

Biochar Boosts Crop Yield and Methane Mitigation for Rice Paddies in Improved Cultivation Systems

First-year findings from a field trial in Punjab, India

April 2026





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Table of Contents

Summary	06
• Key findings	07
Why this work matters	08
• The Punjab rice challenge	08
• Background: Biochar in India	09
• The PRANA program	10
What we did	11
• Trial design	11
• Treatment matrix	12
What we found	14
• Crop yield: Biochar improves water-saving systems outcomes	14
• Methane emission: Biochar adds to the cultivation effect	15
• Water use and co-benefits	17
Conclusions and next steps	18
• First-year takeaways	18
• Next steps	19



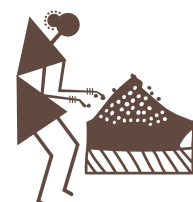


Summary



Punjab, as the breadbasket of India, produces large volumes of crop residues each year, and residue burning remains a persistent policy concern for air quality and soil health. At the same time, groundwater depletion is at critical levels across the state and is closely linked to the energy–water–food nexus in rice cultivation. Additionally, over-fertilization to meet the desired crop yield has resulted in diminishing soil health and quality across the state. Solutions that simultaneously address all these pressures will deliver the highest public value. PRANA (Promoting Regenerative and No-burn Agriculture) program in India has partnered with the International Rice Research Institute (IRRI) to fill critical evidence gaps for large-scale biochar amendment as a transformational solution in India, offering the benefit of carbon sequestration, soil enhancement and sustainable agriculture.

This report presents first-year results from an on-station trial conducted during the 2025 kharif season at Punjab Agricultural University (PAU), Ludhiana. The trial tested rice-residue biochar at five application rates (0, 1.25, 2.5, 5.0 and 10.0 t/ha) across four cultivation systems combining puddled transplanted rice and direct-seeded rice (DSR) with continuous flooding (CF) and alternate wetting and drying (AWD).





Key findings



8-19%

Yield increase
at 2.5–5.0 t/ha biochar



5-14%

Irrigation reduction
under biochar + CF



40-65%

Irrigation reduction
under biochar + DSR/ AWD



Up to 30%

GWP reduction
under biochar + AWD vs. CF

- Rice-residue biochar raised yields and lowered irrigation water requirements across all cultivation systems.
- Biochar used with water-saving crop-establishment and irrigation methods (DSR and AWD) maintained or increased grain yields while sharply reducing irrigation inputs.
- Moderate biochar rates (around 2.5 t/ha) delivered the strongest near-term agronomic benefits.
- Higher biochar rates paired with AWD produced the largest reductions in total global warming potential (GWP).
- Biochar also delivered meaningful methane mitigation even under conventional puddled, continuously flooded conditions, an important result for settings where soil type precludes water-saving practices.

Bottom line

A practical balance emerges at around 2 t/ha biochar. At this rate, farmers can lower irrigation demand and methane emission while sustaining yield, a feasible and scalable entry point that supports progress on greenhouse gas emissions, water use and crop productivity together.



Why this work matters

The Punjab rice challenge

Northwest India is one of the world's most important rice-producing regions and, at the same time, a hotspot for agricultural greenhouse gas emissions and water stress. Conventional production relies on continuously flooded fields, which generate large volumes of methane. Post-harvest residue burning adds to air pollution and emissions, while intensive groundwater pumping for irrigation has drawn water tables down to critical levels. Heavy fertilizer use has further degraded soil health across the state.

Biochar as a multi-benefit intervention

Biochar is a carbon-rich material produced through pyrolysis of organic biomass under limited or no oxygen. Within the PRANA program, biochar is approached as a multi-benefit intervention rather than a single-outcome technology. Its potential contributions include:



Providing productive, no-burn end use for rice residues, supporting air quality goals.



Strengthening soil structure, microbial activity, cation exchange capacity and nutrient retention.



Reducing methane emissions by improving soil aeration, limiting anaerobic conditions and supporting methane-consuming microorganisms.



Enhancing water-holding capacity and water-use efficiency.

Water-saving rice practices such as Direct Seeded Rice (DSR) and Alternate Wetting and Drying (AWD) are independently known to reduce methane emissions. However, field evidence remains limited on how biochar and water management interact, and on whether combining them can deliver climate benefits without compromising yields. This is a question that is central to farmer adoption and that this trial is designed to address.

