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Waste-to-Value Biochar from Agricultural and Woody Residues: Global Drivers of Crop Yield Enhancement and Greenhouse Gas Mitigation

Mondragon Unibertsitatea

Faculty of Engineering, Mechanics and Industrial Production, Loramendi 4, Mondragon, 20500, Gipuzkoa, Spain

***Corresponding author:** Mondragon Unibertsitatea, dibarra@mondragon.edu

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Abstract

The use of agricultural and woody residues in the circular economy is being implemented more actively, and biochar can be suggested as one of the areas of integration linking waste management with agronomic and environmental impacts. This study quantified the overall effects of residue-derived biochar on crop yield and greenhouse gas response ratios (CO_2, N_2O, and CH_4), compared straw- and wood-derived feedstocks, and examined key climatic, soil, and management drivers associated with response variability. A quantitative secondary analysis was conducted using a global treatment–control dataset. Effects were expressed as log response ratios and converted to percentage change for interpretation. Overall means and confidence intervals were estimated, and feedstock-specific summaries were calculated. Multivariable ordinary least squares regression models with centered predictors assessed associations with climate variables, soil properties, pyrolysis temperature, biochar application rate, nitrogen input, and their interaction. Biochar application was associated with a 10.17% increase in crop yield and significant reductions in N_2O (−21.43%) and CH_4 (−14.83%), while CO_2 responses were not statistically significant. Yield responses were positively associated with biochar rate and soil organic carbon and showed a significant interaction with nitrogen input. Variability in N_2O responses was linked to climatic factors, soil pH, pyrolysis temperature, and nitrogen rate. These results imply that biochar can be used to convert agricultural and woody residues into biochar and aid productivity and lower some greenhouse gases, with results that depend on the environmental conditions and the intensity of management.

Keywords: *biochar, sustainable agriculture, climate change, soil health, biomass waste*

1. INTRODUCTION

The growing need for agricultural systems to be more productive while lessening their impact on the environment has increased the focus on circular resource strategies. Waste-to-value strategies aim at converting agricultural and forestry residues into useful products, which both solve the waste generation problem and the resource use problem (Haque et al., 2023). In larger concepts of the circular economy, biomass residue recovery and valorization are considered essential steps towards minimizing material losses and are vital in bridging the nutrient and carbon cycles (Sondh et al., 2022). The re-evaluation of disposal burdens as residues to productive inputs is an indication of a general change in valuing the nature of material flows in agro-industrial systems (Angstmann, 2025). Woody and agricultural residues constitute one of the largest portions of the world's biomass waste products, such as straw, pruning wastes, and forestry wastes (Thakur et al., 2024). The thermochemical conversion methods, especially the pyrolysis technology, have allowed the conversion of these materials into biochar that is a rich source of carbon and has possible uses in a soil system (Gupta et al., 2022). Recent evaluations point to biochar as a prospective interface between biomass waste management and climate-oriented land management approaches (Ufitikirezi et al., 2024). In addition to energy recovery processes, there is a possibility of waste reduction in the form of biochar production, which offers the possibility to combine the reduction of waste and the improvement of agriculture (Hoang et al., 2024).

Ample evidence on the effects of biochar made of residues on soil characteristics and crop yield has been studied through substantial experimental studies. The alteration in the soil structure, nutrient retention, and water dynamics reported to be linked to biochar amendment can affect the crop yield under certain environmental conditions (Khan et al., 2024). Simultaneously, researchers have checked its impact on greenhouse gas emissions, specifically nitrous oxide and methane, because biochar may have an effect on microbial processes and redox situations in soil (Wijitkosum, 2022). Technoeconomic and sustainability analyses at the systems level define that biomass conversion technologies should not only be evaluated based on their technical properties but also on their environmental performance at the level of spatial scales (Srinadh and Neelanchery, 2023). The reviews on biochar production processes highlight the significance of comprehending the impact of feedstock type, pyrolysis condition, and downstream agronomic and environmental results, which are overwhelming (Ganesapillai et al., 2023). All of this literature makes biochar a subject in waste management as well as in long-term agricultural sustainability. Nevertheless, the literature tends to be restricted to local or regional experiments or studies. Although reviews are synthesizing of reported outcomes, less of the literature describes the use of systematic quantification of the interactions between climatic gradients, soil attributes, feedstock origin, and input intensity to determine the magnitude of observed responses. Specifically, biochar derived from straws and wood is often compared descriptively instead of being modeled and integrated using a quantitative framework. This has left the question of whether there is uniformity in biochar effects in other environmental settings, and whether management drivers play less significant roles in determining yield and emission outcomes.

