



REVIEW ARTICLE

Decarbonising rice cultivation: strategies for methane mitigation and enhanced methane oxidation

M Kaviya¹, K Sivagamy^{2*}, S Anitta Fanish¹, C Tamilselvi³ & D Amirtham⁴

¹Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

²ICAR-Krishi Vigyan Kendra, Tiruvallur, Tirur 602 025, Tamil Nadu, India

³Rice Research Station, Tiruvallur, Tirur 602 025, Tamil Nadu, India

⁴Department of Plant Biotechnology, Centre for Plant Molecular Biology and Biotechnology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - ksivagamy@tnau.ac.in

Received: 16 April 2026; Accepted: 02 June 2026; Available online: Version 1.0: 29 June 2026

Cite this article: Kaviya M, Sivagamy K, Anitta FS, Tamilselvi C, Amirtham D. Decarbonising rice cultivation: strategies for methane mitigation and enhanced methane oxidation. Plant Science Today. 2026; 13(sp2): 1-11. <https://doi.org/10.14719/pst.15034>

Abstract

Rice cultivation is one of the major anthropogenic sources of methane, a potent greenhouse gas. Methane (CH₄) is produced under anaerobic conditions in soils by methanogenic archaea. The magnitude of CH₄ emissions depends on processes such as CH₄ production, oxidation and transport, which are influenced by soil properties, microbial activity, plant traits and management practices. Methanotrophic bacteria significantly contribute to the reduction of emissions through the oxidation of CH₄, especially in the rhizosphere where oxygen is available. This paper reviews various dimensions of CH₄ in rice ecosystems such as methanogenesis pathways, CH₄ oxidation mechanisms, microbial interactions and the environmental controls of redox potential, organic substrates, water and nutrient management. Several strategies for mitigation, such as alternate wetting and drying irrigation, optimised fertilisation, biochar application, crop establishment methods, low-methane rice varieties and emerging technologies like bioinoculants, nanotechnology and precision agriculture, have been discussed. Overall, there is a great need for integrated management approaches that simultaneously enhance CH₄ oxidation and reduce CH₄ production in order to develop climate-smart rice systems that can not only reduce emissions but ensure global food security.

Keywords: climate-smart agriculture; methane mitigation; methane oxidation; methanogenesis

Introduction

Methane (CH₄) is the second-largest contributor to anthropogenic global warming after carbon dioxide (CO₂) (1). The level of CH₄ in the atmosphere has risen from around 700 ppb pre-industrial revolution to 1922.6 ppb in 2023, which is responsible for approximately 33 % of global warming due to its potent radiative forcing. Methane has a global warming potential (GWP) 25–34 times higher than that of CO₂ over a 100-year period, making it a major contributor to climate change despite its shorter atmospheric lifetime. At present, global CH₄ emissions are increasing continuously, with agriculture contributing approximately 42 % of total anthropogenic CH₄ emissions (2). Rice (*Oryza sativa* L.) feeds more than half of the global population. It is grown on approximately 165 million hectares of land scattered over more than 100 countries, with around 90 % of the production occurring within Asia (3). Nevertheless, flooding of paddy fields results in anaerobic conditions which supports the activity of methanogenic microbes, leading to considerable CH₄ emission. The rice sector contributes approximately 10–12 % of the total global anthropogenic CH₄ emissions and generates around 25–37.5 Tg CH₄ annually (4). Methane emissions from rice fields vary across crop growth stages and are influenced by soil properties, water

management, nutrient inputs and rice cultivars (5). Therefore, reducing CH₄ production while enhancing CH₄ oxidation through improved water, nutrient and crop management practices is essential for developing climate-smart and sustainable rice production systems (6). Atmospheric CH₄ emissions have been increasing continuously over the last few decades. The global CH₄ emission trajectory from 2000 is presented in Fig. 1, highlighting the need for appropriate rice field-based mitigation measures to address this issue (7, 8). Although several studies have reported CH₄ mitigation strategies in rice ecosystems, a comprehensive synthesis integrating CH₄ production, oxidation mechanisms, microbial interactions and emerging climate-smart mitigation technologies remains limited. Therefore, this review focuses on understanding CH₄ dynamics in rice cultivation and critically evaluates agronomic, biological and technological strategies for methane mitigation and enhanced CH₄ oxidation in rice ecosystems.

Methane dynamics in rice ecosystems

Methanogenesis refers to the biological generation of CH₄ under anaerobic conditions and is carried out exclusively by methanogenic archaea (9, 10). Common methanogenic archaea reported in flooded rice soils include *Methanobacterium*, *Methanosarcina*, *Methanosaeta* and *Methanocella*, which utilise hydrogenotrophic,

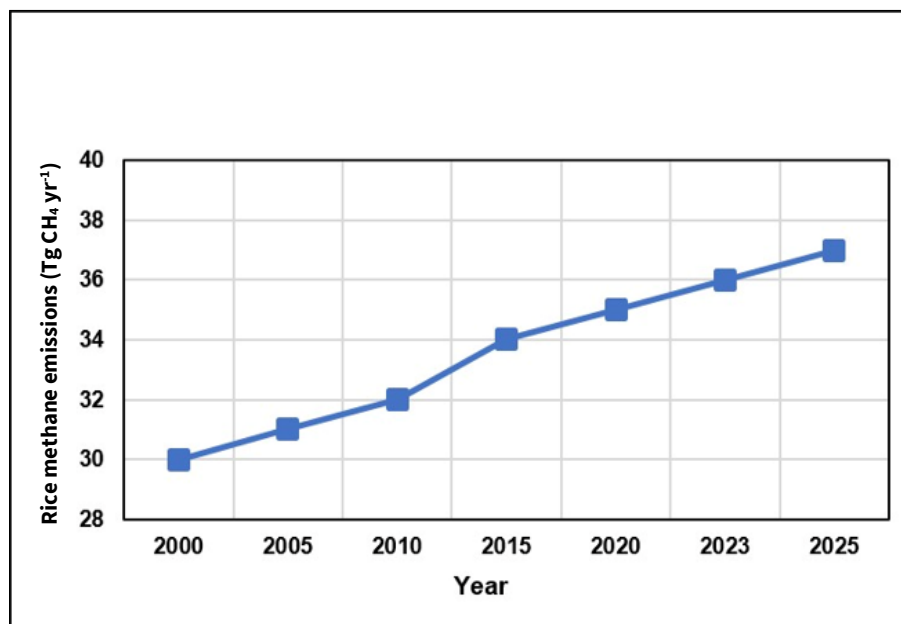


Fig. 1. Global trends in atmospheric methane emissions from 2000–25 (data compiled from (7, 8)).

acetoclastic and methylotrophic pathways for CH₄ production (11, 12). These microorganisms thrive in oxygen-depleted environments such as the anoxic bulk soil and rhizosphere of flooded rice fields. Flooding drastically restricts oxygen diffusion, thereby creating reducing conditions favourable for methanogenic activity (13). Methanogens derive energy and carbon through three principal metabolic pathways: acetoclastic methanogenesis (acetate conversion), hydrogenotrophic methanogenesis (CO₂ reduction using H₂) and methylotrophic methanogenesis involving methylated compounds. Among these, the acetoclastic pathway contributes nearly 60–70 % of total CH₄ production in rice soils, whereas hydrogenotrophic methanogenesis contributes approximately 30–40 % (12). Methanogenesis is most active at pH 6.0–8.0, with methane production generally peaking near neutral pH. Methyl coenzyme reductase (MCR), encoded by the *mcrA* gene, is the key enzyme catalysing the final step of methane formation (14). Methanogenesis is strongly influenced by substrate availability, organic matter incorporation, water management and cropping systems (13). Redox potential (Eh) plays a critical role in regulating methanogenesis in flooded soils. Flooding lowers soil Eh by limiting oxygen availability and promoting highly reducing conditions conducive to CH₄ production. Methanogenesis generally initiates when Eh declines below approximately -150 to -200 mV, while maximum CH₄ production occurs between -200 and -300 mV (15). Organic carbon supplied through root exudates, crop residues and organic amendments serves as an important substrate source for methanogens, thereby stimulating CH₄ formation. Fresh rice straw incorporation has been reported to increase CH₄ emissions by 50–200 % compared with straw removal, whereas composted straw substantially lowers CH₄ release (13). Methane produced in rice soils is emitted through diffusion, ebullition and plant-mediated transport pathways (16). Diffusion involves the gradual movement of dissolved CH₄ through soil and flood water, whereas ebullition occurs when CH₄ accumulates and escapes as gas bubbles (17). Plant-mediated transport through rice aerenchyma represents the dominant pathway, accounting for nearly 60–90 % of total CH₄ emissions in flooded rice ecosystems (18). Overall CH₄ emissions are governed by the interaction among microbial processes, soil physicochemical properties, plant traits and environmental conditions (19).

