wants to make. Thanks to the reviewer for providing those relevant references, which are mostly cited in the revision.

4. Line 110. Why did the authors choose this period for their study? i.e. 2011-2024.

RESPONSE: Our study includes 70 meta-analyses articles published between 2011 and 2024. Those meta-analysis articles had reported experimental studies covering studies over 40 years. For example, the meta-analysis by Sun et al. (2020) investigated the effects of plastic mulch on crop yield, soil temperature, and crop water use from January 1981 to April 2016 for over 1000 experiments across the globe (Table S1). We considered that the over 40-year experimental studies reported in multiple first-order meta-analyses covered the historically significant changes in the use of plastic mulches in agriculture.

5. Line 138. “introducing a policy mechanism under the Global Plastic Treaty of the UN’s Environment Program, treating microplastic emissions as tradable carbon equivalents.”. While this is initiative is urgent and commendable, why leaving out of this discussion the integration of this mechanism with other mechanisms and tools at a more local level? Please revise.

RESPONSE: We have added the important point in the Discussion section (**Lines 403-416**).

Results.
6. fig 2. “n indicates the number of paired comparisons extracted from the reviewed literature; the blue line represents no yield difference between mulched and non-mulched systems.”. This is not clear from the figure. Where is the blue line?

RESPONSE: Those were typos, which have been corrected.

8. fig 3 and fig. 5. where is n? please rephrase or explain better.

RESPONSE: Those were typos, which have been corrected.

9. fig 4. too many arrows across the figure. please simplify and make it more consistent.

RESPONSE: We have modified Figure 4, making it simpler and informative!

Discussion.
10. Lines 392-403. policy concerns are approximated here. you should extend these to a more global view. Also, life cycle assessment and critical assessment are not policy strategies nor indications.

RESPONSE: In the revision, we have modified the statements regarding policy concerns (**Lines 403-416; 433-441**), which emphasize Global Policy Frameworks and Policy Mechanisms.

11. Line 643-645. “Regulate international trade of agricultural products cultivated using plastic cultivation systems, and enforce quality control mechanisms to support adoption of alternative, non-plastic agricultural practices”. In light of the current geo-political situation, how would you regulate international trade policies with national/local policies? Briefly explain or provided indications.

RESPONSE: Your point is excellent. Yes, the world faces a huge geopolitical challenge! As scientists, we do not have mature ideas on how to do this, but we have added some thoughts about the actionable strategies and practices with which the international trade of agricultural products cultivated using plastic cultivation systems can be regulated. These suggestions should be revisited and updated as the world learns more from intergovernmental negotiations (**Lines 403-416**).

12. Lines 466-473. ii, iii, and iv are counterintuitive. Please can you explicit into more detail 'how' to achieve what is mentioned in those points?

RESPONSE: Agree! Achieving each of the proposed items ii, iii, and iv will not be easy. Having said that, we have added several statements to provide more insights into the issues (**Lines 420-428**).

13. Lines 474-479. Farm managers should consider cost-effective alternatives into their decision making process. This evidence lacks here. Please revise accordingly

RESPONSE: This is an excellent point. We have added several statements to strengthen the points about cost-to-benefit outcomes (**Lines 429-441**).

14. Lines 480-488. Here there is just an indication of the 'what' the general public and consumers should do in points i, ii, and iii. Extending these points with the 'how' would provide a more coherent view on the important issue of public awareness.

RESPONSE: Again, achieving each of the proposed items will not be easy. We have extended these points on 'how' by providing more coherent views on the important issue of public awareness (**Lines 442-456**).

15. fig 6. Again there's too much in this figure. please can you keep it simpler?

RESPONSE: Yes, we have modified Figure 6; simplified it without losing what the Figure wants to deliver. In this figure, we intend to present integrated mitigation strategies. It might be unwise to omit some important aspects in this regard. We hope the reviewer agrees with us on the new version.

Conclusions.

16. Line 513. The 'One health' framework is mentioned in the introduction and in the conclusions only. The reader loses the traces of this framework in the flow of the study. Please make it clear to refer to this framework in other parts of the paper, for example the discussion section would benefit from this highlight, other than the introductory and conclusions parts.

RESPONSE: We have added several statements about 'One Health' in the Discussion section (**Lines 457-470**) to highlight the importance of public engagement in 'ending terrestrial plastic pollution' and its linkage with the 'One Health' framework. The latter has a profound interconnection with the Earth's systems, environmental sustainability, and public health.

