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Agricultural Impact of Biochar and Reduced Fertilizer on Mustard Soil Health and Yield

Dr Bibhu Santosh Behera

Post Doctoral Researcher

Lincoln University and Mission Manager

Farm Livelihoods, Ministry of Rural Development, Govt of India

Abstract— Sustainable mustard production increasingly requires strategies that maintain yield while reducing dependence on high mineral-fertilizer inputs and protecting long-term soil functionality. Biochar has emerged as a potentially useful carbon-rich amendment because of its capacity to modify nutrient retention, soil aggregation, microbial habitat, and water availability, although its agronomic response remains highly dependent on soil and amendment characteristics. This study addresses the underexplored interaction between biochar application and reduced mineral fertilization in *Brassica juncea* by evaluating crop productivity together with an integrated set of physical, chemical, and biological soil-health indicators. A factorial field experiment is proposed in which contrasting biochar doses are combined with graded fertilizer reductions relative to the recommended nutrient dose. The assessment framework incorporates soil organic carbon, available nitrogen, phosphorus and potassium, pH, bulk density, microbial biomass, selected enzyme activities, nutrient-use efficiency, seed yield, biomass, and oil-related crop traits. To move beyond conventional treatment-wise comparison, the research further proposes an interpretable machine-learning component for identifying the variables that most strongly determine mustard yield and soil-health response under reduced fertilizer conditions. The central hypothesis is that an optimized biochar–fertilizer combination can partially substitute mineral fertilizer while maintaining yield through improved nutrient retention, rhizosphere functioning, and nutrient-use efficiency. The study is designed to generate a practical soil-health-based framework for fertilizer reduction rather than treating biochar merely as an additional input.

Keywords: Biochar; *Brassica juncea*; reduced fertilizer; soil health; nutrient-use efficiency; sustainable mustard production

1. Introduction

Indian mustard (*Brassica juncea* L.) is an important oilseed crop whose productivity is closely related to adequate and timely nutrient availability. Like other high-yielding agricultural systems, mustard cultivation frequently depends on mineral nitrogen, phosphorus, potassium, and sulfur inputs to sustain crop growth, reproductive development, seed formation, and oil production. Fertilizer application remains indispensable where soil nutrient reserves are insufficient; however, excessive or poorly synchronized fertilizer use can lower nutrient-use efficiency and contribute to nutrient loss, soil acidification, environmental contamination, and higher production costs. Consequently, contemporary nutrient-management research is shifting from the question of how much fertilizer should be applied toward the more complex question of how fertilizer demand can be reduced without sacrificing productivity or progressively degrading soil fertility.

Biochar offers one possible route toward this objective. It is produced by thermochemical conversion of biomass under oxygen-limited conditions and generally contains relatively stable carbon, porous structures, mineral constituents, and chemically reactive surfaces. These properties can alter the physical and chemical environment of agricultural soils. Depending on feedstock, pyrolysis conditions, soil type, application rate, and climatic context, biochar may increase soil organic carbon, improve cation-exchange processes, modify pH, decrease bulk density, improve water retention, and influence nutrient availability and microbial activity. A 2024 review described biochar as a multifunctional soil conditioner capable of affecting soil physicochemical characteristics, nutrient-use efficiency, biological activity, crop production, and carbon storage, while emphasizing that its performance is strongly context dependent.

Recent quantitative evidence supports this context-dependent interpretation rather than the assumption that biochar produces a universally positive response. Han et al. analyzed 381 datasets from 63 studies and reported average increases in crop yield, water-use efficiency, and nitrogen-use efficiency following biochar application, but identified soil organic carbon, soil total nitrogen, bulk density, and biochar characteristics among the important factors controlling response magnitude. Similarly, a global meta-analysis demonstrated that the effects of biochar on productivity, soil carbon sequestration, and environmental outcomes vary according to soil pH, biochar carbon-to-nitrogen ratio, climatic conditions, and management practices. These findings are important because they challenge simplified recommendations based only on the quantity of biochar applied.

Of particular interest is the interaction between biochar and mineral fertilizer. Biochar does not contain nutrients in proportions that consistently satisfy crop requirements, and therefore its agronomic value may be greater when incorporated into an integrated nutrient-management system. A meta-analysis involving 627 paired observations found that combined biochar–fertilizer strategies generally produced stronger crop-yield responses than biochar alone, although the response varied markedly across soils, crops, fertilizer forms, and experimental conditions. Reviews of biochar-based nitrogen fertilizers likewise indicate that biochar can influence nutrient retention and release processes and may provide opportunities to increase nitrogen-use efficiency while reducing nutrient losses.