Methane oxidation

Methane oxidation is one of the most important microbial processes in flooded rice ecosystems because it significantly lowers CH₄ emissions through the conversion of CH₄ into carbon dioxide. This process is mediated by CH₄-oxidising bacteria, commonly known as methanotrophs, which utilise CH₄ as their sole carbon and energy source. Major methanotrophic genera identified in rice soils include *Methylomonas*, *Methylobacter*, *Methylocystis* and *Methylosinus* (20, 21). Methane oxidation primarily occurs at the oxic-anoxic interface, where CH₄ produced in anaerobic soil layers encounters oxygen supplied through atmospheric diffusion, soil pores and the aerenchyma tissues of rice roots (22). Depending on oxygen availability and environmental conditions, methanotrophic activity may oxidise approximately 10–80 % of gross CH₄ produced in rice soils before its release into the atmosphere. Methane oxidation efficiency is influenced by methanotrophic community composition, oxygen availability, soil redox potential, metal cycling and plant-mediated oxygen transport. Methane oxidation varies considerably across rice growth stages. During the vegetative stage, root oxygen release enhances methanotrophic activity and stimulates CH₄ oxidation. In contrast, during the reproductive stage, increased root exudation and higher organic carbon availability promote methanogenesis, while reduced oxygen diffusion results in peak CH₄ emissions. During crop maturity, CH₄ production declines because of reduced substrate availability and lower root metabolic activity (21). The seasonal interaction between CH₄ production and CH₄ oxidation across rice growth stages is illustrated in Fig. 2 (20).

Methanotrophic bacteria in rice soils

Aerobic methanotrophs are broadly classified into two groups: Type I and Type II. Type I methanotrophs (Gammaproteobacteria), which include *Methylomonas* and *Methylobacter*, employ the ribulose monophosphate (RuMP) pathway and grow rapidly in environments with high CH₄ and oxygen (22). Meanwhile, Type II methanotrophs (Alphaproteobacteria) represented by genera like *Methylocystis* and *Methylosinus*, make use of the serine pathway and are more fit for low CH₄ and oxygen conditions. Some Type II methanotrophs can fix atmospheric nitrogen thereby linking CH₄ oxidation with nitrogen cycling (23). A comparison of the characteristics of Type I and Type II methanotrophs is presented in Table 1.

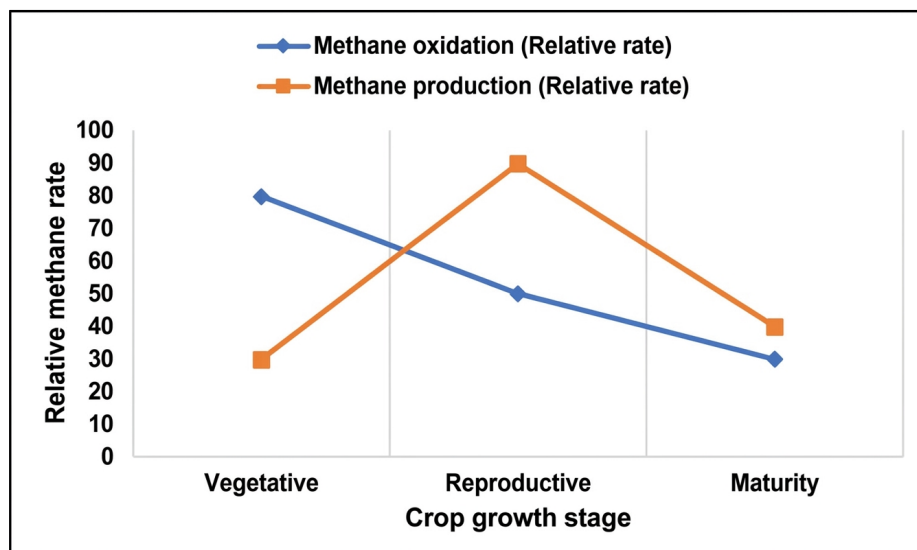


Fig. 2. Seasonal interaction between methane production and methane oxidation across rice growth stages (data compiled from (20)).

Table 1. Comparison of Type I and Type II methanotrophs

Feature	Type I methanotrophs	Type II methanotrophs
Phylogeny	Gammaproteobacteria	Alphaproteobacteria
Carbon fixation	RuMP pathway	Serine pathway
Internal membranes	Bundles of disc-shaped vesicles	Layers parallel to the cell wall
Dominant methane monooxygenase (MMO)	Mostly pMMO (particulate)	Both pMMO and sMMO (soluble)
N ₂ fixation	Generally absent	Frequently present
Response to CH ₄	High growth at high concentrations	Capable of survival at low concentrations
Carbon conversion efficiency	Higher	Lower

Environmental and plant regulation

Methane oxidation is predominantly localised in the rice rhizosphere because this is where root oxygen release raises soil redox potential and enables methanotrophic growth. Additionally, iron and manganese oxides, by serving as alternative electron acceptors under conditions of low oxygen, affect CH₄ oxidation (24). Rice plants control methanogenesis by oxygenating the rhizosphere through root oxygen release (ROL) that occurs in aerenchyma tissues, leading to the formation of aerobic microsites which enhance methanotroph activity and reduce methanogenesis (25). Therefore, differences among rice varieties in terms of not only aerenchyma development but also oxygen release can have a significant influence on methane emissions.

Biological interventions to enhance methane oxidation in rice ecosystem

Bioinoculants of methanotrophs along with appropriate agronomic and water management practices enhance the methanotroph population in rice rhizosphere and bring about a significant increase in CH₄ oxidation (26). Many methanotrophs promote plant growth through nitrogen fixation, phosphate solubilisation, potassium mobilisation and phytohormone production (27). For instance, *Rhizobium pusense* MB4 improved plant growth and grain yield by up to 75 % and may indirectly support CH₄ mitigation through enhanced rhizosphere activity and nutrient cycling, while a

genetically modified strain of *Methylovimicrobium alcaliphilum* 20Z oxidised CH₄ and produced indole-3-acetic acid (IAA) (28). *Peribacillus frigiditolerans* AE95, decreased CH₄ emissions by 66.8 % and enriched methanotroph communities achieved mitigation up to 74.3 % (29). Inoculation with *Methylobacterium oryzae*, azolla and blue-green algae also reduced CH₄ emissions (30). Phototrophic bacteria such as *Rhodospseudomonas palustris* and diazotrophs like *Azotobacter* and *Azospirillum* enhance plant root systems, stimulate oxygen diffusion and promote methane oxidation (31). The overall CH₄ dynamics in flooded rice systems, including CH₄ production, oxidation and plant-mediated transport pathways are illustrated in Fig. 3.

Methane mitigation strategies in rice cultivation

Water management strategies

Water management contributes significantly to reducing CH₄ emissions and global warming potential of rice systems while simultaneously assisting in saving irrigation water and keeping the crop productivity at the same level. Irrigation affects soil aeration and redox potential which control methanogenesis, CH₄ oxidation and plant mediated CH₄ transport thus determining the magnitude and seasonal dynamics of CH₄ emission (32).

Drip irrigation

Drip irrigation is a water saving eco-friendly technique that improves water use efficiency while reducing CH₄ emissions. According to multi location trials in Tamil Nadu drip irrigation resulted in a 60–68 % decrease in CH₄ emissions and 65 % decrease in GWP when compared to continuous flooding along with 40–45 % less irrigation water use and 50–64 % higher water productivity with only minor yield reductions (33). Subsurface drip irrigation leads to further increased mitigation of CH₄ emissions while maintaining or improving grain yield or even improved. Drip irrigation with plastic mulch lessened CH₄ emissions by 69–94 % (34). In controlled environment experiments, drip irrigation caused CH₄ emissions to decrease by more than 90 % in all tested rice varieties, through higher soil oxygen availability and redox potential (35). Recent studies have demonstrated that subsurface drip irrigation combined with direct-seeded rice cultivation significantly reduces CH₄ emissions compared with conventional flooded systems because of improved soil aeration, enhanced methanotrophic activity and reduced anaerobic conditions (34).

