# Trends and research features on greenhouse gas emissions from rice production: review based on bibliometric analysis

**Article** *in* Environmental Science and Pollution Research · September 2022

DOI: 10.1007/s11356-022-22921-0



**4 authors**, including:

Coffi Leonce Geoffroy Sossa
West African Science Service Center on Climate Change and Adapted Land Use (W…


Souleymane Sanogo
University of Sciences, Techniques and Technology of Bamako

Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-022-22921-0

REVIEW ARTICLE

# Trends and research features on greenhouse gas emissions from rice production: review based on bibliometric analysis

Coffi Leonce Geoffroy Sossa[1,2] · Souleymane Sanogo[3] · Jesse B. Naab[4] · Luc O. Sintondji[2]

Received: 15 March 2022 / Accepted: 3 September 2022


## Abstract

Greenhouse gas from rice production has become a great concern and the focus of a lot of research in recent years. The main aim of the study was to explore the research trend of GHG emissions from rice production by exploring the research hotspots and providing suggestions for future research directions over the period 1991 to 2020. A bibliometric analysis was conducted using the Scopus database, and the sample included 2535 articles. The methodology was based on descriptive analysis, co-occurrence analysis, factorial analysis, word dynamic over time, and the author's keyword analysis over time. The results indicate a remarkable increase in the number of articles published on this topic, mainly in the journals of "Agriculture," "Ecosystems," and "Environment." The main authors were Conrad R. and Wassmann R. Relating to the number of published articles, very few were contributed by African countries, whereas China, Japan, and India were the main contributors. The co-occurrence analysis showed that rice, methane, and nitrous oxide are the core keywords of the network. The multiple factorial analysis pointed out that greenhouse gas emissions from rice production depend on the farming practices, the environmental factors, and the plant growth as well. The evolutionary path showed that the current author's keywords are more related to global warming potential, climate change, and biochar. The findings of this review can help researchers and scholars by providing a better overview of development trends that have emerged over the past 30 years and suggestions for the future direction in this field.

**Keywords** Bibliometric analysis · Greenhouse gas · Climate change · Rice

## Introduction

Rice, a nutritious staple cereal, is critically important for global food security (GRISP 2010; Islam et al. 2020). Rice farming is a major contributor to methane and nitrous oxide emissions and can also be a source or sink of carbon dioxide ($CO_2$) (IPCC 2007). According to the Global Rice Science Partnership, global rice consumption is projected to increase to nearly 550 Mt by 2030. To face this dual challenge of satisfying the projected food demands of the population while overcoming issues such as climate change and greenhouse gas (GHG) emissions, different cropping patterns and management intensities have been developed (FAO 2009; IPCC 2007). However, these different agricultural practices that include the use of irrigation water and fertilizer application are qualified as a source of GHG emissions, mainly methane and nitrous oxide in the atmosphere (Ku et al. 2017). During the last century, it has become evident that there has been a major increase in the use of nitrogen fertilizers in rice agriculture, thus

Responsible Editor: Philippe Garrigues.

✉ Coffi Leonce Geoffroy Sossa
sogeof1992@gmail.com

1 West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) - Graduate Research Program on Climate Change and Agriculture, Université des Sciences, des Techniques et des Technologies de Bamako (USTTB), BP E 423, Bamako, Mali

2 Laboratoire d'Hydraulique et de Maîtrise de l'Eau (LHME), Institut National de l'Eau (INE/UAC), Université d'Abomey-Calavi, 01 BP 526, Abomey-Calavi, Benin

3 Faculté des Sciences et Techniques (FST), Université des Sciences, des Techniques et des Technologies de Bamako (USTTB), BP E 423, Bamako, Mali

4 West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), Competence Center, 06 BP 9507 06, Ouagadougou, Burkina Faso

Published online: 14 September 2022

making rice fields a potentially significant source of man-made GHG as well. Methane and nitrous oxide combined makeup 25% of global warming and both are included in treaties such as the Kyoto Protocol to reduce global warming (Aslam and Khalil 2009). The global warming potential from rice fields is 467 and 169% higher than other crops like wheat and maize (Linquist et al. 2012). Rice production has attracted much attention in recent years from many organizations and researchers around the world since it plays a critical role in achieving food security while being a source of environmental pollution. Many studies conducted on the GHG emissions from rice cultivation have covered many aspects, from field measurements to emission reduction measures. However, there are very few studies that have tried to answer the key following questions: (1) which subject category is the most popular in the fields of GHG emissions from rice production? (2) Which country is the most contributor to research related to GHG from rice production? (3) Which journal and author are most representative of the research related to GHG from rice production? (4) What are the hotspots commonly researched in this field and how have they developed over time? Giving answers to these concerns are important to provide a comprehensive insight into the field of GHG emission from rice production, which will help scholars to decide where to focus their current and future research. In addition, GHG emission from rice production is an interdisciplinary research field, covering many disciplines including agriculture, environmental science, ecology, soil science, atmospheric science, and economics (Peng 2017). Regarding the interest and development of this research field, it is still very difficult to effectively organize, summarize, and quantitatively analyze the development of this topic for the several studies that have been conducted in different aspects and regions over the world. To create a comprehensive and better overview of these studies, bibliometric analysis is needed.

Bibliometrics is a mathematical and statistical approach to analyzing pertinent literature and understanding global research trends in a specific area to evaluate the results of scientific research (Glänzel 2003). Although over time, the use of bibliometrics has been extended by many researchers to all disciplines (Guler et al. 2016). Numerous studies have shown the importance of rice production systems in relation to the emission of greenhouse gases (Glänzsel 2003; Huang et al. 2017; Islam et al. 2020). This research field can be grasped by examining recent papers using bibliometric analysis. Using a bibliometric approach, this article analyzes the relevant literature specializing in GHG emissions from rice production using the Scopus database for the period covering 1991 to 2020. It explores the research trend of GHG emissions from rice production by exploring the research hotspots and providing suggestions for future research direction. Therefore, the goals of this study include the following:

(1) Performing a descriptive analysis of the characteristics of articles concerning GHG emissions from rice production over the period from 1991 to 2020.
(2) Identifying the main authors' keywords during the study period.
(3) Investigating the research topics and changing trends in research hotspots over time.
(4) Identifying possible opportunities for future research.

## Methods and materials

### Data sources

The bibliometric analysis was carried out by selecting papers indexed by the Scopus database, using the advanced search to define the field of interest. Scopus, widely used to create datasets for systematic reviews of research, is also the largest abstract and citation database of peer-reviewed literature (Mongeon and Paul-Hus 2016). It is a typical online academic database that has a great impact on academic literature due to its access to a wide range of journals and sources in all kinds of knowledge areas (Baas et al. 2020). Compared to other scientific databases such as the Web of Science, Scopus has a broader coverage and presents a better option for a research review and numerous reviews have also been used for the bibliometric analysis (Falagas et al. 2008; Vatananan-Thesenvitz et al., 2019). In this study, the retrieval strategy was TITLE (Rice) AND KEY (GHG OR GWP OR CO2 OR CH4 OR NO2 OR "Greenhouse gas*" OR "Global Warming Potential" OR "Carbon dioxide" OR " Methane " OR "Nitrous Oxide"). We selected "article" from the document types and "English" as a language option. Accordingly, the data span of this study is from 1991 to 2020. In addition, a preliminary screening was carefully done in terms of removing duplicate articles and articles without the names of the authors. In total, 3062 articles were initially found and 2535 publications were finally selected on April 16, 2021. The dataset extracted from Scopus for the bibliometric analysis was downloaded as bib (BibTeX Bibliographical Database) file. These extracted data comprised much information such as the author's name, author affiliation, article title, keywords, abstracts, and multiple citations. The data. Bib file format is used with the statistical tool R using Bibliometrix.

