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Rice with a Lighter Footprint

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Flooded rice fields feed half the world but are also a major agricultural source of methane, with nitrous oxide adding to their warming footprint. This article explains how methane and nitrous oxide arise in paddy soils and reviews five practical levers for cutting emissions without sacrificing yield or farm income: controlled alternate wetting and drying, the 4R approach to nitrogen management, direct-seeded rice, better use of crop residues, and the choice of suitable genotypes together with emerging tools such as nano-iron oxides. It highlights the trade-offs that accompany each practice, including nitrous oxide pulses, weed pressure and the cost of biochar, and argues that practices should be judged by their net warming potential and emissions per kilogram of grain. Evidence from recent studies shows that combining practices works better than relying on any single one. The article also discusses the relevance of these options to the rice–wheat system of the Indo-Gangetic Plains, the need for credible measurement and verification, and the extension and incentive support required to take low-emission rice to farmers' fields.

Keywords: low-emission rice, methane, alternate wetting and drying, direct-seeded rice, nitrogen management, Indo-Gangetic Plains

Rice feeds half the world, yet its flooded fields are a major source of methane. Smarter management of water, nitrogen and crop residue can shrink that footprint while protecting yield and farm income.

The paradox in our paddies

Stand at the edge of a flooded rice field in July and everything looks like abundance. The seedlings are bright green, the water gleams in the sun, and a season's food is quietly taking shape. What the eye misses is the gas rising from the soil beneath that water. Rice supplies staple food to about half of the world's people. It is also among the thirstiest crops we grow, and the same flooded soil that suits the crop also makes rice a major source of methane. A global assessment put average rice emissions at roughly 7,870 kg CO₂-equivalent per hectare per year, with about 94 per cent of that coming from methane (Qian et al., 2023).

So the challenge is no longer just to grow more rice. It is to grow it with less water, less nitrogen lost to the air and fewer greenhouse gases, while keeping the farmer's income safe. That is what a *low-emission rice system* aims to do.

What happens beneath the flood

To cut methane, we must first understand where it comes from. When a field stays continuously flooded, water fills the soil pores and oxygen can barely enter. Methane-producing microbes called methanogens thrive in this oxygen-starved world. Fed by root exudates, crop residues and soil organic matter, they turn simple carbon compounds into methane. The rice plant plays a double role. Its roots and stems contain aerenchyma, a network of air channels that carries oxygen down to the roots. The same channels act as chimneys through which methane travels from soil to air; smaller amounts escape by

diffusion through floodwater and as bubbles. Nature also provides a brake: around the roots, oxygen-rich pockets host methane-eating bacteria, the methanotrophs, which consume part of the gas before it escapes. Net emission is the balance between what methanogens make and what methanotrophs eat, and good management tips that balance in our favour. Nitrous oxide (N₂O) is the second gas to watch. It forms when fertilizer nitrogen is transformed in the soil by nitrification and denitrification, especially when fields swing between wet and dry. Excess or badly timed nitrogen makes matters worse.

Five practical levers

1. Manage the water. Continuous flooding gives the highest methane. In alternate wetting and drying (AWD), the field is allowed to dry to a safe, defined level before it is irrigated again. The aeration suppresses methanogens and encourages methane oxidation. A recent meta-analysis found that, compared with continuous flooding, AWD cut methane by 51.6 per cent and total global warming potential (GWP) by 46.9 per cent, even though N₂O rose by 44.0 per cent (Zhao et al., 2024). The key word is *controlled*: letting the crop suffer water stress is not AWD, and over-drying can hurt yield.

2. Feed nitrogen by the 4R rule. Right source, right rate, right time, right place. Applying only what the crop needs, splitting doses around peak uptake and placing fertiliser near the roots raise nitrogen-use efficiency and lower N₂O. Losses can be large: a synthesis of 127 studies from China found that, on average, 16.2 per cent of applied urea-N was lost as ammonia from paddy fields, with losses rising with high N rates, surface application and high floodwater pH (Sha et al., 2022). Deep placement, neem-coated urea, urease inhibitors and leaf-colour-chart-based dosing all help.

3. Rethink crop establishment. Puddling and transplanting keep soils saturated and anaerobic and demand heavy labour and energy. Direct-seeded rice (DSR) skips both, saving water and labour and avoiding the prolonged flooding that favours methane. DSR works best as part of an integrated package (see “Combinations beat single practices” below), and because practices that cut methane can raise N₂O, nitrogen must be managed carefully. Weeds are DSR’s weak spot, so timely weed control makes or breaks the system.

