Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 01 (JAN-FEB, 2026)
Available online at http://www.agriarticles.com

The Science Underlying Paddy Fields and Methane Emissions

*Vundela Harshavardhan Reddy[1] and Pamirelli Ranjith[2]
[1]M.Sc. Scholar, Department of Plant Breeding and Genetics, College of Agriculture, OUAT, Bhubaneswar, Odisha, India-751003
[2]Assistant Professor, Department of Plant Breeding and Genetics, College of Horticulture, OUAT, Chiplima, Sambalpur, Odisha, India- 768001
*Corresponding Author's email: harshavardhanvundela8@gmail.com

The growing atmospheric concentration of methane (CH_4), a powerful greenhouse gas with a potential for global warming that is almost 28 times larger than that of carbon dioxide (CO_2), is a serious threat to the stability of the climate. Rice farming in particular is one of the main human-caused sources of methane emissions. Anaerobic conditions produced by flooded paddy soils encourage the growth of methanogenic archaea, which break down organic substrates to release CH_4. Diffusion, ebullition, and transport via the aerenchyma of rice plants allow the released methane to escape into the atmosphere. The mechanisms of methane production and emission in paddy ecosystems are explained in this article, with special attention to the interactions between plant physiology, soil conditions, and microbial activity. According to global methane budgets, rice fields account for around 10% of all CH_4 emissions, with Asia being the largest emitter. Alternate wetting and drying (AWD) irrigation, better fertilizer management, residue integration, and the creation of low-emission cultivars are just a few of the agronomic and technological treatments that have demonstrated significant promise in reducing emissions. According to recent research, aromatic rice cultivars play a significant effect in reducing methane production because the chemical 2-acetyl-1-pyrroline (2-AP) increases methanotrophic activity. Achieving emission control without sacrificing productivity also depends on improving rhizosphere microbial interactions, controlling organic matter inputs, and optimizing nitrogen cycling. A sustainable approach to striking a balance between environmental preservation and food security is provided by the combination of molecular breeding and climate-smart agriculture techniques. Therefore, it is crucial for both sustainable agricultural development and global greenhouse gas mitigation to comprehend the biochemical and ecological foundations of methane dynamics in rice fields.

Key words: Methane emissions, Paddy fields, Climate change mitigation, Rice cultivation, Greenhouse gases, Methanogenic archaea, water management, sustainable agriculture.

Introduction

Among the most powerful greenhouse gases, methane (CH_4) has a significantly higher potential for global warming than carbon dioxide. Enteric fermentation, manure management, and rice agriculture are the main anthropogenic sources of methane, accounting for roughly 145 Tg CH_4 annually. Anaerobic soil conditions produced by flooded rice fields encourage the growth of methanogenic archaea, which break down organic matter to release methane. Around 10% of worldwide CH_4 emissions are attributable to rice agriculture alone, with tropical Asia especially China and India being mostly to blame. High soil temperatures, organic additions, and ongoing flooding are some of the elements that increase methane generation. Sustainable management techniques, such as better rice varieties, optimal fertilizer use, and alternate wetting and drying (AWD), however, have encouraging mitigation possibilities. New research also emphasizes how aromatic chemicals, such as 2-acetyl-1-pyrroline (2-AP), in fragrant rice improve methane oxidation and lower emissions, so bringing agricultural innovation into line with climate mitigation objectives.

Routes of Methane Emissions in Agriculture

Approximately 10–12% of greenhouse gas emissions worldwide are caused by agricultural operations; when land-use changes like deforestation are taken into account, this number increases to over 30%. The primary agricultural sources of methane are crop residue burning, rice farming, enteric fermentation, and manure management (FAOSTAT, 2017). Methanogenic archaea break down organic materials, including plant waste and root exudates, in flooded paddy fields in anaerobic environments, yielding methane as a byproduct. The rest of this methane escapes into the atmosphere through diffusion, ebullition, or plant aerenchyma channels, while some is oxidized by methanotrophs in oxygen-rich soil layers (Cheng *et al*., 2022).

Rice Field Methane Emissions and Their Influential Factors

A number of management and environmental factors influence methane emissions from paddy soils:

Anaerobic conditions are improved by continuous flooding, but CH_4 emissions are considerably decreased by alternate wetting and drying (AWD) (Islam *et al*., 2022).

- Temperature and Soil: Microbial activity and methane production are stimulated by warmer, organic-rich soils (Li *et al*., 2022).
- Use of Fertilizer: While slow-release or nitrification-inhibiting fertilizers assist reduce CH_4 production, organic supplements like manure might enhance it (Banger *et al*., 2012).
- Rice Varieties: Because of particular physiological and biochemical characteristics, several cultivars particularly aromatic ones have demonstrated reduced CH/$_4$ emissions (Chen *et al*., 2021).

Aromatic Rice and the Function of 2-Acetyl-1-Pyrroline (2-AP)

Lately, fragrant rice cultivars have drawn interest due to their reduced methane emissions as well as their perfume. Research indicates that as compared to non-fragrant types, the aromatic chemical 2-acetyl-1-pyrroline (2-AP) helps to reduce cumulative methane emissions by about 14.8% (Ding *et al*., 2022). The BADH2 gene is implicated in this reduction and affects nitrogen metabolism as well as fragrance production. Higher levels of 2-AP encourage methanotrophic activity in the rhizosphere, which raises the oxidation of CH_4 (Jiang *et al* 2017.). For sustainable breeding projects, fragrant rice is a desirable target because of its dual-purpose features, which improve quality and reduce emissions.

Techniques for Methane Reduction Mitigation

Methane emissions from rice production can be significantly reduced by a number of agronomic improvements and management techniques:

- Comparing alternate wetting and drying (AWD) to continuous flooding, methane is reduced by 30–70% (Cheng *et al*., 2022).
- To maximize efficiency and reduce microbial methanogenesis, fertilization should balance both organic and inorganic nitrogen sources (Liu *et al*., 2024).
- Incorporating Straw and Composting: According to Zhang et al. (2017), incorporating post-harvest or composting leftovers rather than burning them reduces the production of CH_4 and N_2O.
- Compared to traditional tillage, no-tillage systems minimize emissions and encourage soil carbon absorption (Gangopadhyay *et al*., 2023).
- Breeding Low-Emission Rice Varieties: To reduce CH_4 flux, focus on characteristics linked to root structure, aerenchyma production, and enzyme activity (Zhang *et al*., 2019).

Consequences for Mitigating Climate Change

In order to achieve climate stabilization objectives, the Intergovernmental Panel on Climate Change (IPCC) recommends a minimum 30% decrease in worldwide methane emissions by 2030.Increasing 2-AP synthesis in rice cultivars, implementing sustainable rice management, and boosting soil microbial activity could all help achieve these global goals (Qian et al., 2023). These integrated strategies open the door to climate-resilient food systems by balancing environmental preservation with agricultural development.

Conclusion

Sustainable agriculture faces both opportunities and challenges as a result of methane emissions from rice growing. With enhanced management, new breeding techniques, and knowledge of microbial ecology, it is possible to significantly lower CH_4 emissions without sacrificing yields. Aromatic rice types and techniques like AWD irrigation show how agricultural innovations can improve environmental sustainability and productivity at the same time.

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