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A Systematic Review of Research Trends in Methane Emissions from Rice Fields in Asia

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Abstract: Global greenhouse gas levels are significantly impacted by methane emissions from rice fields, especially in Asia, where most of the world's rice is produced. This review analyzes research trends on methane emissions from rice fields in East, Southeast, and South Asia, focusing on factors influencing emissions and the effectiveness of mitigation strategies. We synthesized data about 169 papers published between 2000 and 2023 from Web of Science and Google Scholar, which were merged in Mendeley. The results were visualized using VOSviewer. It covers key aspects such as water management, soil types, farming practices, and rice varieties. Our findings suggest that water management practices, including intermittent drainage and pulse irrigation, are critical in reducing methane emissions. Soil types, farming practices, and rice varieties also influence variations in emissions levels. The research highlights significant regional differences, with China and Indonesia major contributors to emissions, while countries such as Japan and South Korea have implemented effective mitigation measures. Emerging research topics include the impact of organic matter inputs and innovative rice cultivars on emission levels. This review underscores the need for region-specific strategies and research in less studied, such as rainfed and peatland rice fields, to enhance global understanding and control of methane emissions from rice cultivation. The boundary of this review is this manuscript only focuses on methane emissions in artificial wetlands, such as rice field areas, not other water bodies. Therefore, further research review in other freshwater ecosystems is encouraged.

Keywords: methane emissions, Asia, rice field, research trends

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1. Introduction

Anthropogenic factors are the main source of methane emissions, with about 70% of emissions coming from agriculture, mining, natural gas use, enteric fermentation in ruminants and insects, manure storage systems, wetland soils, wastewater treatment, landfill sites, wetland soils, forest fires, hydroelectric reservoirs, transportation, biogas production and industrial processes such as coal burning or cement production (Khalil *et al.*, 1993; Topp and Pattey, 1997; Mer *et al.*, 2001; Minamikawa *et al.*, 2006; Choi *et al.*, 2017). In Asia, where most of the world's rice is produced, and 90% of rice fields are flooded, most methane emissions come from the agricultural sector (Wassmann *et al.*, 2009). Since anaerobic conditions facilitate methane production by methanogens, inundated rice fields and domesticated ruminants are responsible for up to 40% of emissions and are considered the major anthropogenic sources (Mer *et al.*, 2001; Ariani *et al.*, 2021).

In Asia, numerous studies have focused on methane emissions from rice fields, with much of the research investigating the factors influencing these emissions. Factors such as irrigation management, cultivation techniques, rice varieties, soil types, soil amendments, and their interactions remain dominant research topics in several Asian countries. In addition, recent studies have focused on emission modeling such as process-based, empirical and statistical, remote sensing and geospatial, machine learning and data-driven models, and top-down inverse models (Schulz *et al*., 2006; Van Dingenen *et al*., 2018; Zhu *et al*., 2018; Conrad, 2020; Gwon *et al*., 2022; Mboyerwa *et al*., 2022; Ouyang *et al*., 2023). However, no comprehensive review synthesizes previous studies to identify recent knowledge gaps, particularly in Asia, the largest methane producer. This study addresses that gap, with the primary objective of synthesizing existing research on methane emissions from rice fields in Asia, focusing on identifying knowledge gaps and emerging trends.

To address this gap, we have prepared a follow-up manuscript that expands on the existing research and examines the status of methane research in East, Southeast, and South Asian countries, focusing on rice field ecosystems. A systematic review was conducted using keywords related to methane emissions and rice fields in Asia. Combining traditional review techniques and novel visualization methods allowed for a more comprehensive analysis of research trends across different Asian countries.

The review is limited by variability in the quality and availability of data across regions and challenges in merging bibliometric network outputs with empirical field data. Despite these limitations, this synthesis provides valuable insights into methane emission patterns across Asia, filling a critical gap in understanding global methane emissions and their environmental impacts.

2. Methods

This study was a comprehensive literature review to synthesize existing research on methane emissions from rice field ecosystems in Asia. A literature review was chosen over primary research to consolidate existing knowledge and identify trends and gaps in the literature across different regions. This approach allows for a more efficient approach to provide an overview of existing studies and inform future research directions, ensuring a broad understanding of methane emissions without primary data collection that needs intensive resources.