Despite the focus of the waste-to-value stories on how agronomic and woody residues can help towards sustainable land management, there is little empirical synthesis between the origin of the residues, agronomic attributes and greenhouse gas responses on a global scale. Although past studies have identified the theoretical possibilities of biochar to improve soil and emissions reduction, fewer studies have compared these effects at the same time, taking into consideration the issue of environmental heterogeneity and interaction between management variables. Moreover, the climatic gradient and the intensity of nitrogen input on the performance of biochar have not been systematically measured on the same analytical platform. The limitation of this gap is the inability to determine the impact of residue-derived biochar on crop productivity and the mitigation of greenhouse gases in a variety of field conditions. There is a need to conduct a systematic assessment of the treatment-control response ratios on various environmental situations to help demystify the drivers that precondition biochar efficacy.

To fill these gaps, the current research provides a quantitative worldwide analysis of biochar obtained from agricultural and woody residues to determine its application in improving crop yield and altering the greenhouse gas response. The objectives of the study include quantifying the total treatment effects on crop yield, significant greenhouse gases (CO2, N2O and CH4), contrasting the magnitude of response of the biochar of straw and wood, and determining the major climate, soil, and management variables that contribute to the change in the observed ratios of responses. The study offers a solid analysis of the correlation between residue conversion into biochar and sustainable agricultural intensification and emission processes by incorporating the agronomic and environmental outcomes into a waste-to-value process.

2. MATERIALS AND METHODS

2.1 Research design and data source

The research followed the quantitative design of the secondary data analysis using a publicly archived list of data collected globally by Lu (2026). The data is made up of experimentally obtained treatment-control comparisons that gauge the impacts of biochar amendment in the cropland systems. It combines crop production with greenhouse gases (CO2, N2O and CH4) response ratios and the corresponding environmental and management factors. Covariates that have been recorded are mean annual temperature, mean annual precipitation, soil organic carbon, soil total nitrogen, soil pH, bulk density, feedstock type, pyrolysis temperature, biochar application rate, nitrogen fertilizer input and crop type. Only those observations that contained enough information to calculate response ratios were taken into the analysis.

2.2 Effect size calculation

Treatment effects were quantified using the natural logarithm of the response ratio (lnRR), defined as:

$$\mathrm{lnRR} = \ln\left(\frac{X_{\mathrm{biochar}}}{X_{\mathrm{control}}}\right)$$

where X_{biochar} and X_{control} denote the mean value of the outcome variable under biochar and control treatments, respectively. The lnRR metric standardizes proportional treatment effects and enables comparability across heterogeneous experimental contexts.

For descriptive interpretation, lnRR values were transformed to percentage change using:

$$\%\mathrm{Change} = \left(e^{\mathrm{lnRR}} - 1\right) \times 100$$

This transformation facilitates agronomic and environmental interpretation while preserving the statistical properties of the lnRR metric during modeling.

All analyses were conducted separately for each outcome variable.

2.3 Data preparation and variable treatment

Mean-centered continuous predictions were done before regression modeling. The centering process entailed the subtraction of the global mean of each variable from individual observations. The process enhances the interpretability of the regression coefficients, and it minimizes on non-essential multicollinearity in situations where interaction terms are introduced. The categorical variables were the biochar feedstock type (straw-derived or wood-derived) and the crop type (maize, rice, or wheat). Straw-derived biochar and maize were considered to be the reference categories. Complete-case filtering was used in the regression analyses. The missing values in any variable used in a particular model were not included in the model. There was no data imputation that was conducted, so that experimentally derived observations remain intact.

2.4 Estimation of overall effects

To get the mean lnRR of each outcome dataset, the mean lnRR was then computed of all observed lnRR. Standard error of the mean was used to estimate ninety five percent confidence intervals on a normal approximation framework. Two-sided one-sample t-tests were used to determine statistical significance against a null hypothesis of zero lnRR. Both values of lnRR were saved to report and present the values as percentages.

2.5 Feedstock stratification

In order to determine whether residue origin had an impact on the response to treatment, observations were stratified based on biochar feedstock category. Mean lnRR and percentage change were then calculated on each of the outcome variables within each subgroup. Such stratification allowed evaluating possible differences between straw-derived and wood-derived biochars without changing the response measure.