### Bibliometric tools based on R language

Bibliometrics is a quantitative analysis of the distribution of scientific papers by using mathematical statistics technology

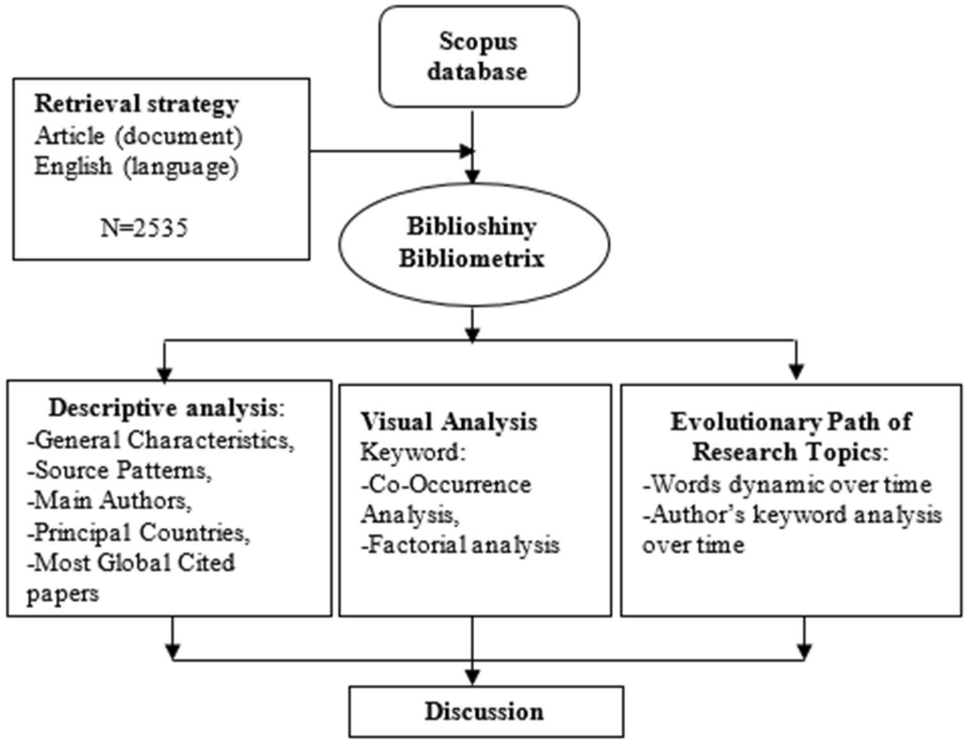



**Fig. 1** Flow chart of the methodology

(Aria and Cuccurullo 2017). Biblioshiny, the shiny interface for the Bibliometrix package from R version 3.6.3, was used for this study. The inputs were the downloaded papers from Scopus datasets. This tool was used to characterize the descriptive analysis, the Visual analysis, and Evolutionary Path of Research Topics over the study period (Fig. 1). More details about Biblioshiny for Bibliometrix can be found here: https://www.bibliometrix.org/Biblioshiny.html.

## Results

### Descriptive analysis

#### General characteristics of the bibliometric analysis

General overview information regarding the data used for this study is presented in Table1.

As revealed in Table 1, Scopus database search output was 2535 publications for the period from 1991 to 2020. These papers have been established by 6131 authors and published in 549 sources with an average number of years from the publication of 9.37. Figure 2 shows the number of publications' repartition over the study period; the curve presents the cumulative publication number. It highlighted an increase in the number of publications from 1991 to 2020.

The cumulative number of publications showed an ascending trend. It could be separated into main phases according to the trend of the plot cumulative number of publications. The first phase spanned from 1991 to 2011. The second one, which had a high rate of increase than the first phase, ranged from 2012 to 2020. However, the period of 2001–2010 was remarkably characterized by less significant increasing numbers of publications.

**Table 1** The main information about the analyzed articles based on our keyword research

| Description | Results |
|---|---|
| Timespan | 1991:2020 |
| Sources (journals, books, etc.) | 549 |
| Documents | 2535 |
| Average years from publication | 9.37 |
| Average citations per documents | 33.76 |
| Average citations per year per doc | 3.326 |
| References | 39,681 |
| Keywords Plus (ID) | 10,472 |
| Author's keywords (DE) | 4928 |
| Authors | 6171 |
| Author appearances | 13,526 |
| Authors of single-authored documents | 40 |
| Authors of multi-authored documents | 6131 |
| Single-authored documents | 41 |
| Documents per author | 0.411 |
| Authors per document | 2.43 |
| Co-authors per documents | 5.34 |
| Collaboration index | 2.46 |

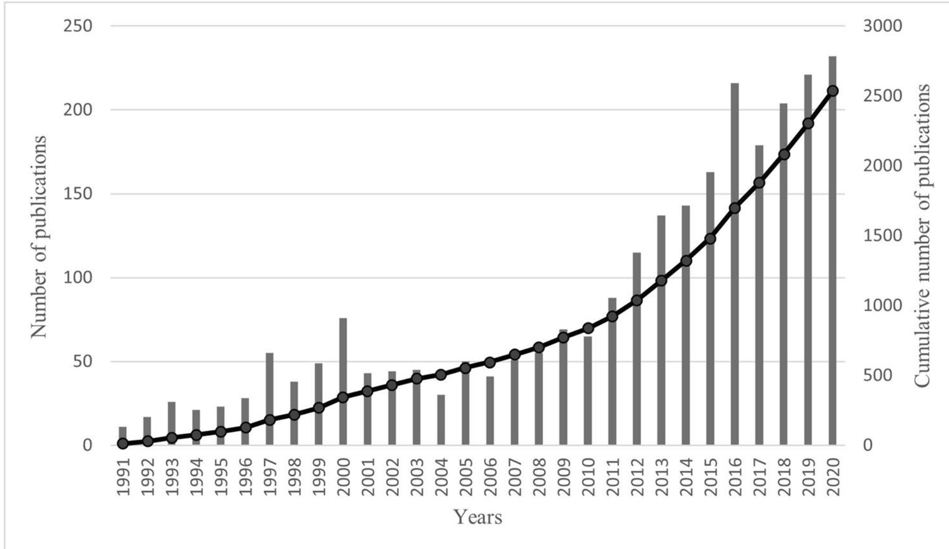



**Fig. 2** Annual evolution and the cumulative distribution of the number of publications over the study period

**Table 2** Journals' classification based on their impact

| Source | *h*-Index | Total citations | Start year |
|---|---|---|---|
| Agriculture, Ecosystems, and Environment | 41 | 4795 | 1994 |
| Nutrient Cycling in Agroecosystems | 35 | 2977 | 1997 |
| Science of the Total Environment | 23 | 1380 | 2000 |
| Bioresource Technology | 34 | 3240 | 1995 |
| Plant and Soil | 31 | 2997 | 1991 |
| Global Change Biology | 38 | 4314 | 1997 |
| Journal of Cleaner Production | 20 | 1165 | 2012 |
| Biology and Fertility of Soils | 29 | 2654 | 1991 |
| Field Crops Research | 27 | 2433 | 1997 |
| Soil Biology and Biochemistry | 27 | 2452 | 1994 |
| Soil Science and Plant Nutrition | 18 | 1069 | 1992 |
| Environmental Science and Pollution Research | 12 | 412 | 2015 |
| Atmospheric Environment | 18 | 1113 | 1999 |
| Global Biogeochemical Cycles | 26 | 3217 | 1991 |

## Source patterns

A total of 2535 scientific papers have been published for the period from 1991 to 2020 in 549 sources.

The *h*-index is a specific index that refers to the number of published papers that have been cited at least *h* times (Bertoli-Barsotti and Lando 2017). As displayed in Table 2, "Agriculture, Ecosystems, and Environment" and "Nutrient Cycling in Agroecosystems" were the two most relevant and top-ranked sources with the highest *h*-index (41 and 35 articles, respectively) and total citations (4795 and 2977, respectively). The "Science of the Total Environment" journal occupied third place with 23 cited articles and 1380 citations.

**Table 3** Top 10 of the most relevant authors

| # | Author | *h*-Index | $T_c$ | $N_p$ | Py_Start |
|---|---|---|---|---|---|
| 1 | Conrad R | 48 | 6250 | 78 | 1991 |
| 2 | Wassmann R | 40 | 4273 | 77 | 1992 |
| 3 | Wang Y | 26 | 2081 | 61 | 2000 |
| 4 | Zhu J | 29 | 2190 | 67 | 2002 |
| 5 | Zhang X | 22 | 2133 | 54 | 2007 |
| 6 | Li Y | 21 | 1400 | 43 | 2007 |
| 7 | Kim P. J | 22 | 1121 | 46 | 2008 |
| 8 | Yagi K | 26 | 3093 | 46 | 1994 |
| 9 | Zhang Y | 16 | 973 | 44 | 2001 |
| 10 | Hasegawa T | 24 | 1697 | 44 | 2006 |

## Main authors

The authors' information presented a sight for the identification of key authors and countries in the field of greenhouse gas from rice production. Table 3 summarizes the author's productivity characterized by the $h$-index, total citations ($T_c$), number of publications ($N_p$), and year of first publication (Py_Start) for the study period.