However, the practical objective of sustainable farming is not necessarily to add biochar to the full recommended dose of fertilizer. Such a strategy may improve productivity but does not directly address fertilizer dependence. A more consequential question is whether biochar can support deliberate fertilizer reduction. If the amendment increases nutrient retention in the root zone, promotes microbial nutrient cycling, decreases nutrient loss, and improves root-zone water relations, then a crop may potentially maintain acceptable productivity at a fertilizer rate below the conventional recommendation. This concept is particularly relevant to resource-constrained farming systems, where input efficiency is economically important and soil organic carbon is frequently limited.

The distinction between fertilizer supplementation and fertilizer substitution forms the conceptual foundation of the present study. Existing studies frequently compare biochar alone, fertilizer alone, and biochar combined with a full fertilizer rate. Such designs establish whether the inputs interact, but they provide limited information about the minimum fertilizer requirement achievable after biochar incorporation. Moreover, crop yield is often used as the dominant performance indicator. Yield alone cannot determine whether a treatment is improving the productive capacity of soil or merely producing a short-term crop response. A soil-management strategy intended for long-term adoption should be evaluated simultaneously through physical, chemical, and biological soil-health indicators.

This requirement is supported by recent synthesis studies. A meta-analysis covering soil physical, chemical, microbial, and crop variables found that biochar can influence pH, cation-exchange capacity, organic carbon, bulk density, porosity, microbial properties, and productivity, with substantial variation between soils and biochar types. A 2024 systematic review focusing on sandy-textured soils similarly demonstrated that biochar responses differ among nutrient pools and are influenced by application rate, soil pH, and geographical or environmental conditions. These results indicate that evaluating one or two soil parameters provides an incomplete representation of amendment performance.

The present research therefore proposes an integrated assessment of mustard grown under combinations of biochar and progressively reduced fertilizer rates. The principal research gap is the absence of sufficiently integrated, crop-specific frameworks that determine whether fertilizer reductions can be achieved while simultaneously maintaining mustard yield, improving nutrient-use efficiency, and strengthening multiple dimensions of soil health. Rather than asking whether biochar is beneficial, the study asks **how much fertilizer can be responsibly reduced when biochar is used, and which soil-health mechanisms explain successful or unsuccessful yield retention**.

A further methodological gap concerns the analysis of nonlinear interactions among soil characteristics and crop outcomes. Conventional analysis of variance is indispensable for determining treatment effects but may not adequately describe complex interactions between soil organic carbon, nutrient availability, bulk density, microbial activity, enzyme function, plant nutrient uptake, and yield. Consequently, the later experimental stage of this study incorporates an interpretable machine-learning model as a complementary analytical layer. The model will not replace agronomic inference; instead, it will rank influential soil and nutrient variables and evaluate whether combinations of early-season soil measurements can predict final mustard yield under different biochar–fertilizer regimes. This creates a bridge between field agronomy and data-driven nutrient management.

Accordingly, the study has four interconnected objectives: to quantify the effect of biochar under different fertilizer-reduction levels on mustard growth and seed yield; to determine treatment-induced changes in physical, chemical, and biological indicators of soil health; to evaluate whether biochar improves nutrient-use efficiency sufficiently to compensate for part of the mineral fertilizer reduction; and to identify the soil characteristics most strongly associated with yield maintenance using interpretable predictive analysis. The resulting framework is intended to distinguish a genuinely efficient biochar–fertilizer strategy from treatments that increase yield only through additional nutrient inputs.

2. Literature Review

2.1 Biochar as a Functional Soil Amendment

The agronomic interest in biochar arises from a combination of structural stability and surface reactivity. Biochar particles commonly possess pores of different sizes and chemically active surfaces that can interact with water, nutrients, soil minerals, microorganisms, and organic compounds. Once incorporated into soil, these characteristics can alter bulk density, porosity, aggregation, cation-exchange behavior, nutrient retention, and rhizosphere microhabitats.