2.6 Multivariable regression analysis

To test the associations between response ratios and environmental or management covariates, ordinal least squares (OLS) regression models were fitted to each of the selected outcomes. Variations in modeling included climatic factors (temperature and precipitation mean per year), soil condition (soil organic carbon and pH), biochar production variables (pyrolysis temperature), biochar application rate, nitrogen fertilizer application, the type of feedstock, type of crop and an interaction term between biochar application rate and nitrogen application. Any continuous predictors were placed in centered form. The interaction between biochar and nitrogen was stated in the multiplicative form in order to evaluate the possibility of changing the response to the treatment in response to an increase in the intensity of nitrogen input. The coefficient of determination (R2) was utilized to assess the model fit. The level of statistical significance was $\alpha = 0.05$. Residual distributions were checked to confirm the approximate normality, and model condition numbers were checked to determine possible multicollinearity between the predictors.

3. RESULTS

3.1 Overall effects of residue-derived biochar on yield and greenhouse gases

Across the compiled global dataset, residue-derived biochar significantly enhanced crop yield while reducing key non-CO_2 greenhouse gases. Mean yield response increased by 10.17% (lnRR = 0.097, 95% CI: 0.090 to 0.104, $p < 0.0001$), indicating a consistent agronomic benefit across environmental contexts. In contrast, N_2O emissions declined by 21.43% (lnRR = −0.241, 95% CI: −0.266 to −0.216, $p < 0.0001$) and CH_4 emissions declined by 14.83% (lnRR = −0.160, 95% CI: −0.208 to −0.113, $p < 0.0001$). CO_2 responses were small and statistically non-significant (−1.12%, lnRR = −0.011, 95% CI: −0.040 to 0.018, $p = 0.449$), suggesting substantial heterogeneity in respiration-related responses across systems. The magnitude and direction of these overall effects are summarized in Table 1 and visualized in Figure 1.

Table 1. Overall effects of residue-derived biochar on crop yield and greenhouse-gas response ratios.

Outcome	N	Mean lnRR	95% CI (lnRR)	p-value	Mean % change	95% CI (% change)
Yield	1086	0.097	0.090 to 0.104	<0.0001	10.172	9.410 to 10.940
CO_2	134	−0.011	−0.040 to 0.018	0.4493	−1.121	−3.957 to 1.800
N_2O	298	−0.241	−0.266 to −0.216	<0.0001	−21.425	−23.367 to −19.434
CH_4	202	−0.160	−0.208 to −0.113	<0.0001	−14.825	−18.803 to −10.653

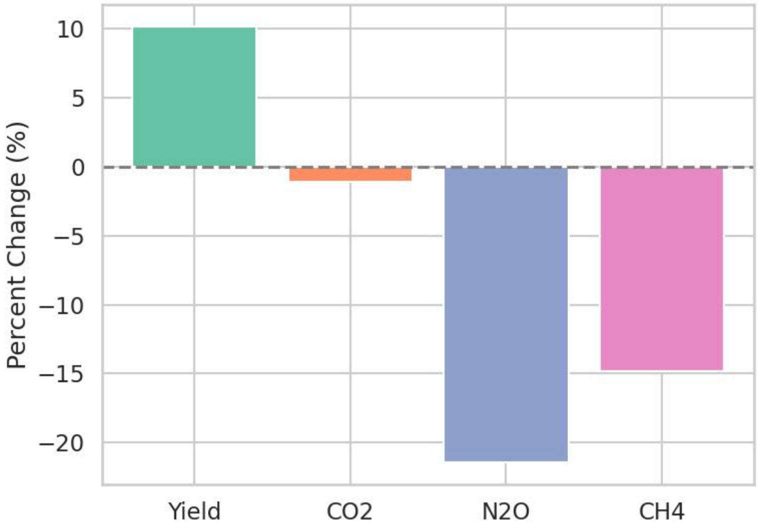

Figure 1: Overall effects of residue-derived biochar on crop yield and greenhouse gas response ratios

3.2 Feedstock-specific differences

Feedstock origin had a moderate effect on the level of responses, but it did not fundamentally change the direction of benefits in yields. Biochar made of straw showed a 9.95% increase in yield (n = 879), and biochar made of wood showed a 11.11% increase in yield (n = 207). In the case of N2O, the two feedstocks led to a reduction in emissions, with the biochar of wood exhibiting a numerically higher reduction (-27.97) than wood (-20.93), although the sample size of the wood is relatively small (n = 20).