Keywords such as "methane and climate change issues," "methanogenesis," "factors influencing methane emissions in aquatic ecosystems," and " methane research methods in rice field ecosystems" were used to gather references for this review from search engines such as Google Scholar, Research Rabbit, and Web of Science (Clarivate). Numerous sources were identified, focusing on specific regions of Asia and rice field ecosystems from 2000 to 2023. The scope was limited to this time frame to capture recent developments in methane research while ensuring enough data to analyze trends over time. Exclusion criteria included studies that addressed methane emissions unrelated to rice fields or focused outside the region of Asia. A total of 169 articles met these criteria, which provided a robust yet manageable sample size for analysis.

Search results from Web of Science and Google Scholar were merged and organized in Mendeley, a reference manager software, to track the sources and remove the duplicates systematically. Articles were further screened based on titles and abstracts to ensure relevance to the focus on methane emission in Asian rice field ecosystems.

In addition, to enhance the literature analysis, the search results were visualized using the VOSviewer, a software tool for constructing and visualizing bibliometric networks (van Eck and Waltman, 2010; Kirby, 2023). The VOSviewer was employed to map key research trends, identify collaborations among institutions, and detect emerging themes in methane emissions research across Asia. This visualization revealed underexplored areas and provided a clearer picture of the evolving research landscape. For a brief step on the methodology, please refer to Figure 1.

As with any literature review, this study is subject to limitations, including the potential for publication bias, where unpublished studies or those not indexed in the selected databases may have been missed. The review focused on English-language and some Korean articles with English abstracts, potentially excluding research in other languages. Diverse methodologies and measurement techniques also challenged consistent conclusions.

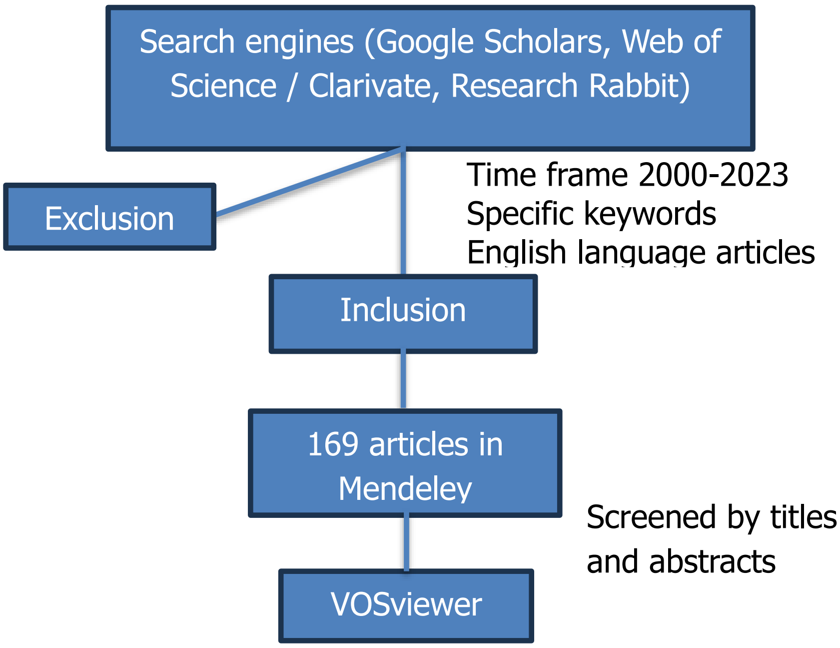

Figure 1. Flow chart of the methods (Source: author's creation).

3. Result

Average seasonal methane emissions from different Asian countries indicate that Indonesia, North Korea, and South Korea have the highest seasonal methane emissions in the region, with a range of 275 to 290 $kgCH_4ha^{-1}$ (Figure 2). Despite the relatively small rice field areas, methane emissions on the Korean peninsula are higher than in other regions. Regarding the variation of rice ecosystems in Asia, irrigated rice fields cover the largest area compared to other types, with $78x10^6$ Ha in total (Figure 3a). However, irrigated and rainfed rice fields in South and Southeast Asia appear almost equal. For example, in South Asia, the comparison between irrigated and rainfed rice fields has the same value of 40.91%, while in Southeast Asia, the proportion is 42.31 and 40.38%, respectively. In East Asia, rainfed rice fields are less common than irrigated ones (Figure 3b). According to Wasmann *et al.* (2000) and Rao *et al.* (2017), various rice production systems are classified based on climate and water availability, geography and topography, agriculture infrastructure, and socioeconomic factors. Some East Asian countries, such as China, South Korea, and Japan, have temperate climates with less predictable rainfall. Therefore, they use modern technology to solve the problem of water limitations. Most Southeast Asia countries such as Indonesia, Thailand, and the Philippines generally have tropical climates with high rainfall prediction supporting rainfed and irrigation rice fields. Like South Asia, which depends on the monsoon rains, Southeast and South Asia rainfed and irrigated rice fields coexist more evenly than in East Asia. Table 1 describes the difference in rice field types.