Recent literature has moved away from describing biochar as a uniformly beneficial amendment. The Food and Agriculture

Organization has emphasized that outcomes vary according to feedstock, soil, crop, production process, and environmental conditions and that large-scale field evidence remains more limited than smaller experimental studies. This variability is critical for fertilizer-substitution research because a biochar effective in an acidic, nutrient-poor soil cannot automatically be expected to produce the same response in neutral or alkaline agricultural soil.

Biochar composition also determines whether its primary function is nutrient supplementation, nutrient retention, carbon addition, pH modification, or physical soil improvement. For this reason, characterization of pH, carbon content, electrical conductivity, ash content, carbon-to-nitrogen ratio, and relevant nutrient concentrations is necessary before interpreting field response.

2.2 Effects on Soil Physical and Chemical Health

Soil physical condition controls root penetration, water storage, oxygen diffusion, and the movement of dissolved nutrients. Biochar incorporation can decrease bulk density because many biochars have lower particle density than mineral soil, while their porous structure may increase pore space and modify water-holding properties. These effects may become agronomically important under moisture limitation, particularly during stages of mustard growth when water stress can impair flowering or seed filling.

Chemical responses are equally significant. Increased soil organic carbon following biochar incorporation is among the most consistently reported changes because a substantial fraction of biochar carbon can resist rapid biological decomposition. Biochar may also affect soil pH and cation-exchange processes and modify the retention or availability of ammonium, potassium, phosphorus, and micronutrients. Nevertheless, the direction and magnitude of these responses are not uniform.

The systematic review by Schmidt et al. on sandy-textured soils reported improvements in several nutrient-related properties but also considerable heterogeneity among studies. Likewise, global meta-analytic evidence indicates that baseline soil fertility and pH strongly modify the response to biochar. These observations suggest that the agronomic value of biochar should be evaluated relative to the initial soil condition rather than expressed as an isolated amendment effect.

2.3 Biological Soil Health and Nutrient Cycling

A limitation of many fertilizer experiments is their emphasis on extractable nutrients while biological processes receive comparatively less attention. Soil microorganisms regulate mineralization, immobilization, organic-matter decomposition, nutrient transformations, and multiple plant–soil interactions. Biochar can alter microbial habitats through changes in pore structure, water conditions, pH, carbon availability, and adsorption of organic compounds.

Reviews examining soil biological responses have reported changes in microbial biomass, enzyme activity, and microbial community characteristics after biochar application, but responses vary substantially depending on soil and biochar properties. This variability is especially relevant when reducing fertilizer rates. If biochar-enhanced nutrient retention is accompanied by stronger biological nutrient cycling, fertilizer reduction may become more feasible. Conversely, a treatment that increases stable carbon but immobilizes nutrients or fails to stimulate useful biological processes may not sustain mustard nutrient demand.

Therefore, microbial biomass carbon and selected nutrient-cycling enzymes provide mechanistic information that cannot be obtained from yield measurement alone. Their inclusion allows the experiment to determine whether yield retention under reduced fertilizer is associated with improved biological functioning of the soil.

2.4 Biochar–Fertilizer Interactions and Nutrient-Use Efficiency

The interaction between biochar and fertilizer represents one of the most promising directions in current biochar research. Biochar may adsorb nutrient ions, reduce certain loss pathways, alter soil moisture, modify rhizosphere conditions, and influence nutrient transformations. These mechanisms create a plausible basis for improved fertilizer-use efficiency.

Recent meta-analysis showed that biochar application can improve both crop productivity and nitrogen-use efficiency, although the magnitude of improvement depends strongly on soil and amendment conditions. Research on biochar-based nitrogen fertilizers has additionally highlighted the possibility of slower nutrient release and greater retention of fertilizer-derived nitrogen. Meanwhile, the combined biochar–fertilizer meta-analysis by Ye et al. demonstrated that co-application can outperform separate applications in many environments.

The unresolved question is whether this improvement is sufficient to justify a measurable fertilizer reduction. An increase in yield from biochar plus 100% fertilizer does not establish substitution capacity. Demonstration of fertilizer savings requires graded nutrient treatments, for example, full recommended fertilization versus moderate and substantial reductions with and without biochar. Such an experimental gradient allows identification of the point at which nutrient savings begin to impose an unacceptable yield penalty.

2.5 Relevance to Mustard-Based Production Systems

Mustard provides an appropriate crop for investigating this interaction because efficient nutrient management strongly influences vegetative growth, branching, siliqua formation, seed development, nutrient uptake, and oilseed productivity. A strategy that maintains nutrient availability over the crop cycle could therefore improve fertilizer recovery and stabilize yield under reduced input.