In the CH4 case, straw-derived biochar was related to a reduction of 15.89 %, and wood-derived biochar was slightly increased (2.31 percent) according to a few observations. The relative response of CO2 to the feedstocks varied in sign but was very variable and had only a limited number of observations based on wood. The results of the stratification of feedstock are presented in Table 2 and demonstrated in Figure 2.

Table 2. Mean percent change and mean lnRR by feedstock type.

Outcome	Straw: % change	Wood: % change	Straw: mean lnRR	Wood: mean lnRR	Straw N	Wood N
Yield	9.95	11.11	0.095	0.105	879	207
CO_2	−1.65	7.65	−0.017	0.074	126	8
N_2O	−20.93	−27.97	−0.235	−0.328	278	20
CH_4	−15.89	2.31	−0.173	0.023	189	13

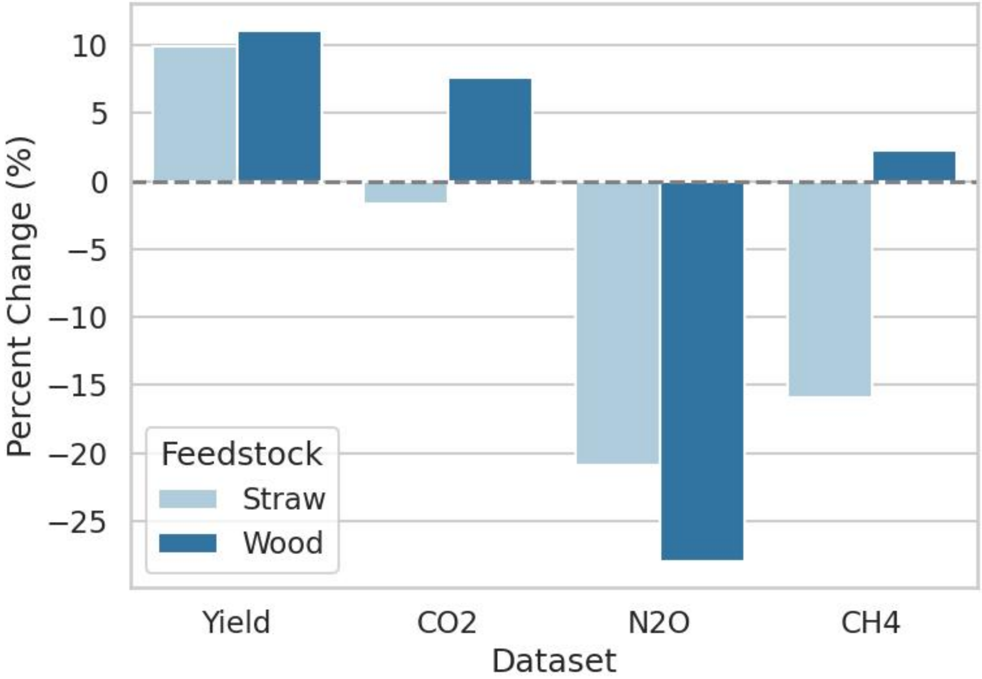

Figure 2: Comparison of yield and greenhouse gas responses between straw- and wood-derived biochars

3.3 Multivariable drivers of yield enhancement and N_2O mitigation

To identify environmental and management controls on biochar performance, interaction-based regression models were fitted for yield and N_2O using centered predictors.

3.3.1 Yield model

Biochar application rate was found to be a strong positive predictor of yield response ($p = 0.0039$) in a yield interaction model ($n = 812$, R2 = 0.076). Yield response also had a positive correlation with soil organic carbon ($p = 0.0027$), but a negative correlation with mean annual precipitation ($p = 0.0010$). Notably, a positive relationship existed among biochar application rate, nitrogen input, and the rate of interaction was significant ($p = 0.0005$), which occurred in the situation of higher nitrogen regimes. The implication of this interaction is that the gains in yield due to the addition of biochar increased with the addition of nitrogen and were no longer independent of the addition of fertilizer.

3.3.2 N_2O model

The N2O model ($n = 270$, R 2 = 0.170) was highly climate sensitive. There was a positive regression of N2O lnRR ($p = 0.0002$) with mean annual temperature, in contrast with negative regression of mean annual precipitation ($p = 0.0080$) and soil pH ($p = 0.0378$). There was also a weak negative correlation between pyrolysis temperature and $p = 0.0162$. The rate of Nitrogen application had a significant negative relationship ($p = 0.0002$), which showed the largest proportional decreases in N2O with increasing nitrogen. Unlike yield, the biochar main rate effect and the biochar x nitrogen interaction were not significant for N2O. The entire regression outcomes on both models are provided in Table 3, and generalized coefficient patterns are provided in Figure 3.

