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Greenhouse gas emission and cadmium contamination in rice paddies: research progresses in trade-off relationships, influencing factors and synergistic mitigation measures

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Rice paddies, critical for global food security, confront dual challenges of greenhouse gas (GHG, e.g., CH₄, N₂O) emissions and cadmium (Cd) contamination. This review systematically summarizes their trade-off relationships, influencing factors, and synergistic mitigation measures. The trade-off is primarily driven by soil redox potential (Eh) fluctuations under alternating flooding-drying. Flooding reduces Cd bioavailability but boosts CH₄ emissions, while drainage lowers CH₄ but increases Cd mobility. The trade-off relationship was further regulated by soil microbial interactions and rice root physiology. Key influencing factors include soil physicochemical properties such as Eh, pH, organic matter, and agronomic practices including water management, agricultural inputs and crop varieties. Synergistic mitigation strategies involve optimized water management for balancing Eh to reduce both risks, modified biochar/combined amendments for immobilizing Cd and inhibiting CH₄, targeted breeding, and optimized fertilization. This review provides a multi-scale framework linking mechanisms to practical management, emphasizing the need for integrated strategies to achieve sustainable paddy production.

KEYWORDS

cadmium contamination, greenhouse gas emission, rice paddy fields, synergistic mitigation, trade-off mechanisms

1 Introduction

Rice paddy fields, as globally significant units for food production, play a crucial role in ensuring food security. However, rice production from paddy fields also face the challenges of greenhouse gas (GHG, such as CH₄ and N₂O) emissions and heavy metals (e.g., cadmium, Cd) contamination simultaneously (Linquist and Perry, 2023; Wang et al., 2025). The potent greenhouse effects of CH₄ and N₂O emitted from rice paddies exacerbate global climate change (Hussain et al., 2023). As a major source of anthropogenic GHG, CH₄ emitted from the rice paddies accounts for approximately 9% of global CH₄ emissions (Wang J. et al., 2023). According to the Fourth Biennial Update Report on Climate Change of the People's Republic of China, the agricultural sources of CH₄ emissions were 23.72

million tons. Rice cultivation contributed 37.3% to this amount, making it the second-largest agricultural source of CH₄, after enteric fermentation from livestock. Notably, N₂O emissions from rice paddies, though lower in total flux than CH₄, have a high global warming potential (GWP) (298 times that of CO₂ for a 100 year time scale) and are predominantly released during drainage periods, constituting a non-negligible part of the paddy GHG budget (Zou et al., 2007). Rice (*Oryza sativa* L.), as an important staple food crop, provides food for more than half of the global population (FAO, 2023). Rice production in Asia accounts for 90.6% of the global rice output, playing a crucial role in ensuring food security (Bandumula, 2018). Approximately 75% of rice worldwide is cultivated in continuously flooded paddy fields (International Rice Research Institute, 2017). Flooded rice cultivation can provide optimal temperatures for rice growth and restrict weed growth (Kraehmer et al., 2017). However, continuously flooded rice cultivation has also brought about issues such as water resource consumption and GHG such as CH₄ emissions. Rice consumes approximately 40% of global irrigation water, accounting for nearly 80% of irrigated freshwater resources in Asia (Mir et al., 2025). In addition, the GWP of rice is 2.5–5.5 times that of other major food crops (Linguist et al., 2012). Among the GHG emissions from rice cultivation, CH₄ from paddy fields is particularly prominent. CH₄ not only contributes significantly to the overall GWP of rice production, but also has become a key focus in global agricultural carbon reduction efforts due to its high warming potential.

Furthermore, Cd accumulates in rice grains via the soil-rice system and enters the food chain, thereby posing a threat to human health (Jallad, 2015). In southern China, the proportion of paddy field soils with Cd content exceeding the standard is relatively high (Wang et al., 2019). According to the National Soil Pollution Survey Bulletin released in 2014, the over-standard rate of Cd pollution in cultivated land sites in China reached 7.0%, ranking first among the over-standard rates of inorganic pollutant sites. Over the past few decades, industrialization and urbanization have accelerated the input of Cd into soil through pathways such as atmospheric deposition, polluted water irrigation, and phosphate fertilizers application (Ke et al., 2015; Nie et al., 2019; Afzal et al., 2024). Cd occurs naturally in phosphate rock. It is estimated that the overall average Cd concentration for sedimentary phosphate rock deposits was 21 mg/kg, while approximately 85% of the world phosphorous fertilizers production is from sedimentary phosphate rock deposits (Roberts, 2014). Due to the high mobility in soil, the bioavailability and bioaccumulation of Cd are much higher than those of other trace elements under the same exposure level (Jiang et al., 2023), and rice usually accumulates more Cd than wheat, barley, and corn (Feng et al., 2021). The effects of Cd on crop plants mainly include hindering the transport of nutrients and water, causing oxidative damage, affecting photosynthesis, and ultimately leading to rice yields reduction (Khaliq et al., 2024; Shaghaleh et al., 2024). Cd can also inhibit nitrification in the rice rhizosphere, simultaneously lowering the IAA content in the rice roots, suppressing root development and microbial colonization, exacerbating nitrogen deficiency indirectly and inhibiting rice growth synergistically (Afzal et al., 2022). A large proportion of China's population takes rice as the staple food, and rice consumption accounts for 56% of

the Cd intake of the Chinese population and up to 65% for the population in southern China (Song et al., 2017). In Bangladesh and Sri Lanka, Cd intakes from rice were also found to be high (Meharg et al., 2013), approaching or even exceeding the tolerable daily intake (TDI, 0.83 µg/kg body weight) recommended by the Joint FAO/WHO (Chen H. et al., 2018). Cd can pose a threat to human health through the food chain. As a Group 1 carcinogen identified by the International Agency for Research on Cancer, Cd exposure mainly causes kidney damage and may have adverse effects on the lungs, cardiovascular system, and musculoskeletal system (Hu et al., 2016).

GHG emissions and Cd contamination in rice paddies are closely interrelated, and they exhibit a prominent trade-off effect in terms of environmental (greenhouse effect) and agronomic (heavy metal contamination) impacts. This trade-off relationship is primarily regulated by soil physicochemical properties and biological traits, including redox potential (Eh), soil pH, organic matter content, microbial activity, and rice plant physiological traits. The trade-off between GHG emissions and Cd contamination can be regulated by key agronomic measures including water management strategies, the application of agricultural inputs and the selection of crop varieties. For instance, continuous flooding maintains soil in a long-term anaerobic state, lowering Eh and altering microbial community composition, thereby reducing Cd bioavailability but increasing CH₄ emissions (CH₄ accounts for 94% of GHG emissions from rice fields, Qian et al., 2023). In contrast, non-continuous flooding improves soil aeration, elevating Eh and promoting the growth of methanotrophs, but simultaneously accelerates the oxidation of Cd-bound sulfides and increased Cd accumulation in rice grains (Linguist and Perry, 2023). The application of lime increases soil pH, which not only promotes Cd immobilization but also enhances methanotroph activity. The selection of low-Cd-accumulating rice varieties modifies root physiological traits (e.g., reducing radial oxygen loss or altering iron plaque formation), thereby regulating rhizosphere Eh and Cd uptake. Thus, agronomic practices act as upstream drivers, shaping soil physicochemical properties and biological traits, which in turn determine the intensity and direction of the trade-off between GHG emissions and Cd contamination in rice paddies.

Therefore, revealing the trade-off relationships and mechanisms between GHG emissions and Cd contamination in rice paddy fields, identifying key influencing factors, and exploring strategies to balance the mitigation of both issues are of great significance for sustainable paddy production and environmental safety. This review distinguishes itself through several innovative perspectives. Firstly, the trade-off relationship between GHG emissions and Cd contamination in rice paddies was systematically integrated, moving beyond isolated analyses of either issue to clarify their spatiotemporal coupling mechanisms driven by redox conditions, soil microbial interactions, and rice root physiology. Secondly, the synergistic potential of mitigation measures is emphasized, with a highlight on how optimized water management, modified biochar application, and targeted breeding can simultaneously address both challenges—an aspect often overlooked in single-issue studies. Furthermore, by quantifying the trade-offs under different agricultural practices

(e.g., alternating wetting and drying vs. continuous flooding) and clarifying the role of key factors like soil pH and microbial functional genes, a multi-scale theoretical framework that bridges mechanistic understanding and practical agricultural management was provided in this review, offering novel insights for green and sustainable paddy production. Specifically, this review focuses on three core areas: (i) Unraveling the trade-off mechanisms mediated by soil Eh, soil microbial interactions (e.g., methanogens-methanotrophs dynamics, Cd-tolerant microbial communities), and rice root physiology (radial oxygen loss, iron plaque formation); (ii) Identifying key influencing factors, which fall into two categories: soil physicochemical properties including soil Eh, pH, and organic matter content, and agronomic practices including water management strategies, agricultural inputs and crop varieties; (iii) Proposing synergistic mitigation measures, such as staged flooding combined with lime amendment, iron-modified biochar application, and targeted breeding of low-GHG/low-Cd rice varieties, to achieve simultaneous control of GHG emissions and Cd contamination.

