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Review of agricultural biomass burning and its impact on air quality in the continental United States of America

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ABSTRACT

Burning is a common method to dispose agricultural biomass residue. This practice is widely used by farmers during pre- and post-harvest seasons for crops such as wheat, rice, grass seed, soy, cotton, sugarcane, and corn. Farmers choose this method because it is cost and time effective. These burning activities emit several types of pollutants into the atmosphere, including CH_4, SO_x, NO_x, CO, CO_2, and particulate matter of different sizes (i.e., PM_1, $PM_{2.5}$ and PM_{10}). Globally, the United States of America ranks third, preceded by China and India, in greenhouse gas emissions due to agricultural burning activities. According to the 2020 U.S. National Emissions Inventory, agricultural field burnings produced 67,309.81 tons i.e., approximately 20 % of total $PM_{2.5}$ emissions. The main aim of this review paper is to summarize the existing literature on agricultural biomass burning and its effect on air quality in continental USA. This review utilizes databases such as Web of Science, Science Direct, PubMed and ProQuest for this endeavor. Various types of emissions and their emission factors are presented for each type of crop. Additionally, the review also compiles available data from the biomass burning emission inventories to characterize the spatial and temporal patterns of pollutant emissions resulting from agricultural burning. States such as Iowa, Illinois, Indiana, North Dakota, South Dakota, and Nebraska are home to significant amounts of croplands; however, no studies were found focusing on these states. Pollutant emissions from 2008 to 2020 revealed an upward trend from 2017 onwards, suggesting an expansion in agricultural burning areas in contrast to previous years.

1. Introduction

Agriculture plays a vital role in the survival of mankind on this planet. It contributes to the world's economic growth by accounting for 4 % of global gross domestic product (GDP) (The World Bank, 2023). Agricultural production relies heavily on natural resources such as land and water. Climate change and its associated impacts are unfolding across various sectors and are presenting challenges for agricultural practices. Climate change is expected to increase the frequency of heavy precipitation resulting in soil erosion and depletion of soil nutrients consequently harming crop productivity (Gowda, P., et al. 2018). Additionally, agricultural activities have some negative impacts on the climate. For example, pesticide and chemical fertilizer usage, soil tillage, rotation, and stubble burning have a detrimental effect on the climate, despite offering temporary advantages (Onder et al., 2011).

Stubble burning (commonly known as straw burning), crop residue burning, agricultural burning, are common methods used globally by farmers to remove excess crop residue from the fields (Yang et al., 2008).

Abbreviations: CAP, Criteria air pollutant; CARB, California Air Resources Board; CE, Combustion efficiency; CONUS, Continental United States of America; dNBR, differencing of Normalized burn ratio; EF, Emission Factor; FEI, Fire Emission Inventory; FINN, Fire Inventory from NCAR; GFED, Global Fire Emissions Database; GDP, Gross domestic product; GHG, Greenhouse gases; GOME, Global ozone monitoring experiment; MODIS, Moderate Resolution Imaging Spectrometer; NEI, National Emissions Inventory; NMVOC, Non-methane volatile organic compounds; OCDD, Octachlorodibenzodioxin; PCDDs/Fs, Polychlorinated dibenzodioxins and dibenzofurans; VIIRS, Visible Infrared Imaging Radiometer Suite.

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Stubble or straw refers to the residual material that remains after the harvest of grains such as soy, cotton, grass seed, wheat, rice, corn, or similar crops. This process of burning is the most preferred method in most countries as it is the cheapest available option in straw management. In addition, it is a preferable method adopted by farmers to get the land ready for the next harvesting season and increase crop yield. However, research demonstrates that the process of burning can have both positive and negative impacts on the overall yield.

Burning activity increases the availability of nutrients like phosphorus and potassium for a limited period with the potential to increase the growth productivity of the crop (Ahmed et al., 2015). But the negative effects of stubble burning far outnumber the positives. Stubble burning results in harmful levels of various pollutants such as methane (CH_4), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), black carbon (BC), and particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$) and less than 10 micrometers in diameter (PM_{10}) (Chanana et al., 2023, Ravindra et al., 2019), and can, therefore, be a major public health concern. The process of burning also releases hazardous polycyclic aromatic hydrocarbons (PAHs) into the atmosphere. Long term exposure to even low levels of some PAHs including Benzo(a)pyrene were observed to cause cancer in laboratory animals (Moubarz et al., 2022). Exposure of naphthalene through breathing or swallowing might cause breakdown of blood cells (IDPH, 2019). A study conducted in India by Chakrabarti et al. (2020) documented that the risk of acute respiratory infections, after adjusting for socioeconomic and household factors, increased by more than three times in a district with high agricultural crop residue burning and the most susceptible group were children.

South Asian countries such as India (Lan et al., 2022), Pakistan (Azhar et al., 2019), Nepal (Bajracharya et al., 2021) and Bangladesh (Lin & Begho, 2022) are affected substantially by agricultural stubble burning. Actions have been undertaken in these countries to reduce the impacts associated with burning; however, it is prudent to mention here that the effects of pollution are not localized. The burning activities produce heavy smoke that spread not only to nearby regions but also neighboring countries causing complex transboundary air pollution issues in Southeast Asia (Mehmood et al., 2022) and Europe (The Task Force on Hemispheric Transport of Air Pollution., 2022).

In 2019, the U.S. agricultural sector provided more than $1.1 trillion to the gross domestic product and accounted for 10.9 % of total U.S. employment—more than 22 million jobs (Economic Research Service, 2023). The U.S. uses 44.36 % of its land for agricultural purposes, which is higher than the global average land utilization (36.5 %) (The World Bank Group, 2022). Corn, cotton, soybeans, and wheat are the major crops that are grown in the continental United States (CONUS). Now, in the U.S, the practice of sugarcane stubble burning is very prevalent in the states of Florida, Louisiana, and Texas (McCarty et al. 2009). But the US ranks third, after China and India, among the countries globally that contribute to greenhouse gas (GHG) emissions resulting from crop residue burning (FAOSTAT, 2023). This resulted in a release of 102.67 kt of CH_4, 3580 kt of CO_2eq and 2.66 kt of N_2O on average from 1961- 2020 as shown in Fig. 1. Table 1 presents the emission values in 2020 and projected values for 2030 and 2050, which suggest an expected increase in emissions in the coming years (FAOSTAT, 2023). Stubble burning on an annual basis also leads to decrease in the surface cover, thereby leaving the soil highly vulnerable to wind erosion and evaporative water loss. (Roper et al., 2021). Hence it is paramount to study the causes of stubble burning and initiate requisite steps to decrease these emissions.

This review examines the existing literature in the field of agricultural biomass burning in CONUS through Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), Social Network Analysis (SNA), and analysis of scientific production. The main aims of the current review are to (1) examine the topic of agricultural biomass

Table 1
Emissions of GHGs and projected values in USA (Source: based on FAOSTAT data)

Element	Emissions (kt) in 2020	Projected Emissions (kt) in 2030	Projected Emissions (kt) in 2050
CH_4	108.6371	122.5547	126.4414
CO_2eq (AR5)	3788.2169	4273.5269	4409.059
N_2O	2.8165	3.1773	3.2781

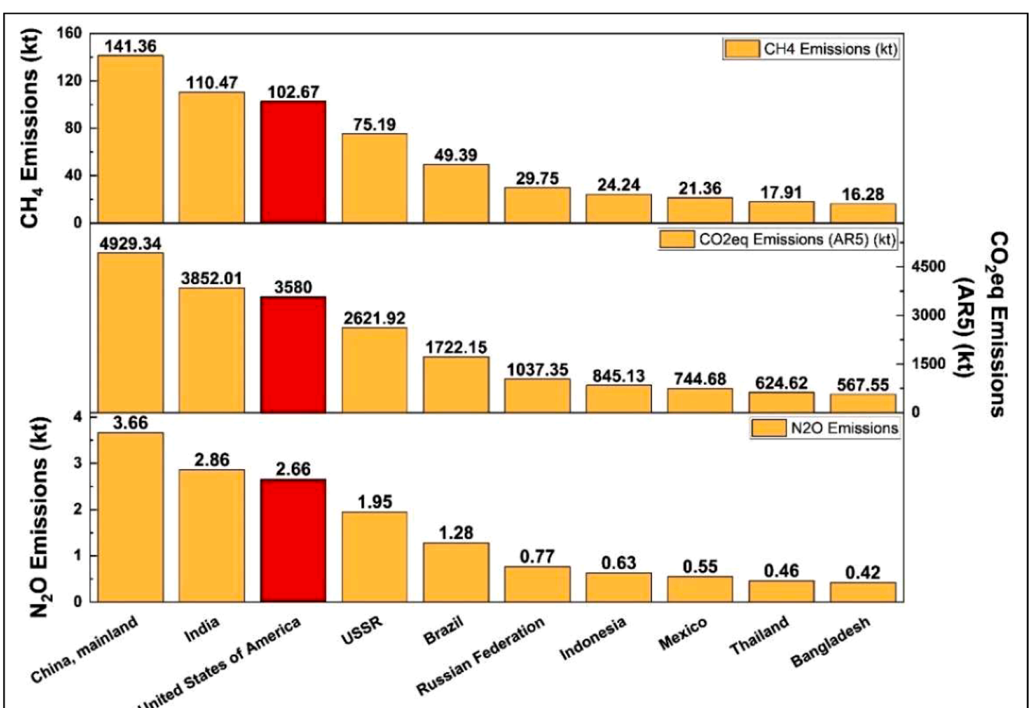

Fig. 1. Top 10 emitters of GHG (Average 1961 – 2020) from Burning of Crop residues (Source: based on FAOSTAT data)

burning and its impact on air quality, (2) explore the emissions of various air pollutants emitted, and (3) review the spatial and temporal impact of air pollutant emissions through agricultural biomass burnings in CONUS using Fire Emissions Inventory (FEI) databases.

2. Agriculture & Residue Production in CONUS

Crops which are mostly grown in CONUS are Corn (*Zea mays*), Soybean (*Glycine max*), Wheat (*Triticum aestivum*), Sorghum (*Sorghum bicolor*), Rice (*Oryza sativa*), Barley (*Hordeum vulgare*), Peanut (*Arachis hypogaea*), Rapeseed (*Brassica napus*), Sunflower seed (Helianthus annuus), and Cotton (*Gossypium spp.*) (USDA FAS, 2023). Fig. 2 represents the national cultivated area of CONUS in 2022.

The United States is the largest producer, consumer, and exporter of corn in the world. It holds 32 % of the world's corn production. U.S farmers plant about 90 million acres of corn each year on average, with the majority in the Mid-western states (Economic Research Service, 2023a). The states that account for the most percent of national production of corn are Iowa (17 %), Illinois (15 %), Nebraska (12 %), Minnesota (10 %) and Indiana (7 %). These five states combinedly share 61 % of national corn production among themselves (USDA FAS, 2023). After Brazil, CONUS is the 2nd largest producer of soybean globally with production at around 30 %. Iowa (14 %), Illinois (13 %), Minnesota (9 %), Nebraska (8 %) and Indiana (7 %) are the major producers of this crop. CONUS is the 5th largest producer of wheat after European Union, China, India, and Russia with a global production percent of 6 %. Most of the wheat crop is grown in Kansas (18 %), North Dakota (16 %), Montana (10 %), Washington (8 %) and Oklahoma (6 %) (USDA FAS, 2023). 15 % of total world's sorghum production is in CONUS, with Kansas (55 %) and Texas (21 %) being the major producers. CONUS ranks as the third largest producer, accounting for 14 % of the total cotton production in the world (USDA FAS, 2023). Texas (42 %), Georgia (13 %), Mississippi (8 %), Arkansas (6 %) and Alabama (5 %) are the major states producing this crop. Additionally, CONUS contributes 6 %, 3 %, 2 %, and 2 % of the global production of barley, peanut, rapeseeds, and sunflower seeds, respectively (USDA FAS, 2023*)*. North Dakota produces 96 % of rapeseeds, 26 % of barley and 42 % of sunflower seeds in CONUS (USDA FAS, 2023). Table 2 presents the production statistics of various crops in CONUS. Corn, soybean, wheat, and cotton are the most produced crops.