Table 3. Multivariable regression (interaction models) for yield and N_2O outcomes.

Term	Coef	Std. error	t	p-value	Outcome	N used	R²	Sig.
Biochar application rate (centered)	0.0006	0.0002	2.895	0.0039	Yield	812	0.076	**
Nitrogen application rate (centered)	0.0000	0.0000	−0.505	0.6134	Yield	812	0.076	
Biochar × Nitrogen (centered)	0.0000	0.0000	3.473	0.0005	Yield	812	0.076	***
Soil organic carbon (centered)	0.0021	0.0007	3.004	0.0027	Yield	812	0.076	**
Mean annual precipitation (centered)	−0.0001	0.0000	−3.305	0.0010	Yield	812	0.076	**
Mean annual temperature (centered)	0.0004	0.0010	0.426	0.6705	Yield	812	0.076	
Soil pH (centered)	0.0042	0.0051	0.825	0.4099	Yield	812	0.076	
Pyrolysis temperature (centered)	−0.0000	0.0000	−0.020	0.9844	Yield	812	0.076	
Feedstock: Wood (vs Straw)	0.0153	0.0130	1.173	0.2410	Yield	812	0.076	
Crop: Rice (vs Maize)	−0.0017	0.0132	−0.132	0.8948	Yield	812	0.076	
Crop: Wheat (vs Maize)	0.0135	0.0098	1.375	0.1696	Yield	812	0.076	
Biochar application rate (centered)	0.0001	0.0007	0.211	0.8331	N_2O	270	0.170	
Nitrogen application rate (centered)	−0.0005	0.0001	−3.717	0.0002	N_2O	270	0.170	***
Biochar × Nitrogen (centered)	0.0000	0.0000	1.543	0.1241	N_2O	270	0.170	
Mean annual temperature (centered)	0.0175	0.0047	3.749	0.0002	N_2O	270	0.170	***
Mean annual precipitation (centered)	−0.0002	0.0001	−2.674	0.0080	N_2O	270	0.170	**
Soil pH (centered)	−0.0434	0.0208	−2.088	0.0378	N_2O	270	0.170	*
Pyrolysis temperature (centered)	−0.0003	0.0001	−2.421	0.0162	N_2O	270	0.170	*
Soil organic carbon (centered)	−0.0053	0.0030	−1.765	0.0787	N_2O	270	0.170	
Feedstock: Wood (vs Straw)	−0.0487	0.0617	−0.788	0.4313	N_2O	270	0.170	
Crop: Rice (vs Maize)	0.0230	0.0476	0.483	0.6297	N_2O	270	0.170	
Crop: Wheat (vs Maize)	0.0604	0.0333	1.815	0.0707	N_2O	270	0.170	