Table 1. Description of rice field types that are commonly found in Asia

Rice field type	Locations	Water sources	Flooding pattern	Methane emissions
Irrigated	Lowlands, valleys, and deltas	Rivers, reservoirs, canals	Consistent shallow flooding	High
Deepwater	River basins, flooded-prone areas	Natural flooding, monsoon	Flooding >50 cm	High
Rainfed	Southeast Asia and parts of India	Rainfall	Seasonal with variable depths	Moderate
Upland	Hilly or mountainous areas	Rainfall	No standing water (well-drained)	Low

Source: modified from Wassman (2000); Yuan *et al*. (2022); FAO (2024).

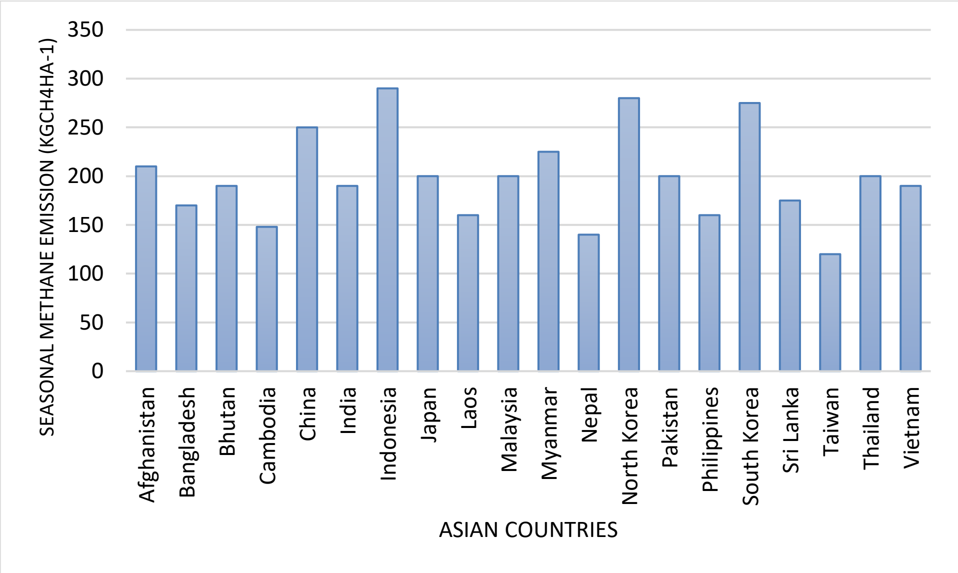

Figure 2. Average seasonal methane emissions from several Asian countries (Source: modification from Yan, *et al*. 2003).

3.1. Methane emissions in East Asia region

Many reports and publications on methane emissions from rice field ecosystems have been produced in some East Asian countries. Most of these publications are in English, but some are in local languages, such as Chinese, Japanese, or Korean. China, the world's largest rice producer, has been the leading source of methane emissions from rice field ecosystems since the 1980s (Yan *et al*., 2003). A significant proportion (91.4%) of China's methane emissions come from anthropogenic sources, including agriculture (Ito *et al*., 2019). According to a model-based assessment by Ito *et al*. (2022), methane emissions from Chinese paddy fields between 2005 and 2015 they were ranged from 2.0 to 13.7 $TgCH_4$ yr^{-1}, with the highest emissions occurring in central and southern China.

Although Japan has lower methane emissions than China, it is still the second-largest contributor in East Asia (Ito *et al*., 2022). This is probably because, in 1995, about 99.1% of Japanese rice fields were irrigated, resulting in an average seasonal emission of 21 g CH_4 m^{-2} across 47 prefectures (Yan *et al*., 2003). The methane budget of Japan's agricultural sector alone has been estimated to be about 0.84 Tg CH_4 yr^{-1} (Ito *et al*., 2019).

Reports from the Korean peninsula highlight water management as a key factor in controlling methane emissions, though specific water management practices are not always clearly identified. Average methane emissions from different treatments, including water regimes and rice varieties, at three sites (Suwon, Milyang, and Iksan) in South Korea ranged from 6.02 to 15.52 mg CH_4 m^{-2} h^{-1} during one growing season (Yan *et al*., 2003).