2 Overview of GHG emissions, Cd contamination, and the trade-off relationships

2.1 GHG emissions from rice paddy fields

CH₄ emissions from rice paddy fields resulted from the net effects of three processes including CH₄ production, oxidation, and transportation. The factor that influences these three processes can affect CH₄ emissions. In rice paddy fields under long-term flooding, the aerobic decomposition of organic matter is inhibited in the extreme anaerobic environment. Additionally, the limited supply of electron acceptors such as NO₃⁻, SO₄²⁻, and Fe³⁺ in the soil suppresses the anaerobic respiration of microorganisms. Labile organic matter in soil from sources like plant and animal residues, root exudates, and organic fertilizers undergoes decomposition. Methanogens subsequently produce CH₄ using these decomposition products such as CO₂, acetate, and methyl compounds as substrates (Qi et al., 2025). About 80–90% of the CH₄ produced in paddy field soils is oxidized by methanotrophs before its emission (Huang et al., 1998). Most methanotrophs oxidize CH₄ under aerobic conditions, while a small portion of CH₄ is oxidized under anaerobic conditions. For many years, sulfate was considered the sole terminal electron acceptor in the anaerobic oxidation of methane (AOM) process, where anaerobic methanotrophic archaea (ANME) and sulfate-reducing bacteria (SRB) serve as the key microorganisms (Knittel and Boetius, 2009). Yet advancements in research have shown that nitrate, nitrite, ferric iron, humic acid, etc., can also act as electron acceptors in the AOM process (Ettwig et al., 2009; Knittel and Boetius, 2009; Scheller et al., 2016; Luo et al., 2021). The unoxidized CH₄ is emitted into the atmosphere through gas diffusion, bubble formation, and plant aerenchyma, with 60–90% of CH₄ being emitted through the aerenchyma of rice plants (Tokida et al., 2013; Zhang et al., 2016).

In addition to CH₄, N₂O emissions from paddy fields caused by anthropogenic nitrogen input cannot be ignored. According to statistics, the direct N₂O emissions during the rice growing season in mainland China were 29.0 Gg, accounting for 7–11% of the

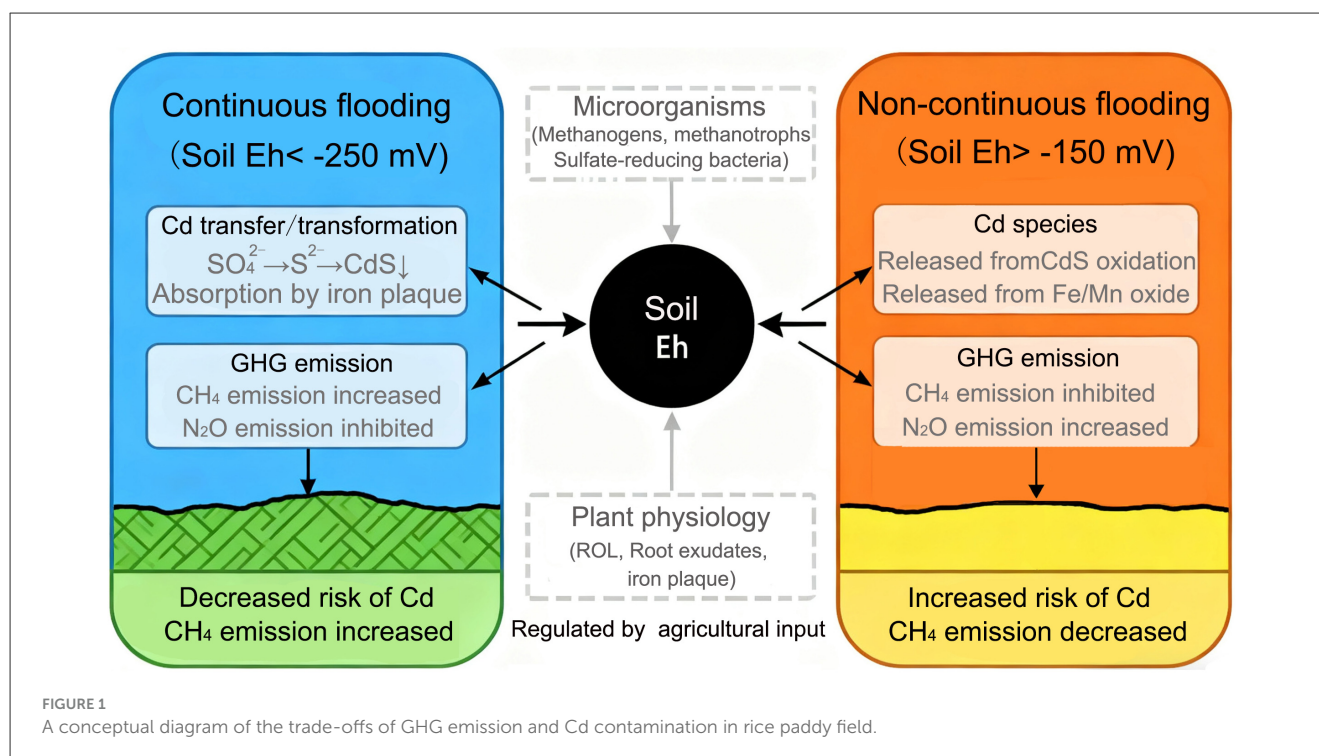
total annual N₂O emissions from farmlands (Zou et al., 2007). N₂O emissions are mainly concentrated during the drainage period of paddy fields, showing a reciprocal trend with CH₄ emissions. Compared with the long-term retention of CO₂, CH₄ is a “short-lived” GHG, with an average atmospheric lifetime of 11.8 years (Arias et al., 2021). Due to its strong infrared absorption property, CH₄ has a 20-year GWP that is 81.2 times that of CO₂ and a 100-year GWP 27.9 times that of CO₂ (IPCC Sixth Assessment Report). CH₄ is characterized by a short lifetime and high warming potential, and for this reason, reducing CH₄ emissions is regarded as the easiest way to alter the future trajectory of global temperature change. The IPCC assessment report points out that to achieve the goals of the Paris Agreement, the world needs to significantly reduce CH₄ emission levels by 2030.

2.2 Cd species and uptake in rice paddy fields

Cd uptake in rice is a complex process influenced by soil Cd speciation, root transport mechanisms, and genetic regulation. In paddy soils, Cd exists in multiple forms including water-soluble, exchangeable, organically bound, Fe-Mn oxide-bound, and residual fractions (Li et al., 2021). Among these, water-soluble and exchangeable Cd are often referred to as bioavailable Cd, which are the primary forms absorbed by rice roots. The bioavailability of Cd is dynamically regulated by soil redox conditions. This redox-driven transformation highlights the critical role of water management practices in modulating Cd bioaccessibility. Rice roots primarily take up Cd²⁺ through plasma membrane transporters originally evolved for essential divalent cations like Fe²⁺, Mn²⁺, and Zn²⁺. The natural resistance-associated macrophage protein 5 (OsNRAMP5) is a key transporter mediating Cd²⁺ influx in the root epidermis and cortex, with its expression upregulated under Fe/Mn deficiency (Ishimaru et al., 2012). Another transporter, OsIRT1, contributes to Cd uptake under Fe-limiting conditions by facilitating non-specific divalent cation transport (Chang et al., 2020). Additionally, recent studies reveal that calcium channels such as OsaAN4 and OsGLR3.4 may participate in Cd²⁺ entry, particularly in the root tip where these channels are highly expressed (Chen X. et al., 2018). Once inside root cells, Cd can be either sequestered in vacuoles to limit translocation or loaded into the xylem for shoot transport through transporters. The translocation of Cd from roots to shoots and grains involves coordinated activities of xylem and phloem transporters. For instance, OsLCT1, a low-affinity cation transporter, mediates Cd loading into the phloem at the nodes, facilitating its distribution to developing grains (Songmei et al., 2019). Genetic variations in these transporters significantly impact Cd accumulation.