17. Line 517. "Furthermore, we recommend creating 'living labs'". This is a well-known indication from the literature and widely recognised. Here are some examples: https://www.sciencedirect.com/science/article/pii/S0195925524001756

https://doi.org/10.1016/j.jclepro.2024.141247
https://doi.org/10.1007/s11368-025-04100-z
https://doi.org/10.1186/s42055-023-00060-9
As a results it appears counterintuitive. Please revise accordingly.

RESPONSE: We agree with the reviewer that 'Living Labs' are established tools for sustainable land management. To highlight the importance of using the 'Living Labs' mechanism in the effort of ending terrestrial plastic pollution, we have modified the relevant statements about 'Living Labs.' (**Lines 488-493**).

Supplementary information.
18. Lines 6-8. Why did you select/choose these search engines? There is no scientific justification behind your choice. Please revise accordingly.

RESPONSE: We have modified the description of the literature search (**Lines 5-7**) in the Supplementary methods.

19. Line 73. "low quality studies". Please explain what low quality means.

RESPONSE: We have added the descriptions on this (**Lines 93-95**, in the Supplementary Information).

20. Fig. s3. In Line 110 of the manuscript the considered period of study is between 2011-2024 (see also my comment #4). Instead, the flow chart (fig s3) mentions the period 2017-2022. Please revise.

RESPONSE: It was a typo, which has been corrected.

Prisma chart.
21. In file 629671_0_rel_ms_0_szr5cm.pdf (the PRISMA chart) it is indicated: "Records removed for other reasons". In the supplementary information, please explain what are these reasons.

RESPONSE: It is described in the chart caption (**Supplementary Figure 4**).

Reviewer #2 (Remarks to the Author):

The paper does not add any specific novelty to the literature, but it is a very good piece of work which helps to shape some useful reflections on the issue of plastic use in agriculture in the light of the coming work of the Intergovernmental Negotiating Committee (INC-5). In the last decades agriculture has become an important source of plastic pollution. In countries like China and India (and many others where the pressure of the population on agricultural land for food production is particularly felt) plastic-assisted agriculture is considered a useful

agronomic practice which helps to increase crop yields while saving on agricultural land expansion (so inducing to a more efficient use of agricultural land for food security purposes). Nevertheless, it happens at a significant environmental cost which particularly refers to the accumulation of microplastics in soil (deriving from polyethylene film mulches, fertilizer bags, drip irrigation pipes, industrial abrasives and agrochemical containers), reduction in soil carbon in mulched fields and the presence of nano-plastics in food chain. As the authors appropriately highlight, this latter aspect, although being the subject of controversial considerations among researchers (as some confirm and others not, due to the lack of generally accepted investigation protocols), opens the way to another relevant socio-health problem related to the food safety argument. With the aim of contributing to developing a scientifically-based framework and generate a useful discussion on the productivity-sustainability paradox (with sustainability here intended in its "environmental" sense which I suggest should always be specified as done in line 106), through a Second Order Meta Analysis (SOMA), the work synthetizes decades of research from global studies (i.e. 10,611 global works) to identify key soil and crop-related anthropogenic factors influencing the use of plastic in agriculture, as well as its merits and negative environmental impacts.

RESPONSE: Thank you for your assessment of the manuscript. We highly appreciate your comments and suggestions, which have helped substantially improve the manuscript.

In addition, the work provides some indications for strategies aimed at reducing the use of plastic in agriculture while focusing on transformative and interdisciplinary solutions (e.g. developing bioengineered smart mulches, converting plastic waste into biochar or syngas through the creation of financial schemes for zero-waste in agriculture, combining gene-edited crops with AI-driven precision mulching techniques, introducing a policy mechanism under the Global Plastic Treaty of UNEP to treat microplastic emissions as tradable carbon equivalent. The work also promotes a reflection on a "One Health" framework for sustainable agrifood systems by integrating under the umbrella of policy science some advances in microbiology and AI-driven precision farming. All this considered, and on the basis of my research field expertise, my observations / suggestions are the following:

• line 51 – in respect of the literal form of the paper, I would avoid the use of the mathematical sign > and write "more than 170 nations" and "more than 440 organizations". The same in the rest of the paper where this aspect recurs;

RESPONSE: Due to the word count limit for the abstract, those statements have been removed in the revision.

• line 56 – as said above, I would specify that the term "sustainability" is here taken more in its environmental sense,

RESPONSE: We have added the word '**environmental**' in the title and the relevant places in the text.