Background: Biochar in India

Evidence from global literature review

To set local expectations, we first reviewed the global field evidence base, drawing on more than 160 field-scale studies, including many from tropical and subtropical climates and many using rice-based feedstocks such as husk and straw.

Across this body of work:

- Biochar tends to perform especially well in sandy and silty soils.
- Reported methane reductions fall commonly in the range of about 29–40% under relevant conditions.
- Yield responses are typically neutral to positive, with gains often in the range of 9–20%.
- Optimal application rates for methane reduction in rice paddies generally sit between about 3 and 17.5 t/ha, with peak yield gains often reported at 10–15 t/ha. Rates above 20 t/ha can further improve water retention and yield stability but are often not feasible at scale.
- Effects on nitrous oxide (N₂O) production are less consistent, though some studies report reductions linked to improved nitrogen-use efficiency.
- Combining biochar with AWD can further reduce methane while conserving water.

These ranges serve as benchmarks against which the Punjab results are compared.

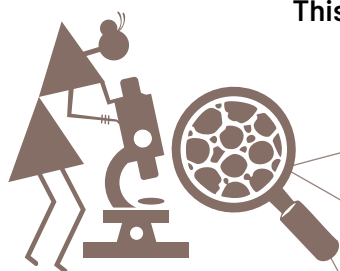


The PRANA program

PRANA, Promoting Regenerative and No-burn Agriculture, is a project started by The Nature Conservancy (TNC). It focuses on reducing crop residue burning and tracks progress by charting farmer adoption, hectares placed under no-burn practices, water savings and emissions reductions. PRANA is structured as a portfolio of pathways, reflecting the reality that farmers face different constraints across soils, timing, labor and access to equipment. Biochar is one pathway within this broader solutions set, alongside other residue and crop management approaches. To strengthen the evidence base for biochar in India, PRANA has partnered with the International Rice Research Institute (IRRI) and Punjab Agricultural University (PAU) to fill critical gaps on large-scale biochar amendment.

Research questions

This project was designed to answer three core questions:



Can biochar made from rice harvest residues enhance the climate benefits of water-saving rice systems?



How do different biochar application rates interact with rice establishment and irrigation methods to influence methane, nitrous oxide and overall greenhouse gas emissions?



Can these practices simultaneously improve crop yields and water-use efficiency, strengthening the case for real-world adoption?

Figure 1: Transplanting rice into flooded fields.



What we did

Trial design

A factorial field experiment was carried out during the 2025 kharif season at Punjab Agricultural University, Ludhiana, as part of a three-year collaboration between TNC and IRRI. The experiment crossed three factors:



Establishment methods: puddled transplanted rice (PTR), dry direct-seeded rice (DDSR) in dry soil and vattar direct-seeded rice (VDSR), i.e., sown into soil at field capacity.