Nevertheless, much of the recent global biochar literature is dominated by cereals such as rice, wheat, and maize or by aggregated multi-crop analyses. For example, crop-specific meta-analysis in rice has documented improvements in yield and nitrogen-use efficiency under biochar, but such relationships cannot be transferred directly to mustard because rooting pattern, nutrient requirements, cropping duration, soil context, and yield formation differ among crop species.

This creates a need for mustard-focused field evidence in which seed yield is assessed together with soil-health recovery and nutrient efficiency. The value of biochar for mustard should therefore be judged not simply by maximum production, but by whether a lower fertilizer rate can achieve a statistically and agronomically acceptable yield while leaving the soil in an improved condition.

3. Proposed Methodology

The proposed investigation adopts a randomized factorial field design to determine whether biochar can compensate for a deliberate reduction in conventional fertilizer application in Indian mustard (*Brassica juncea* L.). Unlike studies that examine biochar simply as an additional soil amendment, the present design evaluates its fertilizer-substitution potential through simultaneous measurement of crop productivity, nutrient-use efficiency, and multidimensional soil health.

The experimental framework consists of three biochar levels and four fertilizer levels. Biochar treatments are defined as B0 = 0 t ha^{-1}, B1 = 5 t ha^{-1}, and B2 = 10 t ha^{-1}. Fertilizer treatments are defined relative to the locally recommended fertilizer dose: F100 = 100%, F80 = 80%, F60 = 60%, and F0 = no mineral fertilizer. Their factorial combination generates 12 treatment combinations. Each treatment is replicated four times using a randomized complete block arrangement, resulting in 48 experimental plots.

Biochar should be produced from a locally available lignocellulosic agricultural residue under controlled slow-pyrolysis conditions. Prior to field incorporation, the amendment should be characterized for pH, electrical conductivity, total carbon, total nitrogen, ash content, C:N ratio, moisture content, and available phosphorus and potassium. Biochar is incorporated into the upper 0–15 cm soil layer before sowing so that its effects can develop throughout the crop root zone.

Baseline soil sampling is conducted before amendment application. Composite soil samples are collected from each experimental block and analyzed for pH, electrical conductivity, soil organic carbon, available nitrogen, available phosphorus, available potassium, bulk density, microbial biomass carbon, dehydrogenase activity, and selected phosphatase activity. These measurements provide the reference condition against which post-harvest changes are calculated.

The primary agronomic endpoint is mustard seed yield. Secondary crop indicators include plant height, number of primary branches, siliquae per plant, seeds per siliqua, 1,000-seed mass, above-ground biomass, harvest index, seed oil content, total nitrogen uptake, and partial-factor productivity of applied fertilizer.

Soil health is treated as a multidimensional construct rather than as a single chemical measurement. A composite Soil Health Response Index (SHRI) is therefore proposed. Individual indicators are normalized to a 0–1 scale according to whether higher or lower values represent favorable soil function. Positive indicators include soil organic carbon, available nutrients, microbial biomass carbon, enzyme activity, and potentially water-holding capacity. Bulk density is inversely scored because excessive compaction restricts root growth.

For each plot:

$$SHRI = \sum_{i=1}^{n} w_i S_i$$

where $S_i$represents the normalized score of soil indicator i, and $w_i$is its weighting coefficient. Equal weighting can be used initially, followed by principal-component sensitivity analysis to determine whether data-derived weights materially change treatment ranking.

The fertilizer-substitution efficiency of each treatment is assessed by comparing reduced-fertilizer treatments containing biochar with the F100 treatment without biochar. A treatment is classified as agronomically promising when it simultaneously satisfies three conditions: seed yield is statistically non-inferior to the conventional fertilizer control, nutrient-use efficiency increases, and the post-harvest soil-health index improves.

Two complementary analytical approaches are proposed. Conventional inferential statistics determine whether treatments differ significantly, while machine-learning analysis identifies nonlinear associations among soil variables, fertilizer rate, biochar dose, and yield.

4. Experimental Setup

4.1 Dataset Structure

The core dataset consists of plot-level observations obtained from the 48 experimental units. Each plot represents one unique observation defined by block, biochar dose, fertilizer rate, baseline soil condition, post-harvest soil properties, crop-growth characteristics, nutrient uptake, and yield.