In terms of the $h$-index, Conrad R. has the largest influence, with an index value of 48, followed by Wassmann R. and Zhu J., who have a value of 40 and 29, respectively. Regarding the number of citations, the first two places are occupied by Conrad R. and Wassmann R., with 78 and 77 articles, respectively. The third one is Wang Y., who has contributed to 68 articles. Figure 3 shows the authors' production over time. The volume and the color depth of the sphere are related to the annual number of article citations. It confirms that Conrad R. and Wassmann R. have the largest number of publications over the years. Also, it shows that high-yield authors in the database published many

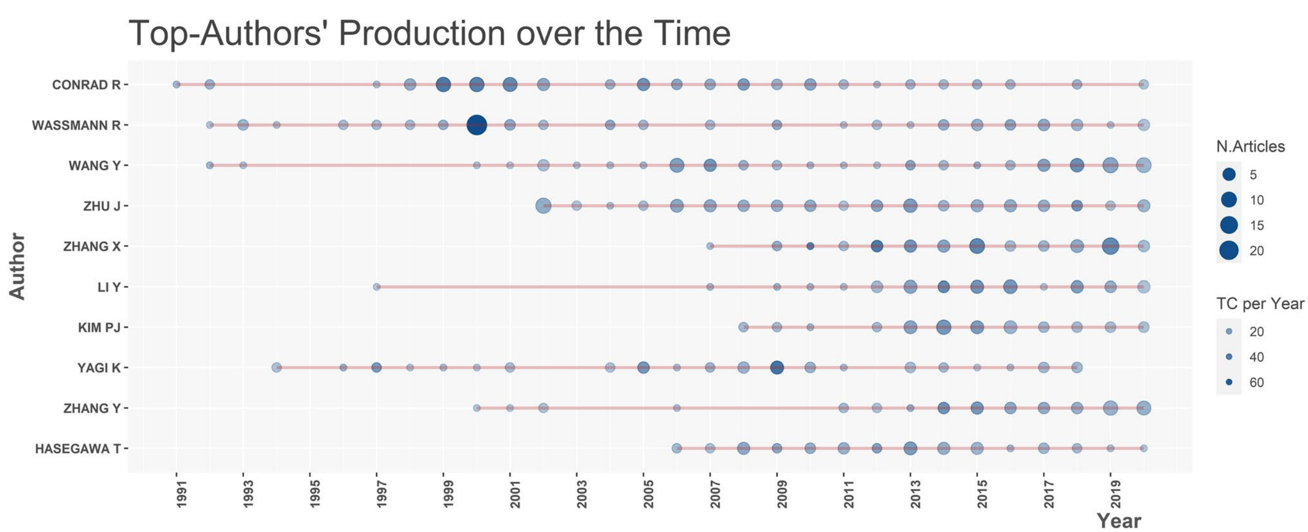



Fig. 3 Authors' production over time

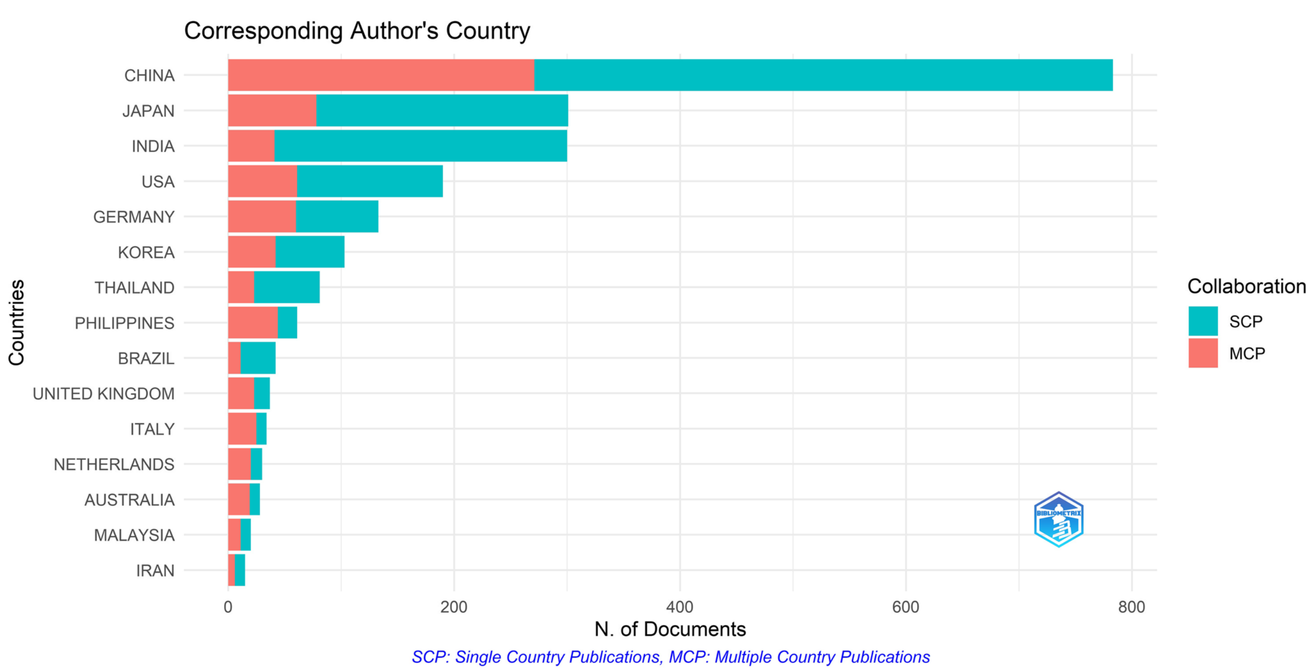



Fig. 4 Top 15 countries of study's authors

articles. This is one of the pieces of evidence that studies of GHG emissions from rice cultivation have gained much attention during the period from 1991 to 2020.

### Principal countries

The publication of papers in different countries can generally reflect the influence and importance of a given topic. Seventy-seven countries are involved in this study. Figure 4 describes the top 15 countries where authors collaborated inside the same country: single-country publications (SCP) and between countries: multiple-country publications (MCP). The number of total articles is the sum of SCP and MCP.

China is in the first position with 783 publications, representing around 33.76% of the total published papers (domestic and international), followed by Japan with 301 articles, representing 12.97% of the total publications. Single-country publications dominate the selected set of documents. China is far ahead of other countries in terms of multiple-country publications (272 articles), which partly reflects the fact that China is more active in the field of greenhouse gas emissions from rice production. Regarding the average citation quantity of the articles, Italy and the Philippines have the highest multiple-country publication ratios (0.735 and 0.7121, respectively). Most of the top 15 countries are developed countries, and none of them is from Africa. Country scientific production is presented in Fig. 5. The higher number of articles published in terms of frequency is materialized by the darker blue. The different clusters illustrate the differences in studies related to GHG emissions from rice production experienced by each country. Most of the articles are published in Asia, America, and Europe. Only 14 African countries were involved out of the 77 countries considered in this study. The most contributable African country is Egypt, with 31 papers. This result also shows the scarcity of research on GHG emissions from rice production in Africa's countries. A lot of work remains to be done in this perspective since rice is one of the major staple foods in Africa.

### Most global cited papers

The commonly cited references of a specific research area can reveal the knowledge base of this field (Marx et al.