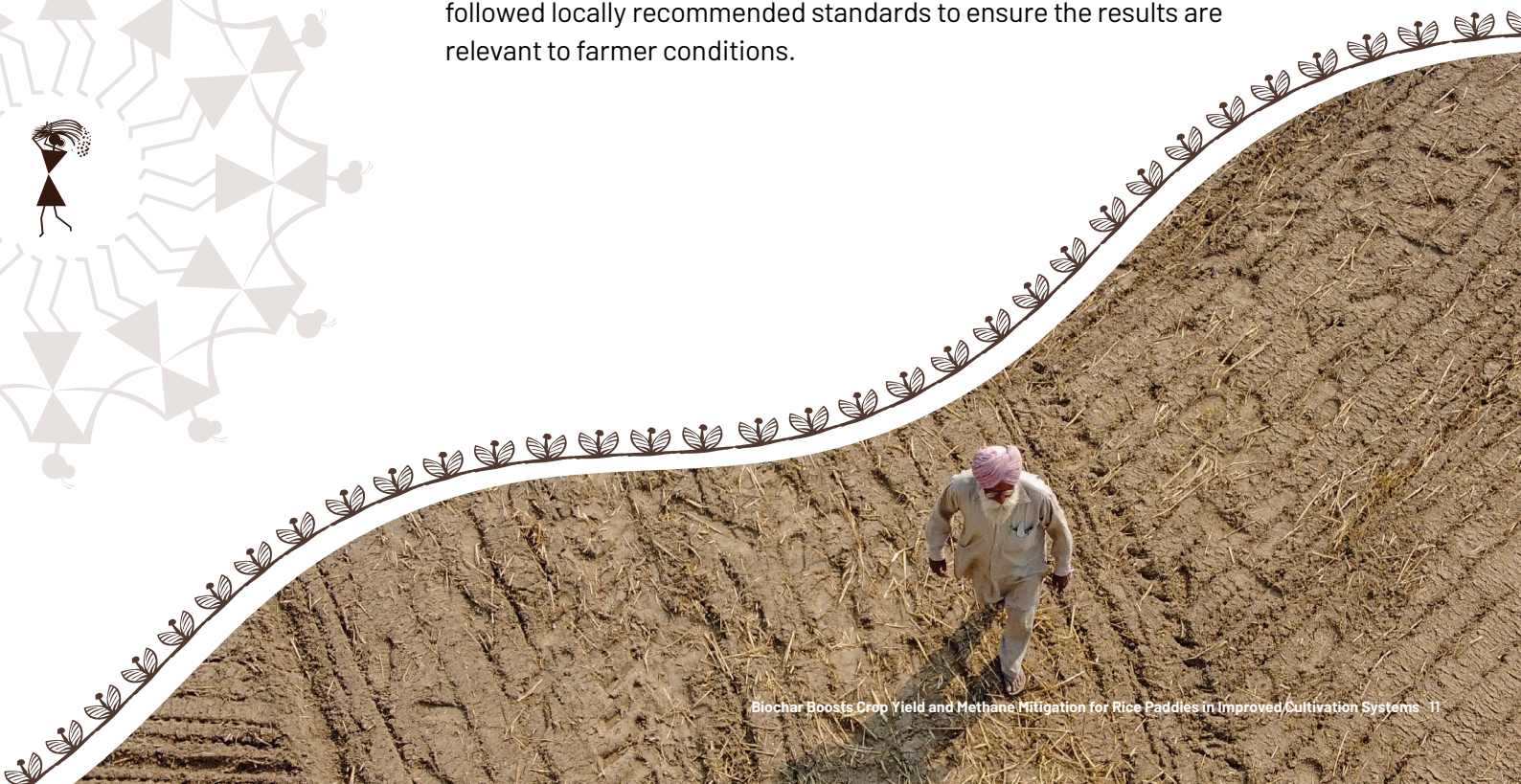


Irrigation regimes: continuous flooding (CF) and alternate wetting and drying (AWD).



Biochar application rate: 0, 1.25, 2.5, 5.0 and 10.0 t/ha, produced from rice residues and incorporated into the soil before crop establishment.

Fertilization, weed control and other crop-management practices followed locally recommended standards to ensure the results are relevant to farmer conditions.



Treatment matrix

Twenty treatments were tested, combining cultivation, water management and biochar rates as shown in Table 1.

Table 1. Treatment names and associated details: PTR (Puddled Transplanted Rice); DDSR (Dry Direct Seeded Rice); VDSR (Vattar Direct Seeded Rice); CF (Continuous Flooding); and AWD (Alternate Wetting and Drying).

#	Treatment Name	Biochar (t/ha)	Cultivation Method	Water Management
1	0 t/ha + PTR-CF	0.00	Puddled Transplanted Rice	Continuous Flooding
2	1.25 t/ha + PTR-CF	1.25	Puddled Transplanted Rice	Continuous Flooding
3	2.5 t/ha + PTR-CF	2.50	Puddled Transplanted Rice	Continuous Flooding
4	5 t/ha + PTR-CF	5.00	Puddled Transplanted Rice	Continuous Flooding
5	10 t/ha + PTR-CF	10.00	Puddled Transplanted Rice	Continuous Flooding
6	0 t/ha + PTR-AWD	0.00	Puddled Transplanted Rice	Alternate Wetting & Drying
7	1.25 t/ha + PTR-AWD	1.25	Puddled Transplanted Rice	Alternate Wetting & Drying
8	2.5 t/ha + PTR-AWD	2.50	Puddled Transplanted Rice	Alternate Wetting & Drying
9	5 t/ha + PTR-AWD	5.00	Puddled Transplanted Rice	Alternate Wetting & Drying
10	10 t/ha + PTR-AWD	10.00	Puddled Transplanted Rice	Alternate Wetting & Drying
11	0 t/ha + DDSR	0.00	Dry Direct Seeded Rice	Improved Irrigation ¹
12	1.25 t/ha + DDSR	1.25	Dry Direct Seeded Rice	Improved Irrigation
13	2.5 t/ha + DDSR	2.50	Dry Direct Seeded Rice	Improved Irrigation
14	5 t/ha + DDSR	5.00	Dry Direct Seeded Rice	Improved Irrigation
15	10 t/ha + DDSR	10.00	Dry Direct Seeded Rice	Improved Irrigation
16	0 t/ha + VDSR	0.00	Vattar Direct Seeded Rice	Improved Irrigation
17	1.25 t/ha + VDSR	1.25	Vattar Direct Seeded Rice	Improved Irrigation
18	2.5 t/ha + VDSR	2.50	Vattar Direct Seeded Rice	Improved Irrigation
19	5 t/ha + VDSR	5.00	Vattar Direct Seeded Rice	Improved Irrigation
20	10 t/ha + VDSR	10.00	Vattar Direct Seeded Rice	Improved Irrigation