2.3 Trade-off relationships between GHG emissions and Cd contamination

The alternating flooding-drying hydrological regimes in rice paddies drive dynamic changes in soil Eh, which mediate the trade-off relationships between GHG emission and Cd availability. This trade-off is mainly regulated by agricultural management measures,



with water management and agricultural input application as core drivers. The conceptual diagram was depicted in Figure 1.

Soil Eh is the core driving factor and is positively correlated with Cd. Partial correlation analysis shows that sulfur in pore water is positively correlated with Cd (Cd is released from sulfide oxidation) (Seyfferth et al., 2025). For water management, continuous flooding (CF) keeps soil in a long-term anaerobic state ($\text{Eh} < -250 \text{ mV}$). Low Eh promotes the formation of insoluble CdS precipitates to reduce Cd bioavailability (Wang et al., 2020), but it also provides favorable conditions for methanogens to decompose organic matter, significantly increasing CH₄ emissions while inhibiting N₂O emissions (Wang Y. et al., 2023). In contrast, alternate wetting and drying (AWD) or mid-season drainage (MD) improves soil aeration, raising Eh above -150 mV . This inhibits methanogen activity, promotes methanotrophs growth, reducing CH₄ emissions by 42%–46% (Haque et al., 2016). However, it stimulates nitrification and incomplete denitrification, increasing N₂O emissions and reverses Cd immobilization reactions, increasing Cd bioavailability and rice uptake (Carrijo et al., 2022). In a study through laboratory incubation experiments on rice paddy soils under AWD and permanent flooding conditions, it was found that AWD consistently promoted higher N₂O fluxes than permanent flooding, with the highest N₂O flux of $1.94 \text{ mg/m}^2/\text{h}$ observed under AWD (Abid et al., 2019).

Agricultural inputs modify soil physical-chemical properties and microbial community structure, affecting the intensity of the trade-off relationships. Biochar regulates GHG emissions through competing electrons with methanogens and increasing the relative abundance of methanotrophs (Han et al., 2016; Qi et al., 2021). Meta-analysis results show that the application of biochar on East Asian paddy fields can reduce methane emissions by 22.9% (Lee et al., 2023). Biochar immobilizes Cd by increasing pH and via

adsorption (Lee et al., 2023). Lime application in acidic paddies ($\text{pH} < 5.5$) increases soil pH by 0.5–1.0 units, promoting stable Cd form conversion and reducing rice Cd absorption by 47.3%. It also enhances methanotroph activity, reducing CH₄ emissions by 32.6% under CF and 48.6% when combined with mid-season drainage, without promoting N₂O emissions, effectively alleviating the trade-off (Haque et al., 2016). Soil minerals such as iron oxides could affect the availability of Cd in rice plant by soil Fe redox reactions. In the red soil paddy fields of South China, pH and iron composition are the key factors affecting the availability of Cd, and the redox cycle of iron will change the morphological distribution of Cd in the soil, thereby affecting its bioavailability (Yu et al., 2016).

Overall, the trade-off is a cascading effect of “management measures—key indicators (Eh, pH, adsorption capacity)—biogeochemical processes—environmental impacts,” and clarifying this chain is fundamental to designing synergistic mitigation strategies for simultaneous control of GHG emissions and Cd contamination.

3 Trade-off mechanisms between GHG emissions and Cd contamination in rice paddies

The trade-off between GHG emissions and Cd contamination in rice paddies is essentially driven by multi-scale processes, including microscopic processes involving soil redox chemistry, microbial community interactions, and rice root physiology coupled with carbon-nitrogen metabolism, as well as macroscopic regulation mediated by regional environmental condition variations. This section focuses on the molecular, cellular, and metabolic mechanisms underlying the microscopic trade-off

mechanisms (e.g., redox-driven element transformation, microbial functional gene expression, and root radial oxygen loss), while also clarifying the regulatory role of regional environmental differences in the macroscopic trade-off relationships. The goal is to systematically unravel the intrinsic drivers of the GHG-Cd trade-off across scales. The trade-off mechanisms between GHG emissions and Cd contamination in rice paddy fields are illustrated in Figure 2.

3.1 Driving role of soil Eh

The redox fluctuations caused by alternating flooding and drying in paddy fields result in significant spatiotemporal coupling and trade-off relationships between GHG emissions and Cd migration. Flooding during the tillering stage promotes CH₄ emissions and reduces Cd migration (Sarwar et al., 2010; Sebastian and Prasad, 2014), while drying during the filling stage decreases CH₄ production but increases Cd uptake and N₂O emissions (Wu et al., 2023; Huang et al., 2024), although the proportion of N₂O emissions in total GHG emitted from rice paddy fields is relatively small. The anaerobic environment during the flooding period of rice paddy fields is a common inducement for both CH₄ production and Cd immobilization (Meng et al., 2019). During the continuous flooding stage, the soil Eh in rice fields can be reduced to below −250 mV (Jiao et al., 2006), and the methanogens decompose organic matter into CH₄. Meanwhile, the reduction of Fe(III), Mn(III/IV) oxides, and SO₄^{2−} in the soil, coupled with the binding of Cd²⁺ by carbonates induced by increased pH, enhances the immobilization of Cd²⁺ and reduces the bioavailability of Cd in the soil solution (Gao et al., 2022; Li et al., 2022; Wang et al., 2024; Zhang T. et al., 2024). During the drying stage with high Eh, the *pmoA* gene in methanotrophs is activated, increasing methane monooxygenase activity and promoting CH₄ oxidation, but N₂O emissions was increased accordingly. Simultaneously, Fe(II), Mn(II), and S^{2−} in the soil are re-oxidized to Fe(III), Mn(III/IV), and SO₄^{2−} during the drying stage, which lead to the release of Cd²⁺. The decrease in pH leads to the dissolution of carbonates, resulting in the release of Cd²⁺ and increased mobility of Cd²⁺. Compared with continuous flooding, intermittent drainage can raise soil Eh above the critical value of −150 mV for methanogenesis, leading to a 42%–46% reduction in CH₄ emission fluxes and a 17%–31% decrease in GWP compared with continuous flooding (Haque et al., 2016). Cd immobilized during the flooding period exhibits a rapid increase in mobility after soil drainage (Yan et al., 2021).

3.2 Interactive regulation of soil microbial communities

Soil microorganisms are not only the main agents responsible for CH₄ production (methanogens) and consumption (methanotrophs) but also participate in the transformation of Cd species. Methanogens are metabolically active in anaerobic environments, and their metabolic activities promote the decomposition of organic matter for H₂ and acetic acid production.

The decomposition of organics provides electron donors for the reduction of Fe(III), Mn(III/IV), and SO₄^{2−}, thereby reducing Cd mobility. Under the reduction potential condition, SO₄^{2−} was reduced to S^{2−} by microbial sulfate reduction, and then Cd²⁺ binds to S^{2−} to form CdS. Fe(III) and Mn(IV) are reduced to Fe(II) and Mn(II), and Cd²⁺ in acidic soil forms FeO-Cd and MnO-Cd. In addition, the increase of pH may promote Cd adsorption by increasing the negative charge on the soil particles and increasing the hydrolysed substance Cd (OH)⁺ (Li et al., 2022).

Cd can affect C and N metabolism in paddy soil, which in turn affects GHG emissions. Cd reduces methane emissions through dual effects. On the one hand, Cd inhibits the activity of methanogens (by decreasing the abundance of *mcrA* genes), and on the other hand, Cd enhances methane oxidation by improving the competitiveness and metabolic activity of methanotrophs (by increasing the abundance of *pmoA* genes) (Jiang et al., 2023; Hao et al., 2025). Cd inhibited soil nitrification by eliminating ammonia-oxidizing bacteria (AOB) while stimulating ammonia-oxidizing archaea (AOA), and the combination of nitrogen fertilizer and biochar restored nitrification by promoting AOB recovery without causing soil acidification, thereby reducing soil available Cd and modifying the negative feedback between soil nitrification and Cd availability in acidic Cd-contaminated soils (Zhao et al., 2020). Regarding methanogenesis, adding 4.0 mg/kg Cd reduced CH₄ emissions by 16–99% across four tested paddy soils. The methanogenesis was suppressed by lowering the abundance of methanogens and decreasing the ratio of methanogens to methanotrophs (*mcrA*/*pmoA*), which was positively correlated with methane emissions (Jiang et al., 2023). Cd inhibited methanogenic taxa like *Methylobacter* (sensitive to Cd even at 0.2 mg/L) that are less abundant in Cd-contaminated soils (Hao et al., 2025). For CH₄ oxidation, 4.0 mg/kg Cd increased the abundance of methanotrophs (via elevated *pmoA* gene copies), and that methanotrophs (e.g., *Methylobacter*, *Methylocystis*) showed high Cd tolerance in pure cultures. However, in soils with high organic matter and sulfate, the effect on CH₄ oxidation was negligible due to low Cd bioavailability (Jiang et al., 2023). A positive correlation between soil Cd concentrations (up to 0.4 mg/kg) and AOM rates, with low Cd additions (0.04–0.1 mg/kg) stimulating AOM in low-Cd soils and higher concentrations (≤2 mg/kg) not inhibiting AOM in Cd-tolerant communities (Hao et al., 2025). Additionally, Cd-tolerant methanotrophs (*Methylobacter*, *Methylocystis*) enhance oxidation via robust antioxidant systems (such as glutathione synthase) and increased loosely bound extracellular polymeric substances (Hao et al., 2025).