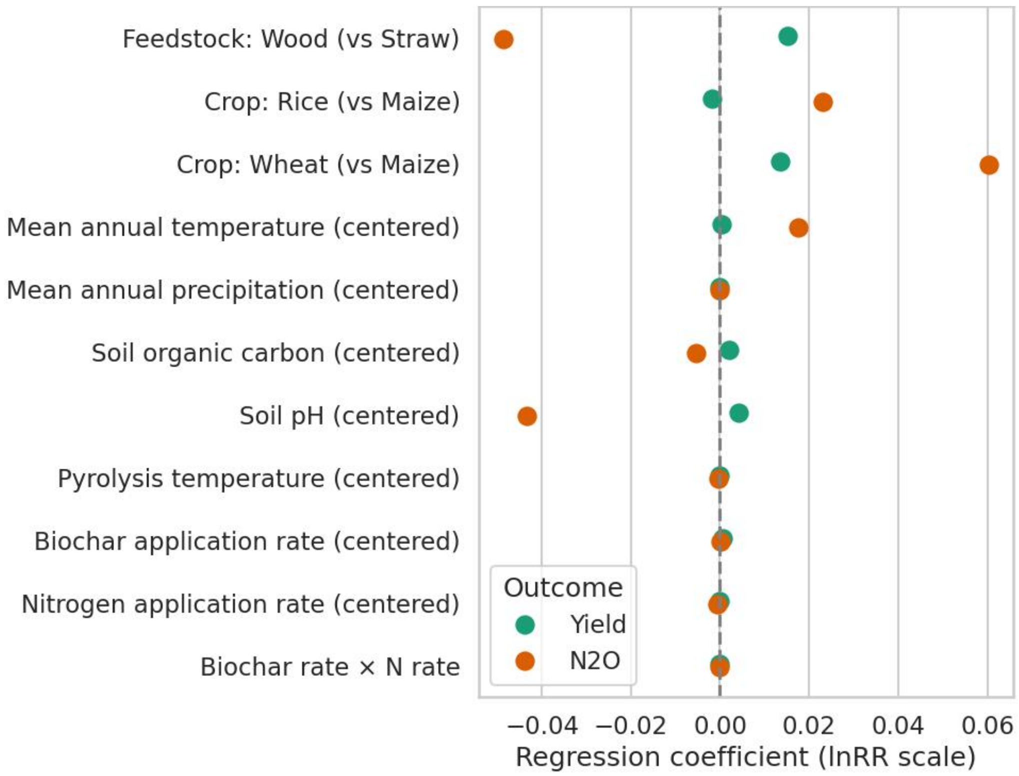

Figure 3: Multivariable regression coefficients identifying environmental and management drivers of yield and N_2O responses

3.4 Interaction dynamics between biochar and nitrogen inputs

All response surfaces predicted using the yield interaction model showed that the most pronounced growth of the yield lnRR was observed where high rates of biochar application were in combination with high nitrogen inputs. Increasing the rate of nitrogen did not produce similar yield gains at low biochar rates. This interaction surface has a conditional management effect but not an additive effect. Figure 4 demonstrates the interaction surface, which is modeled.

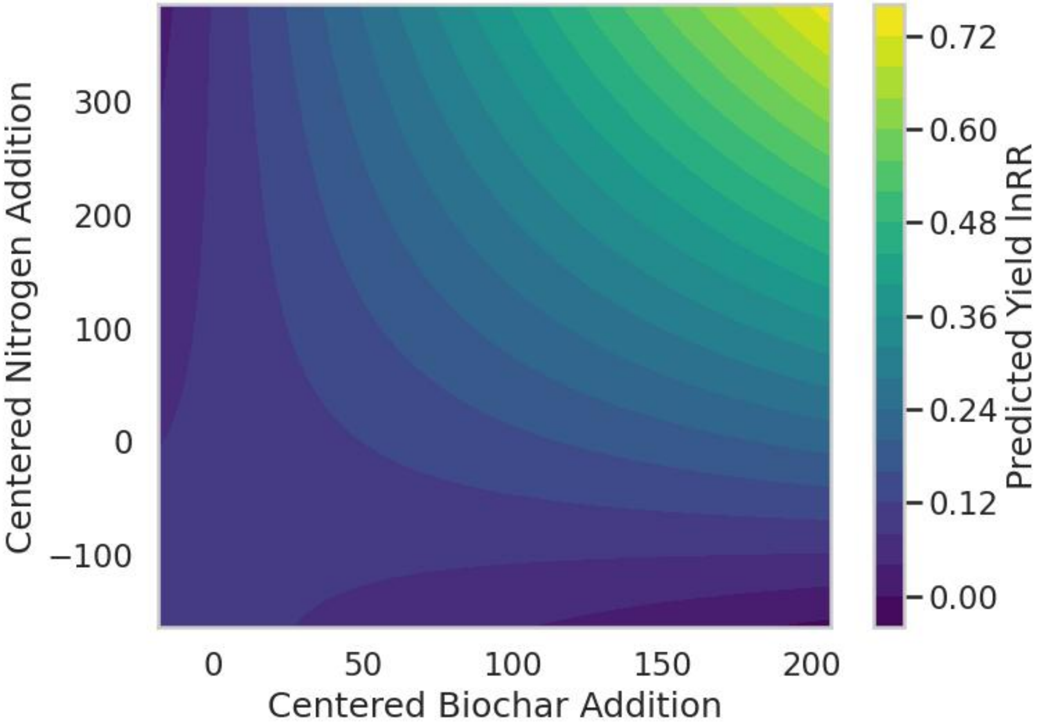

Figure 4: Interactive effects of biochar application rate and nitrogen input on crop yield response

3.5 Climatic gradients and greenhouse gas responses

The reaction to greenhouse gases differed across climatic gradients, especially temperature. Climate plots based on regression showed that the N2O response ratios rose with rising average annual temperature, but the CO2 responses were relatively low and variable with temperature range. These patterns indicate that climate moderates gas-phase response more than agronomic response. Figure 5 shows the temperature response relations of CO2 and N2O.