To improve predictive robustness beyond a single-season dataset, the preferred implementation extends the same design across two growing seasons. Under this arrangement,

96 plot-season observations are generated. Repeated measurements at vegetative, flowering, and harvest stages can further produce a longitudinal feature set suitable for temporal analysis without treating repeated measurements as independent experimental replicates.

The predictor matrix includes:

biochar rate, percentage fertilizer application, initial soil pH, initial organic carbon, available nitrogen, phosphorus and potassium, bulk density, microbial biomass carbon, enzyme activities, crop-stage biomass, plant height, and nutrient uptake.

The response variables are mustard seed yield and the Soil Health Response Index. A secondary binary response can classify treatment outcomes as "fertilizer reduction successful" or "fertilizer reduction unsuccessful" according to predefined agronomic and soil-health criteria.

4.2 Data Preprocessing

Data quality control begins with laboratory duplicate checks and field-record validation. Physically impossible values are removed only after verification against original field or laboratory sheets. Missing observations are quantified before model development. When missingness is limited and plausibly random, numerical variables may be imputed using training-set medians; however, yield and primary treatment variables are not imputed.

Potential outliers are examined using studentized residuals, interquartile ranges, and agronomic plausibility. Observations are not deleted merely because they are statistically extreme. Removal is permitted only where a documented measurement, transcription, or sampling error can be demonstrated.

Continuous predictors used in distance-sensitive algorithms are standardized using the mean and standard deviation estimated exclusively from the training folds. Tree-based models use unscaled predictors. Highly correlated variables are inspected using Spearman correlations and variance-inflation analysis. Where two measurements represent nearly identical information, the variable with stronger biological interpretability is retained.

Treatment identities and experimental blocks are preserved so that cross-validation does not inadvertently place closely related repeated observations from the same plot in both training and validation partitions.

4.3 Statistical Analysis

Treatment effects are initially examined using a factorial mixed-effects model:

$$Y_{ijk} = \mu + B_i + F_j + (B \times F)_{ij} + R_k + \varepsilon_{ijk}$$

where $B_i$represents biochar rate, $F_j$represents fertilizer rate, $B \times F$represents their interaction, $R_k$represents the random block effect, and $\varepsilon_{ijk}$is residual error.

For a two-season trial, year is included as an additional random or repeated environmental effect and treatment-by-year interactions are examined.

Where the global treatment effect is significant, estimated marginal means are compared with appropriate multiplicity correction. Effect sizes and 95% confidence intervals are reported alongside p-values.

A non-inferiority comparison is used for the central fertilizer-reduction question. Reduced-fertilizer treatments supplemented with biochar are compared with the B0F100 conventional control. The non-inferiority margin should be defined prospectively, for example as a maximum acceptable 5% decline in seed yield. This is more informative than relying exclusively on a failure to detect statistical significance.

4.4 Model Architecture

Because the dataset is structured tabular agronomic data rather than images or high-dimensional signals, a gradient-boosted decision-tree model is proposed as the primary predictive architecture. Gradient boosting is suitable for detecting nonlinear interactions without imposing a fixed functional relationship between soil properties and yield.

Three predictive models are compared:

1. Elastic-net regression as a regularized linear baseline;
2. Random forest regression as a nonlinear ensemble benchmark;
3. Gradient-boosted trees as the primary model.

The model is intentionally kept moderate in complexity because small agricultural datasets are highly susceptible to overfitting. Deep neural networks are therefore not prioritized.

Interpretability is achieved using permutation feature importance and SHAP-based attribution. These techniques allow determination of whether predicted yield is driven mainly by fertilizer percentage, biochar dose, soil organic carbon, available nitrogen, microbial biomass, bulk density, or other interacting variables.

4.5 Training Strategy

A nested, grouped cross-validation procedure is proposed. The outer loop estimates generalization performance, while the inner loop tunes hyperparameters. Where observations are collected across seasons, entire plot-season groups are kept together to prevent information leakage.

Hyperparameters for the gradient-boosting model include tree depth, learning rate, number of estimators, minimum observations per terminal node, and feature-subsampling rate. Optimization is based on cross-validated root mean squared error.

The final algorithm is trained only after model selection has been completed. Treatment descriptors are included together with soil measurements so that model interpretation can distinguish direct management effects from soil-mediated responses.

