REGEN REGISTRY

Removal of atmospheric nitrous oxide (N2O) using Photocatalytic Technology

Review

External R1 Review Round

Reviewer #1_2025

February, 2025

CONTENT referenced by reviewer's comment *e.g. Section number + paste exact text*	**REVIEWER'S COMMENT** *Please paste the comment from the reviewer*	**AUTHOR'S RESPONSE** *Please describe how the comment was addressed and include new content in quotations*	**Reviewer's Conclusion** [PASSED/ REJECTED WITH COMMENTS]
e.g. 2.1 - "approximately 25%	***e.g. Replace*** *with "adequate"*	*e.g. This was changed to **"The majority of the material must have a moisture content of 25% or less, as measured in the field."***	*PASSED*
The following comments refer to the credit class			

Section 1.1: the proposed methodology is the1	Additional 1 can be removed	Please see Author's Response below	
Section 1.2: "273 times greater than that of Carbon dioxide (CO2)"	Need to clarify this is over a 100-year period. For example over 20 years, the GWP is closer to 120.	Please see Author's Response below	
Section 2: "N2O"	Needs a subscript for 2	Please see Author's Response below	
Section 2.1.3: "Furthermore, equipment for accurately measuring the removal of N2O emissions, as outlined in this methodology, is required to ensure that the outcomes can be reliably verified and reported."	Would be beneficial to outline what these requirements are: the proposed methodologies for gaseous analysis (e.g.a portable gas analyser, or GC fitted with an electron capture detector.	Please see Author's Response below	
Section 2.1.4: "Application of agrochemical input onto a plant canopy by spraying is standard practice in crop production; the photocatalyst for N2O removal can be mixed with the agricultural inputs (e.g., fungicides) and therefore no further activity than the farm standard would be required."	This is of course standard practice, but its not clear whether mixing the product with fungicides or similar agents would impact the efficacy or either. If evidence of no impact on efficacy of either amendment is available, it would be beneficial to highlight here.	Please see Author's Response below	

Section 2.2.1: "investment barriers (the technology/product to be used in the project is expensive due to the price of the photocatalyst and the required margin of the distribution network; standard inputs are more affordable and therefore an easy choice)."	A further barrier is the analytical equipment for measuring/validating N2O reduction. Portable gas analysers are available globally for hire, but at substantial cost; GCs with ECDs (required for N2O analysis) are even more expensive, and often only available through specialist labs. DNA (mentioned in section 2.4.1) as a tool for security is a further cost and technical barrier.	Please see Author's Response below	
Section 2.2.1: "Technological barriers (use of equipment for implementing the technology i.e., accessing the canopy of trees)."	Similarly technological barriers from using monitoring equipment.	Please see Author's Response below	
Section 2.4.1: "Deoxyribonucleic acid (DNA) based tracing technology or similar (biomarker) will be incorporated into the product."	Further information should be provided on how this approach of validation would work: DNA can degrade relatively quickly in the environment (days to weeks). It is not clear if this approach has been validated as yet? Other biomarker options could also be included (e.g. phospholipid fatty acids), for example, but these can also degrade quickly in the environment.	Please see Author's Response below	

Section 2.5: "The period of the residence time of the photocatalyst on the suitable surface defines the duration of the project."	Can examples be given here of how long this might be? Its not clear except further down where perennial crops/trees are described.	Please see Author's Response below	
Section 2.5: "The by-products of N2O breakdown are Nitrogen (N2) and Oxygen (O2), they are not required to be monitored."	This is true and a significant positive. Its not clear, however, whether the photocatalyst may be a problem for crop performance, food quality, human health, or the wider environment. If so, these should be highlighted elsewhere, and if not, described (in brief). Otherwise adoption will be limited.	Please see Author's Response below	
Section 3.1: "Since the by-products of N2O breakdown are N2 and O2, they are not required to be monitored"	This is true, but its not clear from evidence presented if the photocatalyst itself requires environmental monitoring.	Please see Author's Response below	
Section 3.1 (table 1):	CO2 emissions from application would need to be included, if the spray is separate to any normal farm activity. Even if applied alongside another agrochemical application, a proportion may need to be	Please see Author's Response below	