Agriculture in North and South Korea contributed 0.14 and 0.37 Tg CH_4 yr^{-1}, respectively, accounting for 1.4% and 2.2% of total emissions (natural and anthropogenic) (Ito *et al.*, 2019).

In northern China, South Korea, and Japan, methane emissions increased mainly during flooding. As most rice fields in East Asia are irrigated, rainfed and deepwater rice fields are considered negligible contributors compared to those in Southeast and South Asia (Wassmann *et al.*, 2000).

Annual methane emissions from East Asian countries increased from the 1990s to 2012 due to economic and population growth and dietary changes. In Japan and South Korea, however, GDP and per capita emissions decreased between 1997 and 2012. This decrease is attributed to the implementation of greenhouse gas (GHG) and slower population growth, which has limited emissions (Ito *et al.*, 2019).

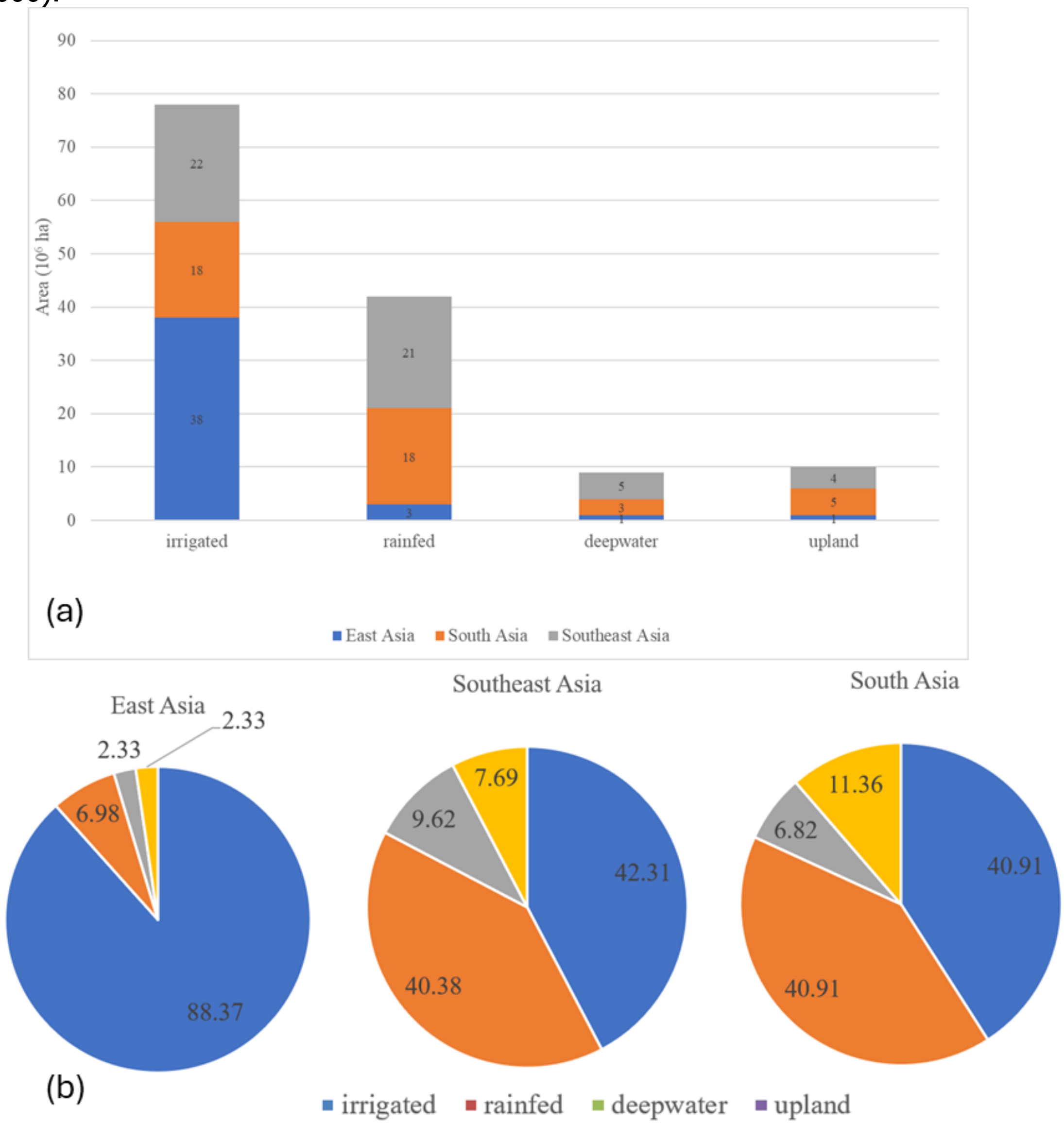

Figure 3. a. Area and relative emission potential of various Asian rice ecosystems; b. Percentage comparison of four types of rice ecosystems in Asia (Source: modification from Wassman *et al.* 2000).