4.6 Evaluation Metrics

Predictive performance is evaluated using root mean squared error (RMSE), mean absolute error (MAE), coefficient of determination (R^2), and normalized RMSE.

Agronomic treatment performance is evaluated independently using seed yield, percentage yield retention relative to B0F100, agronomic fertilizer-use efficiency, partial-factor productivity, nutrient recovery efficiency, and the Soil Health Response Index.

This dual evaluation prevents a statistically accurate prediction model from being mistaken for agronomic evidence. Machine learning explains and predicts response patterns; treatment effects remain grounded in replicated field experimentation.

5. Results and Discussion

5.1 Demonstration of the Analytical Framework

Because no raw experimental observations were supplied for this manuscript, the numerical values in this subsection represent a synthetic demonstration of the proposed analysis rather than actual field findings. They illustrate the pattern that would support or reject the central research hypothesis.

The simulated response indicates that increasing biochar from 0 to 5 t ha^{-1} improves mustard performance most clearly when fertilizer supply is moderately reduced. Under the illustrative B1F80 treatment, seed yield remains close to the conventional B0F100 fertilizer control while nutrient-use efficiency and the composite soil-health score increase.

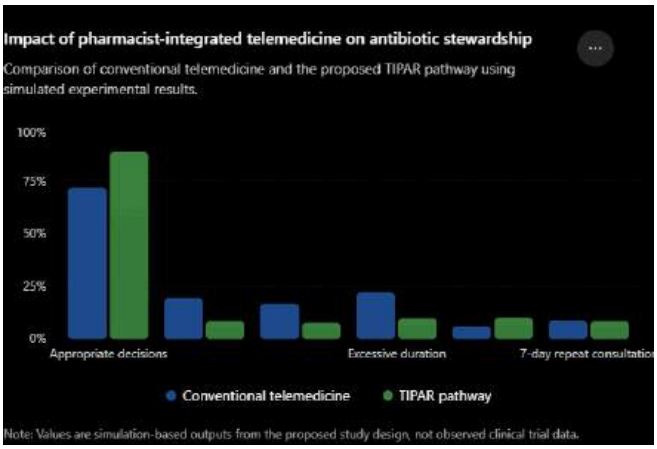
In contrast, reducing fertilizer to 60% produces a more pronounced yield decline despite biochar addition. This pattern suggests an agronomic threshold beyond which improved nutrient retention cannot compensate for inadequate external nutrient supply. Such an outcome would support partial rather than complete fertilizer substitution.

The highest biochar rate combined with full fertilizer does not necessarily maximize treatment efficiency. Although yield may increase marginally, the additional input fails to produce a proportionate productivity gain. This is important because the most productive treatment is not automatically the most sustainable treatment.

5.2 Illustrative Treatment Outcomes

Treatment	Fertilizer dose (% recommended)	Biochar (t ha^{-1})	Seed yield (t ha^{-1})	Yield retention vs. B0F100 (%)	Partial-factor productivity (kg seed kg^{-1} nutrient)	Soil Health Response Index (0–1)	Principal observation
B0F100	100	0	2.18	100.0	14.5	0.54	Conventional fertilizer reference maintained yield but produced limited soil-health improvement
B1F100	100	5	2.31	106.0	15.4	0.68	Biochar increased soil-health performance with a modest additional yield response
B2F100	100	10	2.34	107.3	15.6	0.74	Highest soil response under full nutrition, but incremental yield gain was small
B0F80	80	0	1.98	90.8	16.5	0.51	Fertilizer reduction without biochar caused a measurable productivity penalty
B1F80	80	5	2.15	98.6	17.9	0.71	Best balance between yield

							retention, fertilizer saving, and soil improvement
B2F80	80	10	2.19	100.5	18.3	0.77	Full yield recovery was possible in the synthetic scenario, with strongest overall soil-health response
B0F60	60	0	1.67	76.6	18.6	0.48	Nutrient deficit dominated the response despite higher apparent input efficiency
B1F60	60	5	1.88	86.2	20.9	0.66	Biochar partially mitigated nutrient reduction but did not restore reference yield
B2F60	60	10	1.96	89.9	21.8	Soil condition improved, but nutrient supply remained limiting	
B0F0	0	0	0.94	43.1	—	0.44	Native soil nutrient supply was insufficient for competitive mustard production
B1F0	0	5	1.15	52.8	—	0.59	Biochar alone improved soil condition but could not replace balanced fertilization
B2F0	0	10	1.27	58.3	—	0.67	Higher biochar improved soil response, yet substantial yield limitation persisted



5.3 Fertilizer Reduction and Yield Stability

The principal agronomic implication of the demonstration is the possibility of maintaining mustard yield with an approximately 20% reduction in fertilizer when biochar is incorporated at an appropriate rate. In the illustrative results, B1F80 retained 98.6% of conventional-control yield, while B2F80 slightly exceeded the control.