¹Dry-DSR (DDSR) and Vattar-DSR (VDSR) were not managed under continuous flooding; because fields are direct-seeded without puddling, water does not stand for long and plots typically dry between irrigations. Farmers irrigate when the fields are dried. Therefore, water management functionally resembles intermittent/ improved irrigation.

Measurements

- Irrigation water inputs were measured directly using water meters.
- Greenhouse gas fluxes (CH₄ and N₂O) were measured throughout the season using static closed chambers. Cumulative seasonal emissions were converted to global warming potential (GWP) in CO₂-equivalent terms.
- Standing water and water-table depth were monitored to characterize water management.
- Crop yield was measured using standard agronomic methods.
- Soil properties were tracked to assess agronomic responses.

Figure 2: Field implementation showing biochar incorporation (left) and contrasting flooding regimes (right). Photo credit: IRRRI



Figure 3: In situ static (closed-cover) flux chamber greenhouse gas sampling process in the experimental plots. Photo credit: IRRRI

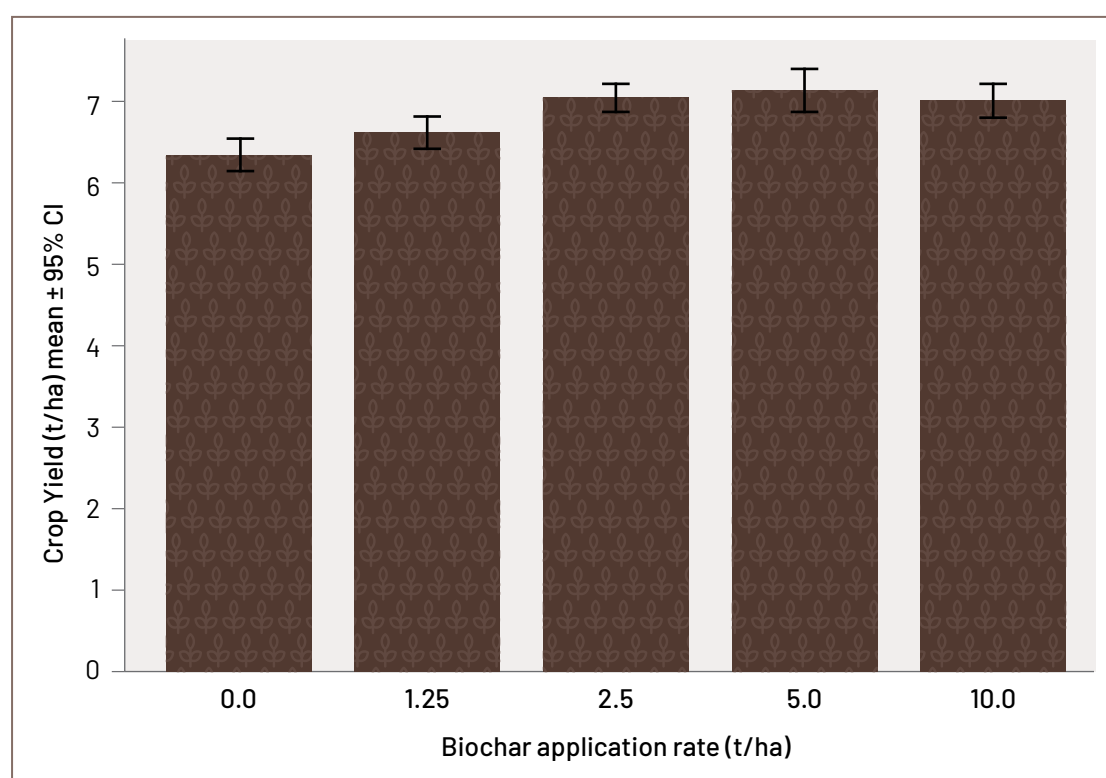


What we found

Crop yield: Biochar improves water-saving systems outcomes

Biochar enhanced crop productivity under alternative establishment and irrigation methods (DSR and AWD), which was equal to or higher than conventional puddled transplanting under continuous flooding without biochar application. While yields ranged between 6.75 and 6.92 t/ha under the alternative systems, the strongest response occurred at 2.5–5.0 t/ha biochar application rate, dropping slightly at higher rates, corresponding to an 11–13% yield increase relative to the no-biochar control (Figure 4). This is a notable finding, since earlier work has often suggested that high biochar rates (around 10 t/ha) are needed for meaningful agronomic benefit, while these results indicate that more modest, and therefore more actionable, rates can deliver substantive gains.

Figure 4: Crop yields under biochar treatments across combined cultivation systems.



Methane emission: Biochar adds to the cultivation effect

Conventional puddled transplanted rice under continuous flooding with no biochar produced the highest methane emissions. Both direct-seeded approaches showed substantial declines in emissions (Figure 5), confirming that water management exerts the dominant influence on methane and total GWP from rice systems.

Biochar added a further layer of reduction to that brought by water management. The largest biochar effect appeared under puddled transplanted AWD: up to a 30% additional reduction in methane emissions and total GWP compared with continuous flooding (Figure 6, left). Under conventional PTR-CF, where biochar acts as a standalone intervention, methane reductions ranged from roughly 12% to 37%, driven primarily by suppression of methanogenesis (Figure 6, right). Across all cultivation practices combined, the highest application rate yielded more than a 30% reduction in methane emissions (Figure 7).

Figure 5: Mitigated methane emission relative to baseline (0 t/ha biochar + Puddled Transplanted Rice) across the combination of crop establishment and biochar application rates.