3.2. Methane emissions in Southeast Asia region

Indonesia had approximately 4.8 million hectares of irrigated rice fields in 2016 (Ariani *et al*., 2021). Total methane emissions from irrigated and rainfed rice fields were 30.74 and 20.25 mg CH_4 m^{-2} h^{-1}, respectively. Research on methane emissions in Indonesia has focused on factors such as water regime, rice variety, soil type, and fertilizer use (Yan *et al*., 2003). According to Wassmann *et al*. (2000), rainfall significantly affects methane emissions in rainfed rice fields. Methane emissions in Indonesian rice fields vary by region and cropping practices, with emissions typically higher in continuously flooded fields and lower in intermittently flooded fields (Yan *et al*., 2003).

There is a difference between rice fields in Indonesia and Thailand. In Indonesia, rice fields are mainly irrigated or rainfed, while in Thailand, rice fields are found in three forms: rainfed, irrigated, and deepwater. Emission measurements taken in five regions of Thailand showed values of 45.98, 32.45, and 15.5 mg CH_4 m^{-2} h^{-1} in irrigated, rainfed, and deepwater rice fields, respectively (Yan *et al*., 2003).

Along with Indonesia and Thailand, Vietnam is also a major rice producer in Southeast Asia and the third largest rice exporter in the world (Wassmann *et al*., 2004), with a rice cultivation area of about 6.7 million hectares in 1995 (Yan *et al*., 2003). Extensive rice cultivation in Vietnam, particularly in the Mekong Delta, is a significant source of methane emissions. Similarly, the Philippines has increased rice production to meet the needs of its growing population of 70 million people (Corton *et al*., 2000). Yan *et al*. (2003) reported that methane emissions from irrigated rice fields in the Philippines were estimated to be 7.69 mg CH_4 m^{-2} h^{-1}, while emissions from rainfed rice fields were 4.0 mg CH_4 m^{-2} h^{-1} during one growing season.

In general, methane emissions in the Southeast Asia region are primarily influenced by factors such as water management, organic matter inputs, soil type and texture, rice varieties, and fertilization. Paramitha (2023) notes that proper irrigation management, selection of rice varieties, soil types, and cultivation practices can significantly affect methane emissions from rice fields.

3.3. Methane emissions in South Asia region

South Asia also contributed significantly to methane emissions, with India accounting for 5.88 Tg CH_4 yr^{-1} of the total emissions of about 25.1 Tg CH_4 yr^{-1} for East, Southeast, and South Asia in 1995. Like Indonesia, approximately half of India's rice fields are irrigated, while the rest are rainfed or upland rice fields (Yan *et al*., 2003). Despite having the largest cultivation area in the world, India's methane emissions are lower than China's due to less extensive irrigation and rainfall. In contrast, Bangladesh, which predominates rainfed rice fields (with only 22% irrigated), has relatively high methane emissions (Wassmann *et al*., 2000; Yan *et al*., 2003). With 100% of its rice fields irrigated in 1991 (Wassmann *et al*., 2000), Pakistan emits approximately 200 kg CH_4 ha^{-1}. In Pakistan, irrigated rice fields contribute over 70% of methane emissions, while rainfed rice fields account for only 27.5% (Yan *et al*., 2003).

4. Discussion

There has been extensive research on methane emissions from rice fields in Asia. The most common topic, summarized in Table 1, is the impact of water management practices. This research focuses on how different water regimes, such as continuous flooding, intermittent drainage, and pulse irrigation, affect methane emissions in various locations. Other common themes include soil types and management, cultivation techniques and crop management, and rice varieties. These recurring themes suggest that water and soil management and rice variety selection are key areas of focus for methane research related to rice production in Asia. Table 1 provides an overview of some of this research.

In Japan and Indonesia, extensive research has been conducted on water management strategies to reduce methane emissions. Studies ranging from one crop cycle to three years have shown that intermittent drainage significantly reduces emissions (Setyanto and Bakar, 2005; Hadi *et al*., 2010; Itoh *et al*., 2011; Nishimura *et al*., 2020).