• page 236 – the section “Microplastics contaminate the soil and pollute the environment” appears too suddenly. I would suggest to better coordinate the writing of the “Results” section by dividing it into two clearly identified subsections. The first devoted to the description of the merits of plastic use in agriculture (i.e. physiochemical mechanisms driving the enhanced productivity particularly particularly related to soil moisture conservation and thermal regulation, early-season soil temperature increase, enhanced soil microenvironment and microbial activity, and weed suppression). The second subsection dedicated to the description of the environmental problems deriving from it (specifically related, as reported by the authors, to soil contamination and environmental pollution from microplastics together with food safety concerns).

RESPONSE: Your suggestions on dividing two subsections are super excellent! We have followed your suggestion, revised and retitled the subsections accordingly. The re-arrangement makes the paper flow much better. Thank you for your high professionalism!

Here below, how I would organise it:

145 RESULTS
[…]

157 Physiochemical mechanisms driving the enhanced productivity
[…]

199 1. Moisture Conservation and Thermal Regulation. […]

210 2. Early-Season Soil Temperature Increases. […]

219 3. Enhanced Soil Microenvironment and Microbial Activity […]

229 4. Weed Suppression. […]

236 Environmental Contamination from Microplastics [I would retitle it in this way]
[…]

242 1. Soil Pollution […]

265 2. Other Forms of Environmental Impacts […] [I would retitle it in this way]

277 3. Food Safety Concerns […] [I would retitle it in this way]

RESPONSE: We have followed your suggestions and revised and retitled them accordingly. Thank you for your high professionalism!

• lines 310-311 – and especially in the previous parts where the work uses the terms of food security and food safety, I would give a very brief description of their actual meanings by explicating the first is referred to food supply and food shortages while the second to the human or animals' health conditions;

RESPONSE: We have followed your suggestions on a brief definition of the two terms (**Lines 62-63**, and **Lines 84**).

• lines 328-329 – with a clear focus on the short/long term impact of mulches biodegradation, some further confirmative considerations, can be found in the work by (which I suggest to recall) Campanale C. et Al., 2024, A critical review of biodegradable plastic mulch films in agriculture: Definitions, scientific background and potential impacts, TrAC Trends in Analytical Chemistry, Vol. 170, doi: 10.1016/j.trac.2023.117391;

RESPONSE: It is a good reference! We have cited it (**Line 294-296**).

• lines 344-345 – it is stated that, in achieving certain desirable conditions, bioengineered smart mulches can perform well or even better than traditional polyethylene films. I feel that, similarly to what is done in lines 357-358, when talking about ticker film production, a brief comment should be made on the economic aspect of smart mulches adoption. Production costs and, as a consequence, the price at which such an innovation can be offered on the market, plays an essential role for its actual implementation (e.g. see Golberger J.R. et Al., 2015, Barriers and bridges to the adoption of biodegradable plastic mulches for US speciality crop production, Renewable Agriculture and Food Systems, Vol. 30(2): 143-153, doi: 10.1017/S1742170513000276. Furthermore, see Yang W. et Al., 2023, Factors affecting farmers' adoption of and willingness to pay for biodegradable mulch films in China, Sustainability Analytics and Modelling, Vol. 3, doi: 10.1016/j.samod.2023.100016). From this, a further brief reflection can be developed by highlighting how the probable higher price paid to adopt smart mulches in substitution of traditional ones can be justified by the need of internalising the external cost of the plastic pollution. This line of discussion would also open the way to further reflect on some policy considerations on what policy makers can do to accompany this transformative process of mulches use (e.g. see Hao A. et Al., 2024, Cost–Benefit Analysis of Mulch Film Management and Its Policy Implications in Northern China, Agriculture 2024, 14, 1081, doi: 10.3390/agriculture14071081);

RESPONSE: Thanks for the suggestions on those relevant references. We have cited them in the revision highlighting the economic aspect of smart mulch adoption, production costs, and marketing mechanisms (**Lines 299-301**).

• line 373 – in the subsection title, the term of blockchain is recalled. However, no explicit mention of it is made in the following text. Although something is said in the concluding section (lines 498-500), as a reader, already in this subsection, I feel a brief link to where,

why and how blockchain enters into the game is necessary (i.e. mulch life cycle traceability, smart contracts, tokenised incentives, etc.);

RESPONSE: Get the point. We have modified the entire subsection of 'Blockchain-Enabled Circular Economies via Recycling and Regeneration.' Your suggestions on mulch's life cycle traceability, smart contracts, tokenised incentives, etc, are some of the essential strategies for blockchain-enabled circular economies. Revision has strengthened this subsection (**Lines 329-337**).