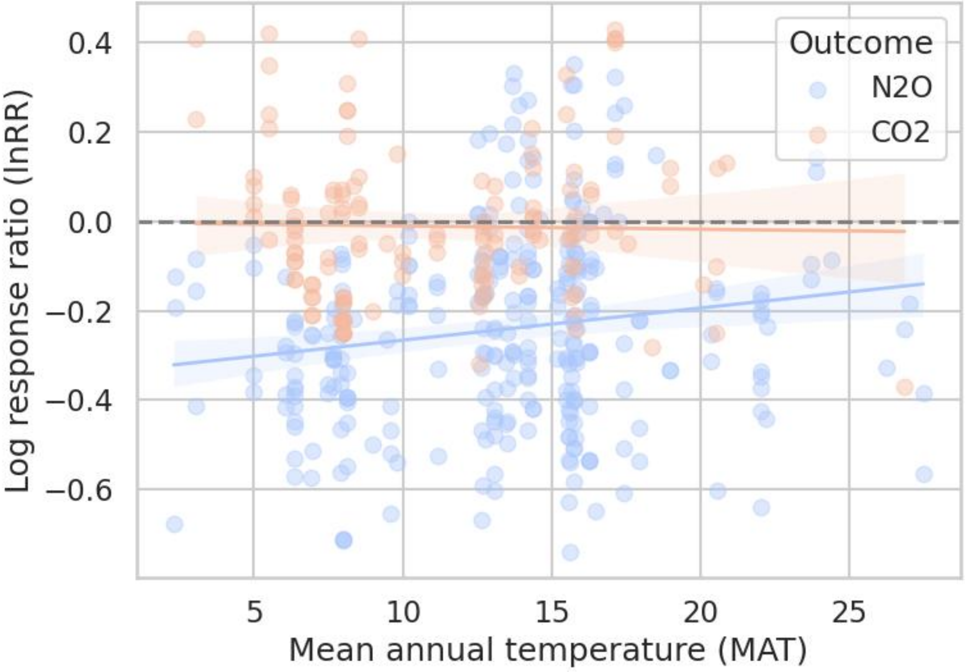

Figure 5: Influence of mean annual temperature on greenhouse gas response ratios (CO_2 and N_2O)

4. DISCUSSION

The paper is a quantitative evaluation of residue-based biochar in the world, as part of a waste-to-value model, by combining agronomic and greenhouse gas effects. Results of the observed improvements on yield indicate that further transformation of agricultural and woody residues to biochar could create scalable productivity improvements when implemented in cropland systems. The correlation between soil organic carbon and yield response is positive, which means that the biochar performance can be determined by the baseline soil properties, especially those connected with the nutrient retention and stability of the structure. On the other hand, the adverse correlation between yield response and mean annual precipitation means that climatic water regimes might moderate achieved agronomic gains. The noticeably high interdependence between the rate of biochar application and nitrogen input further illustrates the fact that the agronomic activities of biochar are not agnostic, as they vary with context. The environment in which the gain in the yield became greater with increased nitrogen regimes, which means that biochar can be used to increase nutrient-use efficiency in combination with the fertilization approach. This justifies the relevance of concerted administration as opposed to single-handed application of amendments. In the case of greenhouse gases, the decrease in N2O and CH4 indicates that biochar formed by the residue could affect the biogeochemical processes in soils related to the nutrient’s nitrification-denitrification and methanogenesis. The lack of a consistent directional response to CO2 evidences the complexity of the soil respiration process that consists of the combination of microbial degradation, root respiration and priming action. The difference in behavior between gases highlights the specificity of mitigation potential to individual gases and probably relies on the redox state of the soil, the effect of microbial communities, and the availability of substrates.

The results are consistent with the larger economic and environmental evaluations according to which agricultural waste transformation can be seen as a channel that has the capacity to produce various types of value when properly incorporated into production systems (Oyedeji et al., 2024). Specifically, the fact that yield improvement and emission reactions are considered simultaneously makes the case that biomass valorization plans need to be considered through the lens of productivity and environmental change. The measured greenhouse gas reduction is related to the mechanical syntheses that explain the effects of biochar on soil carbon fixation and CO2-removal pathways, especially regarding nitrogen cycling (Liu et al., 2023). Meanwhile, the CO2 discrimination is heterogeneous, and the data are consistent with the fact that soil carbon and respiration processes are dissimilar among feedstocks and pyrolysis conditions.