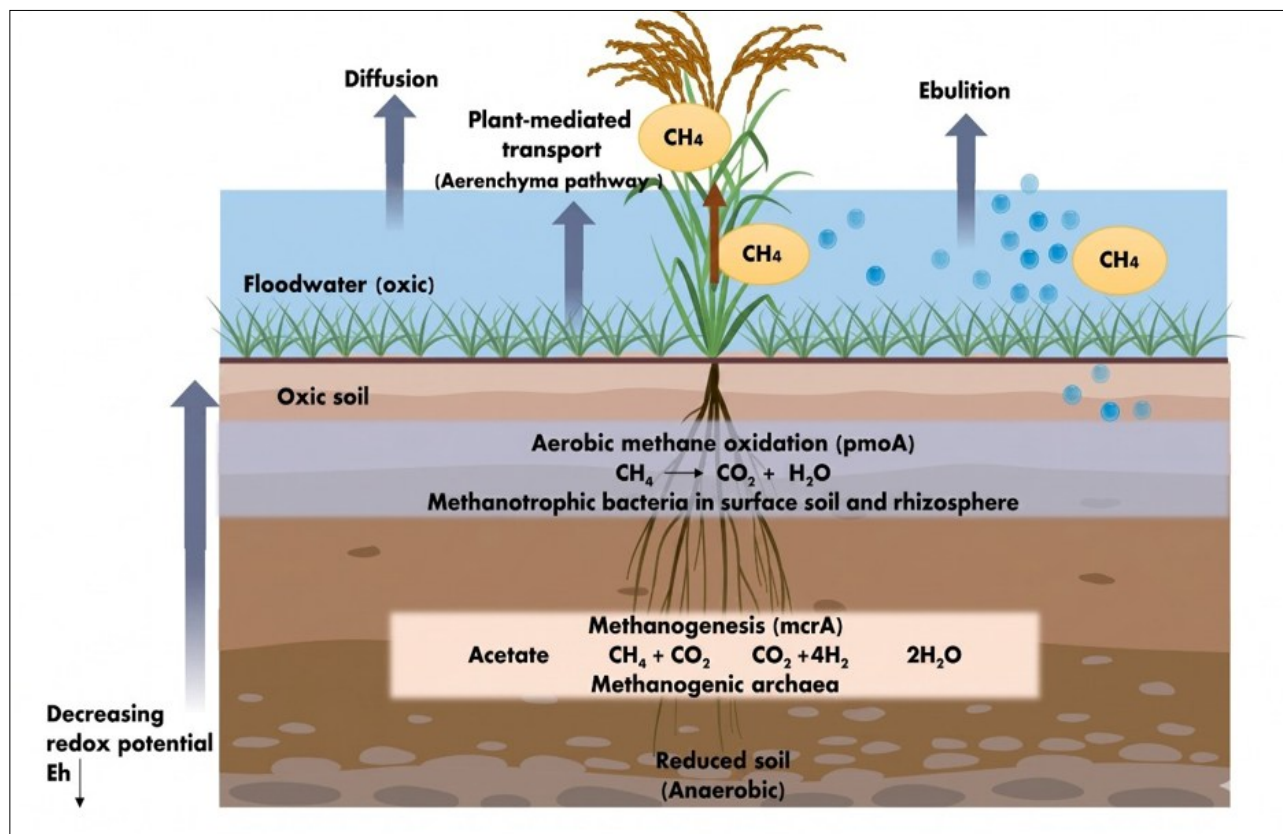


Fig. 3. Methane dynamics in flooded rice systems showing production, oxidation and transport pathways.

Alternate wetting and drying

Alternate wetting and drying (AWD) is a climate smart irrigation practice that decreases CH_4 emissions, preserves water and maintains stable crop yields. It entails a series of drying and wetting of the soil surface thus inhibiting methanogenesis and boosting CH_4 oxidation because of increased soil oxygen. Some research shows that CH_4 emissions drop by 20–70 % and the GWP decreases by 18–77 % under AWD as compared to continuous flooding (36, 37). Methane emission reductions were more significant in the case of tropical soils (68.2 %) and clay soils (71.3 %) (38, 39). Modified AWD practices lowered CH_4 emissions by 24–48 % and the total GWP by 18–39 %, with a slight increase in N_2O emissions (40). Precision water saving techniques like alternate partial root zone drying and deficit irrigation boosted water productivity by 31–51 % and lowered CH_4 emissions by up to 78 % (41). The effects of AWD on CH_4 emissions in rice systems across different regions are summarised in Table 2.

Optimal drainage

Field drainage introduces oxygen into the soil, thereby suppressing methanogens and enhancing CH_4 . It has been shown that CH_4 emissions can be cut down 45 % through drainage in the early stage

of the season (18–20 days after transplanting) while drainage after a long delay only reduces emissions by about 25 % (46, 47). Multi-year field experiments conducted across different climatic zones revealed that periodic drainage reduced CH_4 emissions by 21–91%, with no significant reduction in grain yield (48, 49). Therefore, the timing and duration of drainage as being the key factors in the successful implementation of a CH_4 reduction strategy.

Smart water management

Internet of things (IoT) based irrigation systems allows for precise control of flooding and soil moisture which in turn reduces the anaerobic conditions that lead to methanogenesis. These systems reduced CH_4 emissions by 35–65 % while maintaining grain yield (50). Besides that, sensor driven irrigation lessened water consumption by 25–40 % compared to traditional irrigation methods (51). Automated threshold-based irrigation which is activated when the water level drops 10–15 cm below the soil surface limits the activity of methanogens and improves CH_4 oxidation without causing any loss in the yield (52). These findings indicate that IoT-based irrigation is a viable climate-smart strategy for CH_4 mitigation and water conservation. Although IoT-based irrigation systems effectively reduce CH_4 emissions and improve water-use efficiency, their adoption may be constrained by high

Table 2. Effects of alternate wetting and drying (AWD) on methane emissions in rice across regions

Region	AWD implementation	CH_4 emission reduction range	Consolidated methane-related insight	References
Indonesia	AWD triggered at 15 cm water table; site-specific AWD	35–38 %	AWD consistently suppresses methanogenesis, even in wet seasons	(42)
Thailand	AWD and modified AWD thresholds	31–49 %	Strong methane mitigation in dry seasons	(43)
China	AWD evaluated using coupled crop-GHG models	34–71 %	Strong regional variability; higher methane reduction in northeastern rice areas	(44)
USA (Arkansas)	Multiple AWD regimes	45–90 %	Strong CH_4 mitigation with economic feasibility	(45)

AWD: alternate wetting and drying; CH_4 : methane.

initial installation costs, sensor maintenance and technical expertise requirements. Compared with conventional AWD, IoT-based systems provide more precise water management but are relatively expensive for small and marginal farmers. Therefore, AWD and controlled irrigation practices may be more economically feasible for resource-limited farming communities, whereas IoT-based smart irrigation may be suitable for large-scale or technologically advanced farming systems.

Tillage

Tillage impacts CH₄ emissions mainly through its effect on soil aeration and microbial activity. Aerobic tillage practices increase oxygen supply to the soil thereby lowering the availability of substrates for methanogens (53). Methane emissions decreased by 15.6 % under no tillage systems and by 10–40 % under conventional or rotary tillage, depending on the type and land use practices (54, 55). The benefits of tillage in terms of CH₄ reduction are thus significantly increased when combined with water management practices.

Crop establishment methods

Methane emissions from direct seeded rice (DSR) and aerobic rice systems can be significantly mitigated because they enhance soil aeration and thus reduce the formation of anaerobic microsites. It has been demonstrated that the dry method could turn rice fields from a source of CH₄ ($85.1 \pm 18.5 \text{ kg CH}_4 \text{ ha}^{-1}$) to almost a neutral or even a CH₄ sink ($1.1 \pm 0.11 \text{ kg CH}_4 \text{ ha}^{-1}$). According to system of rice intensification (SRI) decreased methane release by 17–27 %, grain yield increased by 10.5 %. Dry DSR with drip irrigation not only cut CH₄ emissions by 79.3 % but also enhanced water productivity and lessened the labour requirement (56). Zero tillage and green manuring also play a part in the mitigation of CH₄ and the enhancement of soil productivity (57).

Nutrient management

Balanced fertilisation along with integrated nutrient management (INM) are two of the most effective ways to keep CH₄ emissions low and at the same time preserve or improve soil fertility and yield. The INM not only enhances nutrient utilisation efficiency but also manages soil carbon and redox conditions, lowers yield-scaled global warming potential and promotes the storage of soil carbon (58). Biological amendments such as blue-green algae (BGA) and azolla have been reported to reduce methane emissions by 38 % and improving soil redox conditions (59). Moreover, the combination of vermicompost and fertilisers further intensify the mitigation effect. Electron accepting amendments like gypsum, silicate fertilisers and iron slag decrease CH₄ emissions by 14–54 % through increasing soil

redox potential and supporting CH₄ oxidation (60). Additionally, straw management plays a crucial part: fresh straw leads to a rise in CH₄ emissions, whereas composting, burning or using straw together with mineral nitrogen helps in reduction by 50–77 %. Moreover, straw incorporation together with water, saving irrigation with drop in emissions by 58–63 % and the use of straw in combination with humic acid iron complexes contributes to a reduction in total greenhouse gas emissions by 33.9 % (61).