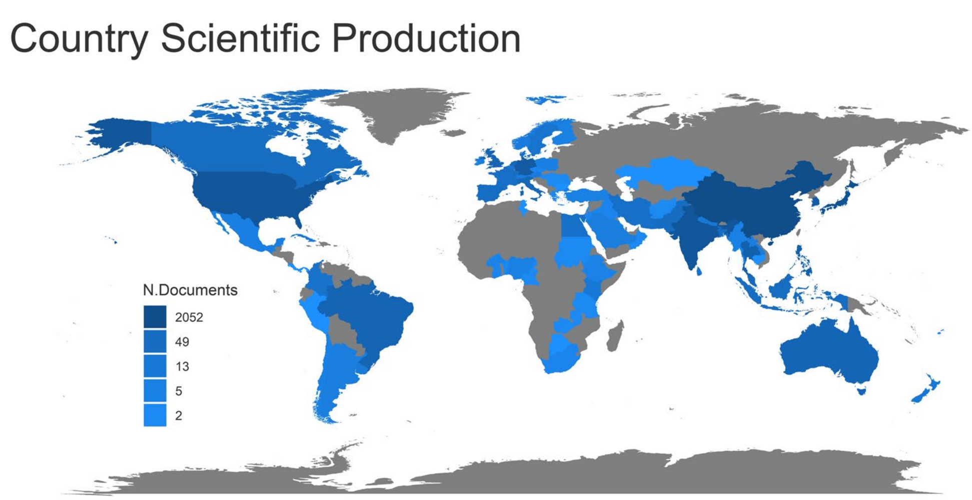



**Fig. 5** Country scientific production

**Table 4** Ten global cited documents dealing with greenhouse gas from rice production over the period from 1991 to 2020

| # | Paper | Journal | Year | Total citations |
|---|---|---|---|---|
| 1 | Edwards J | Proceedings of the National Academy of Sciences—USA | 2015 | 795 |
| 2 | Zou J | Global Biogeochemical Cycles | 2005 | 530 |
| 3 | Zhang A | Agriculture, Ecosystems, and Environment | 2010 | 500 |
| 4 | Cai Z | Plant and Soil | 1997 | 496 |
| 5 | Toan T. L | Geoscience and Remote Sensing | 1997 | 490 |
| 6 | Bodelier P | Nature | 2000 | 365 |
| 7 | Zhang A | Field Crops Research | 2012 | 360 |
| 8 | Wu W | Biomass Bioenergy | 2012 | 348 |
| 9 | Shang Q | Global Change Biology | 2011 | 325 |
| 10 | Wang Z. P | Soil Science Society of America Journal | 1993 | 312 |

2017). Table 4 presents the 10 global cited documents dealing with greenhouse gas from rice production over the period from 1991 to 2020.

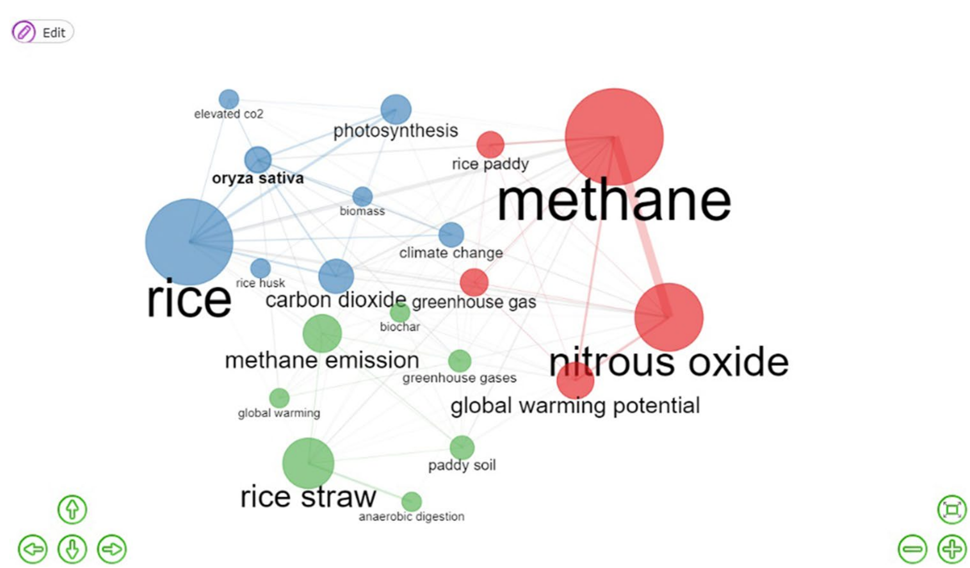
The publications by Edwards et al. (2014) discussed the structure, variation, and assembly of the root-associated microbiomes of rice. In this study, the authors confirmed that rice cultivation is a major source of global methane emissions and that cultivation practices are part of the key factors contributing to microbiome variation. The paper by Zou et al. (2005) emphasized the field measurement of methane and nitrous oxide emissions from rice paddies in China as affected by different agricultural management practices. The outputs of this research indicated that water management by flooding with midseason drainage and frequent waterlogging without the use of organic amendments is an effective option for mitigating $CH_4$ and $N_2O$ emissions from paddy rice production. Zhang et al. (2010) investigated the yield and methane and nitrous oxide emissions from a rice paddy by applying biochar amendment. Results from this work revealed that biochar significantly increased rice yields and decreased $N_2O$ emissions but increased total $CH_4$ emissions. In addition, the authors drew attention to the potential reductions in GHG emissions that may be achieved by incorporating biochar into rice paddy soils. In their paper, titled "Methane and nitrous oxide emissions from rice paddy fields as affected by nitrous fertilizers and water management," Cai et al. (1997) showed that the flooded rice paddies emitted less $N_2O$ flux. Also, they suggested that it is important to evaluate the integrative effects of water management and fertilizer application for mitigating greenhouse gas emissions contributed by rice paddy fields. Le et al. (1997) used experimental and modeling results to establish rice crop mapping and monitoring using ERS-1Data. In this paper, they agree that the strong temporal variation of the radar response of rice fields is influenced by the wave-vegetation water interaction, which increases from the transplanting stage to the reproductive stage. Bodelier et al. (2000) evaluated the stimulation by ammonium-based fertilizers of methane oxidation in the soil around rice roots. The result of this research showed that fertilization can also enhance methane production due to higher plant biomass and subsequent carbon availability for methanogens. Most of the remaining papers discussed mainly the effects of different management practices on GHG emissions from rice production. For instance, Zhang et al. (2012) revealed that biochar application improves soil quality, decreases $N_2O$ emissions, and enhances crop productivity. Wu et al. (2012) pointed out that for improving soil quality, rice straw-derived biochar generated at 400 °C might be a better option.

## Visual analysis

### Keyword co-occurrence analysis

Analysis of keywords used by authors in publications is an important tool for investigating trending topics and scholars focus on the field (Song et al. 2019). It presents the correlation measures between words and reveals their appearance relationships (Abdallah et al. 2021). This study investigated the keyword co-occurrence network to gain further insight into the trends in the field of GHG emissions from rice production. Figure 6 identifies the keyword network related to rice production and greenhouse gas emissions. The color represents the cluster, and the thickness of the connecting line between nodes shows the strength level of the relationship between these keywords. In addition, the size of the node and the number of lines are proportional to the frequency of each keyword.

**Fig. 6** Keyword co-occurrence analysis



Three clusters were identified to represent different viewpoints on GHG emissions from rice production. The first cluster (red) indicated that the global warming potential of rice cultivation depends mainly on methane and nitrous oxide emissions. The second cluster (green) demonstrated that farming practices such as biochar and rice straw application can affect methane emissions from paddy soil. The third cluster (blue) highlighted the relationship between plant biomass and photosynthetic activities on $CO_2$ emissions from rice production.

### Factorial analysis

Multiple-correspondence analysis (MCA) displays a large amount of data in two-dimensional (or three-dimensional) graphics to reflect the similarity between them. It uses the conceptual structure–function to perform analysis to draw a conceptual structure of the field and *K*-means clustering (Aria and Cuccurullo 2017). Figure 7 presents the MCA of the high-frequency author's keywords. The keywords that have received more attention are those that are closer to the center of the graph and distributed in a more concentrated manner. However, those that are more evenly spread are related to less frequently discussed research topics or transitions to other topics.