Cd can also slow down the nitrogen transformation process in paddy soils by decreasing the abundance of genes related to nitrification and denitrification, with a more significant inhibitory effect on nitrogen reduction and N₂O production under non-flooded conditions (Afzal et al., 2019). In soils supplemented with nitrogen, Cd accelerated the N/C transformation process, resulting in a 19% and 14% reduction in N₂O and CO₂ fluxes, respectively (Zhao et al., 2021). CH₄ alleviates Cd toxicity through two mechanisms: it not only mitigates the production of reactive oxygen species under Cd stress but also reduces the bioavailability of Cd in the soil (Gu et al., 2018; Meng et al., 2019). The regulatory role of Cd-tolerant methanotrophs in GHG-Cd trade-off has been preliminarily confirmed, but the targeted domestication

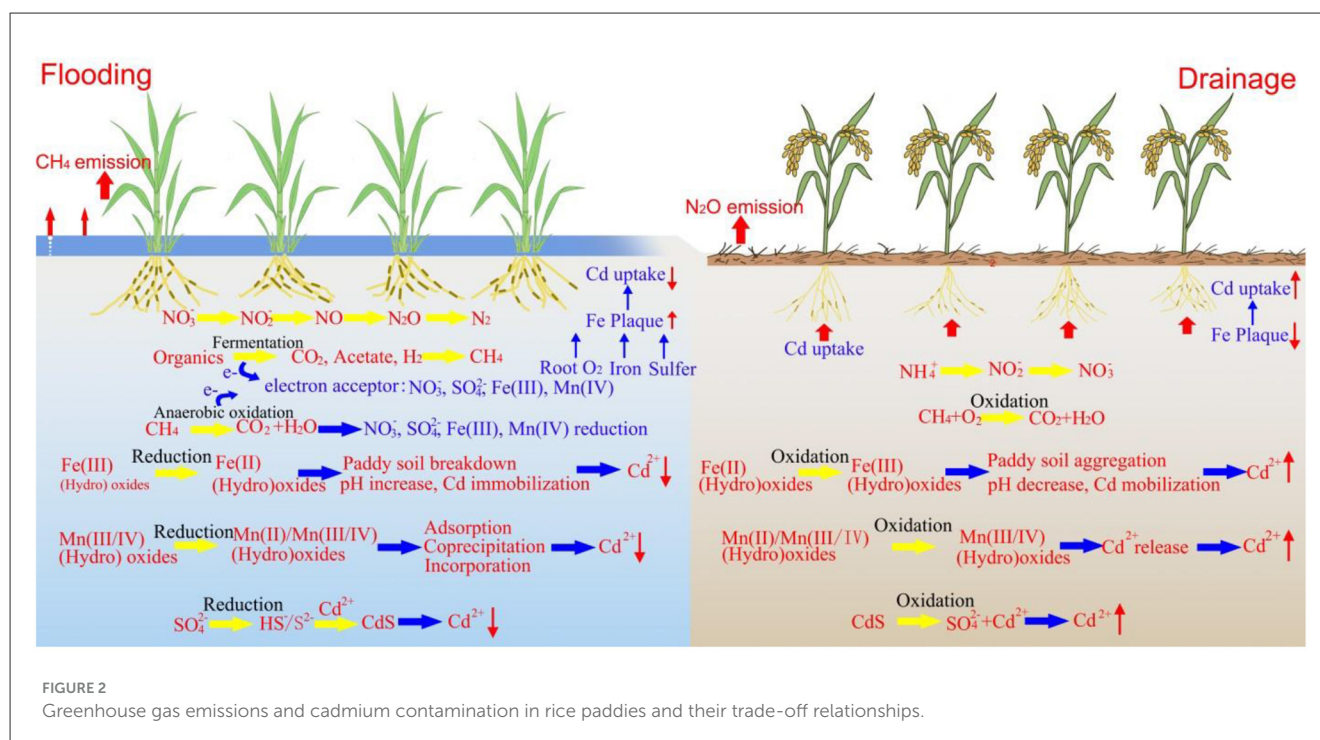


FIGURE 2

Greenhouse gas emissions and cadmium contamination in rice paddies and their trade-off relationships.

of functional microorganisms and their synergistic application with amendments still need further exploration (see Section 6 for specific future directions).

3.3 Correlation between rice root physiology and carbon-nitrogen metabolism

Rice roots influence the rhizosphere microenvironment through radial oxygen loss (ROL) and the secretion of exudates, thereby affecting GHG emissions and Cd migration. During the flooding period, ROL from roots forms oxidized microzones, which inhibit CH₄ production, enhance aerobic oxidation of CH₄, and reduce CH₄ emissions (Zheng et al., 2018). The soil redox environment can be altered by continuous flooding or the processes such as ROL, and these processes will promote the oxidation and deposition of iron and manganese to form iron plaques by affecting the dissolution and precipitation of metals in the soil solution, which enhance the adsorption of Cd and reduce its translocation to above-ground parts (Cheng et al., 2014; Peng et al., 2018; Yu et al., 2024). However, some studies have shown that iron plaques on rice roots can promote Cd uptake (Tian et al., 2023). Iron plaque exhibits a dual or context-dependent effect on Cd absorption by rice roots: It can immobilize Cd in paddy soils by sequestering it on the root surface (serving as a potential barrier to some extent), yet it may also act as a facilitator for Cd uptake by rice roots, with its specific role varying based on root segment, rice growth stage, and environmental conditions.

The presence of iron plaques will accelerate CH₄ emission in paddy soils, and the inhibition of iron plaques may reduce CH₄

emissions from paddy fields (Yao et al., 2024b). Iron plaques on rice roots can also increase N₂O emissions from paddy fields (Liu et al., 2025). Specifically, the iron plaque will promote soil N₂O emissions through the coupling of iron(II) oxidation in the plaques with denitrification (Liu T. et al., 2019). In addition, iron plaques and ROL from rice roots promote the generation of ·OH through the Fenton reaction, which further stimulates N₂O production, making iron plaques on rice roots a hot spot for N₂O generation (Yao et al., 2024a). Rice roots provide substrates for methanogens through the secretion of substances such as organic acids, and the high carbon release from root exudates will increase the methanogenic source strength in the rice paddy soil (Aulakh et al., 2001). Meanwhile, the chelation of Cd²⁺ by small-molecule organic substances secreted by rice roots will increase Cd mobility (Liu et al., 2007), further strengthening the coupling relationship between GHG emission and Cd contamination. Cd stress can increase the content of organic acids in root exudates, thereby increasing substrates for CH₄ production (Fu et al., 2018).

3.4 Trade-off between GHG and Cd contamination in regions with differing environmental conditions

The trade-off between GHG emissions and Cd contamination in paddy systems varies significantly across regions due to differing environmental conditions, such as soil properties and climate. In Mediterranean regions (Ebre Delta, Southern Catalonia, NE Spain), AWD irrigation reduces CH₄ emissions by up to 90% but increases grain Cd by ~20%, though Cd levels remain below the EU threshold of 0.2 mg/kg (Martínez-Eixarch et al., 2021). This is attributed to the region's alkaline soils (pH 8.3) which limit Cd

solubility, even under aerobic conditions (Martínez-Eixarch et al., 2021). By contrast, in acidic paddy soils (pH < 5.5) of southern China, non-flooding practices (e.g., mid-season drain) enhance Cd bioavailability via increased soil oxidation, leading to Cd concentrations in grains exceeding safety limits (Zeng et al., 2022). Here, GHG mitigation (CH₄ reduction by 52%) is offset by higher Cd risks, requiring combined measures like foliar Si spraying to reduce Cd uptake by 33.8–40.8% (Zeng et al., 2022). In California's clay-rich soils, mid-season drains reduce CH₄ by 20–77% without significant Cd increases, as clay adsorption and low soil Cd background (average 7.8 µg·kg⁻¹) limit bioavailability (Perry et al., 2024). Thus, regional environmental conditions dictate the severity of GHG-Cd trade-offs, necessitating site-specific management. Future studies should further quantify the contribution of soil texture (e.g., clay content) and pH (e.g., alkaline soils) to the GHG-Cd trade-off via multi-scale monitoring networks, which could provide a basis for regional-specific management strategies (see Section 6.2 for details).