Table 2
Production of various crops in CONUS *(Source: International Production Assessment Division,* USDA, 2023*)*

Crops	5 Year Average (2018-2022) (1000 Tons)	2022/2023 (1000 tons)	2023/2024 (1000 tons)
Corn	360,063	348,751	387,749
Soybean	113,967	116,377	122,742
Wheat	48,669	44,902	45,321
Sorghum	8,713	4,770	9,144
Rice	6,277	5,092	6,119
Barley	3,446	3,796	3,984
Peanut	2,635	2,526	2,849
Rapeseed	1,552	1,742	1,833
Sunflower seed	1,067	1,276	1,039
Crop	**5 Year Average (2018-2022) (1000 480-lb Bales)**	**2022/23 (1000 480-lb Bales)**	**2023/24 (1000 480-lb Bales)**
Cotton	16,976	14,468	16,500

The residue to grain weight ratio is used to estimate the crop residue that is left after harvesting a particular crop. Oats have the highest ratio of residue to grain weight of 2, followed by winter wheat (1.7), barley (1.5), summer wheat (1.3), corn (1), and sorghum (1) (U.S. Department of Energy, 2016). Even though corn is grown the most in CONUS, its residue is rarely burnt. A study by Pouliot et al., 2017 indicates that burning corn residue is not the preferable way of residue management in the Midwest states. The burning of corn residue accounts for less than 1 % of the total crop acres. Another study by Schmer et al., 2017 states that 83 % of the corn stover was utilized through grazing, and the rest is either baled or harvested. Stubble burning of corn residue is not a primary method of residue utilization in CONUS. However, other studies conducted in various CONUS states such as California (Harnly et al., 2012), Texas (Dennis et al., 2002), and Colorado (Coggon et al., 2016) concluded that the activities associated with corn residue burning do impact the environment negatively. The leftover component of soybean crops after harvest is called soybean hull. These are usually used as

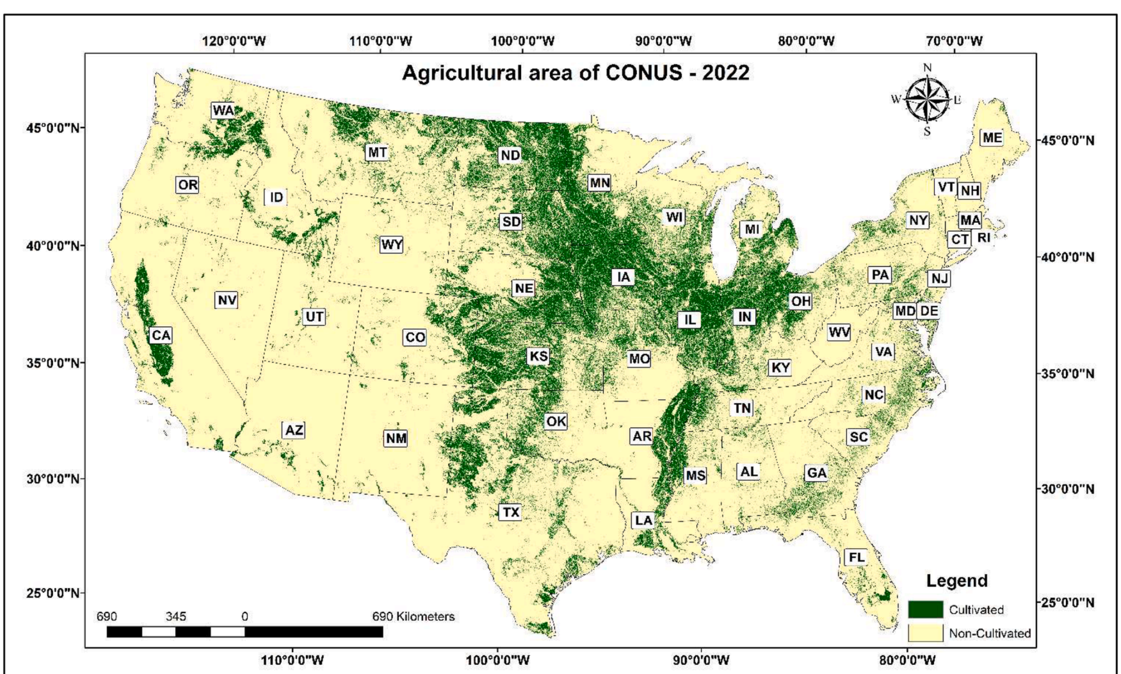

Fig. 2. National cultivated area of CONUS – 2022 (data source: NASS, 2023)

livestock feed. The forecasted estimation of soybean hulls for 2030 in CONUS is 3.09 million dry tons, with a 6 % increase from 2015 (U.S. Department of Energy, 2016). The forecasted estimation of cotton residue for 2030 is 4.53 million dry tons, with a 58.9 % increase from 2015 (U.S. Department of Energy, 2016).

3. Methodology

This review followed a systematic protocol for searching relevant existing literature in the field of agricultural biomass burning. The databases used were Web of Science, Science Direct, PubMed and ProQuest. Web of Science (WoS) (https://www.webofscience.com/wos/woscc/advanced-search) consisted of 21,522 peer-reviewed high-quality scientific journals with 254 research categories according to the Journal Citation Reports from 2023 (Journal Citation Reports, 2023). ScienceDirect (http://www.sciencedirect.com/)is a full text scientific database provided by the medical and scientific publishing company Elsevier. The database consists of more than 2650 peer-reviewed journals, 43,000 e-books, and 19 million articles and book chapters (ScienceDirect, 2022). PubMed (http://pubmed.gov/) is a web-portal of the medical database *MEDLINE* and was developed by the National Center for Biotechnology Information (NCBI), a United States Federal agency for data-processing of biotechnology. It comprises of more than 36 million citations for biomedical literature MEDLINE, life science journals, and online books (PubMed, 2019). ProQuest (https://www.proquest.com) is a database with access to more than 5.5 million dissertations and theses records (ProQuest, 2023). The PRIMSA flow chart detailing this information is shown in Fig. 3.

The literature search employed a set of keywords such as “crop residue burning”, “crop waste burning”, “harvest waste burning”, “stubble burning”, “straw burning”, “agricultural biomass burning”, and United States of America. These keywords were utilized individually as well as in combination with Boolean operators such as "And" and "Or" to refine the search results. After the initial search, a total of 1430 results were obtained, which then underwent a screening process based on title, abstract, and full text. Papers that were not published in English and those that did not focus on regions within the CONUS were excluded. The literature identified as relevant for the review was compiled and managed using a reference manager, EndNote X9. All duplicate papers were then removed using this program. There were numerous papers which focused on burning various biomass types including forest residues, industrial waste, and solid waste. But as the primary aim of this paper was to review agricultural burning, papers focusing on other forms were discarded. The final full text review was conducted on a total of 41 articles. Databases and search terms used are summarized in Table 3.

The social network analysis i.e., co-occurrence and timeline maps of the keywords were created using VOS viewer (version 1.6.19., Leiden University, Leiden, The Netherlands). It is a software well known for its ability to generate graphical representations of large co-quotation and

Table 3
Databases and search terms used for review.

Database	Combinations of keywords and Boolean operators	Results
ProQuest	(Agricultural biomass burning) AND (crop burning) AND (stubble burning) AND (straw burning) AND (agricultural burning) AND (UNITED STATES OF AMERICA).	689
PubMed	((((((crop residue [Title/Abstract]) OR (crop waste [Title/Abstract])) OR (harvest waste [Title/Abstract])) OR (stubble [Title/Abstract])) OR (straw [Title/Abstract])) OR (agricultural biomass [Title/Abstract])) AND (BURNING[Title/Abstract]).	533
Web of Science	((((((AB= (crop residue)) OR AB= (crop waste)) OR AB= (harvest waste)) OR AB=(stubble)) OR AB=(straw)) OR AB= (agricultural biomass)) AND TI=(BURNING) AND CU=(USA).	186
Science Direct	(Residue burning) AND (crop burning) AND (stubble burning) AND (straw burning) AND (agricultural biomass) AND (United States of America) & Title, abstract or author-specified keywords – burning.	22
Total		1430

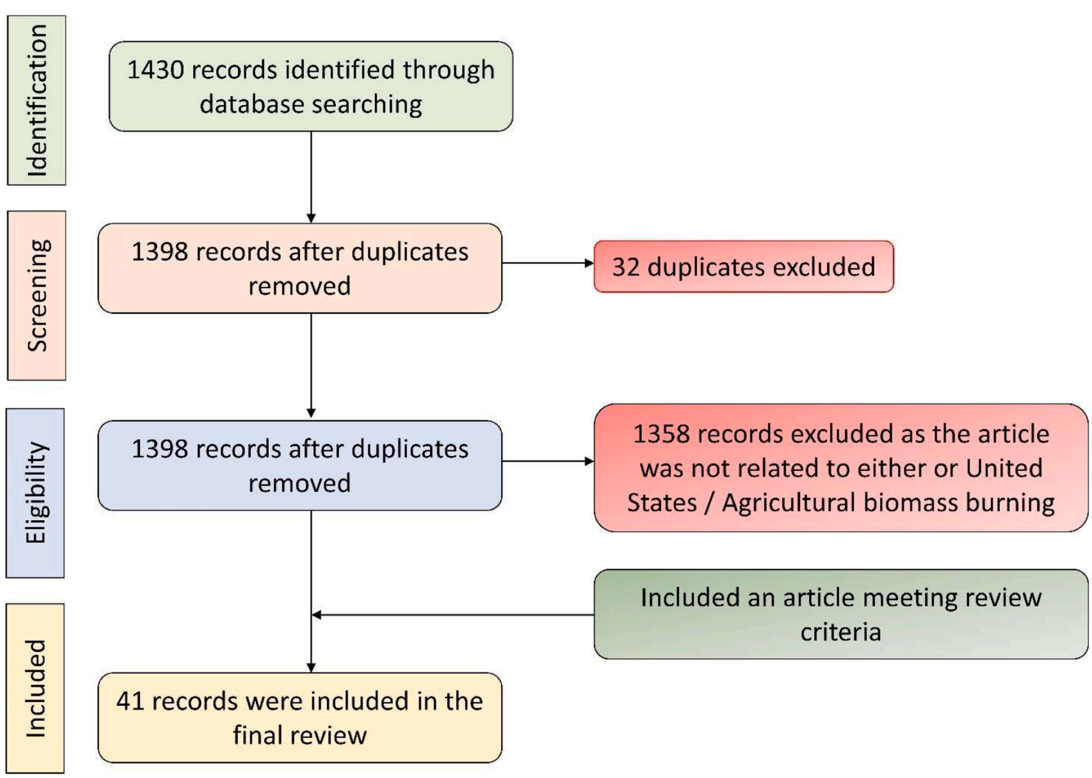

Fig. 3. PRISMA flow chart

co-occurrence maps that are easily interpretable (Van Eck and Waltman, 2010). The demographic maps were made using ArcGIS Desktop (version 10.8.2., Redlands, E.S.R.I). The graphs and tree map were made using OriginPro (version 2022b, Northampton, MA, USA) and Microsoft Excel (v.16.06, Microsoft Inc., Redmond, WA, USA) respectively.

4. Literature analysis

4.1. Distribution of research studies by states

The analysis of publications was conducted state wise as it helped gain a better understanding of their respective agricultural biomass burning. Fig. 4 shows the publications focused on each state. There were seven publications which focused on CONUS as a whole. California exhibited the highest level of emphasis among all states, with a total of 11 publications. Washington and Idaho followed suit with seven and six publications, respectively. Many research papers also focused on the states located in the North-west, and South-east region of the United States. No articles were found for states such as Iowa, Illinois, Indiana, North Dakota, South Dakota, and Nebraska, suggesting a dearth of research in these regions, despite their substantial agricultural activities, and being significant growing hubs for corn, wheat, soybeans, and rapeseeds.