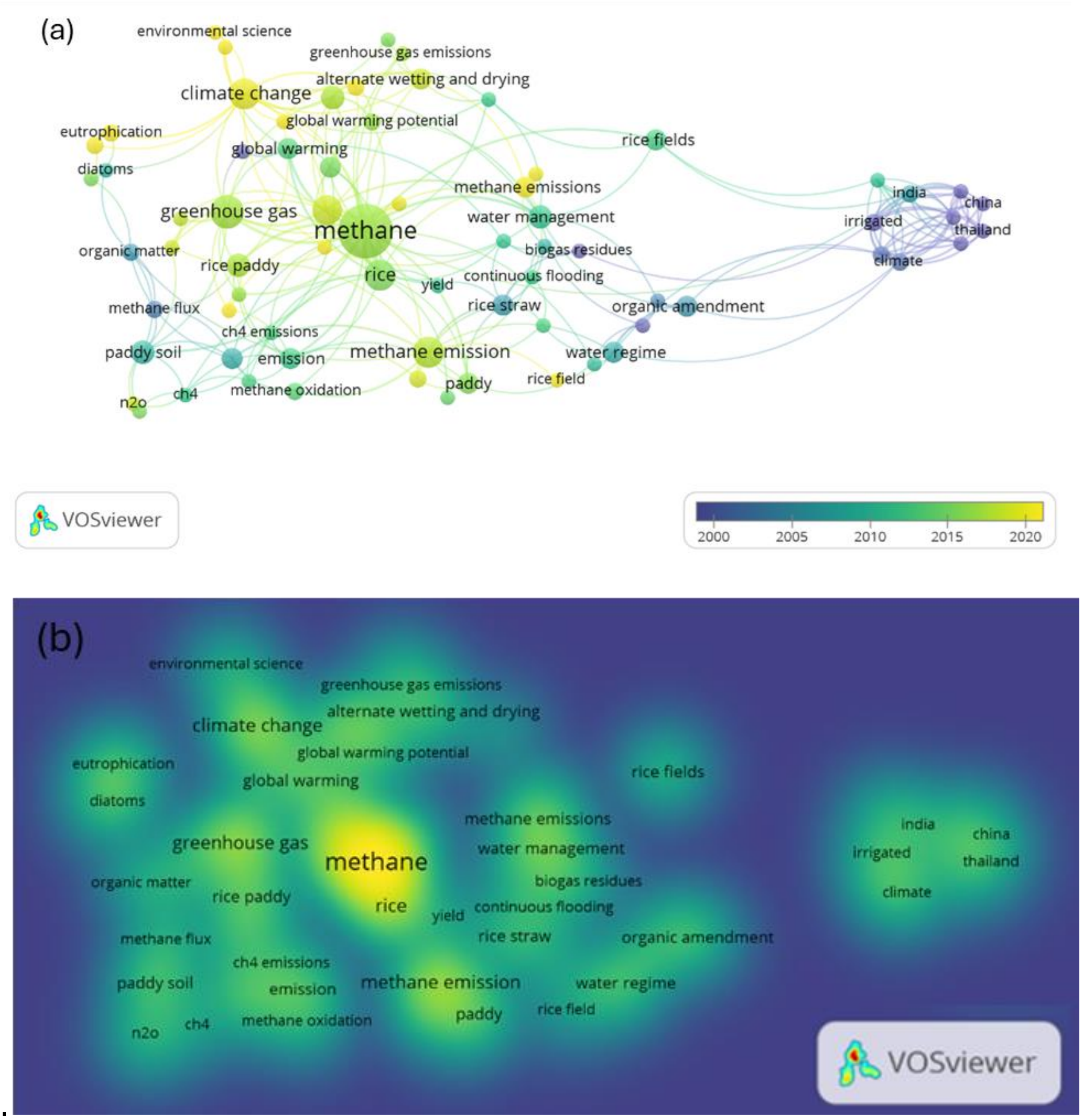

Figure 3. (a). Methane research topic overlay visualization; (b). Methane research topics density visualization through VOS viewer.