Regarding systems, the outcomes are complementary to more general studies on the significance of technology selection in biomass valorization portfolios. The waste-to-energy evaluations observe that conversion pathways ought to be established considering environmental targets and resource limitations as opposed to technological inclination (Raut et al., 2025). On the same note, biofuels-to-residue assessments emphasize that feedstock characteristics and conversion geometry influence the ultimate environmental results (Flores et al., 2024). The current paper has introduced biochar as one of the possible paths to this larger portfolio, especially in situations where there is a need to focus on soil enhancement and non-CO2 reduction. Biomass-based carbon materials are also finding diverse applications in pollution control and environmental engineering, beyond agronomic systems, which implies that residues can be used to facilitate cascading value chains across sectors (Srinadh et al., 2024). This type of diversification is consistent with the models of the circular bioeconomy when there is the derivation of multiple streams of value based on the same source of biomass (Razouk et al., 2024). Policy and regulatory environments also have an effect on residue management pathways. Legal regulations of crop residue burning show how an institutional environment creates the difference between biomass as waste or resource (Singh et al., 2025). Simultaneously, the concept of integrated waste management, which upgrades organic remains into bioenergy or bioproducts, emphasizes the fact that such a system requires the integration of the infrastructure and governance (Hafid et al., 2022). New data-driven methods of biomass valorization also highlight the importance of quantitative models in defining the most successful conversion route with different environmental and economic conditions (Ganesan et al., 2025).

The findings indicate that biogas-derived biochar can be used as an enabling technology in the context of the agricultural systems, which are circular, and the biomass of low value can be used to create soil amendment with quantifiable agronomic effects and agronomic emission reduction potential. Nevertheless, the conditional character of yield responses implies that the deployment strategies must focus on integrating the nutrient management, as opposed to applying the nutrient management alone. In areas where there is a build-up of residues, conversion of residues into biochar might offer an alternative route to aid soil productivity and minimize some greenhouse gas emissions. These findings can be considered at the system level, which means that the waste-to-value approaches in agriculture need to be assessed in terms of various outcomes, such as yield stability, emission dynamics, and resource efficiency. It can be beneficial in terms of matching the conversion technologies with local climatic and soil conditions to improve the overall work of the system.

There are a few weaknesses that should be mentioned. To begin with, the analysis is founded on aggregated response ratios that were obtained based on individual experiments with no clear modeling of study-level clustering. This can reduce the possibility of capturing within-study dependence. Second, complete-case filtering can be biased if the missingness is not random. Third, it is evident that the explanatory regression models only absorb part of the observed variance, meaning that there are unmeasured moderators like the soil texture, biochar surface chemistry, irrigation regimes, or the timing of applications.

The hierarchical modeling approaches need to be considered in future studies to capture the structure of the study and investigate other variables of biochar characterization. The datasets can be expanded with standardized reporting of the parameters of pyrolysis and also soil texture in order to enhance the cross-study comparability. Further, a connection between agronomic and emission results at the field scale and infrastructure and policy analyses may facilitate a better understanding of how a residue-to-biochar system would behave in the context of global circular economy transitions.

5. CONCLUSION

The possibility of transforming agricultural residues and woody residues to biochar has provided a viable waste-to-value alternative, capable of integrating the benefit of managing the residues with the co-benefit of co-managing croplands. In the global dataset that was compiled, biochar as residue was related to higher crop yield and lower ratio of non-CO_2 greenhouse gas response, with CO2 responses being erratic, which highlights the importance of gas-specific interpretation and context-dependent accounting. The relationship between the rate of biochar application and the level of nitrogen implies that agronomic benefits will be achieved when the deployment of biochar is coupled with nutrient regulation instead of being considered as a separate amendment. Environmental gradients, especially climate and important soil properties, proved to be important correlates of outcome variability, meaning a putative consequence of biochar application is where and how it is applied, rather than whether or not. These results encourage the need to consider decision frameworks that agglomerate feedstock sourcing, pyrolysis conditions and field management with local soil-climatic constraints and encourage future synthesis with hierarchical designs and more intense biochar characterization to help reduce unexplained heterogeneity. In general, the residue-to-biochar strategies will have a place in the circular agriculture provided that deployment is focused on site-specific factors and the intensity of management.

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