Bioturbation

Bioturbation involving rice-fish, rice-duck and rice-frog integrated systems has emerged as a promising strategy for CH₄ mitigation and yield improvement in rice ecosystems. The feeding and burrowing activities of these animals improve soil aeration, enhance oxygen diffusion and alter soil redox conditions, thereby suppressing methanogenesis (62). These integrated systems have been reported to reduce CH₄ emissions by up to 86.8 % while increasing yield by 49.2 % (63). Factors such as density of the animals, the nitrogen management, the properties of the soil and even the local climate play a role in determining the effectiveness of the mitigation potential of the rice-duck, rice-fish, rice-frog systems as opposed to that of the rice-crab and rice-crayfish systems (62, 64). Moreover, earthworms can also play a significant role in the mitigation of CH₄ by increasing the population of methanotrophic microbes. However, the efficiency of this process depends on the level of soil moisture (47, 65–67). The role of animal-mediated soil disturbance and co-culture systems in reducing CH₄ emissions in rice fields is illustrated in Fig. 4.

Biochar

Biochar (BC) application improves the soil aeration, increasing the redox potential, decreasing the number of methanogens and stimulating methanotrophic activity (68). Biochar based slow-release fertilisers can additionally help reduce emissions by 33.4 % through inhibition of methanogens and activation of methanotrophs (69). The performance of BC in reducing CH₄ depends on the feedstock and the way it is managed. Biochars derived from rice straw, bamboo and orange-peel reduced CH₄ emissions by 16–21 % (70, 71). Modified BC with silicate or slag fertilisers not only improved the mitigation but also lowered metal toxicity. A summary of the effects of different BC types on CH₄ emissions in rice ecosystems is presented in Table 3.

Low-methane rice varieties

Rice varieties differ significantly in CH₄ emissions, providing opportunities for mitigation through cultivar selection and breeding. Increasing biomass by 10 % can lead to a CH₄ emission decrease of

Table 3. Summary of biochar effects on methane emissions (adapted from (72))

Study types	Important findings	References
Under different nitrogen fertilisation		
Literature review	BC ($> 20 \text{ t ha}^{-1}$) with N ($140\text{--}240 \text{ kg N ha}^{-1}$) decreased CH ₄ by 82 %	(73)
Meta-analysis	BC + N $< 120 \text{ kg N ha}^{-1}$ reduced CH ₄ no effect at $> 120 \text{ kg N ha}^{-1}$	(74)
Field experiment	BC (2 t ha^{-1}) reduced CH ₄ by 34 % urea (90 kg N ha^{-1}) and 36 % (slow-release N 45 kg)	(75)
Under organic inputs		
Incubation experiment	BC + rice straw reduced CH ₄ by 23.5–50.8 %	(76)
Field experiment	Barley straw BC (10 t ha^{-1}) + raw straw (10 t ha^{-1}) reduced CH ₄ by 33 %	(77)
Pot experiment	Rice straw (15 t ha^{-1}) increased CH ₄ by 67.5 %; maize straw BC (45 t ha^{-1}) limited increase to 25 %	(78)
Under different water management		
Field experiment	Mangrove BC (10 t ha^{-1}) reduced CH ₄ under AWD	(79)
Field experiment	BC reduced CH ₄ by 16 % under controlled irrigation but increased it under continuous flooding	(80)

AWD: alternate wetting and drying; CH₄: methane; BC: biochar; N: nitrogen.

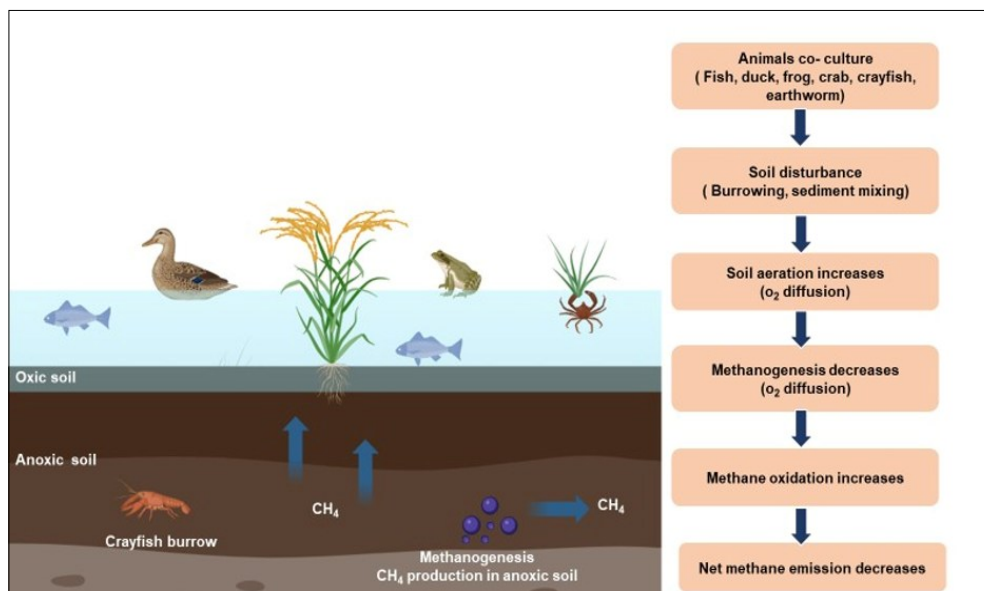


Fig. 4. Bioturbation-mediated methane mitigation in rice fields through animal co-culture systems.

about 10.3 %, which is attributed to a higher root oxidation capacity and more active methanotrophs in high-yielding cultivars (81). In low CH_4 rice cultivars, carbon flow is shifted more towards shoots and grains and less towards roots. This reduces the release of root exudates that serve as substrates for methanogenic archaea, which is consistent with the previous findings (9). Methane emissions were cut by up to 70 % when the SUSIBA2 line was used and cultivars like Heijing 5 and Milyang360 were also producing less CH_4 . Also, improved cultivars in association with better nitrogen management may lead to a further decrease of CH_4 emissions by 24–63 % (81).

Nanotechnology for methane mitigation

Nanotechnology has strong potential for reducing CH_4 emissions by regulating soil redox conditions, controlling nutrient release and altering microbial activity (82). Zinc oxide nanoparticles reduced CH_4 emissions by 26.8–29.0 % mainly through inhibition of methanogens, whereas copper oxide nanoparticles enhanced CH_4 oxidation by stimulating methanotrophs (83). Iron oxide nanoparticles decreased CH_4 emissions by 29.0–61.3 % by facilitating redox cycling and CH_4 oxidation, although their effectiveness varies with soil conditions (84). Similarly, nanobubble and micro-nanobubble technologies improved soil aeration and reduced CH_4 emissions by 75–78 %, showing mitigation efficiency comparable to alternate wetting and drying irrigation (85). In addition, osmium nanoparticle aerosol application achieved nearly 79 % reduction in methane emissions. Despite these promising benefits, the large-scale use of nanoparticles raises environmental

concerns including phytotoxicity, nanoparticle accumulation in soil and water, possible disruption of beneficial microbial communities and risks of entry into the food chain. Moreover, the long-term ecological impacts, persistence and safe application limits of nanoparticles under different agroecosystems remain insufficiently understood. Therefore, comprehensive risk assessment and long-term field studies are essential before the widespread adoption of nanotechnology-based CH_4 mitigation strategies in rice cultivation.

Precision agriculture for methane mitigation

Precision agriculture plays an important role in CH_4 mitigation in rice systems by enabling site-specific management through remote sensing, drones and artificial intelligence. Satellite platforms such as Sentinel-1 and Sentinel-2 monitor rice cultivation and flooding patterns while Sentinel-5P helps detect atmospheric CH_4 over large rice-growing regions (86). Machine learning approaches such as convolutional neural networks and random forest models integrate satellite and ground data to predict CH_4 emissions and support targeted mitigation strategies like AWD and biochar application (87–89). The major CH_4 mitigation strategies employed in rice ecosystems, including precision agriculture-based monitoring and management approaches, are summarised in Fig. 5.

Integrated approaches

Integrated management approaches combining water regulation, balanced nutrient management and soil amendments achieve greater methane reduction than single interventions (Table 4).