4 Factors influencing GHG emission and Cd contamination in rice paddy fields

The factors affecting GHG emissions and Cd contamination in rice paddies can be systematically categorized into physicochemical property-related factors and agronomic practice-related factors. Both categories jointly modulate the trade-off relationship between GHG emissions and Cd contamination, with the former serving as the direct response medium and the latter as the external regulation driver.

4.1 Physicochemical property-related influencing factors

Physicochemical properties of paddy soil are the intrinsic basis for regulating GHG metabolism and Cd speciation transformation. Key factors include soil Eh, pH, and organic matter content, which directly affect microbial activity, Cd bioavailability, and the biogeochemical cycles of C and N.

4.1.1 Soil Eh

Soil Eh is the core physicochemical driver of the trade-off between GHG emissions and Cd contamination. The dynamic changes of Eh driven by hydrological conditions directly modulate the metabolic environment of GHG-producing/consuming microorganisms and the transformation of Cd forms. Under low Eh conditions, the anaerobic environment promotes the reduction of SO₄²⁻ to S²⁻, which binds with Cd²⁺ to form insoluble CdS precipitates, thereby reducing Cd bioavailability (Jiao et al., 2006; Wang et al., 2020). Meanwhile, low Eh provides a favorable habitat for methanogens, which decompose organic matter to produce CH₄, significantly increasing CH₄ emissions (Haque et al., 2016; Wang Y. et al., 2023). Under high Eh conditions, enhanced soil aeration inhibits methanogen activity and promotes the growth

of methanotrophs, reducing CH₄ (Haque et al., 2016). However, high Eh accelerates the oxidation of Fe(II), Mn(II), and S²⁻ to Fe(III), Mn(III/IV), and SO₄²⁻, leading to the release of Cd²⁺ from precipitates. Simultaneously, decreased soil pH dissolves Cd-bound carbonates, further increasing Cd mobility and rice uptake (Yan et al., 2021; Linquist and Perry, 2023; Seyfferth et al., 2025).

4.1.2 Soil pH

Soil pH is also an important factor influencing GHG emissions and Cd contamination in paddy fields. In acidic soils with a pH below 5.5, the activity of Cd²⁺ is relatively high (Wang Y. et al., 2023). Meanwhile, the low-pH environment can inhibit the activity of methane-oxidizing bacteria, resulting in increased CH₄ emissions (Khaliq et al., 2019). In acidic paddy soils, the combination of water management and lime application has been shown to reduce CH₄ emissions and Cd uptake without affecting crop yields (Wang Y. et al., 2023). In alkaline paddy soil, Cd will form stable precipitates such as Cd(OH)₂ or Cd₃(PO₄)₂ (Zhang et al., 2020). In addition, the surface charge of soil particles is negative, making it easier for them to combine with Cd²⁺ to form bound states, which reduces the availability of Cd and thereby lowers its uptake by rice root. For alkaline paddy soils severely contaminated with Cd, maintaining continuous flooding throughout the entire rice growth cycle enables the Cd content in rice grains to meet the relevant standards (Chen et al., 2021). However, while continuous flooding suppresses the mobility of Cd in alkaline rice paddy, the issue of CH₄ emissions cannot be ignored.

4.1.3 Soil organic matter contents

Soil organic matter has dual effects on GHG emissions and Cd contamination. Organic matter reduces Cd bioavailability through adsorption, complexation (via functional groups such as hydroxyl and carboxyl), and co-precipitation with Cd²⁺ (Halim et al., 2015). For example, in Cd-contaminated paddies, supplementation with organic fertilizers or crop straws can form stable Cd-organic complexes, inhibiting Cd uptake by rice (Shaghaleh et al., 2024). However, high organic matter content also provides abundant substrates for methanogens. Labile organic matter from plant residues, root exudates, or organic fertilizers provides abundant substrates for methanogens, promoting CH₄ production and emissions (Qi et al., 2025). However, high organic matter content can also enhance soil water retention and adjust Eh, indirectly mitigating extreme fluctuations in GHG emissions (Halim et al., 2015).

4.2 Agronomic practice -related influencing factors

Agronomic practices serve as external and manageable regulatory drivers for GHG emissions and Cd contamination in rice paddies, differing from the intrinsic physicochemical properties of soils. These practices exert their effects by directly or indirectly

altering soil redox conditions, microbial community composition, and rice physiological traits, thereby shaping the trade-off relationship between GHG emissions and Cd bioavailability. Key agronomic practices mainly include water management strategies, the rational use of agricultural inputs, and the selection of suitable crop varieties, each playing a distinct role in modulating the environmental impacts of rice paddies.

4.2.1 Water management

Water management in rice paddy fields can regulate GHG emissions and Cd migration by affecting soil Eh. The anaerobic environment formed under continuous flooding can reduce the concentration of exchangeable Cd in the soil and inhibit the translocation of Cd to grains (Arao et al., 2009). However, it leads to a significant increase in CH₄ emissions. Under different soil Eh, drier conditions with higher Eh (623 mV and 564 mV) led to a 50%–97% increase in grain Cd concentrations compared to flooded conditions with lower EH (−177 mV and −241 mV), and grain Cd in the driest paddies exceeded the CODEX limit of 0.4 mg/kg (Seyfferth et al., 2025). Flooded conditions with lower EH resulted in high CH₄ emissions, with cumulative emissions of 1.7 to 400 kg CH₄/ha, while drier paddies with higher EH were occasional CH₄ sinks, with cumulative fluxes of 0 to −4 kg CH₄/ha (Seyfferth et al., 2025). Aeration-enhancing irrigation practices, such as AWD and mid-season drainage, can reduce CH₄ emissions from paddy fields but may increase Cd uptake by rice plants (Afzal et al., 2022; Limmer and Seyfferth, 2024). AWD improves soil Eh through alternating wet and dry conditions, thereby reducing CH₄ emissions. Soil Eh was improved through periodic wet-dry cycles. During the drying phases, enhanced soil aeration elevates Eh above the critical threshold of −150 mV for methanogenesis. This aerobic shift directly suppresses the metabolic activity and relative abundance of methanogens, as these anaerobes are highly sensitive to oxygen and elevated Eh. Concurrently, the increased oxygen availability promotes the growth and activity of methanotrophs, which further reduce CH₄ emissions by enhanced CH₄ oxidation. However, the fluctuations in Eh can promote N₂O emissions and Cd uptake (Martínez-Eixarch et al., 2021; Monaco et al., 2021; Abu-Ali et al., 2023; Vitali et al., 2024). MD is easier to implement than AWD and can significantly reduce seasonal CH₄ emissions from paddy fields (Liu X. et al., 2019). Studies have shown that under water management strategy of MD, CH₄ emissions can be reduced by 20%–77%, with no significant impact on Cd uptake. Although MD may increase N₂O emissions, N₂O only contributes 3% to the GWP (Perry et al., 2024).

4.2.2 Use of agricultural inputs

Agricultural inputs exert distinct regulatory effects on paddy GHG emissions and Cd contamination, with notable differences among input types. Nitrogen deficiency weakens the antioxidant system function by reducing the ascorbic acid content in the leaves of rice seedlings and the activities of antioxidant enzymes, while increasing the absorption of Cd, thereby intensifying the toxicity of Cd (Lin et al., 2011). Appropriate ammonium-based fertilizers [e.g., (NH₄)₂SO₄] reduce Cd toxicity (Rizwan et al., 2016). Under cadmium stress, the absorption of Cd and nitrogen

by rice is significantly affected by the form of nitrogen. Compared with nitrate nitrogen, ammonium nitrogen is more conducive to reducing Cd absorption in rice and increasing nitrogen accumulation, and can be used as a preferred nitrogen source to alleviate cadmium poisoning in cadmium-contaminated soil in rice (Hassan et al., 2008; Jalloh et al., 2009). The form and application rate of nitrogen in paddy fields affect nitrogen migration and transformation processes such as ammonia volatilization and nitrate leaching, which in turn influence direct or indirect N₂O emissions.