4.2. Publications per journal

Fig. 5 lists all the journals with the frequency of articles published on the topic of agricultural biomass burning. Atmospheric Environment is the journal with the highest number of articles (12). The tree map incorporates journals covering diverse disciplines such as atmospheric sciences, geophysiology, remote sensing, aerosol science, agricultural science, and waste management. This collective representation highlights the extensive impact of agricultural biomass burning on different research domains.

4.3. Keyword analysis

The social network analysis using co-occurrence map for the literature reflects the main terms selected by the authors and the database managers (Van Eck and Waltman, 2010). The terms were automatically selected by VOS viewer software based on the number of occurrences (minimum two). This allowed the software to visually represent the strongest links between terms using lines and color clusters. (Van Eck and Waltman, 2010). The keywords were extracted from both titles and abstracts of the literature.

Fig. 6 provides the co-occurrence map based on the keywords. The first cluster (green) reflects the strongest terms in the network, i.e., “agriculture” and “emissions”, representing the main aim of the study. Other words in the cluster are “carbon dioxide”, “United States”, “crop residue” and “harvest”. This cluster is directly connected to the blue cluster with terms “California” and “atmospheric emissions”, highlighting the importance of this state as 11 studies emanated from there. The second largest cluster (red) is related to the air quality aspect of this review and contains various terms including “biomass burning”, “PAH”, “chemical composition”, “particulate air pollution”, “aerosol”, and “emission factors”. Various air pollutants analyzed in the studies are highlighted in this cluster. The cluster (orange) with the terms “pm2.5” and “air pollution” connects all the clusters together.

Fig. 7 represents the timeline evolution map of the keywords from 1969 till 2023, which allows for more detailed visualization. As observed on the map, keywords such as “agricultural crops”, “combustion”, “temperature”, and “fires” were the oldest terms. From the 2000s onward, there was a noticeable increase in the usage of terms such as “agriculture”, “pm2.5”, “wheat”, and “emissions”, indicating a significant shift in focus towards the issue of air pollution. The most recent terms i.e., “aircraft” and “aerosol mass spectroscopy” accentuates the advances in air pollution measurement technology. The keyword occurrences and timeline evolution are useful when determining the design and framework of new air pollution studies due to agricultural biomass burning.

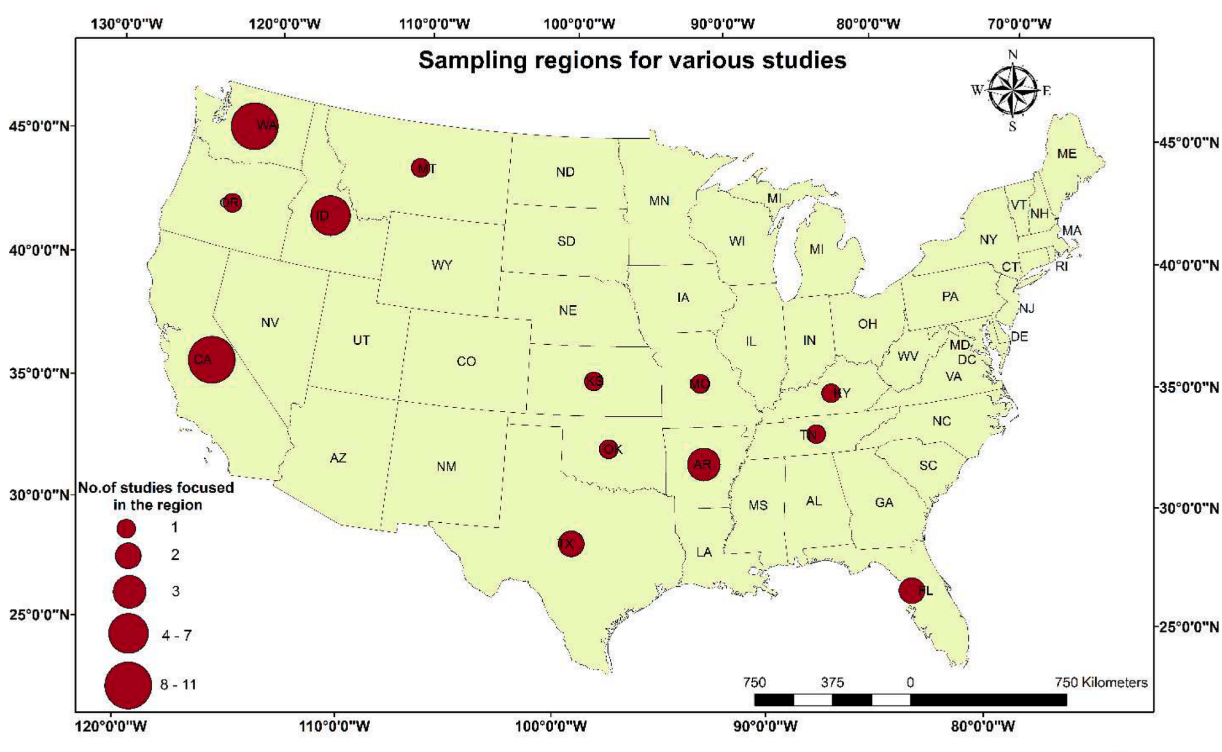

Fig. 4. Demographic distribution of sampling regions across CONUS in the field

Fig. 5. Tree map of the academic journals publishing articles reviewed in this study.

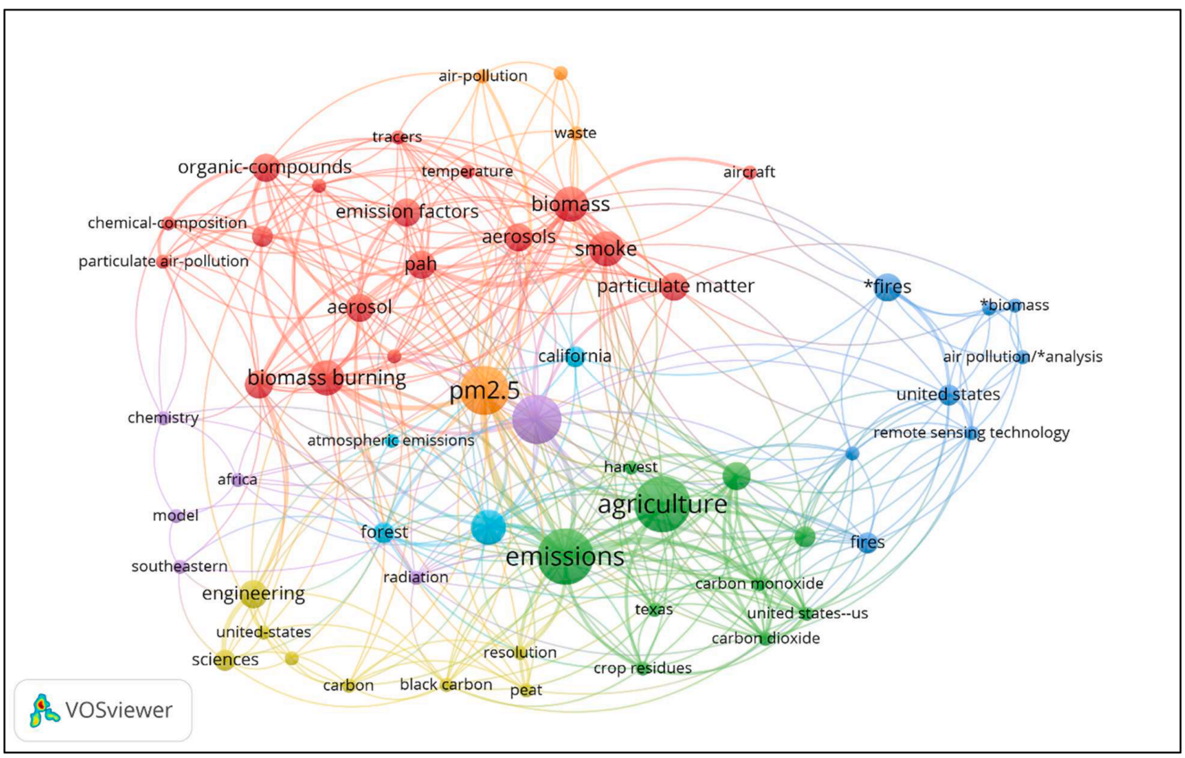

Fig. 6. Co-occurrence map based on keywords.

5. Review of findings

This review paper has studies covering stubble burning of various crops across different regions in CONUS. Crops studied in the literature review are rice, wheat, corn, barley, sugarcane, and soybean. Table 4 outlines the sampling region, measurement or instruments that were used, varieties of straw studied, and major findings emanating from the literature.

5.1. Residue burning of different crops

5.1.1. Corn residue

In Texas, more than 2 million acres is typically dedicated for planting corn (United States Department of Agriculture, 2023). A study conducted in Texas by Dennis et al., 2002 showed that an estimated 131, 203 acres of corn was burnt in 1996-1997, and the said activities led to 2634 short tons of PM, 2502 short tons of $PM_{2.5}$ (PM < 2.5 μm in aerodynamic diameter) and 2595 short tons of PM_{10} (PM < 10 μm in aerodynamic diameter), per year. Turn et al., 1997 studied the elemental characterization of different sizes of PM from corn stover burning to understand the chemical composition of the particles. This study, using atomic absorption spectrophotometry (AA), indicated that PM_{10} emissions had NH_4^+ concentration at 6 %. The emission factor of Cl^- and $NH4^+$ amounted for large portion of $PM_{2.5}$, 1300 mg/kg and 670 mg/kg, respectively.

Jenkins et al., 1996 used isotope dilution mass spectrometry to analyze various polycyclic aromatic hydrocarbons (PAHs) emissions from corn stover burning. The study observed 19 different PAHs such as

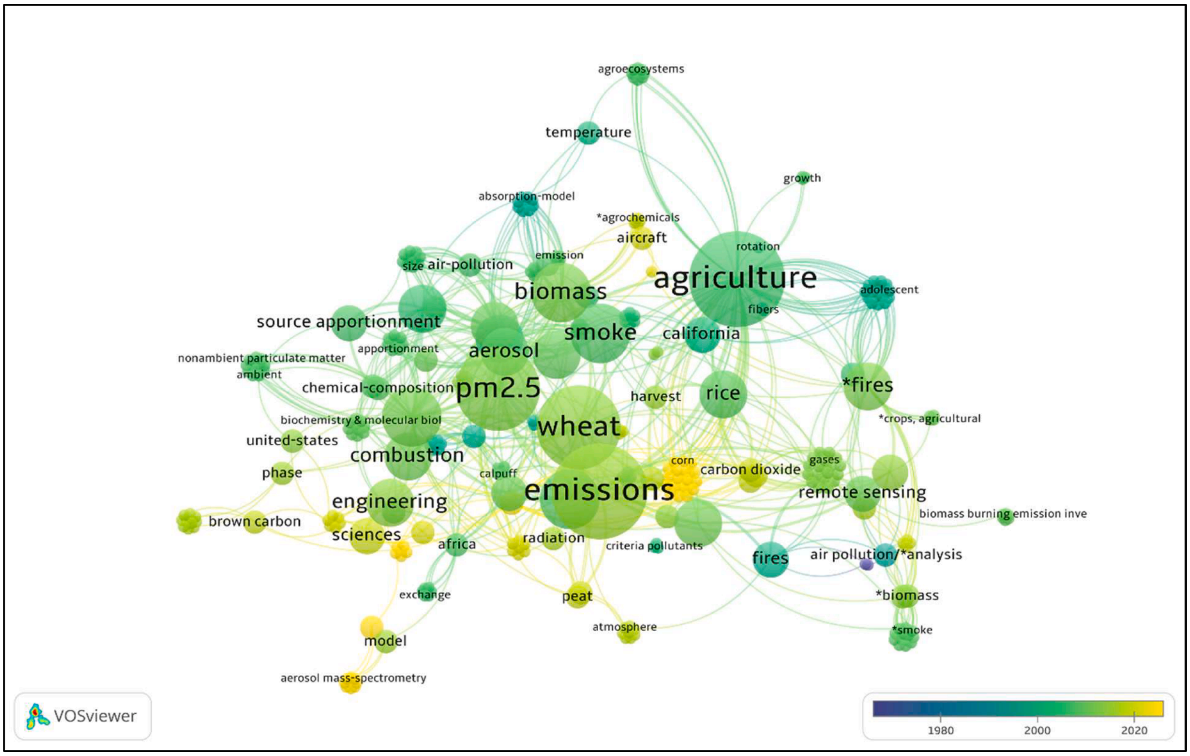

Fig. 7. Timeline map of evolution of keywords.