Table 4. Integrated agronomic strategies for methane mitigation in rice

System / treatment	Methane mitigation outcomes	Reference
Water and nitrogen management		
Water-saving irrigation + fertiliser types	CH_4 emission reduced by 71.25 % vs continuous flooding	(90)
AWD + urea deep placement	CH_4 reduced due to improved soil aeration	(91)
Modified AWD (MAWD) + optimised N fertilisation	Lower CH_4 via improved soil redox conditions	(92)
AWD + controlled-release N fertiliser	Significant CH_4 reduction without yield loss	(93)
Water and organic inputs		
AWD + organic fertiliser	CH_4 emissions reduced by 12–14 % with 32–38 % water saving	(94)
AWD + cow manure	AWD reduced CH_4 emissions by ~32 % vs continuous flooding	(95)
System-level integrated strategies		
Dry direct-seeded rice + reduced N + plastic mulch	CH_4 reduced by >90 % vs flooded rice	(96)
Direct sowing + NPK + sulphur + mechanised transplanting	Very low CH_4 flux (1.57–2.24 mg m ⁻² hr ⁻¹)	(97)
Phosphogypsum + BC + NPKSZn in saline soils	Reduced CH_4 intensity and improved soil conditions	(98)

K: potassium; S: sulphur; Zn: zinc.

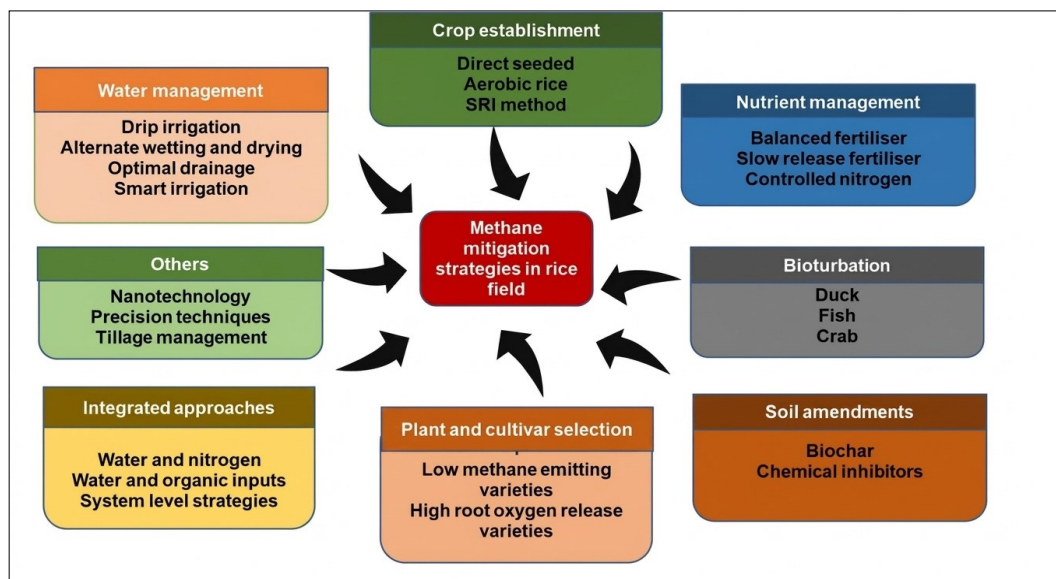


Fig. 5. Major methane mitigation strategies in rice fields.

SRI: system of rice intensification.

Monitoring and modelling

Monitoring and modelling are essential for accurately estimating CH_4 emissions from rice field. Field-based techniques such as static chambers and eddy covariance systems provide reliable measurements of CH_4 flux at plot and field scales helping to evaluate the effects of water, nutrient and residue management. Remote sensing using satellite and drone platforms enables large-scale monitoring of flooding conditions, crop growth and environmental factors influencing CH_4 emissions (99). Process-based biogeochemical models such as DNDC, DayCent and CH_4 MOD simulate CH_4 production, oxidation and transport by incorporating soil, water and plant dynamics. Monitoring-reporting-verification (MRV) frameworks integrate these tools to generate accurate emission estimates for greenhouse gas inventories and climate mitigation programs (100).

Research gaps and future perspectives

Research on CH_4 mitigation in rice production is still facing challenges due to a number of knowledge gaps related to CH_4 oxidation processes, microbial cross-talks and long-term field performance of different agroecosystems. For example, most experiments are short-term and location-specific, restricting their wider application in different soil, climate and management conditions. Better tools for monitoring, modelling and MRV need to be developed to efficiently estimate emissions. Besides that, studies conducted so far have largely focused on isolated aspects. However, future research should be based on an integrated approach combining water-saving irrigation, optimised nutrient management, low-emission cultivars, BC and microbial inoculants. Advanced molecular techniques, precision agriculture and satellite-based remote sensing can improve CH_4 monitoring and mitigation assessment. Artificial intelligence (AI) and machine learning models can further improve CH_4 mitigation by enabling real-time prediction of CH_4 emissions, automated irrigation scheduling, precision nutrient management and remote sensing-based monitoring of rice ecosystems. AI-assisted decision support systems can help farmers optimise resource use while minimising greenhouse gas emissions.

Conclusion

Rice cultivation is a major source of methane (CH_4) emissions because flooded anaerobic soils promote methanogenesis. However, CH_4 oxidation by methanotrophs significantly reduces net CH_4 emissions, particularly in the rhizosphere. Methane emissions are influenced by soil properties, microbial activity, plant traits and management practices. Climate-smart approaches such as AWD, optimised nutrient management, biochar (BC) application and low- CH_4 rice varieties effectively reduce CH_4 emissions while maintaining productivity. Compared with conventional flooded cultivation, these methods are eco-friendly, water-efficient and cost-effective, especially for small and marginal farmers. Emerging technologies including methanotroph-based bioinoculants, nanotechnology, precision agriculture and AI-assisted monitoring systems also show potential for CH_4 mitigation, although they may require higher investment and technical expertise. Future research should focus on integrated and location-specific mitigation strategies, long-term evaluation of climate-smart practices under diverse agro-climatic conditions and the development of affordable precision technologies and bioinoculants for wider adoption. Therefore, integrating agronomic, biological and technological interventions is essential for sustainable rice production systems that reduce CH_4 emissions while ensuring long-term productivity and food security.

Acknowledgements

The authors sincerely acknowledge Tamil Nadu Agricultural University (TNAU) for providing the facilities and institutional support necessary for the preparation of this manuscript