Variation in cultivation techniques has been extensively studied in South Korea, China, India, and Indonesia. The studies ranged from 250 days in South Korea to 25 years in China. Results indicate that in South Korea, practices such as avoiding plowing, applying rice straw during cultivation, and using conventional tillage during the fallow period significantly reduce methane emissions (Choi *et al*., 2019; Gwon *et al*., 2022). In Indonesia, direct seeding and rainfed rice fields have lower emissions, whereas alternating water and dry irrigation reduce emissions in India. However, continuous irrigation increases emissions in Indonesia and India (Setyanto *et al*., 2000; Oo *et al*., 2018). Research on rice varieties conducted in India, China, South Korea, and Indonesia, ranging from one cultivation cycle to two years, also contributes to this body of knowledge (Setyanto, 2006; Gogoi *et al*., 2008; Qin *et al*., 2015; Lim *et al*., 2021; Chandrasekaran *et al*., 2022)

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Table 2. Several methane research in several Asian countries

Factors	Location	Peak of methane emission		Research Period	References
		Highest (kg ha^{-1})	Lowest (kg ha^{-1})		
Water regime/ water management	Japan	**786** (Conventional without intermittent drainage)	**31** (Front-loaded Midseason Drainage)	2 years (2008-2009)	(Itoh *et al.*, 2011)
	Japan	**186** (Continuous flooding in light clay soils)	**1** (Intermittent draining in heavy clay soils)	3 years (2016-2018)	(Nishimura *et al.*, 2020)
	Indonesia	**254** (Continuous flood)	**96** (Pulse irrigation)	70 days (March-June)	(Setyanto and Bakar, 2005)
	Indonesia and Japan	**In Indonesia:** **1,585** (Continuous flood + local rice) **In Japan:** **634.2** (Continuous flood in alluvial soils)	**In Indonesia:** **1,065** (Intermittently drained + local rice) **In Japan:** **167.0** (Intermittently drained in peat soils)	One cultivation period (142 days in Indonesia; 125 days in Japan)	(Hadi *et al.*, 2010)
	Indonesia	**303.08** (Wet season with continuous flooding + normal tillage) **255.24** kg $h^{-1}season^{-1}$ (Dry season with continuous flooding + normal tillage)	**61.54** (Wet season with saturated + no tillage 3 L h^{-1} sulfosate) **23.69** kg $h^{-1}season^{-1}$ (Dry season with intermittent + no tillage 3 L h^{-1} paraquat)	85 days per season Wet season (November-March) Dry season (April-July)	(Naharia *et al.*, 2018)
	China	**556.8** (Continuous flooding) **182.6** (Modern Japonica single crop cultivation) **179** (Pig manure)	**216.6** (Intermittent) **89.1** (Japonica hybrid early cultivation) **52.5** (Biogas residue)	3 years (April-July and July-November 1995-1998)	(Lu *et al.*, 2000)
Cultivation technique/ crop management	South Korea	**1071.7** (spring plowing after spring spreading rice straw)	**206.5** (without plowing and rice straw application)	2 years (May-October, each year)	(Choi *et al.*, 2019)
	China	**457.74** (Single crop rice)	**276.6** (Double crop rice)	25 years (1990-2015)	(Jiang *et al.*, 2023)

Table 2. Cont.

	India	**0.06** (Old seedlings, narrow spacing, and continuous flooding)	**0.021** (In between two planting methods- alternate wetting and drying irrigation)	9 months (May-January)	(Oo *et al.*, 2018)
	Indonesia	**2.17** (Dry season, irrigation, prilled urea)	**0.19** (Wet season, rainfed, IR-64, direct seeded)	6 years (1993-1998)	(Setyanto *et al.*, 2000)
	Japan (in mineral soil over peatland)	**1160** (Single drainage + 751 g m^{-2} rice straw application)	**253** (Continuous flood + 277 g m^{-2} soybean stover)	5 months (May-September)	(Naser *et al.*, 2018)
	Indonesia	**0.00063** (Steel slag + compost, 15 cm depth)	**0.00007** (Steel slag + compost, 35 cm depth)	1 month (March)	(Susilawati *et al.*, 2016)
Rice varieties	India (in rice field)	**0.055** (IR-36 cultivar)	**0.083** (Monohar Sali cultivar)	6 months (June-November)	(Gogoi *et al.*, 2008)
	India (in rice field)	**0.446** (vegetative stage CO 45 cultivar)	**0.001** (maturity stage of ADT 39 and ADT 45 cultivar)	120 days for ADT 39 and ADT 45; 135 days for CO 45 (1 cultivation season).	(Chandrasekaran *et al.*, 2022)
	China (in rice field)	**0.82** (Huangxiuzhan cultivar)	**0.0245** (Qihuazhan cultivar)	2 years	(Qin *et al.*, 2015)
	South Korea (in rice field)	**475** (Junam cultivar)	**318** (Ilmi cultivar)	130 days (1 cultivation season).	(Lim *et al.*, 2021)
	Indonesia (in irrigation and rainfed rice fields)	**218** (Cisadane cultivar)	**74** (Dodokan cultivar)	100 days for dodokan. 130 days for Cisadane. (1 cultivation season).	(Setyanto, 2006)
Soil types	China (in peatland and gley marsh)	**0.607** (peatland)	**0.375** (gley marsh)	4 months (June-October)	(Zhu *et al.*, 2018)
	Indonesia	**135** (Inceptisol during dry season) **335** (Inceptisol during rainy season)	**4.99** (Vertisol during dry season) **3.10** (Vertisol during rainy season)	February -July (dry season) October – January (rainy season)	(Susilawati *et al.*, 2015)