The multi-correspondence analysis of keywords confirms what was presented in the keyword co-occurrence. However, studies on GHG emissions from rice production can be summarized into the following two major categories (depending on the clusters' colors). The first category (the red group) mainly highlights the relationship between different management practices (rice straw incorporation, biochar, rice husk, etc.) and greenhouse gas emissions (mainly methane and nitrous oxide) from rice production, which leads to global warming. The second category (the blue group) mainly focuses on the interaction between carbon dioxide emissions and rice production. For rice production, significant carbon dioxide is emitted from the soil and the rice plants as well. The emission from the plant depends on the growth stage (biomass, physiology) and the natural conditions of production (photosynthesis). Concerning the emissions from the soil, it is more related to elevated temperatures. Table 5 summarizes the most important articles that have contributed to each group.

## Evolutionary path of research topics

### Words dynamic over time

Words over time for a given subject show the changing rules, evolutionary relationships, paths, and trends of the content (Fig. 8).

Authors' keywords regarding studies related to GHG emissions from rice production have noticeably increased over the years. Two main periods were clearly identified. The first period was from 1991 to 2009, when the evolution trend was very low, and the second period was from 2010 to 2020, when the evolution trend was very fast. Over these sub-periods, the increase in the occurrence of the words "methane," "global warming potential," "rice straw," and "climate change" was noted. This showed that, during this second period, many studies were focused on global warming potential and climate change under different rice production management practices, such as the use of rice straw.

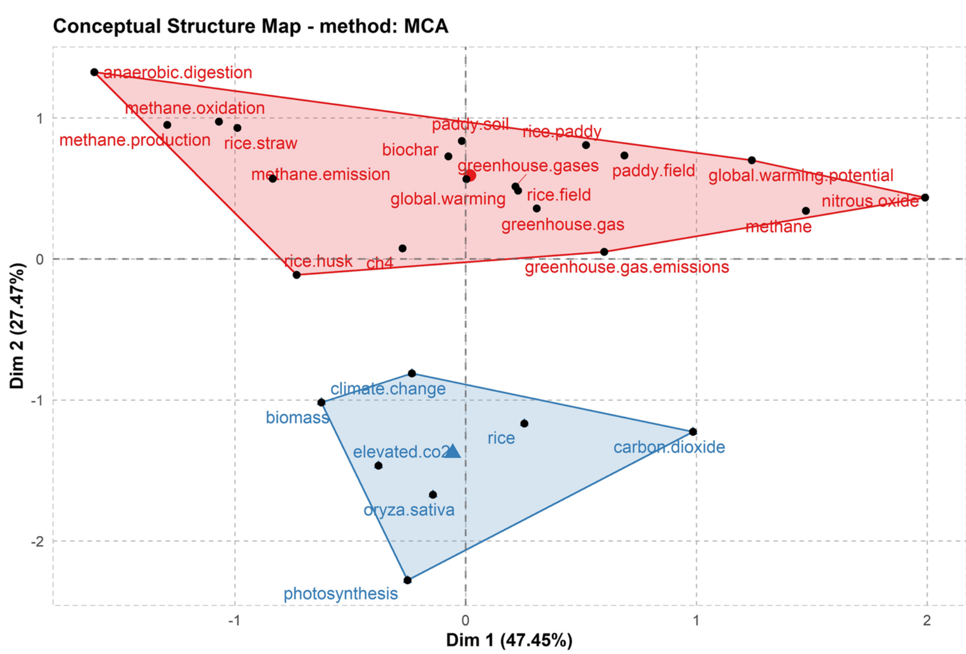



**Fig. 7** Multiple-correspondence analysis of high-frequency keywords

**Table 5** The most contributing papers

| # | Paper | Journal | Year | Group |
|---|---|---|---|---|
| 1 | Hussain S | Environmental Science and Pollution Research | 2015 | Red |
| 2 | Xu Y | Science of the Total Environment | 2015 | Red |
| 3 | Bhatia A | Greenhouse Gases: Science and Technology | 2012 | Red |
| 4 | Yao Z | Agriculture, Ecosystem, and Environment | 2012 | Red |
| 5 | Shang Q | Global Change Biology | 2011 | Red |
| 6 | Liu G | Environmental Pollution | 2012 | Red |
| 7 | Pathak H | Agricultural Systems | 2007 | Red |
| 8 | Ziska L | Plant Physiology | 1992 | Blue |
| 9 | Kanno K | Plant and Cell Physiology | 2017 | Blue |
| 10 | Aben S | Australian Journal of Plant Physiology | 1999 | Blue |
| 11 | Tsutsumi K | Plant & Cell Physiology | 2014 | Blue |
| 12 | Morita R | Plant & Cell Physiology | 2016 | Blue |
| 13 | Centritto M | Journal of Experimental Botany | 2009 | Blue |
| 14 | Vu J | Plant Physiology | 1998 | Blue |

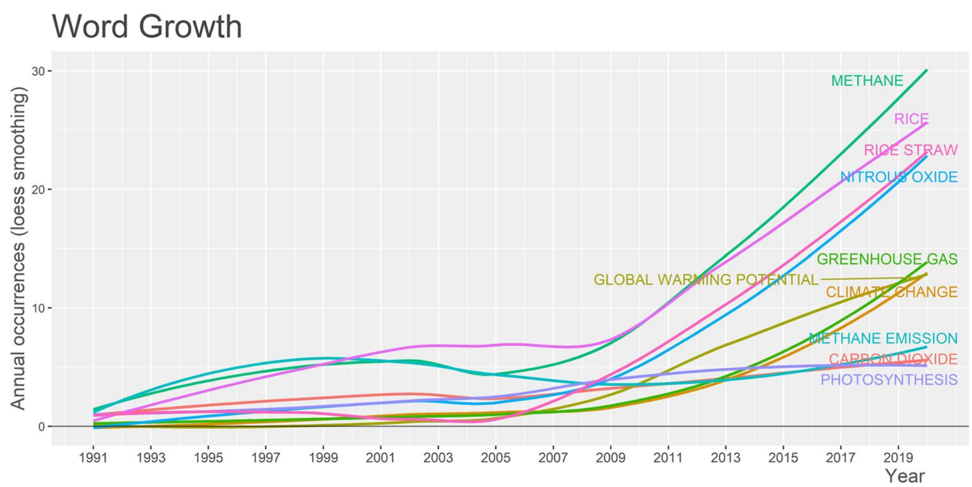



**Fig. 8** Change and evolution of keyword annual occurrence over time

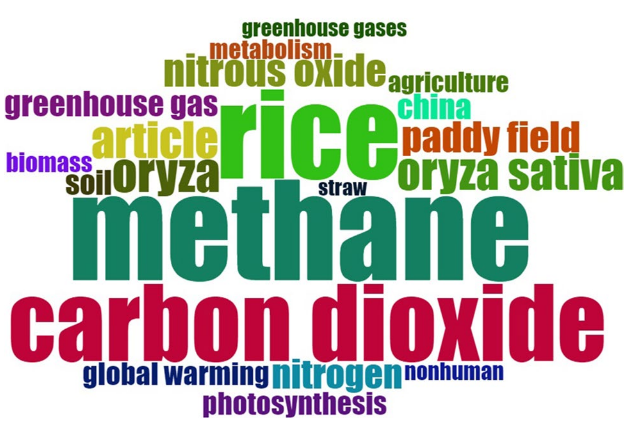



**Fig. 9** Word map of keywords

As displayed in the previous figure, Fig. 9 confirms that methane, rice, carbon dioxide, and nitrous oxide are always at the core of the analyzed research papers. The words "nitrogen," "soil," and "fertilizer application" are also present with importance in the world map of keywords. However, a relationship could be established linking GHG emissions and soil fertility management.