	ascribed to both practices.		
Section 4: “The carbon footprint of the field/farms included in the project is taken as the baseline. The greenhouse gas (GHG) emissions generated by standard agricultural practices without the application of the photocatalyst for N2O removal will be compared to the N_2O removals achieved through the application of the photocatalyst.”	This is indeed essential, but this could only really be achieved by permanent paired plot/split plot designs, given the scale of N2O emissions is a function of management, soil physicochemical properties, and environmental variables - uncertainties in N2O measurements are generally high as a result - how could the baseline be confidently validated (using the GHG monitoring methods described by the submission, or other similar methods?)	Please see Author’s Response below	
Section 5.1.2: ”The air samples are collected following the steps below:”	The subsequent section outlines methods for GHG sampling - it's not quite clear why this approach for sampling GHGs has been selected as opposed to chamber based methods? More detail is required on the frequency of sampling for validation (e.g. on how many days etc). Is there any form of statistical	Please see Author’s Response below	

	validation included? This is largely lacking in the proposed methodology, and not immediately apparent in other provided materials. Moreover, it surely would have been beneficial to investigate additional GHGs (e.g. CO_2) - it seems likely that foliar application will have at least some impact on crop performance, and impact therefore plant-soil interactions (or even directly by impacting soil microbial communities) - this requires clarification (and possibly monitoring)		
Field Trials for N_2O Quantification Document, Section 2.1.1. "Data from every visit to the field table"	This data appears confusing - the units in the first data column include negative concentrations for the control (e.g. "-0.38" ppb - how is a negative concentration possible? The treated concentration for the sample replicate is 0.26 ppb i.e. higher which would imply N_2O emissions rather than reductions? There is presumably a reason for this,	Please see Author's Response below	

	but as currently presented appears confusing. The same is true for other fields. It is also unclear why the N2O concentrations are lower than atmospheric concentrations (around 330 ppb) including for the control.		
Paper field data_final in table 3: “Table 3. N2O fluxes estimated for every field visit in control and R-Leaf treated fields and extrapolation to CO2eq per hectare and crop season”	This table includes data from calculated fluxes comparing the photocatalyst to a control not included in the methodology. This data does not, as currently presented, appear to provide evidence for the mitigation potential of the photocatalyst: The three measured fluxes reported for the control treatment are all negative - in conventional parlance this would imply the system is already acting as a slight sink for N2O. The treated N2O fluxes, however, are all higher implying an increase in N2O or reduced soil sink capacity i.e. the treated fields are emitting more N2O than the control. I also think you cannot and should not extrapolate three	Please see Author’s Response below	

	measurements into a growing 'season' for a crop. The same problems are also evident in Table 5 as currently presented. Both currently give concerns regarding the methodology and its effectiveness. Published papers measuring emissions will typically sample for weeks -three measurement points is insufficient to do this. The way the extrapolation has been made from a short daily measurement to a per season measurement is also unclear - when scaling up, this should be done using all three fluxes and calculating the cumulative flux for control and treatment.		

Reviewer's Blind Review Comments regarding Protocol/Methodology

Kindly enter your comments based on these questions in the table below. Also, if referencing specific text, please include text excerpt or row/page number from the protocol/methodology for ease of reference by the authors. All reviewer comments will remain anonymous unless you choose to be named.

Is the protocol/methodology clearly written with adequate detail for implementation?	At present the proposed methodology requires more detail on the proposed monitoring protocol (e.g. sampling frequency across a growing season). The DNA based labelling approach requires more clarity given issues with cross-contamination and environmental degradation of DNA.
Is the underlying foundation of the protocol/methodology clear?	As currently presented, I have significant concerns regarding the underlying scientific foundation for the methodology - the underlying supporting data appears to show that the proposed photocatalyst in fact increases emissions rather than reduces them. This must be clarified by the authors
Is the protocol/methodology feasible?	The proposed methodology for application is feasible overall (i.e. applying through foliar spray in field and monitoring emissions), assuming the queries raised above and below can be addressed regarding monitoring and validation of the technology itself.
Are there any alternative or additional points that should be considered?	The monitoring methods for verification appear insufficient as currently described. The proposed sampling technique appears somewhat over complicated compared to the more widely used