Organic fertilizers improve soil structure but increase CH₄ emissions due to labile organic carbon substrates for methanogens. However, Cd bioavailability can be reduced with organics supplementation through complexation (Shaghaleh et al., 2024). Biochar stands out for synergistic mitigation: it cuts CH₄ emissions via pH/Eh regulation and adsorbs Cd using porous structures. By affecting soil physical and chemical properties and through adsorption, biochar promotes CH₄ consumption; meanwhile, its surface functional groups adsorb Cd, reducing its mobility (Cui et al., 2011; Zhang et al., 2015; Khaliq et al., 2024). Modified biochars like goethite-modified biochar further enhance efficacy, reducing grain Cd and CH₄ emission (Wang et al., 2025). Sulfidated nanoscale zero-valent iron-biochar increases Cd immobilization via pH elevation, addressing passivation issues of unmodified materials (Xu et al., 2024).

4.2.3 Crop varieties and growth stages

Rice varieties and growth stages will also affect the GHG emissions and Cd contamination in rice paddy fields. Differences in genotypes among rice varieties result in variations in root physiological characteristics such as ROL and iron plaques formation, which affect CH₄ emissions and Cd uptake by rice (Martínez-Eixarch et al., 2021). Chen et al. (2019) compared the Cd content in grains of indica and japonica rice varieties under different Cd treatment levels and found that the Cd content in indica rice grains was 1.84–4.14 times that in japonica rice grains. Furthermore, different rice varieties show varying responses to GHG emission reduction under different water management measures (Martínez-Eixarch et al., 2021). The capacity for GHG emissions and Cd uptake differs across different growth stages of rice. When AWD treatment is applied during the early reproductive growth stage, the accumulation of Cd in grains is the highest, however, the Cd concentration in grains is higher compared to that in a single stage when AWD spans multiple rice growth stages (Carrijo et al., 2022).

5 Measures for balancing and mitigating GHG emissions and Cd contamination in rice paddy fields

5.1 New rice varieties breeding and selecting

In the process of rice variety breeding, attentions should be paid to both low GHG emission and low Cd accumulation

characteristics. For example, through biotechnology, the SUSIBA2 gene from barley has been transferred into the rice genome, which not only increases the starch content in rice grains but also significantly reduces CH₄ emissions and decreases the number of methanogenic microorganisms in the rhizosphere (Su et al., 2015). Additionally, gene editing technology can be used to mutate major genes affecting Cd absorption in rice, such as OsNramp5, thereby cultivating rice varieties with significantly reduced Cd content in grains without affecting yield (Zhang W. et al., 2024). On the other hand, appropriate rice varieties should be selected according to the soil conditions of specific planting areas. In medium and high-yield paddy fields, high-yield rice varieties can significantly reduce CH₄ emissions in paddy fields by virtue of their well-developed aerenchyma that promotes CH₄ oxidation. For Cd-contaminated areas, low-Cd-accumulating rice varieties that have been bred can be selected. In areas affected by both Cd contamination and high temperatures, prioritizing the planting of temperature-resistant rice varieties can effectively reduce Cd uptake and accumulation in rice plants. Such varieties also help maintain relatively stable rice yield and grain quality under the combined stress of Cd and high temperature, compared to temperature-sensitive varieties (Munir et al., 2023). However, new rice varieties breeding addresses the long-term ecological risks of genetically modified or gene-edited varieties and the high technical thresholds and costs of gene editing technologies, which may restrict their promotion in resource-limited agricultural regions.

5.2 Optimizing water management

Measures for reducing GHG emissions in rice paddy fields should be selected based on the Cd content in paddy field soils in a targeted manner. In areas with severe Cd pollution, long-term flooding (maintaining a 3–5 cm water layer) can create reducing conditions to form CdS precipitates, thereby significantly reducing the bioavailability of Cd (Afzal et al., 2019; Khanam et al., 2020). However, it is necessary to combine soil improvement measures (such as biochar application) to mitigate the risk of increased CH₄ emissions (Zhang et al., 2015; Rizwan et al., 2016). In areas without severe Cd pollution, the Cd content in rice tissues can be reduced by delaying the flooding stage and extending the flooding time. A staged flooding strategy should be developed, for example, moist irrigation during the tillering stage to promote root development, continuous flooding from the booting to the filling stage to inhibit Cd absorption, and intermittent drying during the maturity stage to reduce CH₄ emissions (Khanam et al., 2020; Li et al., 2023). When flooding treatment is applied for 20 days during the filling stage (FG20), the Cd concentration in brown rice decreases by 28.61%–82.74% compared with continuous flooding, and by 3.67%–74.82% compared with flooding during the vegetative growth stage (Wu et al., 2025). FG20 can simultaneously increase soil pH, promote the formation of iron plaques on the root surface, regulate the soil microbial community, and significantly reduce the bioavailability of soil Cd. For ratoon rice, the most Cd is absorbed within 15–18 days from the initial heading to full heading; maintaining flooding conditions during this period is most effective for reducing the Cd concentration in grains (by 62.7%) and the total Cd accumulation

at maturity (by 49.9%) (Yang et al., 2024). Nevertheless, water management fails to consider the high water consumption of long-term and continuous flooding, which is not feasible in water-scarce regions, and the challenge of accurately controlling the timing and degree of flooding/drying in large-scale paddy fields, which can lead to unstable mitigation effects across different plots.

5.3 Application of amendments and remediators

The amendments used for the synergistic mitigation of greenhouse gas emissions and Cd contamination in rice paddy fields are shown in Table 1. Biochar is a widely used soil amendment for reducing CH₄ emissions in paddy fields. Biochar application reduce CH₄ emissions in paddy fields by affecting soil physical and chemical properties, soil microorganisms, and enzyme activities (Liu et al., 2024). Meanwhile, the porous adsorption, alkalinity, and pH buffering capacity of biochar can reduce the availability of Cd in the soil (Lu et al., 2022; Islam et al., 2024; Meng et al., 2025). Through artificial intelligence-assisted multi-task deep learning models, the synergistic mitigation of biochar on CH₄ emission reduction and Cd pollution in paddy fields can be achieved (Yin et al., 2023). Iron-loaded modification of biochar is an important modification measure for the synergistic remediation of GHG emissions and heavy metal pollution. Iron-modified biochar can not only increase soil available potassium, alkaline hydrolyzable nitrogen, and soil organic carbon, but also the goethite-modified biochar can further enhance the formation of iron plaques on the root surface, reducing the Cd content in rice by 80.4% (Wang et al., 2025). Biochar-supported nanoscale zero-valent iron (n ZVI-BC) is also increasingly used for Cd immobilization, which can reduce Cd accumulation in rice grains under the AWD water management mode (Yang et al., 2022), achieving synergistic mitigation of GHG emissions and Cd contamination. The mitigation mechanisms of Cd contamination using biochar-nanoparticle composites including immobilizing Cd through physicochemical processes such as adsorption, complexation, and precipitation to reduce its bioavailability, restructure soil microbial communities by enriching metal-resistant taxa and enhancing functional pathways like glutathione metabolism and nitrogen fixation, and reprogram maize transcriptomic networks to upregulate antioxidant enzyme activities and modulate phytohormone signaling (Yasin et al., 2025). However, n ZVI-BC is prone to passivation and agglomeration, and has poor electron transfer. Biochar-supported sulfidated nanoscale zero-valent iron (S-n ZVI/BC) can increase soil pH, Eh, and organic matter, among which pH is the main factor affecting the mobility of soil Cd (Xu et al., 2024). The combined use of amendments with CH₄ emission reduction and Cd remediation is also an important means to achieve synergistic remediation of GHG emissions and Cd pollution. For example, the combined use of phosphogypsum and the cadmium remediation agent mercapto-modified palygorskite can effectively reduce Cd pollution in brown rice and CH₄ emissions in paddy fields (Lu et al., 2024, 2025). In acidic paddy fields, water management combined with lime application can reduce CH₄ emissions without increasing Cd absorption by rice (Wang Y. et al., 2023). The potential secondary environmental

TABLE 1 Amendments used for the synergistic mitigation of greenhouse gas emissions and Cd contamination in rice paddy fields.