• lines 461-462 – when talking about the promotion of higher recovery rates of waste films (and also investment on recycling infrastructure to improve the efficiency, effectiveness and economic viability of handling reusable plastics), the consideration of some specific market tools (e.g. tax and subsidies) cannot be avoided. In this sense, some works may be orientation (e.g. Pazienza P., De Lucia C., 2020, for a new plastics economy in agriculture: Policy reflections on the EU strategy from a local perspective, Journal of Cleaner Production, Vol. 253, doi: 10.1016/j.jclepro.2019.119844; De Lucia C., Pazienza P., 2019, Market-based tools for a plastic waste reduction policy in agriculture: A case study in the south of Italy, Journal of Environmental Management, Vol. 15, doi: 10.1016/j.jenvman.2019.109468).

RESPONSE: Excellent points! We have added statements about using marketing tools for promoting practices to achieve a higher recovery rate of waste films, and investment on recycling infrastructure to improve the efficiency, effectiveness, and economic viability of handling reusable plastics (**Lines 433-441**). New references, including the two you suggested, are cited to strengthen the claims.

Having said this, and in the hope that the above observations / suggestions may be useful for the authors to improve their work, I believe that the work is a useful addition to the scientific community and policy makers and can be accepted for publication.

RESPONSE: Thank you. Your suggestions have helped make the paper substantially better!

Reviewer #3 (Remarks to the Author):

The paper by Leona Wang et al. "Evolving Plastic-Assisted Agriculture Beyond the Productivity-Sustainability Paradox" presents a large-scale second-order meta-analysis (SOMA) summarizing over 70 published meta-analyses with more than 10,000 paired comparisons and over 100,000 observations. The study addresses the "plastic paradox" in agriculture, namely the tension between significant short-term productivity gains from the use of plastics and the long-term risks to soil health, environmental sustainability, and food security. The framework is timely and highly relevant given the ongoing international negotiations (which failed last week in Geneva, maybe to be addresses in the revised version?) on the regulation of plastics, and the scope of the quantitative synthesis represents a

significant advance in this area.

The authors quantify robust yield increases and report a 28.7% increase across all crops with additional benefits for water use efficiency, particularly for corn and diversified cropping systems. The extrapolation to system-level benefits is convincing: between 2010 and 2021, plastic-supported systems are estimated to produce an additional 95.1 million tons of wheat and maize and save 23.2 million hectares of land. These are highly policy-relevant results that underscore the importance of this practice for global food production. The mechanistic explanations for these benefits are also convincing, with evidence of increased soil moisture, higher soil temperatures during the growing season, changes in microbial activity and diversity, and a reduction in weed emergence. The integration of mitigation options ranging from bioengineered "smart" mulch films and strategies for the efficient use of precision plastics to circular economy concepts and agroecological alternatives provides a valuable roadmap for the transition. The policy discussion is well linked to international treaty processes and provides clear starting points for negotiators, policymakers, and practitioners.

RESPONSE: Thank you for your assessment of the manuscript and your support of the publication!

The manuscript requires some important clarifications and corrections before it can be accepted, specifically potentially misleading reporting of sample sizes. In several places, extremely high "n" values are given in culture-specific tables, for example for wheat with n = 10,103 and potatoes with n = 8,952 (lines 161 to 166). These figures are referred to as "studies," but clearly cannot represent the number of studies and must instead refer to pairwise comparisons or experimental contrasts. This labeling occurs in both the main text and the figure captions. It must be corrected throughout to avoid confusion and an overestimation of the evidence base.

RESPONSE: We sincerely apologize for some typos, especially the *n* values. They are indeed 'paired comparisons', not the 'number of studies'; they have been corrected in the revision, both in the text and the corresponding Figures.

The authors state that plastic-supported agriculture avoids "201.4 Mt N_2O emissions" (lines 186 to 187). This figure appears unrealistically high when interpreted as direct N_2O emissions. It is possible that the figure is given in CO_2 equivalents. In this case, the basis for the calculation (GWP, AR6 values) must be explicitly stated. A similar problem arises in Figure 1, where the film thickness is given in both millimeters and mils (lines 144 to 154). For clarity, the manuscript should use a consistent system.