## Author's keyword analysis over time

The author's keyword analysis studies a theme's content and its evolutionary relations over time. In this paper, the evolution of the author's keyword over the three-decade study period is analyzed. Table 6 shows the 12 most frequently used keywords during each of the three decades, which can provide an overview of the evolution of the author's keywords during the study period. In terms of the use frequency, except for "rice" and methane, which are the most cited over the whole period, the first period from 1991 to 2000 is more focused on soil $CO_2$ emission using the keywords "carbon dioxide" (18 times), "paddy soil" (18 times), and "temperature" (13 times). The second decade, starting from 2001 to

**Table 6** The 12 most frequently used author's keywords during the three decades of the study period

| # | 1991–2000 | | 2001–2010 | | 2011–2020 | |
|---|---|---|---|---|---|---|
| 1 | Methane emission | 46 | Rice | 70 | Methane | 205 |
| 2 | Methane | 42 | Methane | 50 | Rice | 183 |
| 3 | Rice | 34 | Methane emission | 39 | Rice straw | 150 |
| 4 | Oryza sativa | 21 | Photosynthesis | 27 | Nitrous oxide | 143 |
| 5 | Methane production | 19 | Nitrous oxide | 25 | Global warming potential | 95 |
| 6 | Carbon dioxide | 18 | Carbon dioxide | 23 | Greenhouse gas | 74 |
| 7 | Paddy soil | 18 | Oryza sativa | 19 | Climate change | 69 |
| 8 | Methane oxidation | 15 | Free-air $CO_2$ enrichment | 18 | Biochar | 58 |
| 9 | Photosynthesis | 15 | Rice straw | 17 | Rice husk | 56 |
| 10 | Rice straw | 14 | Rice paddy | 15 | Rice paddy | 56 |
| 11 | Temperature | 13 | Yield | 15 | Greenhouse gases | 54 |
| 12 | Hydrogen | 12 | Elevated $CO_2$ | 14 | Carbon dioxide | 51 |

2010, is specifically related to the assessment of methane and nitrous oxide emissions from rice production and the introduction of rice straw as a soil management practice. It is focused on the following keywords: "photosynthesis" (27 times), "nitrous oxide" (25 times), "nitrous oxide (17 times), and rice straw (14 times). The last decade, from 2011 to 2020, used mostly the keywords global warming potential (95 times), climate change (69 times), "greenhouse gas" (74 times), and climate change (69 times), "biochar" (58 times), and "rice husk" (56 times). However, during this last decade, more scholars have begun to pay attention to climate change and global warming potential assessment from rice production as affected by different farming practices. Therefore, recent dynamic seems focus on climate change and different agricultural practices as the primary subject of GHG assessment from rice production.

## Discussion

Rice production is one of the major anthropogenic sources of greenhouse gas (GHG) emissions (Carlson et al. 2017; Kritee et al. 2018; Zhang et al. 2019). Research on greenhouse gas emissions from rice production has received much attention during the last three decades, with several annual publications, which have increased from 11 in 1991 to 232 in 2020. This increasing number of publications shows a trend of continuous growth, demonstrating that more and more researchers have paid attention to this research field. A total of 77 countries or regions have been published in that research field. Among these countries, Asia is more represented by China and Japan, which are headed by more published papers. China has a great interest in this research field because rice is a major food in the country and its agroecological conditions allow for large-scale rice cultivation (Peng et al. 2009). Most of the countries that have also contributed to this research field are from Europe and Asia, which is not the case for Africa. However, research on African rice cultivation systems is characterized by the limited availability of literature about GHG emissions in peer-reviewed journal publications (Boateng et al. 2017). In the same perspective, Das and Baruah (2008) and Eshun et al. (2013) agreed when they stated that the environmental impact of rice cultivation in Africa has not received much attention from the research community. In their paper related to available data on GHG emissions from sub-Saharan African natural and agricultural lands, Kim et al. (2016) found that only 2 out of 73 rice production studies related to this topic. Therefore, with all the above mentioned, more similar studies reinforce the need for continuous research and knowledge generation since rice cultivation contributes significantly to food security and employment in the world, especially in Africa.

Research on greenhouse gas emissions from rice production is a multi-disciplinary field that combines agriculture, ecosystems, the environment, bioresource technology, biochemistry, and plant and soil science. The evolution of the keywords over the study period revealed that rice production contributes methane, carbon dioxide, and nitrous oxide to the atmosphere. Among them, methane is the most emitted and contributes the most to global warming potential (GWP) (Le Mer and Roger 2001; Linquist et al. 2015). Dioxide carbon from rice production is emitted from the soil via autotrophic and heterotrophic respiration, as well as from the rice plants via photosynthetic activity. In addition, GHG emissions from rice production also depend on different agricultural management practices (rice cultivars, fertilizer application, water management, biochar, rice straw, etc.). However, these determinants have widely been recognized as the key factors that account for GHG emissions from rice cultivation systems, and it is through their manipulation that emissions could be reduced (Boateng et al. 2017).

The current direction of studies related to GHG emissions from rice production showed that more studies on GHG emissions are related to climate change and crop management practices. Indeed, the increase in temperature by 1.1 °C leads to an increasing concentration of greenhouse gases, which could affect rice yields by 10% (FAO 2009; Wang et al. 2018a, b). This reveals how rice production is affected by climate change and, therefore, adaptation and mitigation strategies need to be developed (Islam et al. 2020). In the future, rice cropping systems will need to combine increased rice yields with decreased GHG emissions. Several studies conducted by various authors and different regions in the world confirmed that management practices during the growing phase of rice cultivation affect GHG emissions (Wassmann et al. 2000; Aulakh et al. 2001; Islam et al. 2020). Rice varieties have been found in various field studies as one of the drivers of GHG emissions (Zheng et al. 2014). Several studies have confirmed variations in the emission levels of different rice cultivars (Eshun et al. 2013; X. Qin et al. 2015). In terms of water management practices, several studies indicated that alternate wetting and drying is one of the most promising approaches to reducing CH4 emissions by 48–93% compared to continuous flooding systems (Qin et al. 2010; Linquist et al. 2015; Sun and Yuan 2020) . In the same regard, Tarlera et al. (2016) showed that the alternate wetting and drying system emitted 55% less $CH_4$ emissions compared to the continuous flooding system. Pandey et al. (2014) also indicated that compared to straw compost, biochar in combination with alternate wetting and drying systems has the potential to maintain the yield-scaled global warming potential of rice production at a lower level than the farmers' practice. In addition, biochar and rice husk have been introduced as a climate-change mitigation approach that also improves soil properties. Wang et al. (2018a, b) stated that biochar amendment could markedly mitigate GHG emission risks under a straw return practice while regulating the physicochemical properties of soil.

## Conclusion and future research

This bibliometric study quantified the publication output of research on GHG emissions from rice production using scientific journals covered by Scopus. This study can help researchers to better understand how the topic has evolved over time and varied from one place to another. The keyword analysis of the relevant publications illustrates the importance of the topic, and the analysis of the cited references highlights the starting point of the newly emerging discussion. The result revealed that the topic of research has received increasing attention and the number of annual publications has followed an increasing trend. Nevertheless, a lot of work must be conducted in Africa where enough gaps have been identified. Considering the evolution of keywords over the last decade and the importance of rice in the world, more research fields will be improved to deal with the climate change impact to meet the needs of the growing world population.

Many aspects might be considered for the future direction of effective GHG mitigation in rice production. Firstly, it might be interesting to understand the social drivers for GHG emissions from rice production. However, there are a lot of factors that influence farmers' willingness to adopt different farming practices, such as income, knowledge, and policy. Secondly, a trade-off analysis between environmental benefits and economic benefits is necessary to be evaluated since most farmers grow rice for the immediate economic benefits and profits. Thirdly, more new policies need to be established to facilitate and increase relevant studies in this research field in different regions of the world, especially in Africa.

Although this study has made some contributions to the field, it also has some limitations. The study analyzed the publications within strict restrictions to obtain relevant search responses. Therefore, we only considered "article" as a document type and "English" as the language for our study period. Because of this restriction, some excellent papers might not be captured in this study. In addition, only the Scopus database is considered for this study, and some good papers might be found on other research databases like WoS or Google Scholar. Furthermore, this study only analyzed the scientific development of GHG emissions from rice production based on the characteristics of the quantity without considering the contents of the papers. Thus, combining this study with content analysis needs to be conducted for further in-depth analysis.

**Acknowledgements** The authors would like to thank Severin Biaou and Olivier B. Ahouandjinou for their helpful contributions to the manuscript. A special thanks also go to the anonymous reviewers for their constructive comments in improving this manuscript.

**Author contribution** Coffi Leonce Geoffroy Sossa: conceptualization, methodology, original draft, and editing; Souleymane Sanogo: methodology, supervision, and visualization; Jesse B. Naab: supervision, visualization, and review; and Luc O. Sintondji: supervision and visualization. All authors have read and agreed to the published version of the manuscript.