Amendments types	Soil type	Dosages	Mitigation effects of GHG emission and Cd contamination	Mechanisms	References
Biochar (BC)	Rice paddy soil with average pH 6.3 (a range of 4.3–8.2)	40.5 t/ha	CH ₄ emission reduced 30%–55% and Cd fixation ratio with 20%–45%	BC with low nitrogen content can reduce the electron transfer promotion effect on methanogenic bacteria and inhibit CH ₄ production; BC with high oxygen content can act as an electron acceptor to promote the oxidation of CH ₄ ; BC can also affects the activity of methanogenic bacteria and methanooxidizing bacteria indirectly by regulating the soil pH and Eh; High specific surface area of BC provides more adsorption sites; Chemical complexation fixation of Cd; Alkaline minerals form precipitates with Cd. Biochar can promote the co-precipitation of iron oxides to fix Cd. Multi-task deep learning optimizes the properties of BC to achieve the synergy of CH ₄ reduction and Cd fixation	Yin et al., 2023
Goethite modified biochar (GBC)	The total Cd concentration was 1.8 mg/kg with a pH of 6.7	1.3% (wt)	The addition of GBC reduced the grain Cd content and CH ₄ emission by 80.4% and 26.3%, respectively	GBC promotes the formation of iron oxides and hydroxides through its porous structure and the chemical reactivity of iron, co-precipitates with Cd, and reduces the bioavailability of Cd. GBC can significantly increase the formation of iron films on the root surface of rice to adsorb Cd. GBC treatment reduced the relative abundance of the CH ₄ emission-related gene mcrA and inhibited the activity of methanogenic archaea. GBC can compete with the methanogenic process for substrates by promoting iron reduction reactions, while converting unstable carbon pools into stable ones, thereby reducing the supply of substrates for CH ₄ production	Wang et al., 2025
Nanoscale zero-valent iron n-ZVI-BC	The soil contained 0.85 mg/kg of Cd with an initial pH of 6.77	0.25–1.00% (wt)	Compared with the control, nZVI-BC combined with alternating dry and wet treatment (AWD) reduced the bioaccumulation of Cd in rice grains by 15.8%–69.16%, but the reduction in CH ₄ emission was not mentioned	n-ZVI-BC reduces Cd mobility by increasing soil pH; The functional groups on the surface of biochar complex with Cd ions; n-ZVI-BC promotes the formation of iron plaque on the root surface, but it has a dual effect on Cd	Yang et al., 2022
Phosphorus/iron-doped biochar (PFBC)	The pH was 5.47 and 5.53, and total Cd concentration was 2.09 and 0.08 mg/kg	2.5%(wt)	PFBC addition reduced porewater Cd by 36.8–47.3% compared to that of CK treatments. Under the alternative wetting and drying regime, except for XG soil, the cumulative CO ₂ flux of PFBC treatment was significantly lower than that of CK	PFBC can provide more binding sites for Cd sorption and coprecipitation, PFBC can function as an electron shuttle for accelerating electron transfer, PFBC can suppress organic materials degradation by soil microbial	Shi et al., 2025
Sulfidized-nZVI/BC(S-nZVI/BC)	The pH of the paddy soil was 7.57	3% (wt)	The addition of S-nZVI/BC increased the immobilization efficiency of leachable Cd by 53.70%	The addition of S-nZVI/BC increased soil pH, Eh and organic matter, among which pH was the main factor affecting the migration of soil Cd	Xu et al., 2024
Phosphogypsum (MG)+sulfhydryl-modified palygorskite (SMP)	The pH was 6.98 with 1.44 mg/kg total Cd and 0.69 mg/kg available Cd	MG 0–2.25 t/ha, SMP 0.05% (wt)	When the dosage of MG was 2.25 t/ha, the effective Cd content was 19.67% lower than that of the control group, CH ₄ emissions were reduced by 56.04%	The hydroxyl and thiol groups on the surface of SMP can form chelates with Cd ²⁺ , reducing its bioavailability. The sulfate in MG is reduced to S ²⁻ under anaerobic conditions and forms CdS precipitate with Cd. Sulfate in MG can enhance the activity of sulfate-reducing bacteria in the soil, which compete with methanogenic archaea for substrates and inhibit methane production. SMP may indirectly reduce CH ₄ emissions by altering the content of soil organic matter and pH value	Lu et al., 2025

(Continued)

TABLE 1 (Continued)

Amendments types	Soil type	Dosages	Mitigation effects of GHG emission and Cd contamination	Mechanisms	References
Liming (L)+water management	0.08 mg/kg total Cd, with 21.6% clay, 53.1% silt, and 25.3% sand, and an initial pH of 5.4	4 t/ha with water management	Under the condition of continuous flooding (F), Liming treatment reduced CH ₄ emissions by 32.6%, but under the conditions of flooding—mid-season drainage—flooding (FDF) and flooding—mid-season drainage - intermittent irrigation (FDI), CH ₄ emissions decreased by 48.6% and 52.7%, respectively. Liming treatment reduces the average Cd absorption of rice by 47.3%	Lime reduces the bioavailability of Cd by increasing soil pH and promoting its transformation into a stable form such as CdS. The FDF model, after mid-term drainage and rewetting, maintains a certain anaerobic environment, promotes the formation of iron plaque, which can adsorb Cd and reduce its migration to the root system. Lime can reduce methane emissions by raising soil pH, enhancing the activity of methane monooxygenase, promoting methane oxidation, and simultaneously decreasing the availability of methane-generating substrates such as organic carbon. AWD enhances soil Eh, inhibits the activity of methanogenic bacteria, and promotes methane oxidation simultaneously	Wang Y. et al., 2023

issues of some amendments cannot be overlooked. For example, nZVI-BC is prone to passivation and agglomeration, reducing its long-term effectiveness, and some modified biochars may have the risk of heavy metal leaching—and there is no discussion on unified dosage standards for amendments, resulting in inconsistent application effects in different soil types.

5.4 Optimizing the fertilization

Priority should be given to ammonium-based nitrogen fertilizers such as (NH₄)₂SO₄, which can reduce Cd uptake and lower N₂O emissions. Studies have shown that ammonium nitrogen promotes the combination and immobilization of Cd with sulfides by reducing soil Eh. Meanwhile, Cd inhibits the nitrification process, thereby decreasing N₂O generation (Rizwan et al., 2016). By reasonably controlling nitrogen fertilizer dosage and using slow-release or controlled-release fertilizers to slow down the nitrogen release rate, the intensity of nitrification-denitrification can be reduced, leading to decreased N₂O emission. Additionally, this approach avoids excessive nitrogen from enhancing the bioavailability of Cd (Zhang et al., 2015).

In Cd-contaminated farmlands, sulfur supply may serve as an effective means to reduce Cd accumulation in rice. Sulfur can reduce Cd translocation by promoting the formation of iron plaques on the root surface and enhancing Cd chelation and vacuolar sequestration in roots (Cao et al., 2018; Miao et al., 2024). However, under non-continuous flooding conditions (when Eh exceeds −42.5 mV), excessive sulfur can increase the risk of Cd contamination (Liu et al., 2022). Rational application of silicon fertilizer can not only reduce CH₄ emissions from paddy fields (Galgo et al., 2025) but also lower the bioavailability of Cd by increasing soil pH (Xiao et al., 2021). Nevertheless, excessive use of silicon fertilizer may result in higher CH₄ emissions (Keteku et al., 2024). However, excessive application of ammonium-based fertilizers may cause soil acidification (which could increase Cd mobility in neutral or alkaline soils) and the contradiction that sulfur fertilizers are effective in reducing Cd under flooding conditions but may increase Cd contamination risks