Naphthalene, 2-Methylnaphthalene, Acenaphthylene, Anthracene, Fluoranthene, Pyrene. The amount of PAH in PM emitted ranged from 20 % to 70.3 %. PAH concentrations of Fluoranthene and Pyrene were in higher amounts, with values of 0.132 and 0.131 g kg^{-1} of PM, respectively, when compared to other PAHs. Coggon et al., 2016 examined the amount of NVOCs (Nitrogen-containing VOCs) from crop residue burning using a H_3O^+ chemical ionization time-of-flight mass spectrometer (H_3O^+ ToF-CIMS). The authors concluded that the amount of NVOC content in VOCs (Volatile Organic Compounds) was directly related to fuel nitrogen content. For every 1 % increase in nitrogen, the amount of NVOCs in VOCs increased by 2.3 % to 6 %. The regions with high nitrogen containing vegetation could emit elevated HNCO (Isocyanic acid) and HCN (hydrogen cyanide) levels. HNCO and HCN are types of NVOCs, which are hazardous to human health (Coggon et al., 2016).

CO, CH_4, non-methane hydrocarbons (NMHC), NOx, and ammonia (NH_3) were some other emissions recorded during corn stover burning activities (Dennis et al., 2002). During 1996-1997, the burning of 131, 203 acres of corn stover in Texas accounted for 22,136 short tons of CO, 931 short tons of CH_4, 2667 short tons of non-methane hydrocarbons, 1030 short tons of NOx and 399 short tons of NH_3 (Dennis et al., 2002).

5.1.2. Wheat residue

In the state of Washington, Dhammapala et al., 2006 assessed emissions from wheat straw burning activity, using various ground-based instruments including DataRAM 2000 (MIE, Inc.) nephelometer for $PM_{2.5}$ and Horiba VIA 510 dual beam non-dispersive Infra-Red (NDIR) for CO. The study showed that wheat straw burning in 10 Washington counties accounted for 3.7 % of the annual $PM_{2.5}$ emissions and 7.7 % of the CO emissions. The emission factor (EF) for $PM_{2.5}$ in the study was 3.0±0.6 g kg^{-1}. Holder et al., 2017 used Cessna 206 aircraft to acquire airplane measurements of a plume emitted from wheat straw burning, complementing the ground-based data in Washington. Ground based measured $PM_{2.5}$ EF was observed to be higher than other measurement methods i.e., 16.0 ± 4.9 g kg^{-1}. Higher EFs of CO_2, polychlorinated dibenzodioxins and dibenzofurans (PCDDs/Fs), and equivalent Black Carbon (eBC) were also observed during the wheat straw burning activity. Jain et al. 2007 developed a ClearSky smoke dispersion forecast system by using the Lagrangian CALPUFF model and illustrated the results for four wheat straw burns in eastern Washington. The model predicted values aligned with observed values, which highlights the efficiency of using forecast systems models for monitoring smoke activities. While the model showed high efficiency in predicting $PM_{2.5}$, emission and plume rise parameters, the efficiency was notably correlated to predicted meteorological parameters.

Methoxyphenols and levoglucosan ratios in $PM_{2.5}$ play an important role as potential tracers in field burning smoke apportionment studies (Kubátová et al., 2002). Jimenez et al., 2007 analyzed the methoxyphenol levels using a turbovap concentrator (Zymark Corp., Hopkinton, MA). High prominent particle-phase methoxyphenols including syringaldehyde, acetosyringone, and coniferylaldehyde were found in the wheat straw burning activities. The study also utilized positive matrix factorization (PMF) model, establishing its capability to generate source profiles, specifically identifying biomass burning smoke among them. Dhammapala et al. 2007 collected smoke samples for analysis from airborne measurements with the help of a single engine Cessna C-172 aircraft, along with ground-based measurements. Each gram of $PM_{2.5}$ emitted during the wheat straw burning activities contained 0.2 ±0.2 mg PAHs. In addition, the study also documented that ground based fixed measurements might not represent the actual combustion efficiency of the plume, starting from ignition to flameout.

Gullett & Touati, 2003 studied the emissions of polychlorinated dibenzodioxins and dibenzofurans (PCDDs/Fs) from wheat straw burning in California. The field campaign consisted of winter wheat specifically with 0.08 % chlorine, 8.89 % moisture. The PCDDs/Fs measurements were made with the use of Grasebyt PS-1sampler by United States Environment Protection Agency's (USEPA)'s ambient method. The emissions factor of PCDD/F ranged between 337 to 602 pg toxic equivalency (TEQ)/kg. The homologue profile of the winter wheat straw burns showed high concentrations of octachlorodibenzodioxin (OCDD), ranging between 7,000 to 18,582 pg/kg. Hays et al., 2005 analyzed the chemical and physical characteristics of PM emitted from

Table 4
Summarization of emission characteristics from the literature

Sampling region	Measurement method/Instruments used	Type of straw studied	Major findings	Author(s)
OR	• Gelman Hurricane with an 8 in. by 10 in. filter holder	• Blue grass • Perennial Rye grass • Bent grass. • Annual Rye grass • Fescue grass • Orchard grass	• No statistically significant correlations were found between the meteorological parameters including the temperature, RH, wind speed and the emission variables.	Boubel et al., (1969)
CA	• Compilation of agricultural burn reports • Direct survey of growers	• All types	• Rice, Almond, walnut, and wheat straw contribute to 95 % of the total agricultural biomass burnings in the state. • 4769 t/year of PM emissions due to the agricultural burnings in the state.	Jenkins et al. (1992)
Watkinsville, GA	-	• Soybean • Wheat	• Crop residue burning was not found to have any permanent effects on the soil microflora	Harris et al., (1995)
Davis, CA	• 47 mm diameter Teflon-coated glass fiber filters (Pallflex type TX40HI20, Pallflex Products Corp., Putnam, Conn.)	• Barley • Corn • Rice • Wheat	• Corn and barley straw burning resulted in a higher fraction of total PAH in PM with 70 % and 12.7 % respectively. • PAH emissions were influenced by burning conditions i.e., wind speed and moisture content	Jenkins et al., (1996)
Davis, CA	• 47 mm diameter Teflon-coated glass fiber filters (Pallflex type TX40HI20, Pallflex Products Corp., Putnam, Conn.)	• Barley • Corn • Rice • Wheat	• PAH emissions were found to be dependent on the fuel type and burning conditions for all the types of crops. • Wheat straw burning resulted in the highest total emission rate of naphthalene comprising 98 % of determined PAH.	Jenkins et al., (1996)
Butte, CA	• CARB's Air Quality Data	• Rice	• Observed air pollutants i.e., O_3, CO, PM_{10} were poorly correlated to rice burn acreage. • Burn acreage showed a small i.e., 6 cases per year, but statistically significant increase in the number of asthma hospitalization cases per acre of rice burnt.	Jacobs et al. (1997)
Davis, CA	• Ion chromatography (IC) (Model 4000i, Dionex, Sunnyvale, California) • Atomic absorption spectrophotometry (AA) (Model 2380 Double Beam Atomic Absorption Spectrometer, Perkin Elmer, Norwalk, Connecticut) • Automated colorimetry (AC) (TRAACS 800 Automated Colorimetric System, Technicon, Tarrytown, New York) • 7-stage cascade impactor (Sierra Instruments model 228, Carmel Valley, California) on 47 mm Teflon-coated glass fiber filters (Pallflex type TX40HI20, Pallflex Products Corp., Putnam, Connecticut)	• Rice • Wheat • Barley • Corn • Sugar Cane	• XRF - X-ray fluorescence spectroscopy analysis of the data resulted that PM composition is mostly dominated by the elements C, K, Cl, and S, with carbon accounting for approximately 50 % of PM. • The aerosols of category PM_{10} emitted from the rice straw burning consisted high concentrations of Si, Ca and Fe when compared with other crop types.	Turn et al., (1997)
TX	• Survey and field data for acres burned. • Land cover and literature data on fuel consumption and emission factors	• All types	• Corn, Hay/grass, Sugarcane, and wheat are the largest contributors in the estimated acres burnt. • Estimated a total of 2502 short tons/yr of $PM_{2.5}$ emissions during a typical year due to agricultural burnings.	Dennis et al. (2002)
Lind, WA and Sutter County, CA	• PS-1 sampler (Graseby Andersen, GA)	• Wheat • Rice	• Emission factor of 0.5 ng TEQ/kg burned for wheat and rice field residue. • Estimated 1g TEQ/year from wheat and rice field residue burning across United states. • Minor source of PCDDs/Fs in the United States.	Gullett and Touati (2003)
Lind, WA and Sutter County, CA	• $PM_{2.5}$ cyclone (URG, Chapel Hill, NC) • 10 stage micro-orifice uniform deposit impactor (MOUDI, Model100; MSP Corp., Shoreview, MN) • Thermal–optical carbon analyzer (Sunset Laboratories, Forest Grove, OR)	• Wheat • Rice	• Rice straw led to higher emissions in all observed chemical classes. • Wheat stubble burning was estimated to contribute up to 15.3 % of the state's $PM_{2.5}$ anthropogenic emissions inventory.	Hays et al. (2005)
Global	• Global Ozone Monitoring Experiment (GOME) • GEOS-CHEM chemical transport model	• All types	• Biomass burning emissions in the United States were found to contribute to a range of 0.05 – 0.17 NOx /TgN $year^{-1}$ in the year of 2000	Jaeglé et al. (2005)
Pullman, WA	• Tapered element oscillating micro-balance (TEOM) monitors (Series 1400a, Thermo Electron Co) • Light scattering nephelometer (M903, Radiance Research, Seattle, WA) • DataRAM with a $PM_{2.5}$ size-selective inlet (Thermo-Andersen, Smyrna, GA)	• All types	• While emissions of LG, NOx, CO_2, OC, and apportioned biomass burning $PM_{2.5}$ were higher during the burning episode, EC episodes were not elevated. • Source specific $PM_{2.5}$ concentration identified by CMB and PMF models highly correlated with each other	Jimenez et al. (2006)
WA, ID	• $PM_{2.5}$ - DataRAM 2000 (MIE, Inc.) nephelometer • CO [Horiba VIA 510, dual beam NDIR] • CO_2 (Rosemount 880A, NDIR) • O_2 (Rosemount 755, paramagnetic susceptibility) • THC (TECO THC 51, Flame Ionization Detector.	• Wheat • Kentucky bluegrass	• In the 10 WA counties, the wheat stubble burning contributed to 3.7 % of the annual $PM_{2.5}$ emissions, whereas CO was responsible for 7.7 % of the emissions.	Dhammapala et al. (2006)

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Table 4 (*continued*)