	‘static chamber’ methods more widely adopted in the literature. These certainly recommend more frequent monitoring Moreover, the current sampling regime as presented in support evidence is insufficient - extrapolating from three daily measurements to a seasonal mitigation potential seems unjustified.
Will the proposed guidelines and regulations achieve the results defined in the protocol/methodology?	As presented described, the results defined do not appear to be achievable, although this may in part arise from a lack of clarity in the nature of the results and their feasibility.
Do you want to be named in the review? (Expert Reviewers will be named after review is completed unless you choose to be anonymous)	No

Recommendation

Kindly mark with an X

Accept As Is:	
Requires Minor Revision:	
Requires Moderate Revision:	
Requires Major Revision:	X

Reject and Re-submit:	
Rejection: (Please provide reasons)	

General/Additional Comments:

In general, this has potential to be a very exciting approach, but I have major concerns that the authors require to address before this could be considered in more detail.

Author's Response:

The R-Leaf® atmospheric nitrous oxide (N_2O) removal methodology has undergone extensive independent review, validation, and approval. While an earlier version was initially submitted to Regen Network, progress was delayed as expert reviewers with the required specialist knowledge were identified. In parallel, the methodology was submitted to the International Carbon Registry (ICR), an ICROA-accredited registry, where it successfully completed a full review process including third-party validation by Enviance Ltd, an experienced Validation and Verification Body (VVB). This independent assessment confirmed that the methodology meets the robustness, conservatism, and transparency requirements of ICR v6.0 and ISO 14064-2.

We would like to acknowledge Reviewer #1's constructive comments regarding air sampling, DNA labelling, field data presentation, and broader methodological clarity. These have now been fully addressed in the approved version. The flux-gradient/micrometeorological method was retained because it measures N_2O exchange across a larger field footprint without interfering with the photocatalytic process. Static chambers only capture emissions directly from the soil surface and require physical enclosure of soil, which wouldn't capture N_2O destroyed in the air above the canopy by the photocatalyst. Additionally, enclosing the canopy with chambers would block sunlight and inhibit the photocatalytic reaction. Micrometeorological flux-gradient techniques are therefore more representative, providing non-intrusive, sunlight-compatible measurement. When paired with control fields, this approach offers conservative, robust and meaningful validation of the photocatalyst performance. Sampling frequency is now explicitly defined for comparison of treatment and control datasets. DNA labelling was removed from the methodology to avoid unnecessary complexity and improve practicality.

Additional clarifications have also been incorporated. R-Leaf® has been extensively tested under real farming conditions as part of standard tank mixes with fungicides, micronutrients, and other foliar products, with no adverse effect on its own performance or that of co-applied inputs. Environmental and health safety is confirmed by the fact that R-Leaf® uses micrometer-sized TiO_2 particles, well above the nanometer range associated with toxicity, with additions negligible compared to natural soil titanium levels. Baseline establishment can be achieved either by comparing farm-level footprints or by using paired control fields undergoing the same management practices, ensuring fair and representative comparisons. A condition has also been included that if spraying of the photocatalyst is conducted as a separate operation, any associated CO_2 emissions must be deducted from the total GHG removal claim.

Finally, peer-reviewed field-scale studies (Bueno-Alejo, Khambhati and Papadopoulos 2025; Bueno-Alejo *et al.* 2025) have since been published, providing evidence of N_2O mitigation in agricultural conditions under standard application practices. These studies, together with VVB validation, confirm that the methodology is scientifically robust, conservative, and suitable for project implementation.

The methodology is now formally approved and published by ICR as a validated carbon credit standard for atmospheric N_2O removal.

References:

Bueno-Alejo, C.J., Khambhati, Y.K. and Papadopoulos, A., 2025. Photocatalytic removal of N_2O in cropped fields using R-Leaf. Applied Catalysis O: Open, 207032.

Bueno-Alejo, C.J., Khambhati, Y.K., Papadopoulos, A., Reli, M. and Ricka, R., 2025. Using photocatalysis for sustainable agriculture: R-Leaf's potential in large-scale N_2O mitigation. Journal of Hazardous Materials Advances, 18, p.100703.