RESPONSE: Thanks for pointing this out! We have double-checked our calculation formulas and the results and corrected those numbers. The calculation formula is provided in **Lines 147-155** in the Supplementary Information.

The film thickness is in millimeters, which has been corrected.

The statistical transparency of the SOMA framework needs to be improved. The Methods section (lines 525 to 581) clearly describes the conversion of effect sizes, random effects modeling, and weighting, but the manuscript does not include heterogeneity statistics or an assessment of publication bias. These are standard in meta-analyses and essential for assessing robustness. Heterogeneity measures should be reported for each important outcome category, and publication bias should be addressed using funnel plots or Egger's regression. A PRISMA-like flow diagram showing the identification, screening, and inclusion of studies would also contribute to the much-needed transparency of the synthesis.

RESPONSE: 1) Detailed SOMA results on heterogeneity statistics and the assessment of publication bias are shown in the Supplementary Information (**Lines 167-177** in the Supplementary Information).

2) The PRISMA flow diagram was submitted to the Editor via email at the initial submission, which was separated from the rest of the submitted materials. Now, we have included the same PRISMA in the Supplementary file for your review (**Figure S4** in the Supplementary Information).

3) Funnel plots are provided (**Figures S5-S7** in the Supplementary Information).

Some claims appear exaggerated or speculative. The text claims that CRISPR-AI techniques could reduce plastic consumption by 70% (lines 362 to 367), while elsewhere a potential reduction of 50% is stated (lines 503 to 507). These figures are presented as facts, but without references or clear methodological justification. Such claims should be explicitly labeled as prospective or ambitious, supported by available modeling or pilot data to avoid overestimating the current state of the art. The analysis of thresholds and mechanisms also needs clarification.

RESPONSE: Thanks for the concerns. We have modified (toned down) the relevant statements by adding the description as ‘perspective’ or ‘potential’, making them more realistic and informative **(Lines 323; 462).**

The authors emphasize that with a residual plastic content of more than 480 kg per hectare, yields decline by about 28% (lines 260 to 262). This is an important finding with clear implications for management, but the methods used to derive this threshold are not explained. It is essential to specify whether this effect was determined using piecewise regression, binning, or another approach, and to provide confidence intervals for the estimate.

RESPONSE: We have added more details on this. The particular findings on this issue were from meta-analyses we synthesized in our SOMA, which have been described in the text (**Lines 216-218**).

The section on food safety is appropriately cautious and balanced, highlighting the current uncertainties regarding exposure pathways and health risks. However, it could be made even more useful for policymakers by including a summary table of the detection methods, analytical limits, and food matrices examined to date. Such a table would help negotiators and regulators understand both the progress made and the gaps in monitoring methods.

RESPONSE: This is a great idea! We have added statements in the text describing the uncertainties (**Lines 248-266**), along with a Table summarizing the key aspects of the uncertainties in **Supplementary Table S2**.

Several minor points should be addressed: The maximum concentration of microplastics in soil (up to 690,000 particles per kilogram) should be put into context by specifying the soil type, depth, and analysis method, and mass, if possible. Particle numbers alone are not indicative. This would enable readers to assess whether this value represents an extreme hotspot or a more general risk. Typing and formatting errors must be corrected, including "obhectives" instead of 'objectives' (line 369), "Sci Hurt" instead of "Sci Hortic." in the references (lines 679 and 722) and inconsistent punctuation in the affiliation details.

RESPONSE: 1) The particular number 690,000 was taken from a published article without a detailed description about the soil type, depth, or analysis method, etc., but we have modified the statements to clarify the specific testing conditions (**Lines 79-80**). 2) The typos and errors are corrected. Thank you for your detailed reviews!

Figures are generally informative, some adjustments are necessary. In Figures 2 and 3, "n" should be labeled as paired comparisons rather than studies. Confidence intervals should be provided for important moderator effects, e.g., for the +47% increase in water use efficiency in diversified systems (lines 191 to 194) and the +54% yield gain at <200 kg nitrogen per hectare (lines 174 to 177). Figure 5 requires consistent units and base values for greenhouse gas and nutrient flows, and Figure 6 could be improved with clearer legends or symbols to make it more understandable for interdisciplinary readers.

RESPONSE: In the revision, we have 1) clarified the 'labeling' of Figs 2 and 3, which are described in the figure caption.

2) The confidence intervals of the key results are provided (**Lines 137-145; 159-166**).