Sampling region	Measurement method/Instruments used	Type of straw studied	Major findings	Author(s)
Corvallis, OR	• Using Trinexapac-ethyl (TE)	• Festuca rubra L.	• TE applications were found not to be dependable alternative to open field burning to increase the harvest index.	María Carolina Zapiola et al. (2006)
Pullman, WA	• TEOM (Series 1400a, Rupprecht & Patashnick Co., Inc). • Nephelometer (Radiance Research, Seattle, WA)	• All types	• During the agricultural burning season, outdoor $PM_{2.5}$ concentrations exhibited substantial spatial variation. • Mean exposure level of $PM_{2.5}$ was observed to be higher during the burning episodes with a value of 8 μg m^{-3} than the non-burning episodes.	WU et al. (2006)
WA, ID	• CNS2000 total carbon analyzer (LECO Corporation, St. Joseph, MI) • Aircraft based sampling - Cessna C-172 aircraft	• Wheat • Kentucky bluegrass	• Each gram of $PM_{2.5}$ emitted during wheat field burns consists of 0.2±0.2 mg PAHs. • Ground based measurements were not observed to represent the combustion efficiency of the whole plume.	Dhammapala et al. (2007)
Davis, CA	• 10 stage Micro Orifice Uniform Deposit Impactors (MOUDI)	• Rice • Almond	• Combustion temperature was the most important factor when determining the PAH composition of the particles. • The rice straw burning activities produced more PAHs when compared to that of almond pruning.	Keshtkar and Ashbaugh (2007)
WA, ID	• CALPUFF modeling system	• Wheat • Kentucky bluegrass	• The accuracy of surface $PM_{2.5}$ predictions and plume impacts are highly correlated to predicted meteorological systems.	Jain et al. (2007)
WA, ID	• LowVols samplers (Air Metrics Inc., Eugene, OR) • 47-mm Teflon filters (2 μm pore size, cat. no. 7592-104, Whatman Inc., Clifton, NJ) • Microbalance (model C-34, Cahn Instruments, CA) • Turbovap concentrator (Zymark Corp., Hopkinton, MA) • Positive matrix factorization (PMF) modeling	• Wheat • Kentucky bluegrass	• High prominent particle-phase methoxyphenols found in wheat stubble burnings are syringaldehyde, acetosyringone, and coniferylaldehyde which can be used to apportion field burning smoke.	Jimenez et al. (2007)
Sacramento Valley, CA	• A thermal extraction–two-dimensional gas chromatography–mass spectrometry (TE–GC–GC–MS) • TE unit [Gerstel Inc., Baltimore, MD] • GC–MS [Model 6890-5973; Agilent Technologies]	• Rice	• Thermal optical analysis exhibited that the biomass burning aerosol matrix comprised over 80 % of organic matter. • Heterocyclic aromatic N compounds comprised 0.7 % (w/w) of the total fine aerosol mass.	Ma & Hays, (2008)
CONUS	• Moderate Resolution Imaging Spectroradiometer (MODIS)	• All types	• Polar orbiting satellites provide a limited view of fire activity in agricultural landscapes. • Better cropland burning monitoring can be achieved through hybrid approach to combine the dNBR based approach with the calibrated active fire detections.	J. L. McCarty et al. (2008)
CONUS	• National Interagency Fire Center's FAMWEB (Fire and Aviation Management Homepage) data • Moderate Resolution Imaging Spectroradiometer (MODIS)	• All crops	• The estimated $PM_{2.5}$ emitted from agricultural burning for 2005 was 232,000 short tons, a 3 % increase from 2002.	Pace et al. (2008)
CONUS	• Moderate Resolution Imaging Spectroradiometer (MODIS)	• All types	• The 3 most burnt crops are sugarcane, wheat, and rice. • Crop residue burning comprises 43 % of the reported wildland burnt area when compared to the total area burned by wildland fires from 2003-2007.	McCarty et al., (2009)
CA	• Literature review	• All crops	• The study generated a framework to utilize the biomass wastes in energy conversion process which reduced the PM, NOx, NMOC, CO and CO_2E emissions by 98 %, 54 %, 99 %, 97 % and 17 % respectively.	Springsteen et al., (2011)
CONUS	• Moderate Resolution Imaging Spectroradiometer (MODIS) • Literature review of EFs'	• Corn • Bluegrass • Cotton • Rice • Soy • Sugarcane • Wheat	• Arkansas, California, Florida, Idaho, Texas, and Washington account for 63 % of $PM_{2.5}$ and 50 % of PM_{10} emissions. • Florida had the highest emissions from burning crop residues among CONUS. • Most of the crop residue burning emissions were found to be in the period of spring, summer, and fall.	McCarty, (2011)
FL	• EPA Method TO-13A • EPA Method TO-11A • EPA Method 18 • EPA's Other Test Methods (OTM) 27 and 28	• Sugarcane	• PAH concentrations on PM emissions of whole stalk burning were higher than of dry leaf burning. • Benzene was the largest VOC component followed by toluene in the emissions.	Hall et al., (2012)
Imperial, CA	• DataRAM (pDR 1000AN and pDR-1200, Thermo Electron Corp., Franklin, MA)	• Bermudagrass	• While both $PM_{2.5}$ and $PM_{10\text{-}2.5}$ values were elevated during the burning periods, $PM_{2.5}$ comprised up to 94 % carbonaceous content. • Most of the surveyed residents regarded agricultural burning as a substantial health concern relative to other issues	Harnly et al. (2012)
Missoula, MT	• High-resolution proton-transfer reaction time-of-flight mass spectrometer (PTR-TOF-MS)	• All types	• S-containing compound named methanethiol which plays a role in acid deposition and aerosol	Stockwell et al. (2015)

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Table 4 (*continued*)

Sampling region	Measurement method/Instruments used	Type of straw studied	Major findings	Author(s)
			deposition was found in the biomass burning smoke.	
Greeley, CO	• H_3O^+ time-of-flight chemical ionization mass spectrometer (ToF-CIMS)	• Corn	• Emission of NVOCs from the burning activities largely depended on fuel nitrogen content i.e., for every 1 % increase in fuel nitrogen content, the total VOCs identified as NVOCs increases by approximately 2.3 to 6 %.	*Coggon et al., (2016)*
WA, ID	• Airplane: Cessna-206 • 4.3 m diameter aerostat (Kingfisher Model, Aerial Products Inc., USA) • SUMMA Canisters (Columbia Analytical Services – CAS, U.S.A.)	• Wheat • Kentucky bluegrass	• Higher emission factors of CO_2, PCDDs/PCDFs, and eBC were observed during the wheat straw burning while lower emission factors for $PM_{2.5}$, OC, PAHs, CH_4 and CO were recorded when compared to Kentucky bluegrass.	*Holder et al. (2017)*
FL, OK	• NOAA WP-3D aircraft	• Sugarcane • Winter wheat	• Primary CHOCHO glyoxal from biomass burning were indicated to be contributing to 12 % of the global CHOCHO according to the models.	*Zarzana et al. (2017)*
GA	• Hazard Mapping System (HMS) data • National Agricultural Statistics Service Information (NASS) Cropland Data	• All crops	• Approximately 6,701 of the HMS detections were detected in snow-covered areas. • Number of fires reported by the satellites were lower than the Department of Natural Resources (DNR) Georgia.	*Pouliot et al., (2017)*
AR	• Gulfstream-1 (G-1) aircraft • 2-stage aerosol impactor sampler (AS-16W, Arios Inc., Tokyo, Japan)	• All types	• Tar balls (TB; spherical organic materials) were found to retain approximately 30 % of the volume even at 600° C. • The risk to underestimate amount of atmospheric organic aerosols using thermal analyzers was found which could impact the numerical simulations.	*Adachi et al. (2017)*
Nez Perce, ID and Walla Walla, WA	• Environmental Beta Attenuation Monitors (EBAMs, Met One Inc., Grants Pass, OR) • Aerial (aerostat and airplane) sampling	• Winter wheat • Bluegrass	• Inputting emissions from burning cropland into surface layer of the modelling system doesn't accurately depict the vertical plume structure of the fire.	*Zhou et al., (2018)*
MO, KY, TN, AR	• NOAA WP-3D aircraft • Ultrahigh sensitivity aerosol spectrometer (UHSAS) • Proton-transfer-reaction mass spectrometer (PTR-MS)	• Winter wheat • Rice	• Fire emissions during the times at near sunset were found to have an influence by decreasing 60 % decrease of fire derived NOx	*Decker et al. (2019)*
AR	• -	• Wheat	• Non burning of the residue was found to have positive impact on the soil health and mitigation of greenhouse gas concentrations in the atmosphere by decreasing the SOM oxidation and CO_2 emissions.	*Desrochers et al. (2019)*
CONUS	• Laser Induced Fluorescence – Sulfur Dioxide (LIF-SO_2) • Aerodyne high-resolution time-of-flight aerosol mass spectrometer (AMS)	• All types	• SO_2 emission factors were found to be less dependent on combustion phase and fuel type, while more dependent on geographical location and land use.	*Rickly et al. (2022)*
ID	• DustTrak DRX 8533 (LI-COR Biosciences, USA) • 47 mm tared Teflon filter (pore size of 2.0 μm) via a Leland Legacy sample pump (SKC Inc., USA)	• Alfalfa	• Burning untreated alfalfa emitted higher amounts of $PM_{2.5}$ when compared to treated alfalfa. • The highest detected PAH in both types of alfalfa was naphthalene, which was 68 % of total PAH EF.	*Aurell et al., (2022)*
Brownsville, TX	• DustTrak™ DRX Aerosol Monitor -8534 (TSI Inc., Shoreview, MN, USA) • Q-Trak™ Indoor Air Quality Monitor 7575 (TSI Inc., Shoreview, MN, USA) • microAeth® MA200, (AethLabs, San Francisco, CA, USA) • Monitor 202 (2B Technologies, Boulder, CO, USA) • 405 nm NO_2/NO/NOx Monitor™ (2B Technologies, Inc., Boulder, CO, USA)	• Sugarcane	• Increase of Black Carbon levels by 55 % during the burning period when compared to non-burning period. • The absorption Ångström exponent increased to 2.03, while the Carbon monoxide levels increased by 67 %. • The amount of $PM_{2.5}$ composition in PM_{10} which was calculated through the $PM_{2.5}/PM_{10}$ ratio increased to 0.87.	*Pinakana et al., (2023)*
KS	• Low-cost PurpleAir monitors • GOES Aerosol Optical Depth • NOAA Hazard Mapping System (HMS) fire and smoke plume product	• Prescribed burnings with major fuel as rare tallgrass prairie	• The median $PM_{2.5}$ levels rose by 3.0 - 5.3 μg m^{-3} during days affected by smoke from fires in the eastern Kansas area, in contrast to unaffected days.	*Sablan et al., (2024)*

wheat straw burning in California using gravimetric analysis. The $PM_{2.5}$ emissions consisted of 80 % weight/weight (w/w) of sulfur and corresponded to 2.4 % of the total $PM_{2.5}$ mass. Wheat stubble burning was also estimated to contribute up to 15.3 % of the state $PM_{2.5}$ anthropogenic emissions inventory. The Emission Factor (EF) of K^+ was found to be 1.5 g kg^{-1}, while EF of Cl- was 1.7 g kg^{-1} in the study. The elevated levels of K and Cl, especially in the region of Pacific Northwest could be attributed to soils naturally high in potassium (Hays et al., 2005).

5.1.3. Rice residue

Keshtkar and Ashbaugh 2007 analyzed the size distribution PAHs in PM emitted from the rice straw burning activity in California. The average particulate concentration for the activity was 28.2 μg m^{-3}. Components including phenanthrene, anthracene, fluoranthene and pyrene accounted for 73 % of the total PAHs emission from rice straw smoke. The study documented that combustion temperature was an important factor in determining the PAH composition of the emitted particles. Hot flames were observed to produce less amount of PM and PAHs. In a study conducted in Butte County, California, Jacobs et al., 1997 analyzed the California Air Resources Board (CARB)'s air quality data from 1983 to 1992 to investigate the relation between rice burning activities and asthma hospitalizations. The study estimated that a total of 70,000 acres of rice stubble was burnt annually during these years. Ma & Hays, 2008 used a thermal extraction–two-dimensional gas chromatography–mass spectrometry (TE–GC–GC–MS) method to assess the nitrogen (N)-bearing organic species in aerosols emitted from rice straw burning in California and these were found to comprise 0.7 % (w/w) of the total fine aerosol mass. The N heterocyclics are typically formed in the fire due to pyrolysis of nitrogen containing constituents in the vegetation.

Decker et al., 2019 analyzed the smoke observations during nighttime using the NOAA WP-3D aircraft. A major part of the rice straw fire emissions was found to consist of furans (33±8 %), phenols (27±4 %), and furfurals (24±6 %), while hydrocarbons and terpene emissions accounted for only 3±1 % of the total emissions.