**Funding** This work was supported by the West Africa Science Service Center on Climate Change and Adapted Land Use (WASCAL), Intergovernmental Panel on Climate Change (IPCC), and the Prince Albert II of Monaco Foundation.

**Data availability** Data were taken from the Scopus using the keywords defined in the methodology section.

## Declarations

**Disclaimer** The contents of this document are solely the liability of Coffi Leonce Geoffroy Sossa and under no circumstances may be considered as a reflection of the position of the Prince Albert II of Monaco Foundation and/or the IPCC.

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

## References


Abdallah MB, Fekete-Farkas M, Lakner Z (2021) Exploring the link between food security and food price dynamics: a bibliometric analysis. Agriculture (switzerland) 11(3):1–19. https://doi.org/10.3390/agriculture11030263

Aben S, Saman P, Ghannoum O, Jann P (1999) Nitrogen requirements for maximum growth and photosynthesis of rice, Oryza sativa L Cv Jarrah grown at 36 And 70 Pa CO2. Aust J Plant Physiol 26(8):759. https://doi.org/10.1071/PP99067

Aria M, Cuccurullo C (2017) bibliometrix: an R-tool for comprehensive science mapping analysis. J Informet 11(4):959–975. https://doi.org/10.1016/j.joi.2017.08.007

Aslam M, Khalil K (2009) *Emissions of greenhouse gases from rice agriculture*. http://www.osti.gov/servlets/purl/959124-11RgaP/

Aulakh MS, Wassmann R, Bueno C, Rennenberg H (2001) Impact of root exudates of different cultivars and plant development stages of rice (Oryza sativa L.) on methane production in a paddy soil. Plant and Soil 230(1):77–86. https://doi.org/10.1023/A:1004817212321

Baas J, Schotten M, Plume A, Côté G, Karimi R (2020) Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. Quantitative Sci Stud 1(1):377–386. https://doi.org/10.1162/qss_a_00019

Bertoli-Barsotti L, Lando T (2017) The *h*-index as an almost-exact function of some basic statistics. Scientometrics 113(2):1209–1228. https://doi.org/10.1007/s11192-017-2508-6

Bhatia A, Aggarwal PK, Jain N, Pathak H (2012) Greenhouse Gas Emission from Rice- and Wheat-Growing Areas in India: Spatial Anal Upscaling 125:115–125. https://doi.org/10.1002/ghg

Boateng KK, Obeng GY, Mensah E (2017) Rice cultivation and greenhouse gas emissions: a review and conceptual framework with reference to Ghana. Agriculture (Switzerland) 7(1). https://doi.org/10.3390/agriculture7010007

Bodelier PLE, Roslev P, Henckel T, Frenzel P (2000) Stimulation by ammonium-based fertilizers of methane oxidation in soil around rice roots. Nature 403(6768):421–424. https://doi.org/10.1038/35000193

Cai Z, Guangxi X, XiaoyuanY HX, Haruo T, Kazuyuki Y, Katsuyuki M (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. Plant Soil 196(1):7–14. https://doi.org/10.1023/A:1004263405020

Carlson KM, Gerber JS, Mueller ND, Herrero M, MacDonald GK, Brauman KA, Havlik P, O'Connell CS, Johnson JA, Saatchi S, West PC (2017) Greenhouse gas emissions intensity of global croplands. Nat Clim Chang 7(1):63–68. https://doi.org/10.1038/nclimate3158

Centritto M, Lauteri M, Monteverdi MC, Serraj R (2009) Leaf gas exchange, carbon isotope discrimination, and grain yield in contrasting rice genotypes subjected to water deficits during the reproductive stage. J Exp Botany 60(8):2325–2339. https://doi.org/10.1093/jxb/erp123

Das K, Baruah KK (2008) Association between contrasting methane emissions of two rice (Oryza sativa L.) cultivars from the irrigated agroecosystem of northeast India and their growth and photosynthetic characteristics. Acta Physiologiae Plantarum 30(4):569–578. https://doi.org/10.1007/s11738-008-0156-4

Edwards J , Johnson C, Santos-medellín C, Lurie E, Kumar N (2014). *Structure, variation, and assembly of the root-associated microbiomes of rice*. https://doi.org/10.1073/pnas.1414592112

Eshun JF, Apori SO, Wereko E (2013) Greenhouse gaseous emission and energy analysis in rice production systems in Ghana. Crop Sci 21(2):119–125

Falagas ME, Pitsouni EI, Malietzis GA, Pappas G (2008) Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. FASEB J 22(2):338–342. https://doi.org/10.1096/fj.07-9492lsf

FAO (2009) Agricultural Outlook 2009-2018 HIGHLIGHTS. 95. http://www.agri-outlook.org/43040036.pdf

Glänzel W (2003) Bibliometrics as a research field: a course on Theory and Application of Bibliometric Indicators. *Researchgate*, *May*, 115. https://www.researchgate.net/publication/242406991_Bibliometrics_as_a_research_field_A_course_on_theory_and_application_of_bibliometric_indicators

GRISP (2010) *Global Rice Science Partnership (GRiSP) full proposal. November*, 746.

Guler AT, Waaijer CJF, Palmblad M (2016) Scientific workflows for bibliometrics. Scientometrics 107(2):385–398. https://doi.org/10.1007/s11192-016-1885-6

Huang Y, Zhu DL, Porter AL, Robinson DKR, Wang X (2017) Early insights on the Emerging Sources Citation Index (ESCI): an overlay map-based bibliometric study. Scientometrics 111(3):2041–2057. https://doi.org/10.1007/s11192-017-2349-3

Hussain S, Peng S, Fahad S, Khaliq A (2014). Rice management interventions to mitigate greenhouse gas emissions: a reviewhttps://doi.org/10.1007/s11356-014-3760-4

IPCC (2007) Intergovernmental Panel on Climate Change, Fourth Assessment Report, Geneva, Switzerland: Inter-governmental Panel on Climate Change. Cambridge; UK: Cambridge University Press; 2007. Available from: www. ipcc.ch. In *Intergovernmental Panel on Climate Change*. https://doi.org/10.1038/446727a

Islam SF, de Neergaard A, Sander BO, Jensen LS, Wassmann R, van Groenigen JW (2020) Reducing greenhouse gas emissions and grain arsenic and lead levels without compromising yield in organically produced rice. Agr Ecosyst Environ 295(January):106922. https://doi.org/10.1016/j.agee.2020.106922

Kanno K, Suzuki Y, Makino A (2018) A small decrease in Rubisco content by individual suppression of RBCS genes leads to improvement of photosynthesis and greater biomass production in rice under conditions of elevated $CO_2$. Plant Cell Physiol 58(3):635–642. https://doi.org/10.1093/pcp/pcx018

Kim DG, Thomas AD, Pelster D, Rosenstock TS, Sanz-Cobena A (2016) Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further research. Biogeosciences 13(16):4789–4809. https://doi.org/10.5194/bg-13-4789-2016

Kritee K, Nair D, Zavala-Araiza D, Proville J, Rudek J, Adhya TK, Loecke T, Esteves T, Balireddygari S, Dava O, Ram K, Abhilash SR, Madasamy M, Dokka RV, Anandaraj D, Athiyaman D, Reddy M, Ahuja R, Hamburg SP (2018) High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. Proc Natl Acad Sci USA 115(39):9720–9725. https://doi.org/10.1073/pnas.1809276115

Ku HH, Hayashi K, Agbisit R, Villegas-Pangga G (2017) Evaluation of fertilizer and water management effect on rice performance and greenhouse gas intensity in different seasonal weather of tropical climate. Sci Total Environ 601–602:1254–1262. https://doi.org/10.1016/j.scitotenv.2017.05.277

Le Mer J, Roger P (2001) Production, oxidation, emission and consumption of methane by soils: a review. Eur J Soil Biol 37(1):25–50. https://doi.org/10.1016/S1164-5563(01)01067-6

Le TT, Ribbes F, Wang LF, Floury N, Ding KH, Kong JA, Fujita M, Kurosu T (1997) Rice crop mapping and monitoring using ERS-1 data based on experiment and modeling results. IEEE Trans Geosci Remote Sens 35(1):41–56. https://doi.org/10.1109/36.551933