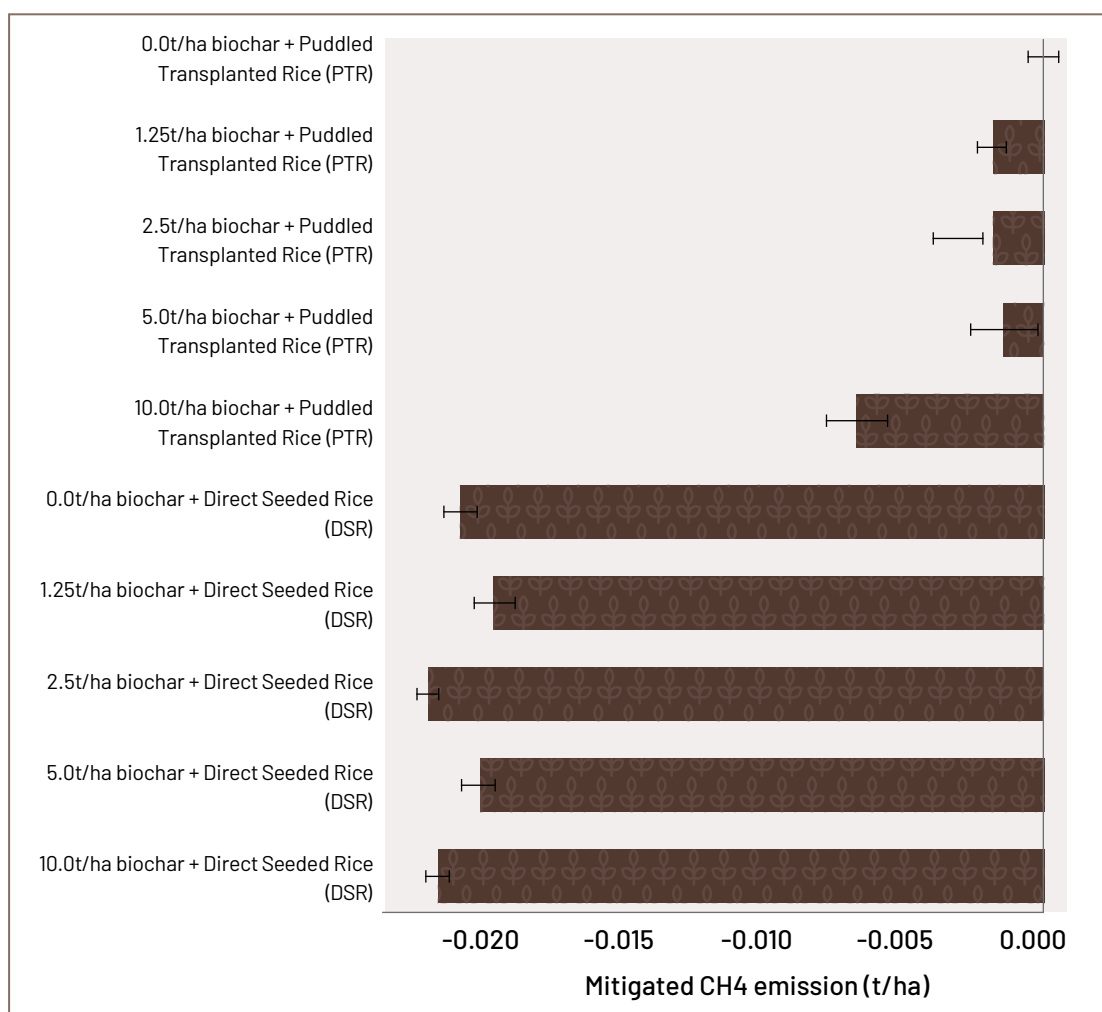