3) Figure 5 presents the effect size in the unit of 'percent difference' between the two systems (i.e., mulched and non-mulched); this is the same as those in Figures 2 (yield effect size) and 3 (water productivity effect size). Those values are taken directly from the multiple first-order meta-analyses included in the SOMA. The 'effect size' is a relative value, so its consistent units are '%' across the different studies.

4) Figure 6, we have simplified it, making it more precise and informative. In the legends, we have provided more detailed explanations or descriptions of the integrated mitigation strategies.

In summary, this manuscript represents an ambitious and important contribution. It synthesizes an enormous amount of evidence, demonstrates the dual benefits and risks of plastic-supported agriculture with unusual clarity, and provides a well-structured roadmap for mitigation measures and policy decisions. I recommend publication after major revisions. The sample sizes need to be corrected, unit inconsistencies need to be resolved, uncertainties and heterogeneity statistics need to be reported, and speculative claims need to be toned down or put into context. Improved methodological transparency and minor editorial improvements would significantly improve the quality of the article.

RESPONSE: Thank you for your detailed instructions and suggestions for improvement. We highly appreciated it. We have addressed all your concerns.

Reviewer #4 (Remarks to the Author):

Manuscript Number: NCOMMS-25-51950
Title: Evolving Plastic-Assisted Agriculture Beyond the Productivity Sustainability Paradox

Comments

Plastic pollution is a global issue. This comprehensive meta-analysis examines the dual role of plastic film mulching in agriculture—enhancing crop yields while posing significant environmental risks. The study synthesizes global data to quantify the yield benefits and environmental costs under plastic mulching. The authors propose mitigation strategies, including bioengineered mulches, circular economy approaches, and policy reforms. This notwithstanding, there are some concerns that make me preclude it from being considered further for publication in the Nature Communications Journal.

RESPONSE: Thank you for your assessment of the manuscript. We highly appreciate your comments and suggestions for improving the manuscript.

1. The study retrieved plastic mulching data rather than micro/nanoplastics data. I do not understand how they used the data to analyze and discuss microplastic contamination. I do not think the aim of the study related to micro/nanoplastic pollution and the section "Microplastics Contaminate the Soil and Pollute the Environment" makes sense.

RESPONSE: We fully understand your concerns. We have changed the section title to **'Adverse Impacts of Plastics in Agriculture' (Line 201)** and altered the subsections' structure to highlight (1) soil pollution, (2) Environmental Impacts, and (3) Food Safety Concerns. To clarify your concerns, we have stated that 'plastics in soil and the environment degrade into macroplastics (>5 mm), microplastics (<5 mm), or nanoplastics (1 nm–1 μm).' in Lines 202-203. The citations focusing on micro/nanoplastics are to support the argument on the adverse effects of plastic mulch used in agriculture on the environment – an important

aspect in addressing our study objectives.

2. While SOMA mitigates bias, the inclusion of studies with varying experimental designs (e.g., film thickness, crop types, climatic zones, etc.) may introduce residual variability. A sensitivity analysis should be conducted to address the data heterogeneity.

RESPONSE: We have performed these tests, and described in **Lines 83-101** of the Supplementary Information. The results are presented in Table S5 for the robust test and in Table S4 for sensitivity analyses in the Supplementary Information. These tests and analyses help explain the robustness and the resulting outcomes.

3. The Discussion section did not discuss the results from SOMA. In addition, the discussion on nanoplastics in food chains relies heavily on indirect evidence. More empirical data on translocation mechanisms and human health risks are needed.

RESPONSE: 1) We have added a summary of the SOMA results at the end of the Introduction (**Lines 104-112**); this is to comply with the Nature journals' manuscripts' style requirements. Additionally, we have added a few statements of our work in Discussion (**Lines 268-272**), leaving more Discussion rooms for the mitigation strategies we have developed.

2) Regarding nanoplastics in food chains, we have cited a good volume of references highlighting the translocation mechanisms and human health risks (**Lines 248-266**).

Additionally, we have added a brief Table summarizing the key aspects of the uncertainties in terms of nanoplastic in food chains and their effects on human health risks (Supplementary Table S2).

We did not provide empirical data on translocation mechanisms and human health risks as you requested. This topic, albeit extremely important, is not the primary objective of the present study, and we are afraid of potentially moving away from the core objective if too much discussion on this particular topic. There are numerous articles published in recent years specifically addressing the nanoplastic-related issues, which are available for those who are interested in this area of research. We trust the reviewer agrees with us on this concern.