5.1.4. Sugarcane residue

Hall et al., 2012 used EPA Method TO-13A, EPA Method TO-11A, EPA Method 18 and EPA's Other Test Methods (OTM) 27, 28 to estimate the emission factors for air pollutants i.e., PAHs, carbonyl, VOCs and $PM_{2.5}$, respectively from a sugarcane burning event in Palm Beach County, Florida. PAH concentrations of PM emissions were found to be higher (223 – 306 μg m^{-3}) during whole stalk burning activity when compared to dry leaf burning (119 – 136 μg m^{-3}). The EF of total PAHs produced from the burning activity was recorded as 0.00818 ± 0.00326 g kg^{-1}. Pinakana et al., 2023 used different ground-based instruments to quantify various pollutants emitted from a sugarcane residue burning activity in Texas. The study documented that during the sugarcane stubble burning, an increase of 10 %, 11.6 %, 25.29 %, 55 %, and 67.57 % was found in the total levels of PM_1, $PM_{2.5}$, PM_{10}, BC, and CO, respectively when compared to days with no burning activity during the study period. The $PM_{2.5}/PM_{10}$ ratio which helps in quantifying the relative dominance of fine/coarse particles in mass concentrations was measured in the study as well and was found to increase to 0.87 during the burning activity.

Stockwell et al. 2015 performed real time analysis of non-methane organic compounds (NMOCs) using a high-resolution proton-transfer reaction time-of-flight mass spectrometer (PTR-TOF-MS). Sugarcane was observed to produce large amounts of acetaldehyde (EF of 4.3 ± 1.4 g kg^{-1}), along with oxygenated and N-containing compounds. The emissions contained high levels of oxygenated and N containing compounds, which could be attributed to high sugar content. McCarty, 2011 used remote sensing data of Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate the annual and seasonal emissions from crop residue burning including sugarcane in CONUS. The results showed that between 2003 to 2007, sugarcane residue burning led to 34 % of all emissions across CONUS.

5.1.5. Barley residue

Jenkins et al., 1996 used the CARB Method 429 to collect and analyze PAH emissions samples. The study recorded a total of 25 PAH derivatives while burning the barley straw. The total percentage of PAH in particulate matter emitted was 12.7 %. EF of naphthalene in the total PAHs was recorded as 0.011053 to 0.149542 g kg^{-1}. Turn et al., 1997 performed XRF - X-ray fluorescence spectroscopy analysis of the PM data that was collected from the burning activity of barley straw in California. After the elemental characterization of PM, the major components found were K^+, SO_4^-, S, Na, K and Br. The PM_{10} concentration emitted from barley straw burning had high content of sulfur (4 %) when compared to PM_{10} emissions from residues of rice, wheat, corn, and sugarcane. Emission factors of Br, K^+ and SO_4^- were recorded as 0.0084 g kg^{-1}, 1.2 g kg^{-1} and 0.58 g kg^{-1}, respectively.

5.1.6. Emissions from burning of crop fields in general

Various studies have used remote sensing data to quantify the emissions from agricultural burning activities in CONUS. Pace et al., 2008 estimated the total $PM_{2.5}$ emissions from agricultural burning activities in CONUS for 2005 with the help of National Interagency Fire Center's FAMWEB (Fire and Aviation Management Homepage) data and Moderate Resolution Imaging Spectroradiometer (MODIS) data. The study showed that 232,000 short tons of $PM_{2.5}$ was emitted in 2005 due to agricultural burning which was 3 % more than 2002. McCarty et al., 2009 used MODIS data to observe the spatial and temporal distribution of crop residue burning in CONUS. The study results showed that sugarcane, wheat, and rice straw were the three most burnt crops when compared to other crops. McCarty, 2011 used MODIS data to estimate crop residue burning emissions in CONUS. The study showed that Florida contributed 17 %, 17 %, 12 % and 9.5 % to annual CO_2, CO, $PM_{2.5}$ and CH_4 emissions respectively, from crop residue burnings. The total emissions of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and CH_4 in CONUS from 2003-2007 were 23.6 Gg yr^{-1}, 34.3 Gg yr^{-1}, 5.24 Gg yr^{-1}, 13.1 Gg yr^{-1}, 278.1 Gg yr^{-1} and 10.5 Gg yr^{-1}. Global Ozone Monitoring Experiment (GOME) device estimated that open field agricultural residue burning produced 0.2 TgN of NO_2 per year for 2000 (Jaeglé et al., 2005).

Pouliot et al., 2017 used Hazard Mapping System (HMS) data along with National Agricultural Statistics Service Information (NASS) Cropland Data to develop an inventory of crop residue burning. HMS is a combined product of Geostationary Operational Environmental Satellite (GOES) Imager, the Polar Operational Environmental Satellite (POES) Advanced Very High-Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), and the Visible Infrared Imaging Radiometer Suite (VIIRS). The top two states for crop residue burning, in terms of both acres and $PM_{2.5}$ emissions [tons yr^{-1}], according to the study were California and Kansas in 2014. For the same year, the study compared the satellite detected fire data to ground based records provided by Department of Natural Resources (DNR) from the state of Georgia. Even though the number of fires detected by the satellites were much lower than the actual data provided by DNR, there was a spatial and temporal agreement between the data (r = 0.73). Dennis et al. 2002 used the data collected through survey, field work and literature to assess air pollutant emissions associated with various types of burning activities including agricultural burning in Texas. The study estimated that a total of 2502 short tons/yr of $PM_{2.5}$ was emitted during a typical year, while corn, hay/grass, sugarcane, and wheat are the crops which are burnt most in Texas.

With the advances in technology, various studies have used aircraft to sample the burning plumes and analyze the emission compositions of PM. Adachi et al. 2017 used Gulfstream-1 (G-1) aircraft to calculate the volume changes in aerosol particles emitted from agricultural burning activity in Arizona, using transmission electron microscopy. Tar balls which are carbon bearing particles were found to retain 30 % of their volume even at a temperature of 600° C. A study by Zarzana et al., 2017 sampled burning plumes by using NOAA WP-3D aircraft to assess the amount of Glyoxal (CHOCHO) and other carbonyl compounds. The researchers documented that carbonyl compounds such as formaldehyde (HCHO), glyoxal (CHOCHO), and methylglyoxal (CH3COCHO) were found in large amounts. Primary CHOCHO glyoxal emissions from biomass burning contributed to 12 % of the global CHOCHO according to the models. Harnly et al. 2012 assessed the air quality in Imperial County, California for a period of 69 days when the bermudagrass burning activities were taking place. Average $PM_{2.5}$ concentrations on the days of burning activity were 23 % higher than days with no burning activity.

5.2. Impact on community health

Studies conducted globally have proved that air pollutants are hazardous to human health. Exposure to $PM_{2.5}$ has been correlated to higher rates of asthma-related emergency visits, increased mortality in chronic obstructive pulmonary disease cases, and a decrease in life expectancy (Chakrabarti et al. 2020). Various studies have been conducted in

CONUS highlighting the effect of air pollutants released from agricultural burning activities on community health. Jacobs et al. 1997 analyzed the CARB's air quality data from 1983 to 1992 to investigate the relation between rice burning activities and asthma hospitalizations in Butte County, California. The study showed a small but significant rise in asthma hospitalizations per acre of rice burnt, with the highest risk of hospitalizations associated with days when the burn acreage reached more than 499 acres. The study results documented that approximately six hospitalization cases per year could be attributed to rice burning activities.

Harnly et al. 2012 conducted a public survey to understand the perspective of community in the bermudagrass burning activities in Imperial County, California. Out of seven interviews conducted, five of them considered the burning activity to be a high or medium health concern when compared to other community problems. In their study, Jacobs et al. 1997 highlighted that just relying on the number of people falling ill with asthma might not accurately reflect the impact of burning activity on human health. Instead, the number of visits to emergency rooms should also be considered as an important factor in finding the effect as burning might not cause illness severe enough to require hospitalization. Wu et al. 2006 conducted a study to measure the personal exposure to $PM_{2.5}$ from agricultural burning smoke for 33 asthmatic adults in Pullman, WA. The mean personal exposures of $PM_{2.5}$ on days with burning activities (19.0±11.8 mg m^{-3}), was noted to be higher than exposure levels on days without burning activities (11.0±9.7 mg m^{-3}). The personal exposure levels to organic carbon (OC) also were noted to be higher on days with burning activities (10.2±2.8 mg m^{-3}), when compared to days without burning activities (7.7+2.2 mg m^{-3}).

6. Impact of agricultural field burning on air quality in CONUS

6.1. Fire emission inventories

The advancements in satellite remote sensing to monitor active fires and burned areas over the past few decades have resulted in the robust computation of aerosol emissions and sources (Ichoku et al., 2012). Some of the major inventories are Global Fire Emissions Database Version 3.1 (*GFEDv3.1;* Randerson et al., 2013), Global Fire Emissions Database Version 4.1 (*GFEDv4.1;* Randerson et al., 2015), Fire Inventory from NCAR (FINNv2.5; Wiedinmyer and Emmons., 2022), Quick Fire Emissions Dataset (*QFED;* Koster et al., 2015*)*, Fire Energetics and Emissions Research algorithm (FEER; Ichoku & Ellison, 2014), Global Fire Assimilation System *(GFAS;* Kaiser et al., 2012*)*, Fire Locating and Monitoring of Burning Emissions *(FLAMBE;* Reid et al., 2009*),* Wildland Fire Emissions Information System *(WFEIS v0.5*; Nancy et al., 2016*)*, and National Emissions Inventory. The inventories are generally developed using a top-down approach (e.g. GFED, FINN) or bottom-up approach (e.g. QFED, GFAS, FEER, FLAMBE, NEI). Top-down method develops the emission inventories using Fire Radiative Energy (FRE), Fire Radiative Power (FRP) and Aerosol Optical Depth (AOD) observed by satellites. Whereas the bottom-up approach calculates emissions by directly using the EFs that are estimated from burned areas and fuel loading (Li et al., 2019).

Fire Emission Inventories (FEI) estimate emissions by utilizing fuel loading values from ground-based measurements and assign them to daily burned areas along with associated vegetation information. The Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE) identified prevalent combustion sources across South Asia, such as crop residue burning, which are often under-sampled. The emission factor of $PM_{2.5}$ for this specific fuel is 11.5 ± 2.2 kg-^{1}. Higher levels of levoglucosan were also present in the emissions of agricultural crop residues containing crops such as rice, wheat, mustard (Jayarathne et al., 2018). In the Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) campaign in 2019, Travis et al. (2023) presented the emission factors for various fuels including corn, rice, soybean, and winter wheat in the Eastern United States. EFs for crop residues associated with agricultural chemicals, fuel composition, and oxygenated non-methane volatile organic compounds (NMVOCs) were observed to be higher which could be attributed to the presence of elements like potassium (Travis et al., 2023). Fire activities also can impact ozone levels by contributing NMVOCs to regions where ozone is VOC-limited (Singh et al., 2012). The crop residue burnings in Indo-Gangetic Plain (IGP) in Northern India were observed to have a significant impact on the ozone levels in the region with up to an increase of 29 % in summer and 10 % in late post monsoon despite the lower temperatures (Kumar et al., 2016). A field measurement repository developed by van Leeuwen et al. (2014) compiled 77 studies across the world that assessed fuel loadings covering 11 biomes including croplands. Akagi et al. (2011) provided a detailed list of emission factors for identifiable pyrogenic substances. These factors were derived from analyses conducted on smoke that had cooled to the surrounding temperature but had not undergone considerable photochemical alterations. Fuel loadings from Akagi et al. (2011) have been used for emission estimates in both GFEDv4.1s and FINNv2.5.

Liu et al., 2020, Pan et al., 2020 compared different biomass burning emissions inventories to find the spatial biases and uncertainties in the applications. Pan et al. (2020) demonstrated that OC and BC emissions obtained from GFED3.1, GFED4s, FINN1.5, GFAS1.2, FEER1.0, and QFED2.4 differed by a factor of 3.8 and 3.4, respectively on an annual average. This difference in the estimates can be caused by uncertainties in small fires, cloud gap adjustments, aerosol emission enhancements, emission factors and land use land cover classification (Liu et al., 2020). To address the problem of uncertainty in detection of small fires, GFEDv4.1s has used a small fire boost (SFB). This is very important in the agriculture burning areas as the crop residues are typically burnt as individual small fires, which impact the local air quality significantly (Zhang et al., 2018). Another Google Earth Engine based app developed by Liu et al., 2020 titled 'Fire Inventories: Regional Evaluation, Comparison, and Metrics (FIRECAM; https://globalfires.earthengine.app/view/firecam), allows users to compare the temporal trends from GFEDv4s, FINNv1.5, GFASv1.2, QFEDv2.5r1, and FEERv1.0-G1.2.