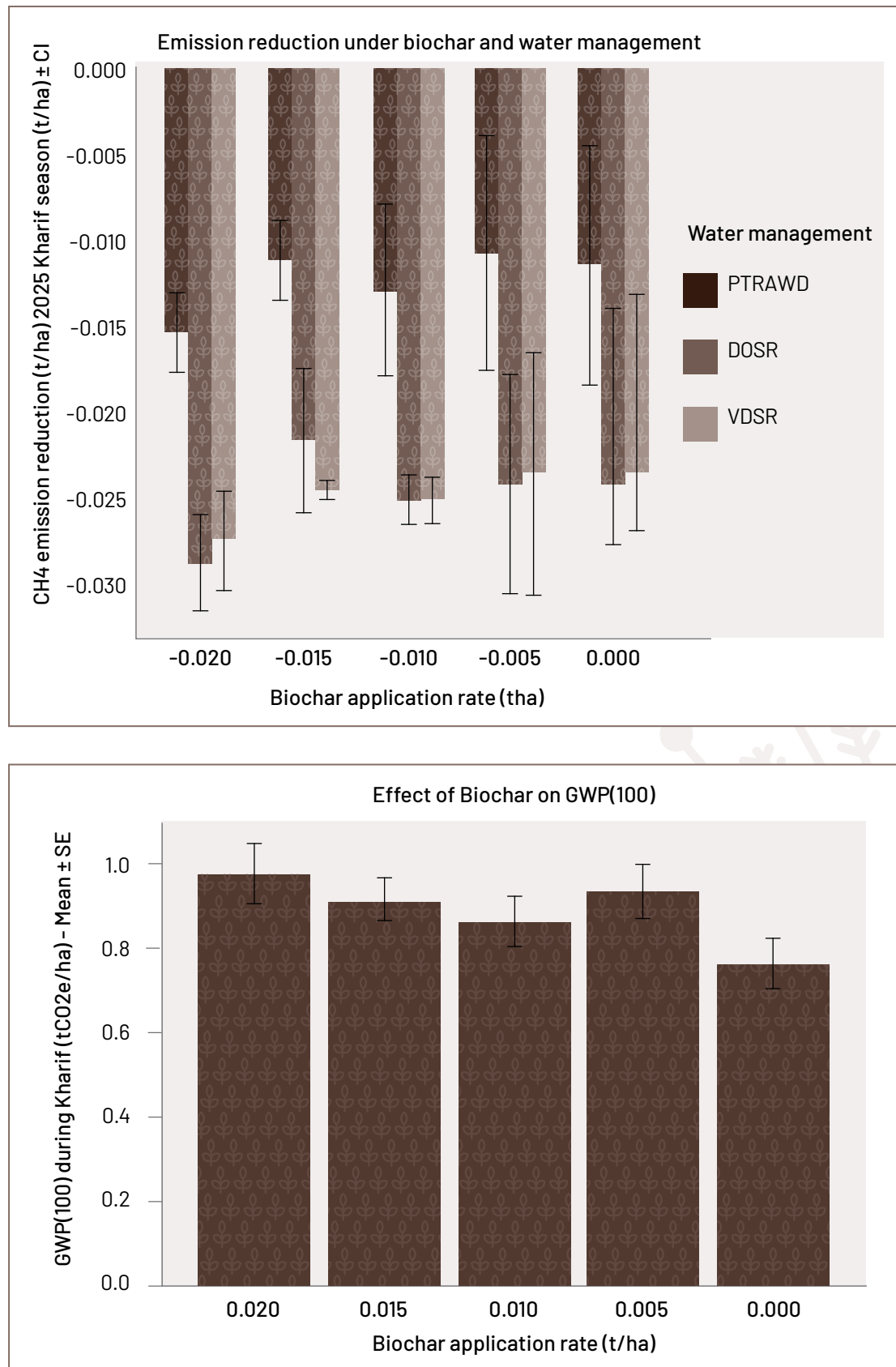