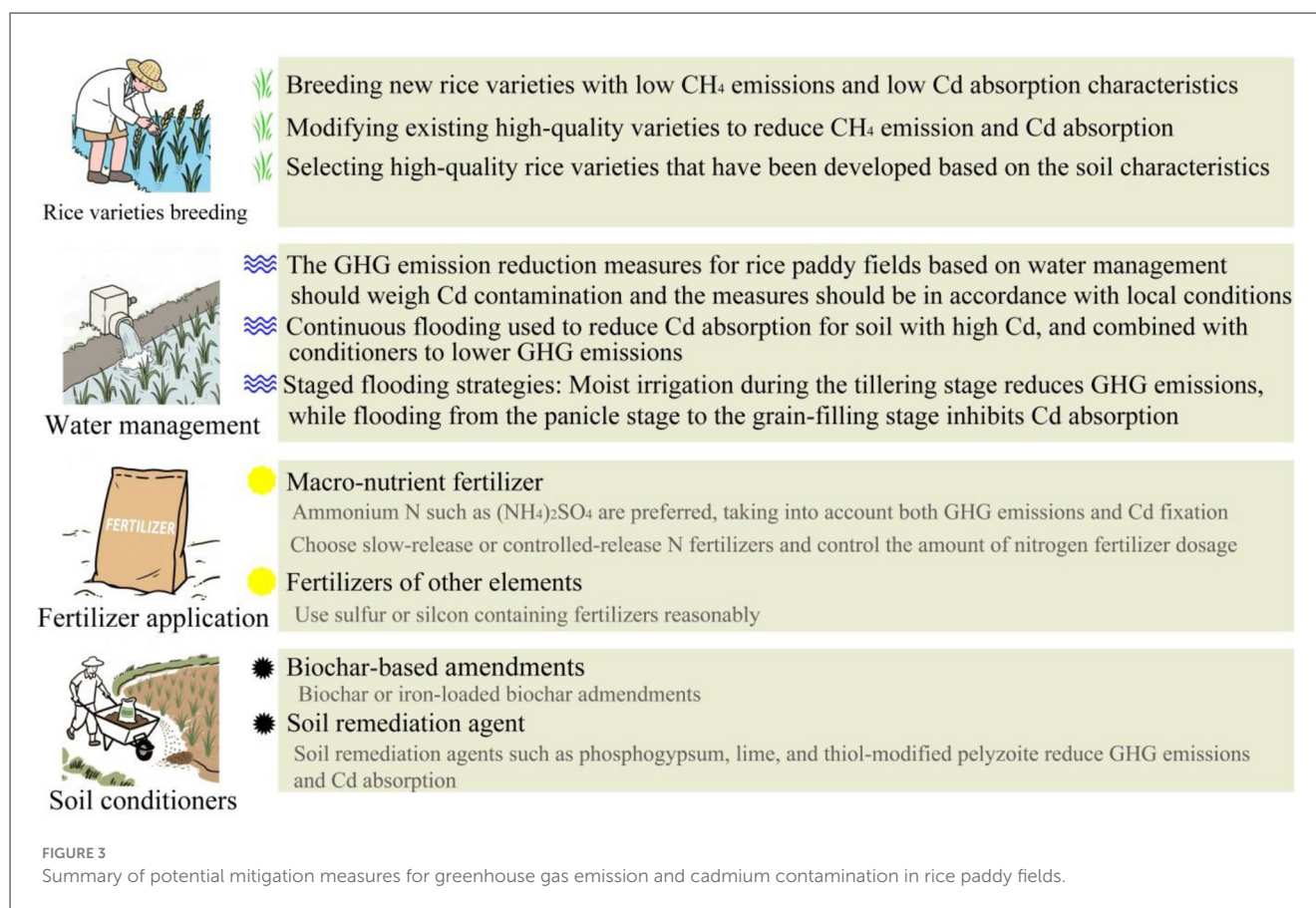
under non-continuous flooding, making it difficult to apply these measures uniformly in practical production.

5.5 Summary of potential mitigation measures for GHG emission and Cd contamination

The measures for balancing and inhibiting GHG emissions and Cd contamination in paddy fields are summarized in Figure 3. In rice variety breeding, varieties with both low GHG emission and low Cd accumulation characteristics are cultivated through biotechnology or gene editing, or appropriate varieties are selected based on the soil conditions of the planting area. In the optimization of water management, strategies such as long-term flooding and staged flooding are adopted according to soil Cd content, and soil improvement is combined to balance GHG emissions and Cd contamination. As for amendments and remediators application, biochar and its modified materials, or amendments with specific functions are used in combination to synergistically mitigate GHG emissions and Cd contamination. For rice paddy field fertilization, priority is given to ammonium-based nitrogen fertilizers, and the nitrogen dosage is reasonably controlled, slow-release or controlled-release fertilizers are used, and sulfur fertilizer, silicon fertilizer, etc., are applied rationally to reduce GHG emissions while lowering Cd uptake by rice plants.

6 Conclusion and perspectives

GHG emissions and Cd contamination in rice paddy fields are closely coupled through mechanisms such as redox conditions, soil microbial communities, and root physiology. Moreover, the mitigation measures for GHG emissions and Cd contamination in paddy fields present a trade-off relationship, and both are jointly regulated by key factors including water management, agricultural inputs and rice varieties. This review systematically summarizes the key findings of current research: (i) Trade-off mechanisms: Soil Eh is the core driver of the trade-off mechanisms between



CH₄ emission and Cd contamination. Flooding ($E_h < -250$ mV) reduces Cd bioavailability but increases CH₄ emissions, while drainage ($E_h > -150$ mV) inhibits CH₄ production but enhances Cd mobility. Soil microbes (e.g., Cd-tolerant methanotrophs, sulfate-reducing bacteria) and rice root processes (radial oxygen loss, iron plaque formation) further modulate this trade-off. (ii) Water management and agricultural inputs are the key and most controllable influencing factors. Continuous flooding reduces Cd but raises CH₄, while mid-season drainage cuts CH₄ emission without significant Cd increase. Iron-modified biochar can reduce grain Cd and CH₄ emission, and ammonium-based fertilizers lower Cd uptake and N₂O emissions. (iii) Synergistic mitigation of CH₄ emission and Cd contamination in rice paddies including staged flooding regimes, use of soil conditioners and targeted breeding strategies.

In the process of accounting for GHG emissions from rice paddy fields, the CH₄ emission factor in potential Cd-contaminated areas may be higher than that in conventional soils, thus requiring correction of the CH₄ emission factor. When formulating GHG emission reduction schemes for paddy fields, it is also necessary to consider changes in the bioavailability of Cd during the implementation of these schemes. In potential Cd-contaminated areas, CH₄ emission reduction schemes based on water management may increase the bioavailability of Cd in the soil, leading to excessive Cd content in rice grains produced under such emission reduction measures. Through measures such as optimizing water

regimes, applying inputs like soil amendments and remediators, regulating nutrients, and breeding varieties, synergistic mitigation of GHG emissions and Cd contamination in paddy fields can be achieved. Notably, the practical application of these measures requires site-specific adjustment: in severely Cd-contaminated soils, long-term flooding combined with biochar amendment balances Cd immobilization and CH₄ control. While in slightly contaminated soils, AWD with silicon fertilizer application achieves dual benefits. This review underscores that integrated management—combining mechanistic insights with local soil-crop conditions—is the key to resolving the GHG-Cd trade-off.

In the future, it is necessary to strengthen multi-scale mechanism research, directional regulation of microbial communities, and development of intelligent management technologies to provide theoretical and technical support for green and sustainable production in paddy fields. Future research can conduct in-depth exploration from dimensions such as multi-scale coupling mechanism quantification, functional microbial directional regulation, intelligent precision management, and long-term environmental risk assessment. For typical regions, establish a multi-parameter monitoring network of the “soil-crop-atmosphere” system equipped with automatic Eh/pH sensors, GHG flux automatic monitors, and rapid detection points for Cd in rice. Quantify the contribution rates of “climatic factors (temperature/precipitation)—soil properties (pH/organic matter)—management measures (irrigation mode)” to the

GHG-Cd trade-off. At the microscale, analyze the correlation between the microstructures of iron plaques on rice roots and Cd adsorption-desorption kinetics. Combine metagenomic sequencing to reveal how the metabolic pathways of rhizosphere microbial functional groups such as sulfate-reducing bacteria, methanotrophs respond to Eh fluctuations, and establish a quantitative correlation model between microscopic interface processes and macroscopic environmental effects. Enrich and screen key functional strains such as Cd-tolerant methanotrophs, sulfide-producing bacteria from long-term Cd-contaminated paddies with the goal of “low methane emission and high Cd tolerance.” Strengthen the expression efficiency of their functional genes through gene editing technology. Develop a composite system of “functional bacterial agents-modified biochar.” Through laboratory batch experiments and field plot trials, determine the optimal dosage of the composite system. Use high-throughput qPCR to monitor changes in the abundance of soil functional genes and reveal the synergistic mechanism of “microbial colonization-amendment adsorption-soil environment.” Integrate data from soil sensors-crop sensors-weather stations, and realize real-time data transmission and preprocessing through edge computing technology. Based on machine learning algorithms, integrate historical field data to construct a dynamic decision-making model of input (soil properties, meteorological conditions)-output (optimal management measures). Develop a mobile application to provide farmers with precise recommendations for “irrigation time-amendment dosage-fertilization plan.” Establish intelligent demonstration bases of over 100 mu in Cd-contaminated paddy concentration areas, and verify the practicality and economy of the system by comparing the effects of traditional management and intelligent management. Conduct 5–10 year long-term located experiments on commonly used amendments such as sulfur-modified nano-zero-valent iron biochar and phosphogypsum, and monitor the accumulation and leaching risk of heavy metals in soil and their effects on soil enzyme activities. Reveal the impact of GHG-Cd synergistic mitigation measures on the paddy food chain, such as detecting Cd content in paddy aquatic organisms and birds, and monitoring GHG concentrations in the atmosphere around paddies to evaluate the long-term impact of measures on the structure and function of the farmland ecosystem. By integrating the above research directions, we can not only deepen the theoretical understanding of the GHG-Cd trade-off mechanism in rice paddies but also provide technical support for the green and sustainable production of paddies in different regions.

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Author contributions

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