In this review, we chose the emission inventories which partitioned the emissions by Land Use/Land Cover (LULC). GFEDv4.1, FINNv2.5 and National emissions inventory were used to assess the emissions from the agricultural burning activities. As the GFEDv4.1, FINNv2.5 are global biomass burning emission datasets, the data is filtered to CONUS and then to vegetation type for both the data sets.

6.2. GFEDv4.1s

The Global Fire Emissions Database Version 4.1 with small fires (GFEDv4.1s) inventory provides monthly-average fire consumed dry matter for individual fire types at a spatial resolution of 0.25° (Liu et al., 2024). The inventory contains emission data for a total of 41 species including carbon (C), carbon dioxide (CO_2), CO, CH_4, NOx, OC, BC, $PM_{2.5}$, total particulate matter (TPM) from 1997 to 2016 (Randerson et al., 2015). The GFEDv4.1s burned area estimate is from the 500-meter MODIS product MCD64A1 after 2001, while before that data from the Visible and Infrared Scanner (VIRS) and the Along-Track Scanning Radiometer (ATSR) were utilized (Randerson et al., 2015). GFEDv4.1 has been employed in diverse research endeavors, such as investigating the impacts of Amazonian fires on atmospheric CO_2 levels (Jiang et al., 2021), tropical Pacific and Indian ocean sea surface temperature influence on vegetation variability in eastern Africa (Kim et al., 2021), and examining the spatiotemporal patterns of carbon emissions induced by biomass burning in China (Chen et al., 2020).

Table 5 presents the descriptive statistics of total emissions estimated from all fire types and agricultural waste burning of different species for the period spanning 1997 to 2016. The total methane emissions during this period were 810 Gg, accounting for approximately 1/3rd of methane emitted from all fire types. The mean $PM_{2.5}$ emissions during the period from all fire types was approximately 355.5 ± 121.46 Gg, whereas

Table 5
Descriptive statistics for burning emissions and sources from GFEDv4.1s

Species	Source	Mean±SD (Gg yr^{-1})	Sum (Gg)	% of contribution in sum
CH_4	CE	123 ± 34.35	2460	32.92
	AWB	40.5 ± 15.38	810	
BC	CE	18.4 ± 5.13	368	27.98
	AWB	5.15 ± 1.87	103	
CO	CE	3030 ± 890.36	60600	24.75
	AWB	750 ± 266.56	15000	
TPM	CE	498.5 ± 164.17	9970	18.15
	AWB	90.5 ± 31.87	1810	
C	CE	17600 ± 5245.55	352000	17.61
	AWB	3100 ± 1333.77	62000	
NOx	CE	99.5 ± 27.24	1990	17.58
	AWB	17.5 ± 7.86	350	
$PM_{2.5}$	CE	355.5 ± 121.46	7110	11.67
	AWB	41.5 ± 15.31	830	
CO_2	CE	57000 ± 18381.91	1140000	11.4
	AWB	6500 ± 5871.43	130000	
OC	CE	210.5 ± 83.19	4210	6.17
	AWB	13 ± 6.57	260	

*CE – Combined emissions
*AWB – Agricultural waste burning emissions

agricultural waste burning contributed around 41.5 ± 15.31 Gg. Other species majorly contributing to the total emissions were BC, CO, and TPM with 27.98 %, 24.75 % and 18.15 % respectively.

6.3. *FINNv2.5*

Fig. 8 depicts the histogram of agricultural waste burning caused by emissions of different species for 1997-2016, along with the moving average. This helps in understanding the temporal trends of emissions from the agricultural waste burning activities across CONUS. The graphs indicate that there has been a substantial increase in all the species' emissions in the year 2010. The values for CO_2, NOx, and SO_2 in 2010 were observed to double compared to their values in 2009, while the values for other parameters increased by 1.5 to 1.8 times those observed in 2009.

The Fire Inventory from NCAR (FINN) provides daily global fire emissions at a spatial resolution of 0.1° (Wiedinmyer et al., 2023). The dataset spans from 2002 to 2021, encompassing 52 different species, including CO_2, CO, CH_4, $PM_{2.5}$, TPM, OC, BC, and PM_{10}. The previous version i.e., FINNv1.5 used only MODIS fire detections which were available at a resolution of 1 km^2 (Wiedinmyer et al., 2011). In contrast, FINNv2.5 introduces the capability to incorporate active fire detections at a 375-meter resolution from the Visible Infrared Imaging Radiometer Suite (VIIRS), which is aboard the Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite (Wiedinmyer et al., 2023). These detections can be utilized either independently or in conjunction with MODIS active fire data and are very useful in capturing small fires. The inventory has been employed in multiple studies to evaluate the effects of biomass burning in Southeast Asia, including its impact on CO_2 concentration in South China (Li et al., 2023), the relationship between solar geoengineering and wildfires (Tang et al., 2023), and the levels of $PM_{2.5}$ in Southeast Asia during hazy months (Fang et al., 2024).

Table 6
Descriptive statistics for burning emissions and sources from FINNv2.5

Species	Source	Mean±SD (Gg yr^{-1})	Sum (Gg)	% of contribution in sum
CH_4	CE	480.44 ± 115.91	9608.76	10.11
	AWB	48.57 ± 8.25	971.31	
CO	CE	11948.54 ± 3500.64	238970.72	6.34
	AWB	757.74 ± 128.78	15154.8	
CO_2	CE	196305.02 ± 56338.59	3926100.49	6.12
	AWB	12022.35 ± 2043.22	240446.98	
TPM	CE	1960.37 ± 579.82	39207.49	5.52
	AWB	108.21 ± 18.39	2164.19	
BC	CE	86.98 ± 23.23	1739.69	4.88
	AWB	4.25 ± 0.72	84.9	
$PM_{2.5}$	CE	1552.20 ± 528.63	31044.02	3.45
	AWB	53.52 ± 9.10	1070.44	
PM_{10}	CE	1783.10 ± 557.20	35662.05	3.28
	AWB	58.43 ± 9.93	1168.66	
OC	CE	712.35 ± 227.53	14247.02	3.11
	AWB	22.14 ± 3.76	442.82	

*CE – Combined emissions
**AWB – Agricultural waste burning emissions*

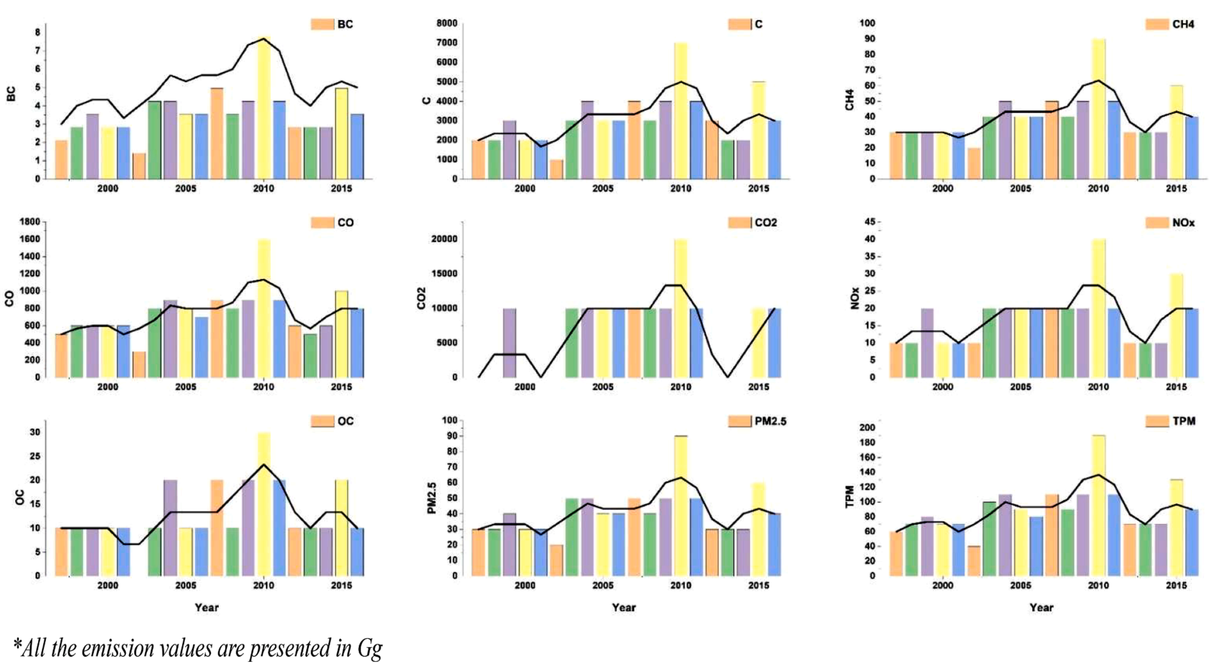

Fig. 8. Temporal trend of various emissions from agricultural waste burning in CONUS

Table 6 displays the descriptive statistics of emissions for various species resulting from agricultural burning in CONUS from 2002 to 2021. On average, 166,555.55 ± 50,317.31 Tg of agricultural waste was burnt annually during this period. Notably, average annual emissions of CO_2 were the highest (12022.34 ± 2043.22 Gg), followed by CO (757.74 ± 128.78 Gg), TPM (108.20 ± 18.39 Gg) and PM_{10} (58.43 ± 9.93 Gg). These values indicate significant impact of agricultural burning activities on air quality in the CONUS region contributing 10.11 % of CH_4, 5.52 % of TPM, and 3.45 % of $PM_{2.5}$ emissions.

Agricultural burning activities take place across the CONUS at different times throughout the year. In Kansas, the agricultural burning season typically occurs during March to May, and in California during April to June and September to November (Sablan et al., 2024). Fig. 9 shows the spatial and temporal distribution of the agricultural burning activities across CONUS and provides valuable insights regarding the seasonal patterns and peak months for agricultural burning activities. There were notable seasonal variations in the number of fires. March, April, September, and October tend to have significantly higher numbers of fires compared to other months. April and October stand out as the peak months, with the highest average number of fires per month. Quarter 2 and Quarter 4 consistently had higher total numbers of fires compared to Quarter 1 and Quarter 3. During the first quarter, burning activities appeared to be primarily focused on Kansas, Arkansas, Georgia, and Missouri. In the second quarter, a rise in agricultural fires particularly in North Dakota, South Dakota, and Minnesota is observed. The third quarter experienced the lowest incidence of fires for all the years. Fig. 9e illustrates the mean frequency of agricultural fires per month in CONUS. The highest average number of fires were observed in April with 3180 activities, followed by October with 3065.

6.4. National Emissions Inventory (NEI)

According to the latest NEI of 2020 (US EPA, 2023), agricultural field burnings produced 20 % of total $PM_{2.5}$ emissions (67,309.81 tons), while the total amount of emissions were 331,458.22 tons in CONUS. While North Dakota was the major producer with 17 % of the agricultural burning emissions, California and Texas accounted for 10 % and 7.3 %, respectively. Other pollutants released due to agricultural field burning were as follows:101,036.74 tons of PM_{10}, 676,124.71 tons of CO, 11, 213.47 tons of SO_2, 30,504.08 tons of NO_X, 145,755.09 tons of NH_3, and 106,089.28 tons of VOCs. The total emissions of $PM_{2.5}$, PM_{10}, CO, SO_2, NOx, NH_3 and VOCs for each state are available in Supplementary Table S1.