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According to the bibliometric analysis using the VOSviewer, which analyzed various journals with keywords related to methane, climate change, rice, greenhouse gases, and other relevant topics, the main research focus from 2000 to 2024 is on methane emissions in rice production about climate change. In the visualization, yellow nodes represent more recent research topics (around 2020-2024) and explore specific mitigation practices like alternate wetting, drying, and organic amendments, suggesting that research is evolving toward solution-oriented approaches. Blue nodes indicate older topics (early 2000) and seem focused on methane flux, greenhouse gases, and climate change. Larger nodes correspond to terms that are mentioned more frequently in the dataset (Fig. 3a). Strong links between methane, rice, and greenhouse gases reflect their conceptual interdependence. The connections between organic amendment and methane emissions reflect the growing interest in sustainable agricultural practices to reduce emissions. This map suggests that the field is evolving from basic emission measurements to applied research focusing on mitigation strategies, with a strong regional focus on major rice-producing countries in Asia.

The second image (Fig. 3b) represents a density visualization where bright yellow areas indicate high research activity, while green and blue areas represent less focus according to the database. Methane and rice are shown as the densest areas, marking them as key research topics. Methane emission and greenhouse gas also have high densities, reflecting their critical importance in methane-related studies. Climate change, water management, and alternate wetting and drying are clustered nearby, suggesting that water management practices (like alternate wetting and drying) are actively evolving and climate-related aspects are integral to the research. Conversely, organic matter, methane oxidation, eutrophication, diatoms, and N_2O have lower densities, indicating that these topics, while still important, are less central compared to others. Some potential insights such as water management, sustainability practices such as biogas residues and organic amendment, multi-GHG interactions, and geographical research represent promising opportunities for further research.

5. Conclusion

This comprehensive review focuses on current research trends related to methane emissions from rice fields in East, Southeast, and South Asia, where most rice is grown. Extensive irrigated rice fields dominate East Asia, whereas Southeast Asia has a greater diversity of rice production systems. The study aimed to examine the role of diverse agricultural practices, such as irrigation methods and rice variety selection, in influencing methane emissions, with particular attention to major contributors like China and Indonesia. Practices such as intermittent drainage and pulse irrigation have been shown to be effective in reducing emissions, whereas continuous irrigation tends to increase emissions. Other critical factors influencing emissions dynamics include rice variety and soil management.

While this review highlights effective mitigation practices such as intermittent drainage and pulse irrigation, it also acknowledges the limitations of current research. Significant gaps remain in understanding the full impact of emerging factors such as alternative rice varieties, innovative organic soil amendments, and less commonly studied rice ecosystems such as rainfed and peatland fields. Addressing these gaps is critical for developing comprehensive strategies for managing methane emissions from rice fields. The integration of methane research with climate change studies reveals a growing emphasis on how climate variability affects methane emissions. This intersection highlights the need for adaptive management practices to mitigate emissions under changing climate conditions.

Despite these challenges, this review emphasizes the need for continued and expanded research in underexplored areas and highlights the importance of targeted strategies to reduce methane emissions from rice fields. The findings also highlight the critical need for localized and regionally specific approaches to managing methane emissions in rice fields, particularly in areas where variability in agricultural systems and climate conditions persist.

Future research should focus on innovative practices and technologies and address regional variability in emission factors. The broader application of such research will be crucial for reducing methane emissions and aligning rice production with global climate goals, thereby contributing to a more sustainable agricultural future. In addition, it will help develop more effective and localized mitigation strategies.

Data availability statement

Data will be made available on request.

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Conflict of interest

The author claimed there is a conflict of interest.

Author contribution

IGAAP: Conceptualization, Writing-original draft, Methodology, Investigation, Data curation, and Writing – review & editing.

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