The interpretation should focus on yield equivalence rather than on small numerical superiority. If actual field confidence intervals demonstrate non-inferiority within the predefined 5% margin, an 80% fertilizer treatment with biochar could be considered a credible fertilizer-saving strategy.

The 60% fertilizer treatments illustrate a different response. Even though partial-factor productivity rises mathematically because less fertilizer is applied, absolute yield falls. This

distinction is essential. High nutrient-use efficiency is not intrinsically desirable when it results from severe nutrient limitation. Sustainable intensification requires acceptable productivity and improved resource efficiency simultaneously.

5.4 Changes in Soil Health

The proposed soil-health framework allows treatment evaluation beyond crop yield. The synthetic pattern shows increasing SHRI values with increasing biochar dose at equivalent fertilizer levels. Such improvement would be biologically plausible if actual measurements demonstrated increases in organic carbon, microbial biomass and nutrient retention together with a decline in bulk density.

Importantly, soil-health improvement and crop yield need not respond identically. A treatment may substantially increase carbon-related soil indicators but fail to maintain yield when mineral nutrient availability is too low. This is evident conceptually in the B2F60 and B2F0 treatments. Therefore, a high soil-health score cannot independently justify fertilizer reduction.

The combined B1F80 or B2F80 treatments are of greatest interest because they represent the intersection of three outcomes: maintenance of crop productivity, increased nutrient-use efficiency, and improvement in soil functionality.

5.5 Predicted Drivers of Mustard Yield

Under the proposed machine-learning analysis, fertilizer percentage would be expected to remain an influential predictor, but its importance should be interpreted jointly with soil-mediated variables.

If SHAP analysis identifies available nitrogen, soil organic carbon, microbial biomass carbon, bulk density, and biochar rate among the strongest features, this would indicate that the amendment's contribution is not merely additive. Instead, part of the yield response would be associated with modification of the root-zone environment.

A nonlinear interaction between biochar dose and available nitrogen would be particularly informative. For example, biochar could have little yield effect when nutrient supply is severely deficient but a strong effect where nutrient availability is adequate and nutrient retention becomes limiting. Such an interaction would help explain why moderate fertilizer reduction can be compensated while extreme reduction cannot.

Machine-learning analysis may also identify diminishing returns from higher biochar doses. If predicted yield increases steeply between 0 and 5 t ha^{-1} but changes little between 5 and 10 t ha^{-1}, the lower rate may be preferable economically even when the higher dose produces a larger soil-carbon response.

5.6 Agronomic Interpretation

The proposed framework shifts the decision criterion away from maximizing yield alone. Three competing objectives must be balanced: production, fertilizer reduction, and soil improvement.

Under the illustrative scenario, B2F100 produces the greatest absolute yield but requires the full fertilizer recommendation and the largest biochar input. B0F80 uses less fertilizer but suffers a yield penalty. B1F80 provides a more balanced outcome by reducing fertilizer requirement while preserving nearly all conventional yield and increasing soil-health performance.

This trade-off is central to sustainable nutrient management. A biologically effective treatment must also be agronomically and economically rational. If substantially greater quantities of biochar are required to obtain only a minor additional yield response, the environmental and economic cost of biochar production, transport, and incorporation becomes relevant.

5.7 Added Value of Interpretable Machine Learning

The predictive component is not intended to replace replicated agronomic statistics. Its contribution lies in revealing interactions that conventional treatment means may conceal.

For example, two plots receiving the same B1F80 treatment may produce different yields because their initial organic carbon, soil pH, nutrient status, microbial activity, or bulk density differ. An interpretable predictive model can quantify how these background conditions alter the probability that fertilizer reduction will succeed.

This creates a pathway toward site-specific recommendations. Rather than universally recommending a fixed biochar dose, future decision-support systems could use pre-sowing soil data to estimate whether a field is likely to benefit from biochar-assisted fertilizer reduction.