Authors' contributions

MK designed the overall review framework and drafted the manuscript. KS supervised the work, refined the focus of the review and provided critical revisions. SAF supported literature collection, contributed to concept development and participated in editing the manuscript. CT organised the structure, enhanced the technical quality and revised the content. DA offered subject expertise and carried out critical evaluation of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used grammarly in order to language improvement and grammar correction. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- Feng C, Chen S, Zeng ZC, Luo Y, Natraj V, Yung YL. Aerosol-calibrated matched filter method for retrievals of methane point source emissions over the Los Angeles Basin. *Earth Space Sci.* 2024;11(8):e2024EA003519. <https://doi.org/10.1029/2024EA003519>
- Tian H, Lu C, Ciais P, Michalak A, Canadell J, Saikawa E, et al. The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature.* 2016;531:225–8. <https://doi.org/10.1038/nature16946>
- Qian H, Zhu X, Huang S, Linqvist B, Kuzyakov Y, Wassmann R, et al. Greenhouse gas emissions and mitigation in rice agriculture. *Nat Rev Earth Environ.* 2023;4:716–32. <https://doi.org/10.1038/s43017-023-00482-1>
- Chen Z, Lin H, Balasus N, Hardy A, East JD, Zhang Y, et al. Global rice paddy inventory (GRPI): A high-resolution inventory of methane emissions from rice agriculture based on landsat satellite inundation data. *Earths Future.* 2025;13(4):e2024EF005479. <https://doi.org/10.1029/2024EF005479>
- Dhanuja C, Tabassum A, Abbasi T, Abbasi S. Assessment of methane emission and the factors that influence it from three rice varieties commonly cultivated in the state of Puducherry. *Atmosphere.* 2022;13:1811. <https://doi.org/10.3390/atmos13111811>
- Nwokolo NL, Enebe MC. Methane production and oxidation: A review on the *pmoA* and *mcrA* gene abundances for understanding the functional potentials of agricultural soils. *Pedosphere.* 2025;35(1):161–81. <https://doi.org/10.1016/j.pedsph.2024.05.006>
- Saunio M, Martinez A, Poulter B, Zhang Z, Raymond PA, Regnier P, et al. Global methane budget 2000–2020. *Earth Syst Sci Data.* 2025;17(5):1873–958. <https://doi.org/10.5194/essd-2024-115>
- Zhang B, Tian H, Ren W, Tao B, Lu C, Yang J, et al. Methane emissions from global rice fields: Magnitude, spatiotemporal patterns and environmental controls. *Global Biogeochem Cycles.* 2016;30(9):1246–63. <https://doi.org/10.1002/2016GB005381>
- Hu J, Bettembourg M, Moreno S, Zhang A, Schnürer A, Sun C, et al. Characterisation of a low methane emission rice cultivar suitable for cultivation in high latitude light and temperature conditions. *Environ Sci Pollut Res.* 2023;30(40):92950–62. <https://doi.org/10.1007/s11356-023-28985-w>
- Jang SH, Park SJ. Characteristics of methane emissions and practical mitigation strategies in rice paddy fields. *J Korean Soc Environ Eng.* 2025;47(6):387–409. <https://doi.org/10.4491/KSEE.2025.47.6.387>
- Hao Q, Wang O, Gong X, Liu F, Zhang Y, Xie Z, et al. Cadmium-induced responses and tolerance mechanisms of aerobic methanotrophs in rice paddy soils. *Environ Sci Technol.* 2025;59(22):11029–38. <https://doi.org/10.1021/acs.est.5c00031>
- Wang Y, Hu Z, Shen L, Liu C, Islam A, Wu Z, et al. The process of methanogenesis in paddy fields under different elevated CO₂ concentrations. *Sci Total Environ.* 2021;773:145629. <https://doi.org/10.1016/j.scitotenv.2021.145629>
- Zhu X, Ji Y, Huang Q, Shen W, Wei Z, Ma J, et al. Temporal variation of methanogenic pathways in rice fields under three different cropping systems. *Biol Fertil Soils.* 2024;60(6):743–56. <https://doi.org/10.1007/s00374-023-01769-7>
- Shen W, Ji Y, Huang Q, Zhu X, Ma J, Zhang G, et al. Differences in methanogenic pathways and communities in paddy soils under three typical cropping modes. *J Geophys Res Biogeosci.* 2023;128(11):e2023JG007443. <https://doi.org/10.1029/2023JG007443>
- Boie F, Shaheen SM, Kandeler E, Rinklebe J. Controlled redox potentials and flooding duration affect microbial community composition and biomass in an arable soil. *Soil Biol Biochem.* 2025;109962. <https://doi.org/10.1016/j.soilbio.2025.109962>
- Jin Y, Liu T, Hu J, Sun K, Xue L, Bettembourg M, et al. Reduced rice paddy methane emission through dual compound mechanism in novel cultivars. 2021. <https://doi.org/10.21203/rs.3.rs-1087173/v1>
- Hamamoto S, Kobayakawa T, Cui D, Ma X, Kajiura M, Tokida T, et al. Seasonal changes in methane emissions via different pathways from a rice paddy field. *Paddy Water Environ.* 2025;23(2):333–42. <https://doi.org/10.21203/rs.3.rs-4701849/v1>
- Qi Z, Guan S, Zhang Z, Du S, Li S, Xu D. Effect and mechanism of root characteristics of different rice varieties on methane emissions. *Agronomy.* 2024;14(3):595. <https://doi.org/10.3390/agronomy14030595>
- van den Berg M, van den Elzen E, Ingwersen J, Kosten S, Lamers LP, Streck T. Contribution of plant-induced pressurized flow to CH₄ emission from a *Phragmites* fen. *Sci Rep.* 2020;10(1):12304. <https://doi.org/10.1038/s41598-020-69034-7>
- Conrad R. Microbial ecology of methanogens and methanotrophs. *Adv Agron.* 2007;96:1–63. [https://doi.org/10.1016/S0065-2113\(07\)96005-8](https://doi.org/10.1016/S0065-2113(07)96005-8)
- Yu K, Patrick WH. Redox window with minimum global warming potential contribution from rice soils. *Soil Sci Soc Am J.* 2004;68(6):2086–91. <https://doi.org/10.2136/sssaj2004.2086>
- Knief C. Diversity and habitat preferences of cultivated and uncultivated aerobic methanotrophic bacteria evaluated based on *pmoA* as molecular marker. *Front Microbiol.* 2015;6:1346. <https://doi.org/10.3389/fmicb.2015.01346>
- Jiang H, Cheng W, Chen C, Fang C, Zhan Y, Tao L, et al. Mutation of rice SM1 enhances solid leaf midrib formation and increases methane emissions. *Plant Sci.* 2025;350:112312. <https://doi.org/10.1016/j.plantsci.2024.112312>
- Yu K, Böhme F, Rinklebe J, Neue HU, DeLaune RD. Major biogeochemical processes in soils-a microcosm incubation from reducing to oxidizing conditions. *Soil Sci Soc Am J.* 2007;71(4):1406–17. <https://doi.org/10.2136/sssaj2006.0155>
- Lee HJ, Jeong SE, Kim PJ, Madsen EL, Jeon CO. High resolution depth distribution of bacteria, archaea, methanotrophs and methanogens in the bulk and rhizosphere soils of a flooded rice paddy. *Front Microbiol.* 2015;6:639. <https://doi.org/10.3389/fmicb.2015.00639>
- Davamani V, Parameswari E, Arulmani S. Mitigation of methane gas emissions in flooded paddy soil through the utilization of methanotrophs. *Sci Total Environ.* 2020;726:138570. <https://doi.org/10.1016/j.scitotenv.2020.138570>
- Kavya T, Singh G, Govindasamy V, Sushmitha C, Sushmitha J. Characterization of methanol metabolism genes and plant growth-promoting traits in bacteria from the rice (*Oryza sativa*) rhizosphere. *Indian J Agric Sci.* 2025;95(10):1232–9. <https://doi.org/10.56093/ijas.v95i10.166827>
- Pham DN, Mai DHA, Nguyen AD, Chau THT, Lee EY. Development of an engineered methanotroph-based microbial platform for biocatalytic conversion of methane to phytohormone for sustainable agriculture. *Chem Eng J.* 2022;429:132522. <https://doi.org/10.1016/j.cej.2021.132522>