4. Treat residues as a resource. Fresh straw ploughed into a flooded field hands methanogens a feast of easy carbon, and methane climbs. Burning removes that problem but replaces it with smoke and carbon loss. Better routes include surface retention, composting, biochar and off-field uses such as fodder, biogas or bioenergy. In a four-year double-season rice study in China, fertiliser combined with biochar cut greenhouse-gas intensity by about 70 per cent relative to the unfertilised control under rotary tillage, whereas fertiliser with straw increased emissions (Yang et al., 2023).

5. Choose the right genotype and test new tools. Cultivars differ widely in methane emission under identical conditions because their biomass, roots, exudates and aerenchyma differ; on average, selecting better-suited varieties lowered emissions by about 24 per cent (Qian et al., 2023). The aim is root anatomy that delivers oxygen to the rhizosphere while limiting methane transport, without sacrificing yield. Newer ideas are emerging too. In a four-year field study, iron-oxide nanoparticles applied as basal fertiliser roughly halved methane and N₂O emissions, raised soil carbon by 7.4 per cent by the fourth year and increased food production by up to 25 per cent (Yu et al., 2024). These are results from a single study; cost, long-term soil effects and farmer-ready application still need testing.

No free lunch: mind the trade-offs

Every good idea has a catch. AWD lowers methane, but wet–dry cycles can trigger N₂O pulses. DSR saves water and labour, but weeds can surge. Straw retention builds soil carbon but can feed methane. Biochar can help, but it costs money and responses vary (Table 1). The lesson is to judge a practice by its *net* effect: compare total warming potential in CO₂-equivalent rather than methane alone, and report emissions per kilogram of grain as well as per hectare. A system that cuts emissions per hectare by sacrificing yield only shifts the problem elsewhere.

Table 1. Main gains and trade-offs of low-emission rice practices.

Practice	Main gain	Watch out for
AWD	Methane down, water saved	N ₂ O may rise; over-drying
Direct-seeded rice	Water, labour and methane down	Weeds; nitrogen management
Precision nitrogen	Higher NUE, less N ₂ O and ammonia	Under-application cuts yield
Residue management	Soil carbon, less burning	Fresh straw can raise methane
Biochar	Stable carbon, lower GHG intensity	Cost; variable response

Combinations beat single practices

A synthesis across major Asian rice regions found that combining AWD with optimised nitrogen raised yield by about 47 per cent, and that regionally nitrogen input could be cut by roughly 31 per cent while maintaining yields and lowering greenhouse-gas intensity by about 49 per cent (Wei et al., 2025). An integrated package from Hainan, China, combining dry direct seeding, a water-saving drought-resistant variety, 53 per cent less nitrogen and plastic mulch, was estimated to cut net emissions by over 90 per cent against traditional flooded rice while sustaining yield (Zhang et al., 2024). Such figures are best-case results from specific sites, but they show what integration can achieve.

Why the Indo-Gangetic Plains matter

India has a special stake. The rice–wheat belt running from Punjab and Haryana through Uttar Pradesh and Bihar to West Bengal is the engine of our food security. It is also water-, energy- and residue-intensive, with falling groundwater, stubble-burning smoke each autumn and heavy fertiliser use. The toolkit is already taking shape: DSR, AWD, zero tillage, neem-coated urea, the Happy Seeder for sowing wheat into rice residue and climate-smart varieties, supported by initiatives such as the IRRI-led PlantDirect project on dry DSR for the Indo-Gangetic Plains. Evidence from other Asian rice regions suggests that such resource-conserving packages can lower emissions while sustaining yield (Wei et al., 2025), and these principles deserve to be tested widely across the Indo-Gangetic Plains.

Measuring, and reaching the farmer's field

What cannot be measured cannot be managed, and certainly cannot earn carbon credits. Scientists measure emissions with closed chambers placed over the crop, automated chambers that sample frequently and eddy-covariance towers that read whole-field exchange, then scale up using emission factors, process models and satellite data. For carbon markets to reward farmers, they need credible baselines, proof that the reduction would not have happened anyway, independent verification and no double counting. And a technology that works on a research plot is only halfway home. Farms vary in soil, water reliability, machinery access, labour and appetite for risk, so extension support, fair incentives, sensible water pricing and sensors that guide water and nitrogen use will decide whether these ideas spread.

The way forward

Low-emission rice is not one technology but a way of thinking. Keep the soil wet only when the crop needs it, feed nitrogen when and where the plant can use it, treat straw as a resource, choose varieties with smart roots, and always weigh the whole balance sheet of yield, water, emissions and income. Get this right and the paddy of the future will still look green and generous, but the gases rising from it will be far fewer, and the farmer will be better off for it.

Key takeaways

- Rice emissions are mostly methane (about 94 per cent globally), driven by flooding and available carbon.
- AWD and DSR can cut methane and save water, but watch N₂O and weeds.
- Efficient nitrogen management protects yield and curbs N₂O and ammonia losses.
- Integrated packages beat single practices; judge them by total GWP and emissions per kg of grain.

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