The county wise $PM_{2.5}$ emissions due to agricultural field burning according to the NEI database are shown in Fig. 10. The map was prepared using data acquired from 2020 NEI database (US EPA, 2023). The county with highest emissions (1671.40 tons) is Palm Beach from Florida, followed by Fresno, California - 1105.65 tons and Cavalier, North Dakota – 98.15 tons. Palm beach is well known as an agricultural hub as it leads the nation in the production of sugarcane and sweet corn. It also leads the state of Florida in the production of rice (Business Development Board of Palm Beach County, 2016). The top 20 counties with various emissions including $PM_{2.5}$, PM_{10}, CO, SO_2, NOx, NH_3 and VOCs are available in Supplementary Table S2. Table 7 shows the pollutant emissions from NEI due to agricultural field burning from 2008 till 2020. There was an increase in all the emission levels except ammonia from 2008 to 2011. From 2011, all the emission levels were showing a decreasing trend till 2017 and then the values increased by 2.18 – 2.78 times in 2020. This clearly shows that the emissions levels of agricultural burnings are increasing in CONUS and necessary control

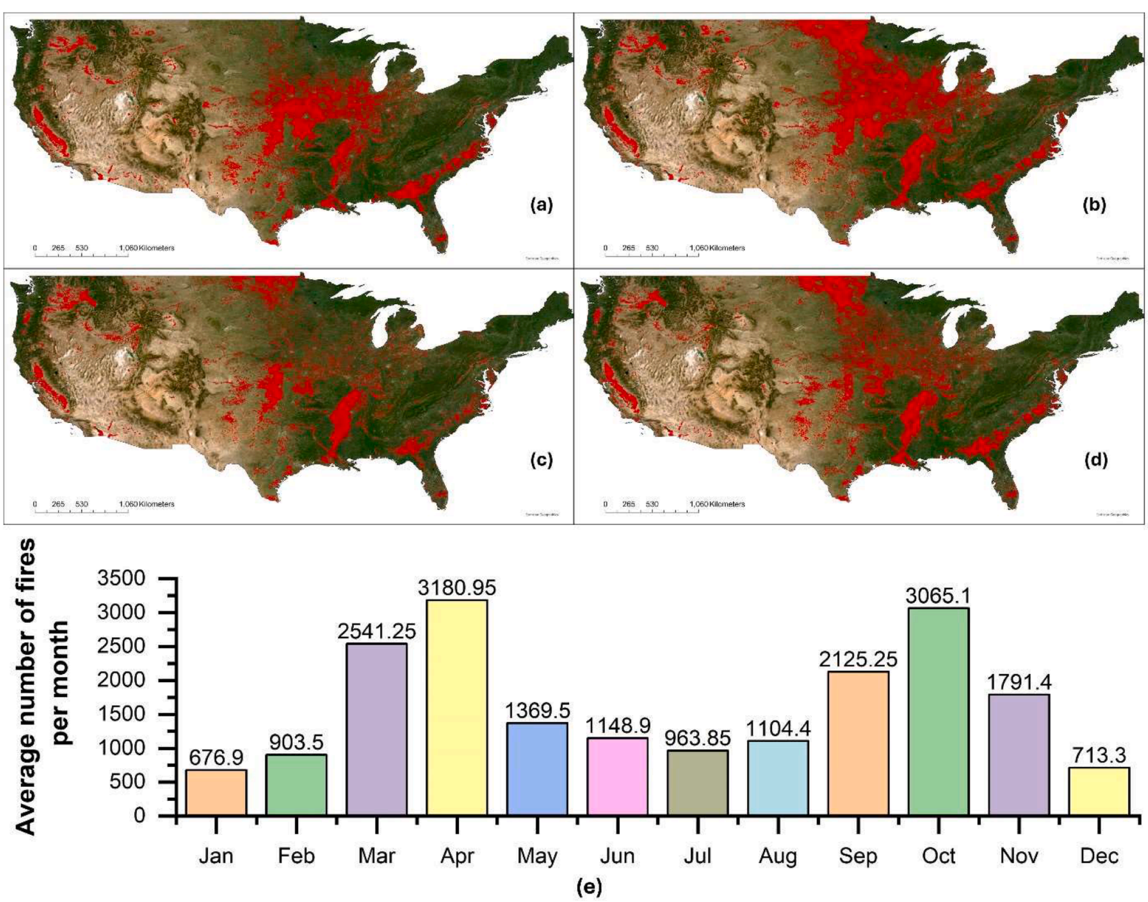

Fig. 9. Spatio-temporal trends of agricultural waste burning activities in CONUS (a) January – March, (b) April – June, (c) July – September, (d) October – December, (e) Average number of fires per month in CONUS.

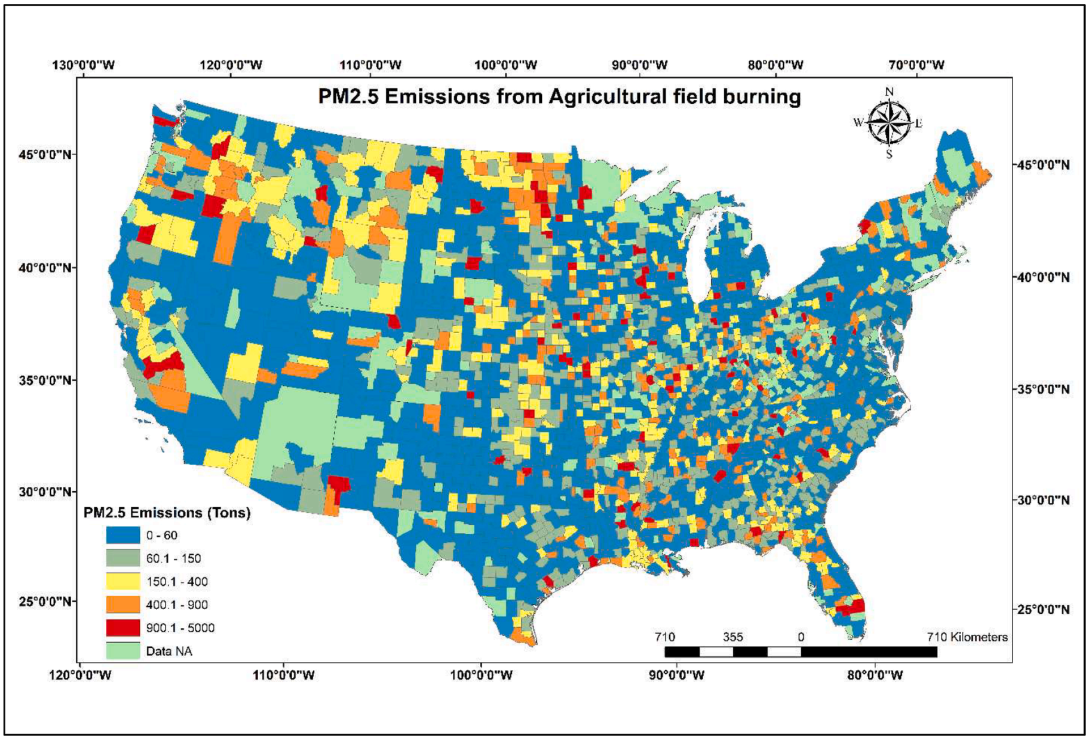

Fig. 10. $PM_{2.5}$ emissions from agricultural field burning in 2020 – County wise (Data Source: USEPA 2023)

Table 7
Emissions of various pollutants from agricultural burning across different years

	2008 (US EPA, 2015)	2011 (US EPA, 2019)	2014 (US EPA, 2016)	2017 (US EPA, 2017)	2020 (US EPA, 2023)
NH_3	3,882	3,469	93,445	63,460	145,755
CO	592,378	965,662	582,953	301,035	676,124
NOx	25,478	43,173	20,358	12,706	30,504
PM_{10}	69,881	142,641	87,356	42,933	101,036
$PM_{2.5}$	67,943	95,728	64,628	30,776	67,309
SO_2	3,416	16,402	6,433	4,237	11,213
VOCs	55,088	75,542	39,786	38,061	106,089

All units of emissions are in tons*

measures need to be undertaken at the local county, state, and federal level.

6.5. Future recommendations

Many farmers perceive that burning the crop residue increases the crop yields and soil qualities (Ahmed et al., 2015). Harris et al., 1995 demonstrated the effects of burning, tillage, and herbicide on the soil microflora in wheat and soybean double crop system. The study concluded that crop residue burning was not found to have any permanent effects on the soil microflora. Desrochers et al., 2019 studied the long-term effects of residue and water management on particulate organic matter of soil in Arkansas. In the study, non-burning of the wheat residue positively impacted not only soil health but also mitigation of greenhouse gases in the atmosphere by decreasing the soil organic matter and CO_2 emissions. These studies demonstrate the potential benefits of non-burning residue management practices for both soil health and air quality. It is very important to educate farmers regarding these positive effects. Harnly et al. 2012 used factsheets in Imperial County, CA documenting information regarding the reasons for burning activities, burn regulations, and potential health impacts due to increased exposures. Similar types of fact sheets could be used to generate awareness regarding the positive and negative effects of residue burning amongst farmers at a local level.

J. L. McCarty et al. 2008 mentioned in their study that remote sensing data from polar orbiting satellites provide a limited view of fire activity in agricultural areas. The new generation geo orbiting satellites including NOAA Geostationary Operational Environmental Satellite (GOES) R-Series can be utilized more efficiently to monitor the fire activities in agricultural landscapes. The Advanced Baseline Imager (ABI) onboard the satellite now provides the multi spectral data with a temporal resolution of 10 minutes, and a spatial resolution of 500M to 2 km (Roy et al., 2021). Low-cost sensors are also being widely used by citizen science groups and regulatory agencies to study the impact of burning activities on the air quality at the spatial and temporal level. Sablan et al., (2024) used purple air low-cost sensors and satellite data to evaluate the effects of prescribed burnings on ambient $PM_{2.5}$. The study also underscored the significance of satellite-derived products for estimating $PM_{2.5}$ levels, particularly in rural regions lacking adequate ground-based monitors. Various studies have integrated satellite observations with data collected by low-cost sensor networks (Gupta et al., 2018, Li et al. 2020, Liang et al. 2023).

7. Conclusions

This review paper summarized the available literature available on agricultural residue burning and its impact on air quality in the continental United States of America. Emissions from the burning of different crops were reviewed and presented individually in the study. The study identified regions in the U.S. that that warrant more research for characterizing emissions from agricultural burning activities. A total of 41 journal articles were reviewed to determine results regarding emissions and composition of various compounds in the plume generated by the burning of crops such as corn, wheat, rice, sugarcane, and barley. The majority of the studies focused on the state of California followed by Washington and Idaho. This review also showed that there is a dearth of research studying agricultural burning emissions in primarily agricultural states such as Iowa, Illinois, Indiana, North Dakota, South Dakota, and Nebraska. The review also addressed the increased risk to human health caused by exposure to pollutants emitted from agricultural burning activities. Additionally, the review study compiled available data from various fire emission inventories for different pollutants over the last 25 years to ascertain the spatial and temporal patterns of pollutant emissions resulting from agricultural burnings. Instead of burning crop residue, options such as composting, using them as animal fodder, or producing biofuel should be explored (Abdurrahman et al., 2020). Future studies should focus on regions like North Dakota and South Dakota where the NEI values were reportedly higher.

CRediT authorship contribution statement

Sai Deepak Pinakana: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Amit U. Raysoni:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Alqamah Sayeed:** Methodology, Formal analysis, Conceptualization. **Juan L. Gonzalez:** Writing – review & editing, Resources, Formal analysis. **Owen Temby:** Writing – review & editing, Methodology, Conceptualization. **Dawid Wladyka:** Writing – review & editing, Conceptualization. **Katarzyna Sepielak:** Writing – review & editing, Conceptualization. **Pawan Gupta:** Writing – review & editing, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Availability of data and material

The GFEDv4.1s is publicly available at the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). The data can be accessed through the link https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1293 (Randerson et al., 2015). The FINNv2.5 emissions dataset is archived at https://zenodo.org/records/7868652 (Wiedinmyer et al., 2023). The NEI data for years 2008, 2011, 2014, 2017, and 2020 which was used in the study is publicly available.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envadv.2024.100546.

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