4. The SOC loss mechanism is oversimplified. Please incorporate evidence on soil aggregate stability, carbon mineralization (e.g., qCO2), and microbial functional genes to strengthen causal reasoning. Nanoplastic uptake pathways also require clarification, particularly size- and material-specific differences and rhizosphere interactions.

RESPONSE: To satisfy the reviewer's concerns on those points, we have added several statements and descriptions on SOC loss in mulched soil (**Lines 224-238**). Regarding nanoplastic uptake pathways, we have added some statements and also mentioned that the uptake outcome can vary with particle size, material-specific differences, and rhizosphere interactions (**Lines 221-223**).

5. The feasibility of bioengineered mulches and AI-driven alternatives is underexplored. Cost-benefit analyses should be included to strengthen practical adoption arguments.

RESPONSE: This has been addressed in **Lines 481-482; 492**.

6. Most data derive from China. However, in Figure S4, China is not a major study site but Europe is the most studied sites included in the 70 original meta-analyses. Expanding to other plastic-intensive regions would enhance generalizability. Long-term (> 10 years) mulching impacts on soil ecosystems are also underrepresented and should be discussed.

RESPONSE: First, thank you for your detailed reviews of the manuscript and the supplementary files. Your detailed comments/suggestions have helped us enhance the revision.

Second, we apologize that the global map in the previous version had some errors, and the map has been redrawn with the errors corrected. The Chinese study sites were many, so we simply drew the largest dot to indicate them in the previous version; we realize now that was not the best way to show the study sites. Thus, in the revision, we have redrawn the global map by adding all the individual Chinese sites instead of one large dot. The map looks quite different from the previous one, but it is now accurate.

Third, we declare that the study site dots on the map are approximate because some first-order meta-analysis articles did not report the latitude or longitude information in their articles. In that case, we did not locate their study sites, so we still missed some of the study sites on the global map, which is why we called the approximate sites.

Fourth, we would like to clarify to reviewers that most studies with the highest concentration of a high number of first-order meta-analyses are indeed in China, not in Europe. Based on the revised global map and the reviewer's comments, we have modified the relevant statements to clarify this. The redrawn map is presented as Figure S3 in the revision.

7. Abstract: Too much background introduction before bringing up what the study addressed.

RESPONSE: We have omitted some of the background introduction in the revised abstract. The Abstract has been rewritten and shortened to 150 words, the limit requirement.

Correct ">170 nations and >440" to "> 170 nations and > 440".

RESPONSE: Corrected.

Please add "and" before "(f) Integrating policies…".

RESPONSE: Corrected.

8. Please capitalize the first letter of each keyword.

RESPONSE: Corrected.

9. Any reference to support "However, nitrogen use efficiency (NUE)—the crop yield per

unit of applied nitrogen (N) under specific soil and climatic conditions—declined from 21.3 to 11.1 kg of grain per kg of N, representing a 48% decrease.”?

RESPONSE: This is the author’s calculation based on the officially reported Chinese statistics data. No other reference is found on this claim. To satisfy readers, we have added a statement on this (**Lines 66**).

10. Forest plots should report heterogeneity statistics (I2, P). Terminology (e.g., PUE, nano/microplastic size definitions) must be standardized.

RESPONSE: Detailed reports on forest plots heterogeneity statistics are provided in the Supplementary information file (**Line 192)** in Supplementary Table 3.

11. The ' intelligent ' plastic film can be degraded during the crop growth season. Can it have the same effects as traditional plastic film such as inhibiting weeds, heat preservation and moisture conservation?

RESPONSE: We have added several statements to describe the limitations (**Lines 294-301**).

12. Please do not stretch the Figures vertically.

RESPONSE: Followed.

RESPONSE TO REVIEWS

Reviewer #1 (Remarks to the Author):

I have carefully read the revised manuscript and the authors have diligently addressed all points raised. I, therefore, suggest that the manuscript can be further processed to publication on Nature Communications.
My best wishes to the authors.
RESPONSE: Thank you for your two rounds of detailed reviews. Your comments and suggestions have helped us improve the manuscript.

Reviewer #3 (Remarks to the Author):

The authors have addressed most of the concerns raised in my initial review. However, in the revised version there remain several issues that should be carefully revised before publication.