29. Leamdum C, Phruksaphithak N, Niyasom C, Birkeland N-K, Mamimin C, O-Thong S. Enriched anoxic methanotrophic consortium augmentation for mitigating methane emissions in rainfed systems and climate-neutral rice production. *J Environ Manage.* 2025;379:124831. <https://doi.org/10.1016/j.jenvman.2025.124831>
30. Malyan SK, Bhatia A, Tomer R, Harit RC, Jain N, Bhowmik A, et al. Mitigation of yield-scaled greenhouse gas emissions from irrigated rice through *Azolla*, blue-green algae and plant growth-promoting bacteria. *Environ Sci Pollut Res.* 2021;28(37):51425–39. <https://doi.org/10.1007/s11356-021-14210-z>
31. Parthasarathi T, Vanitha K, Mohandass S, Ravi V, Robin S, Vered E, et al. Mitigation of methane gas emission in rice by drip irrigation. *F1000Res.* 2019;8:2023. <https://doi.org/10.12688/f1000research.20945.1>
32. Islam SF, Bhat MA, Ghosh A, Roychoudhury A. Alternate wetting and drying irrigation: A climate-smart strategy for reducing methane emissions in rice. *Agric Water Manag.* 2023;286:108398. <https://doi.org/10.1016/j.agwat.2023.108398>
33. Kumar V, Ladha JK. Direct-seeded rice: Recent developments and future research needs. *Adv Agron.* 2011;111:297–413. <https://doi.org/10.1016/B978-0-12-387689-8.00001-1>
34. Linquist B, Groenigen KJ, Adviento-Borbe MA, Pittelkow C, Kessel C. An agronomic assessment of greenhouse gas emissions from major cereal crops. *Glob Change Biol.* 2012;18(1):194–209. <https://doi.org/10.1111/j.1365-2486.2011.02502.x>
35. Nayak D, Saetnan E, Cheng K, Wang W, Koslowski F, Cheng Y, et al. Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. *Agric Ecosyst Environ.* 2015;209:108–24. <https://doi.org/10.1016/j.agee.2015.04.035>
36. Gupta DK, Bhatia A, Kumar A, Das TK, Jain N, Tomer R, et al. Mitigation of greenhouse gas emissions from rice-wheat system through conservation agriculture and water management. *Agric Ecosyst Environ.* 2016;219:15–25. <https://doi.org/10.1016/j.agee.2015.12.001>
37. Chidthaisong A, Cha-un N, Rossopa B, Buddaboon C, Kunuthai C, Sriphirrom P, et al. Evaluating methane emission reduction in rice fields under alternative water management practices. *Soil Use Manag.* 2018;34(4):640–8. <https://doi.org/10.1111/sum.12441>
38. Wassmann R, Hosen Y, Sumfleth K. Reducing methane emissions from irrigated rice. *Nutr Cycl Agroecosyst.* 2009;58:85–99.
39. Pittelkow CM, Adviento-Borbe MA, Hill JE, Six J, Kessel C, Linquist BA. Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. *Agric Ecosyst Environ.* 2013;177:10–20. <https://doi.org/10.1016/j.agee.2013.05.011>
40. Zhao X, Liu SL, Pu C, Zhang XQ, Xue JF, Ren YX, et al. Methane and nitrous oxide emissions under no-tillage farming in China: A meta-analysis. *Glob Change Biol.* 2016;22(4):1372–84. <https://doi.org/10.1111/gcb.13185>
41. Xu Y, Ge J, Tian S, Li S, Nguy-Robertson AL, Zhan M, et al. Effects of water-saving irrigation practices on rice yield and greenhouse gas emissions. *Agric Water Manag.* 2015;162:1–9. <https://doi.org/10.1016/j.agwat.2015.08.007>
42. Jiang Y, Carrijo D, Huang S, Linquist B, Groenigen KJ. Water management impacts on methane emissions from rice fields: A global meta-analysis. *Field Crops Res.* 2019;236:1–11. <https://doi.org/10.1016/j.fcr.2019.03.004>
43. Zhang G, Yu H, Fan X, Yang Y, Ma J, Xu H. Drainage and tillage practices influence methane emissions in rice cultivation. *Soil Tillage Res.* 2017;166:84–92. <https://doi.org/10.1016/j.still.2016.10.005>
44. Li X, Yuan W, Xu X, Cai Z, Yagi K. Methane emissions from rice paddies under different fertilizer treatments. *Nutr Cycl Agroecosyst.* 2011;89:123–35. doi:10.1007/s10705-010-9388-7.
45. Linquist BA, Anders MM, Adviento-Borbe MA, Chaney RL, Nalley LL, Da Rosa EF, et al. Reducing greenhouse gas emissions, water use and grain arsenic levels in rice systems. *Glob Change Biol.* 2015;21(1):407–17. <https://doi.org/10.1111/gcb.12701>
46. Yao Z, Zheng X, Xie B, Mei B, Wang R, Butterbach-Bahl K, et al. Tillage and crop residue management significantly affect methane emissions from rice-wheat systems. *Atmos Environ.* 2013;67:347–55. <https://doi.org/10.1016/j.atmosenv.2012.11.032>
47. Sander BO, Samson M, Buresh RJ. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma.* 2014;235–236:355–62. <https://doi.org/10.1016/j.geoderma.2014.07.020>
48. Carrijo DR, Lundy ME, Linquist BA. Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Res.* 2017;203:173–80. <https://doi.org/10.1016/j.fcr.2016.12.002>
49. Islam SF, Ghosh A, Bhat MA, Ray K. Water-saving irrigation practices for climate-resilient rice production. *Agric Water Manag.* 2024;292:108655. <https://doi.org/10.1016/j.agwat.2023.108655>
50. Sharma PK, Ladha JK, Bhushan L. Soil and water management effects on methane emissions from rice-wheat systems. *Soil Sci Soc Am J.* 2003;67(4):1182–91. doi:10.2136/sssaj2003.1182.
51. Rajkhowa DJ, Gogoi AK, Kandpal BK. IoT-based smart irrigation systems for sustainable rice cultivation. *Smart Agric Technol.* 2024;7:100456.
52. Kumar S, Jain MC, Kumar S, Pathak H, Majumdar D, Gupta DK. Methane emission from irrigated rice as influenced by crop management practices. *Agric Ecosyst Environ.* 2004;104(3):479–88.
53. Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science.* 2004;304(5677):1623–7. <https://doi.org/10.1126/science.1097396>
54. Six J, Conant RT, Paul EA, Paustian K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil.* 2002;241:155–76. <https://doi.org/10.1023/A:1016125726789>
55. Wihardjaka A, Harsanti ES, Setyanto P. Conservation tillage for methane mitigation in rice systems. *IOP Conf Ser Earth Environ Sci.* 2023;1180:012045. <https://doi.org/10.1088/1755-1315/1180/1/012008>
56. Minamikawa K, Sakai N. The practical use of water management based on soil redox potential for decreasing methane emission from a paddy field in Japan. *Agric Ecosyst Environ.* 2006;116(3–4):181–8. <https://doi.org/10.1016/j.agee.2006.02.006>
57. Bodelier PLE. Interactions between nitrogenous fertilizers and methane cycling in wetland and upland soils. *Curr Opin Environ Sustain.* 2011;3(5):379–88. <https://doi.org/10.1016/j.cosust.2011.06.002>
58. Singh Y, Singh B, Timsina J. Crop residue management for nutrient cycling and improving soil productivity in rice-based systems in the tropics. *Adv Agron.* 2005;85:269–407. [https://doi.org/10.1016/S0065-2113\(04\)85006-5](https://doi.org/10.1016/S0065-2113(04)85006-5)
59. Bhatia A, Pathak H, Jain N, Singh PK, Singh AK. Global warming potential of manure amended soils under rice-wheat systems in India. *Agric Ecosyst Environ.* 2005;109(1–2):97–107.
60. Ali MA, Oh JH, Kim PJ. Evaluation of silicate iron slag amendment on reducing methane emissions from floodwater rice cultivation. *Agric Ecosyst Environ.* 2008;128(1–2):21–6. <https://doi.org/10.1016/j.agee.2008.04.014>
61. Yagi K, Minami K. Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Sci Plant Nutr.* 1990;36(4):599–610. <https://doi.org/10.1080/00380768.1990.10416797>
62. Li K, Qin C, Pang Z, Liu Z, Zhou J, He J, et al. Promotion of nitrogen accumulation through enhanced soil-water interface activity in rice-aquatic animal co-culture systems: A review. *Nitrogen Cycling.* 2025;2(1). <https://doi.org/10.48130/nc-0025-0019>
63. Wang C, Shi X, Qi Z, Xiao Y, Zhao J, Peng S, et al. How does rice-animal co-culture system affect rice yield and greenhouse gas emissions? A meta-analysis. *Plant Soil.* 2023;493(1):325–40. <https://doi.org/10.1007/s11104-023-06233-x>