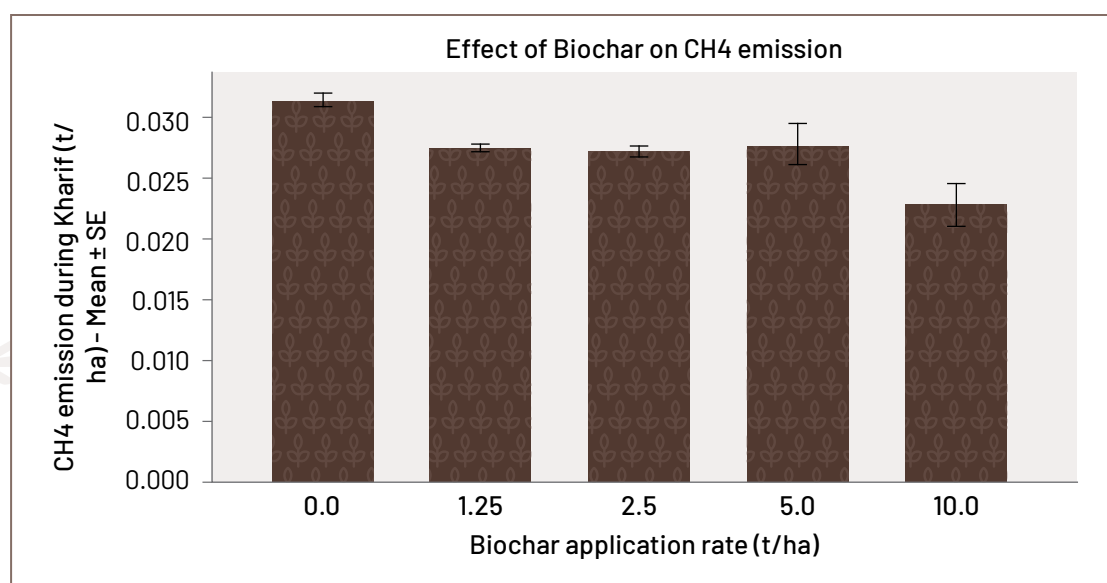
Figure 6: Methane reductions relative to 0 t/ha biochar + PTR-CF across water management methods and biochar application rates (left); and the effect of biochar application rate as a standalone intervention on global warming potential (GWP) in PTR-CF (right).



A consistent biochar signal across systems

The biochar response was consistent across cultivation practices, which is encouraging for generalizability and for implementation flexibility. Because alternative irrigation methods are not suitable for every soil type, biochar offers a methane mitigation pathway in settings where AWD or DSR may not be feasible.