Linquist BA, Adviento-Borbe MA, Pittelkow CM, van Kessel C, van Groenigen KJ (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. In Field Crops Research 135:10–21. https://doi.org/10.1016/j.fcr.2012.06.007

Linquist BA, Anders MM, Adviento-Borbe MAA, Chaney RL, Nalley LL, da Rosa EFF, van Kessel C (2015) Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Global Change Biol 21(1):407–417. https://doi.org/10.1111/gcb.12701

Liu B, Zhang Wang X (2017) Scientometric profile of global rice research during 1985-2014. Current Science 112(5):1003–1011. https://doi.org/10.18520/cs/v112/i05/1003-1011

Liu G, Yu H, Zhang G, Xu H, Ma J (2016) Combination of wet irrigation and nitrification inhibitor reduced nitrous oxide and methane emissions from a rice cropping system. Environ Sci Pollut Res 23(17):17426–17436. https://doi.org/10.1007/s11356-016-6936-2

Marx W, Haunschild R, Bornmann, L (2017) Global warming and tea production—the bibliometric view on a newly emerging research topic. Climate, 5(3). https://doi.org/10.3390/cli5030046

Mongeon P, Paul-Hus A (2016) The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics 106(1):213–228. https://doi.org/10.1007/s11192-015-1765-5

Morita R, Inoue K, Ikeda K, Hatanaka T, Misoo S, Fukayama H. (2016). Starch content in leaf sheath controlled by $CO_2$—responsive CCT protein is a potential determinant of photosynthetic capacity in rice. 0(August) 1–8. https://doi.org/10.1093/pcp/pcw142

Pandey A, Mai VT, Vu DQ, Bui TPL, Mai TLA, Jensen LS, de Neergaard A (2014) Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. Agr Ecosyst Environ 196:137–146. https://doi.org/10.1016/j.agee.2014.06.010

Pathak H, Wassmann R (2007) Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: Gen Tech Coefficients 94:807–825. https://doi.org/10.1016/j.agsy.2006.11.015

Peng S (2017) Booming research on rice physiology and management in China: a bibliometric analysis based on three major agronomic journals. J Integr Agric 16(12):2726–2735. https://doi.org/10.1016/S2095-3119(17)61804-5

Peng S, Tang Q, Zou Y (2009) Current status and challenges of rice production in China. Plant Prod Sci 12(1):3–8. https://doi.org/10.1626/pps.12.3

Qin Y, Liu S, Guo Y, Liu Q, Zou J (2010) Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. Biol Fertil Soils 46(8):825–834. https://doi.org/10.1007/s00374-010-0493-5

Qin X, Li Y, Wang H, Li J, Wan Y, Gao Q, Liao Y, Fan M (2015) Effect of rice cultivars on yield-scaled methane emissions in a double rice field in South China. J Integr Environ Sci 12:47–66. https://doi.org/10.1080/1943815X.2015.1118388

Shang Q, Yang X, Gao C, Wu P, Liu J, Xu Y, Shen Q, Zou J, Guo S (2011) Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. Glob Change Biol 17(6):2196–2210. https://doi.org/10.1111/j.1365-2486.2010.02374.x

Song Y, Chen X, Hao T, Liu Z, Lan Z (2019) Computers & Education exploring two decades of research on classroom dialogue by using bibliometric analysis. Comput Educ 137:12–31. https://doi.org/10.1016/j.compedu.2019.04.002

Sun J, Yuan BZ (2020) A bibliometric analysis of research on rice and irrigation from the “Agronomy” category based on the Web of Science. Current Science 119(3):438–446. https://doi.org/10.18520/cs/v119/i3/438-446

Tarlera S, Capurro MC, Irisarri P, Scavino AF, Cantou G, Roel A (2016) Yield-scaled global warming potential of two irrigation management systems in a highly productive rice system. Scientia Agricola 73(1):43–50. https://doi.org/10.1590/0103-9016-2015-0050

Tivet F., Boulakia S (2017) Climate smart rice cropping systems in Vietnam. *State of Knowledge and Prospects. CIRAD* …. https://asie-sud-est.cirad.fr/content/download/5898/51468/version/1/file/2017-06+CS+rice+Vietnam+final.pdf

Tsutsumi K, Konno M, Miyazawa S, Miyao M (2014) Sites of action of elevated $CO_2$ on leaf development in rice: discrimination between the effects of elevated $CO_2$ and nitrogen deficiency. Plant Cell Physiol 55(2):258–268. https://doi.org/10.1093/pcp/pcu006

Vatananan-Thesenvitz R, Schaller AA, Shannon R (2019) A bibliometric review of the knowledge base for innovation in sustainable development. Sustainability (switzerland) 11(20):1–22. https://doi.org/10.3390/su11205783

Vu JC, Jeffrey T, Bowes G, Kenneth JB (1998) Elevated $CO_2$ and water deficit effects on photosynthesis, ribulose bisphosphate carboxylase-oxygenase, and carbohydrate metabolism in rice, 103(3), 327–339. https://doi.org/10.1034/j.1399-3054.1998.1030305.x

Wang YQ, Bai R, Di HJ, Mo LY, Han B, Zhang LM, He JZ (2018) Differentiated mechanisms of biochar mitigating straw-induced greenhouse gas emissions in two contrasting paddy soils. Front-Microbiol 9(Nov):1–19

Wang J, Vanga SK, Saxena R, Orsat V, Raghavan V (2018a). Effect of climate change on the yield of cereal crops: a review. Climate, 6(2). https://doi.org/10.3390/cli6020041

Wassmann R, Neue HU, Lantin RS, Buendia LV, Rennenberg H (2000) Characterization of methane emissions from rice fields in Asia. I. Comparison among field sites in five countries. Nutrient Cycling Agroecosyst 58(1–3):1–12. https://doi.org/10.1023/A:1009848813994

Wu W, Yang M, Feng Q, McGrouther K, Wang H, Lu CY (2012) Chemical characterization of rice straw-derived biochar for soil amendment. Biomass Bioenerg 47:268–276. https://doi.org/10.1016/j.biombioe.2012.09.034

Xu Y, Ge J, Tian S, Li S, Nguy R, Anthony L, Zhan M, Cao C (2015) Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. Sci Total Environ 505(2):1043–1052. https://doi.org/10.1016/j.scitotenv.2014.10.073

Yao Z, Zheng X, Dong H, Wang R, Mei B, Zhu J (2012) A 3-year record of $N_2O$ and $CH_4$ emissions from a sandy loam paddy during rice seasons as affected by different nitrogen application rates. Agr Ecosyst Environ 152:1–9. https://doi.org/10.1016/j.agee.2012.02.004

Zhang A, Cui L, Pan G, Li L, Hussain Q, Zhang X, Zheng J, Crowley D (2010) Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. Agr Ecosyst Environ 139(4):469–475. https://doi.org/10.1016/j.agee.2010.09.003

Zhang A, Bian R, Pan G, Cui L, Hussain Q, Li L, Zheng J, Zheng J, Zhang X, Han X, Yu X (2012) Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles. Field Crop Res 127:153–160. https://doi.org/10.1016/j.fcr.2011.11.020

Zhang C, Xu T, Feng H, Chen S (2019) Greenhouse gas emissions from landfills: a review and bibliometric analysis. Sustainability (switzerland) 11(8):1–15. https://doi.org/10.3390/su11082282

Zheng H, Huang H, Yao L, Liu J, He H, Tang J (2014) Impacts of rice varieties and management on yield-scaled greenhouse gas emissions from rice fields in China: a meta-analysis. Biogeosciences 11(13):3685–3693. https://doi.org/10.5194/bg-11-3685-2014

Ziska LH, Alan H, Teramura (1992) Intraspecific variation in the response of rice (*Oryza sativa*) to increased $CO_2$—photosynthetic, biomass and reproductive characteristics ,84(2), 269–274. https://doi.org/10.1111/j.1399-3054.1992.tb04664.x

Zou J, Huang Y, Jiang J, Zheng X, Sass RL (2005) A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. Global Biogeochem Cycles 19(2):1–9. https://doi.org/10.1029/2004GB002401