64. Tian X, Wei Y, Shan H, Dong S, Wang F, Yao Z. Bioturbation by Chinese mitten crabs mitigates the global warming potential of integrated rice-crab farming systems in saline-alkaline soils. *J Hazard Mater Adv*. 2025;100909. <https://doi.org/10.1016/j.hazadv.2025.100909>
65. Huang H, Wang Z, Ma Y, Zhu P, Zhang X, Chen H, et al. The impact of rice-frog co-cultivation on greenhouse gas emissions of reclaimed paddy fields. *Biology*. 2025;14(7). <https://doi.org/10.3390/biology14070861>
66. Kaikai F, Huiyan C, Wei D, Jun W, Linkui C, Zhimin S. Microbe-mediated reduction of methane emission in rice-frog crop ecosystem. *Appl Soil Ecol*. 2022;174:104415. <https://doi.org/10.1016/j.apsoil.2022.104415>
67. Zhao L, Dai R, Zhang T, Guo L, Luo Q, Chen J, et al. Fish mediate surface soil methane oxidation in the agriculture heritage rice-fish system. *Ecosystems*. 2023;26(8):1656–69. <https://doi.org/10.1007/s10021-023-00856-y>
68. Qi L, Ma Z, Chang SX, Zhou P, Huang R, Wang Y, et al. Biochar decreases methanogenic archaea abundance and methane emissions in a flooded paddy soil. *Sci Total Environ*. 2021;752:141958. <https://doi.org/10.1016/j.scitotenv.2020.141958>
69. Dong D, Li J, Ying S, Wu J, Han X, Teng Y, et al. Mitigation of methane emission in a rice paddy field amended with biochar-based slow-release fertilizer. *Sci Total Environ*. 2021;792:148460. <https://doi.org/10.1016/j.scitotenv.2021.148460>
70. Fu L, Lu Y, Tang L, Hu Y, Xie Q, Zhong L, et al. Dynamics of methane emission and archaeal microbial community in paddy soil amended with different types of biochar. *Appl Soil Ecol*. 2021;162:103892. <https://doi.org/10.1016/j.apsoil.2021.103892>
71. Keteku AK, Amegbor IK, Frimpong F, Dormatey R, Blege P, Yeboah S, et al. Sustainable agricultural practices: Enhancing rice yield and reducing methane emissions in degraded soils via soil amendments and silicon application. *Int J Agron*. 2024;2024:5928777. <https://doi.org/10.1155/2024/5928777>
72. Baek N, Lee S-I, Pia HI, Park S-W, Shin E-S, Lee J, et al. Biochar effects on methane emission from rice paddy differ with nitrogen fertilization, organic inputs and water management. *Korean J Soil Sci Fert*. 2025;58(1):133–43. <https://doi.org/10.7745/KJSSF.2025.58.1.133>
73. Iboko MP, Dossou-Yovo ER, Obalum SE, Oraegbunam CJ, Diedhiou S, Brümmer C, et al. Paddy rice yield and greenhouse gas emissions: Any trade-off due to co-application of biochar and nitrogen fertilizer? *Heliyon*. 2023;9(11). <https://doi.org/10.1016/j.heliyon.2023.e22132>
74. Jeffery S, Verheijen FG, Kammann C, Abalos D. Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biol Biochem*. 2016;101:251–8. <https://doi.org/10.1016/j.soilbio.2016.07.021>
75. Kim J, Yoo G, Kim D, Ding W, Kang H. Combined application of biochar and slow-release fertilizer reduces methane emission but enhances rice yield by different mechanisms. *Appl Soil Ecol*. 2017;117:57–62. <https://doi.org/10.1016/j.apsoil.2017.05.006>
76. Cai F, Feng Z, Zhu L. Effects of biochar on CH₄ emission with straw application on paddy soil. *J Soils Sediments*. 2018;18(2):599–609. <https://doi.org/10.1007/s11368-017-1761-x>
77. Kang S-W, Yun J-J, Park J-H, Cheong YH, Park J-H, Seo D-C, et al. Effects of biochar and barley straw application on rice productivity and greenhouse gas emissions of paddy field. *Appl Biol Chem*. 2021;64(1):92. <https://doi.org/10.1186/s13765-021-00666-7>
78. Wang Y-Q, Bai R, Di HJ, Mo L-Y, Han B, Zhang L-M, et al. Differentiated mechanisms of biochar mitigating straw-induced greenhouse gas emissions in two contrasting paddy soils. *Front Microbiol*. 2018;9:2566. <https://doi.org/10.3389/fmicb.2018.02566>
79. Sriphrom P, Chidthaisong A, Yagi K, Tripetchkul S, Towprayoon S. Evaluation of biochar applications combined with alternate wetting and drying water management in rice field as a methane mitigation option for farmers' adoption. *Soil Sci Plant Nutr*. 2020;66(1):235–46. <https://doi.org/10.1080/00380768.2019.1706431>
80. Zhang X, Xia J, Pu J, Cai C, Tyson GW, Yuan Z, et al. Biochar-mediated anaerobic oxidation of methane. *Environ Sci Technol*. 2019;53(12):6660–8. <https://doi.org/10.1021/acs.est.9b01345>
81. Kwon Y, Lee JY, Choi J, Lee S-M, Kim D, Cha J-K, et al. Loss-of-function gs3 allele decreases methane emissions and increases grain yield in rice. *Nat Clim Change*. 2023;13(12):1329–33. <https://doi.org/10.1038/s41558-023-01872-5>
82. Chatterjee I, Chakraborty S, Ray M, Ghosh R, Chanda MR, Goswami A, et al. Novel avenues of mitigation of rice paddy methane: A review. *J Crop Sci Biotechnol*. 2025;28(3):321–34. <https://doi.org/10.1007/s12892-025-00290-7>
83. He M, Tang R, Guan F, Peng W, Lu J, Li K, et al. Methanogenic response of paddy soils exposed to zinc oxide nanoparticles and sulfurized products. *J Hazard Mater*. 2025;489:137608. <https://doi.org/10.1016/j.jhazmat.2025.137608>
84. Han Y, Qi Z, Chen P, Zhang Z, Zhou X, Li T, et al. Water-saving irrigation mitigates methane emissions from paddy fields: The role of iron. *Agric Water Manag*. 2024;298:108839. <https://doi.org/10.1016/j.agwat.2024.108839>
85. Sasamoto R, Mirza AH, Matsumura K, Doi T, Kai T, Tamaki M, et al. Micro-nano bubbles application in rice paddy soil for mitigating methane emissions. 2024. <https://doi.org/10.20944/preprints202412.1713.v1>
86. Pazhanivelan S, Sudarmanian N, Geethalakshmi V, Deiveegan M, Ragunath K, Sivamurugan A, et al. Assessing methane emissions from rice fields in large irrigation projects using satellite-derived land surface temperature and agronomic flooding: A spatial analysis. *Agriculture*. 2024;14(3):496. <https://doi.org/10.3390/agriculture14030496>
87. Xuan TD, Minh TTN, Rayee R, Dong ND, Chien NX. Advances in mitigating methane emissions from rice cultivation: Past, present and future strategies. *Environ Sci Pollut Res*. 2025;32(34):20232–47. <https://doi.org/10.1007/s11356-025-36776-8>
88. Louime CJ, Raza TA. Development of artificial intelligence/machine learning models for methane emissions forecasting in seaweed. *Methane*. 2024;3(3):485–99. <https://doi.org/10.3390/methane3030028>
89. Augustin J, Gopinath M, Karali B, Rao Y. Joint prediction of US rice yields and methane emissions: A machine learning approach. *IEEE Access*. 2025. <https://doi.org/10.1109/ACCESS.2025.3562397>
90. Li S, Chen Y, Yu F, Zhang Y, Liu K, Zhuo X, et al. Reducing methane emission by promoting its oxidation in rhizosphere through nitrogen-induced root growth in paddy fields. *Plant Soil*. 2022;474(1):541–60. <https://doi.org/10.1007/s11104-022-05360-1>
91. Islam S, Gaihre Y, Islam M, Ahmed MN, Akter M, Singh U, et al. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. *J Environ Manage*. 2022;307:114520. <https://doi.org/10.1016/j.jenvman.2022.114520>
92. Liang K, Zhong X, Fu Y, Hu X, Li M, Pan J, et al. Mitigation of environmental N pollution and greenhouse gas emission from double rice cropping system with a new alternate wetting and drying irrigation regime coupled with optimized N fertilization in South China. *Agric Water Manag*. 2023;282:108282. <https://doi.org/10.1016/j.agwat.2023.108282>
93. Li J, Li Y, Wan Y, Wang B, Cai W, Qin X, et al. Annual greenhouse gas emissions from a rice paddy with different water-nitrogen management strategies in Central China. *Soil Tillage Res*. 2024;235:105906. <https://doi.org/10.1016/j.still.2023.105906>
94. Viandari NA, Adriany T, Pramono A. Alternate wetting and drying system combined with farmyard manure to increase rice yield and reduce methane emission and water use. *IOP Conf Ser Mater Sci Eng*. 2020. <https://doi.org/10.1088/1757-899X/980/1/012066>
95. Rassaei F. Optimizing methane emissions: Coordinated manure and irrigation practices and their effects on soil carbon dynamics and methanotroph activity. *Environ Prog Sustain Energy*. 2025;44. <https://doi.org/10.1002/ep.70042>

96. Zhang X, Bi J, Wang W, Sun D, Sun H, Bi Q, et al. Ecological and economic benefits of greenhouse gas emission reduction strategies in rice production: A case study of the southern rice propagation base in Hainan Province. *Agronomy*. 2024;14(1):222. <https://doi.org/10.3390/agronomy14010222>
97. Bharadwaj V, Mishra A, Singh S, Pachauri S, Singh P. Selection of suitable planting method and nutrient management techniques for reducing methane flux from rice fields. In: *Challenges and opportunities in agrometeorology*. Dordrecht: Springer; 2011. p. 539–49. https://doi.org/10.1007/978-3-642-19360-6_42
98. Khatun L, Ali MA, Sumon MH, Islam MB, Khatun F. Mitigation rice yield scaled methane emission and soil salinity stress with feasible soil amendments. *J Agric Chem Environ*. 2021;10(1):16–36. <https://doi.org/10.4236/jacen.2021.101002>
99. Velez AF, Alvarez CI, Navarro F, Guzman D, Bohorquez MP, Selvaraj MG, et al. Assessing methane emissions from paddy fields through environmental and UAV remote sensing variables. *Environ Monit Assess*. 2024;196(6):574. <https://doi.org/10.1007/s10661-024-12725-9>
100. Ouyang J, Miao Q, Wei D, Zhang X, Luo E, Zhao Z, et al. Biological treatment of cadmium-containing wastewater with sulfate as the electron acceptor and its microbial community. *Water Cycle*. 2023;4:87. <https://doi.org/10.1016/j.watcyc.2023.03.001>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.