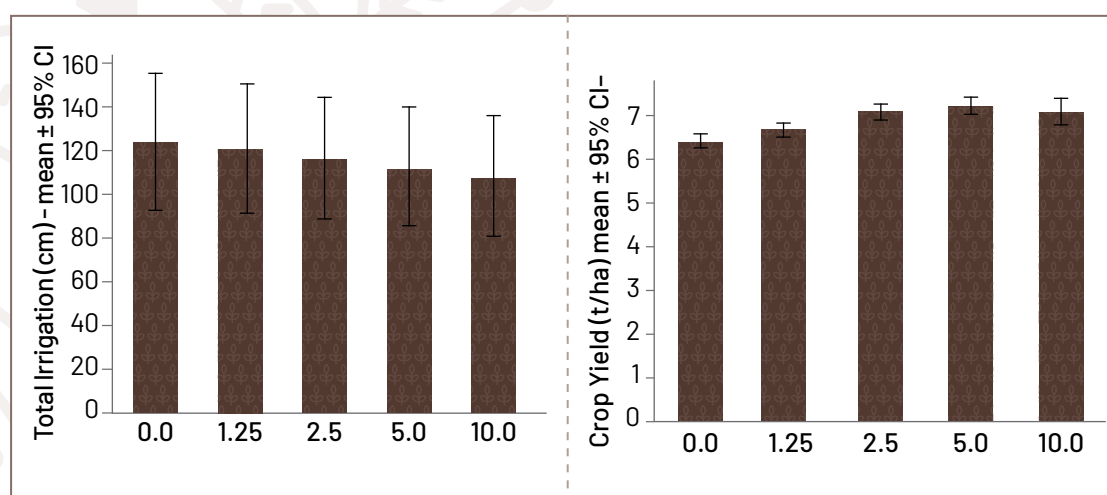
Figure 7: Methane emissions under biochar application rates and different flooding regimes.



Water use and co-benefits

Water productivity increased by 40–65% under DSR and AWD relative to PTR-CF. Biochar was additionally associated with improved water-use efficiency, signals of further yield gains, and reduced irrigation water needs (Figure 8). These co-benefits strengthen the practical case for adoption where farmers can save water without sacrificing productivity.

Figure 8: Water use and yield response by biochar application rates.



Conclusions and next steps

First-year takeaways

The first season of field implementation produced strong preliminary outcomes. Three messages stand out:



Water-saving rice systems (DSR and AWD) are confirmed as effective levers for reducing methane and overall greenhouse gas emissions while maintaining yields.



Rice-residue biochar provides additional methane mitigation on top of that by water management, and is particularly valuable in puddled, continuously flooded systems where alternative irrigation cannot be deployed.



Combining moderate biochar rates with optimized irrigation produces a win-win-win across emissions, water use and crop yield.

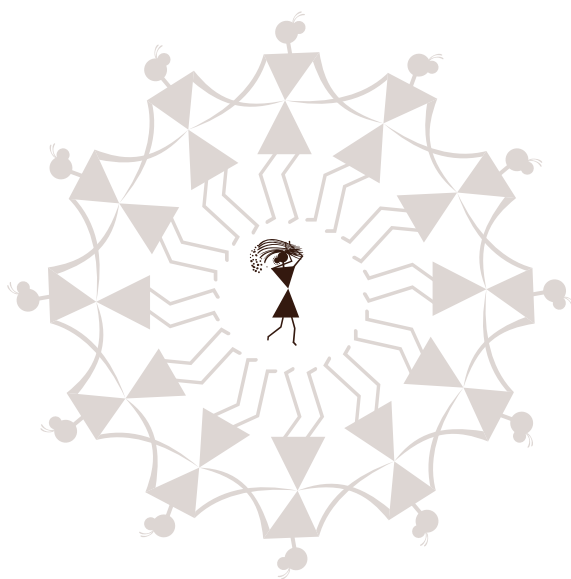
Optimal first-year rate

A practical balance emerges around 2 t/ha biochar, where irrigation demand and methane emissions fall while yields are sustained. This rate is more scalable than very high application rates and supports broad farmer adoption.



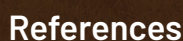
Next steps

- Continue the trial across additional kharif seasons to confirm robustness across years.
- Test biochar performance across a wide range of soil textures and pH conditions, since these factors strongly shape outcomes.
- Integrate farmer-level socioeconomic analyses to evaluate feasibility, adoption barriers and scalability.
- Move from promising technical results toward an implementation package that is agronomically sound, economically viable and scalable.



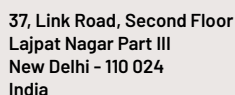
Study partners:





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Together, we find a way.



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