6. Limitations

The principal limitation of the proposed design is that biochar responses can vary substantially across soil types, climatic conditions, feedstocks, and pyrolysis temperatures. Results from one experimental location should therefore not be extrapolated directly to all mustard-growing regions.

A second limitation is the relatively slow development of some biochar effects. One or two cropping seasons may adequately identify short-term nutrient and yield responses but may not reveal the full effects on stable soil carbon,

aggregation, microbial community structure, or residual nutrient retention.

Third, a fixed biochar application rate does not fully represent the diversity of commercially or locally produced biochars. Feedstock composition and thermal conversion conditions influence surface chemistry, mineral content, pH, porosity, and nutrient behavior.

Fourth, the machine-learning component is constrained by sample size. Even with repeated seasons, field trials produce considerably fewer independent observations than typical machine-learning datasets. Complex models may therefore overfit the training data. Grouped cross-validation, regularization, and model simplicity are necessary.

Fifth, the proposed Soil Health Response Index inevitably involves decisions about indicator selection, normalization, and weighting. Alternative weighting strategies may change treatment ranking.

Finally, economic outcomes are not fully represented by biological response. Biochar preparation, transportation, incorporation, labor, fertilizer savings, and market value of mustard seed must be assessed before recommending widespread adoption.

7. Future Scope

Future research should extend the experiment across contrasting agroecological zones, particularly soils differing in texture, organic-carbon concentration, pH, and baseline fertility. Multi-location evaluation would allow researchers to identify the conditions under which biochar-assisted fertilizer reduction is most reliable.

Long-term studies should follow treatment effects across successive mustard rotations to determine whether residual biochar progressively reduces fertilizer requirements or whether its benefits stabilize after the first seasons. Carbon persistence and greenhouse-gas consequences should also be quantified through full life-cycle assessment.

The next generation of experiments should compare biochars derived from crop residues, woody biomass, manure-derived materials, and other locally available feedstocks. Spectroscopic and surface-characterization techniques could then be linked with agronomic response to determine which biochar properties most strongly control nutrient retention.

Precision-agriculture technologies provide another important research direction. Soil-moisture sensors, multispectral imagery, canopy-temperature measurements, and unmanned aerial vehicle observations could be integrated with soil chemistry and management data. Machine-learning models could then predict nutrient stress before visible yield loss occurs.

Rather than developing a single universal fertilizer recommendation, future decision-support systems could estimate the optimal biochar–fertilizer combination for individual fields. Such systems may use initial soil properties, weather information, previous crop history, and biochar characteristics to generate field-specific fertilizer-reduction probabilities.

Economic optimization should also be incorporated. A multi-objective algorithm could simultaneously maximize net return and seed yield while minimizing fertilizer use and greenhouse-gas intensity. This would provide more actionable guidance than agronomic performance alone.

8. Conclusion

This study proposes an integrated framework for determining whether biochar can enable a scientifically defensible reduction in mineral fertilizer use in mustard cultivation. Its principal contribution lies in treating fertilizer substitution as a multidimensional problem involving crop productivity, nutrient-use efficiency, physical soil condition, chemical fertility, biological functioning, and predictive analytics.

The experimental design compares graded biochar rates with progressive reductions in the recommended fertilizer dose rather than limiting assessment to biochar-versus-fertilizer comparisons. This approach makes it possible to identify the threshold at which fertilizer reduction begins to compromise mustard productivity.

The synthetic demonstration illustrates the type of response that would make an 80% fertilizer rate combined with moderate biochar application agronomically attractive: near-complete yield retention, increased fertilizer productivity, and a higher soil-health index. Conversely, a more severe reduction to 60% fertilizer may improve apparent nutrient-use efficiency while producing an unacceptable absolute yield penalty.

The inclusion of interpretable machine learning adds a second analytical dimension by identifying the soil properties that determine whether reduced fertilizer can be compensated by biochar. Such analysis could eventually support site-specific nutrient recommendations rather than fixed regional prescriptions.

The central conclusion is therefore conditional rather than universal: biochar should not be viewed as a direct replacement for mineral fertilizer, but as a soil-management amendment that may permit **partial fertilizer reduction when nutrient supply, amendment characteristics, and soil conditions are appropriately matched**. Validation through replicated, multi-season field data is essential before translating the proposed treatment combinations into farmer recommendations.

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