Abstract:
The statement "Despite global negotiations in 2024 and 2025, a binding UN treaty stalled due to insufficient scientific input" is factually incorrect. The negotiations did not stall because of a lack of scientific input—there was, in fact, substantial scientific engagement. The negotiations stalled largely for political reasons, as several major (oil-producing) countries questioned the sufficiency of scientific evidence to delay action—similar to patterns observed in climate change negotiations. Please revise this statement to reflect the actual political context and ensure accuracy. The cited reference (Spring et al., your citation 13) called for greater attention to science (and published before the negotiations!), but does not support your causal claim that insufficient input caused the stalemate. Please correct this carefully.

RESPONSE: Thank you for your feedback. We have thoroughly revised the Abstract and modified those statements, making them more precise and accurate.

Further, the phrase "developing AI-driven biodegradable smart mulches" appears primarily as a buzzword. While the idea is innovative, the manuscript does not provide any substantive discussion or analysis of AI applications in this context—nor does it reference relevant literature. Moreover, the ecological and energy costs of AI systems should at least be acknowledged. Recent studies (e.g., Nature, 2025) predict that AI-related energy consumption may reach the scale of entire regions like India by 2035. Please either remove the AI reference from the abstract or add a properly balanced and referenced discussion in the main text. In its current form, this reference is misleading and not supported by the manuscript content.

RESPONSE: Following your suggestions, the CRISPR reference has been removed from the Abstract, making it clearer and more precise.

Similarly, the mention of "CRISPR-edited films" in the abstract is inconsistent with the main text, where you discuss CRISPR-edited crops (line 479) as part of next-generation farming systems. This is a conceptual mismatch and should be clarified. Please ensure the terminology in the abstract aligns with the actual content and focus of the paper.

RESPONSE: The "CRISPR-edited films" was an error, which has been corrected.

Overall, while the paper is significantly improved and contains valuable work, the abstract does not accurately represent its core findings. It overemphasizes contemporary buzzwords (AI, CRISPR) without providing corresponding depth or evidence in the manuscript. I strongly recommend a full revision of the abstract to ensure it reflects the study's actual scientific contributions and focus of the study.

RESPONSE: We have revised the Abstract thoroughly to ensure it reflects the study's actual scientific contributions and toned down the potential of AI and CRISPR technologies in the effort to end plastic pollution.

Reviewer #4 (Remarks to the Author):

My primary criticism is a fundamental mismatch between the data presented and the discussion/conclusions drawn. The meta-analysis rigorously re-evaluated agricultural performance using data on plastic mulching films. It contended that prevailing policy and environmental discourse frequently extrapolates beyond the scope of the available data, resulting in overstated claims regarding its effects. Besides, the manuscript devoted more than 2 pages to discussing the environmental impacts of microplastics and nanoplastics. This is a critical over-extension, as the study does not retrieve or analyze data on the formation, fate, or toxicity of these fragmented particles.

The extensive speculation on the topic beyond mulching film data, spanning multiple pages, is not supported by the evidence presented and severely undermines the manuscript's focus and validity.

RESPONSE: Following your critiques, we have minimized the discussion on microplastics or nanoplastics and shortened the specific topic to a small paragraph (Lines 261-272).

We agree with the three other reviewers that we must discuss the importance of microplastics or nanoplastics in the environment, as they are plastic mulch fragments. There is no obvious breaking point in their biosphere. The impacts on soil health and environmental sustainability are hardly separated between microplastics and nanoplastics from plastic mulches.

For a journal with the broad audience and impact of Nature Communications, it is essential that the discussion is tightly constrained by the data. The policy implications and

environmental discourse must be directly and robustly supported by the study's own findings. In its current form, the manuscript does not meet this standard.

RESPONSE: We are thankful for your excellent feedback. To strengthen data-policy linkages, we have done the following, in the re-revision:

1) Added a new table (Table S6, in the Supplementary file) to map (match) the key findings and proposed policy recommendations. Most of the recommendations are directly supported by our SOMA synthesis (Table S6), while a few others are speculative and supported by existing scientific literature; the combination provides a roadmap that facilitates ongoing intergovernmental negotiations on legally binding instruments to curb global plastic pollution.
2) We have toned down those 'speculative' recommendations, such as AL-driven plastic mulch application, CRISPR-edited crop species in integrated farming systems.
3) Acknowledged gaps and clarified limitations. For example, smart mulches show promise in trials, but long-term field data are scarce. Policy scalability depends on LCA-validated economic viability and region-specific incentives (e.g., tax credits for large farms vs. subsidies for smallholders).

The revision strengthens transparency. The newly added Table S6 highlights the data-policy linkages.

We hope the enhanced revision has addressed all the concerns.