Quantifying Crop Residue Burning in Punjab, Pakistan: A GEE-Based Assessment of Air Pollution

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Crop residue burning has become a common agricultural practice in developing countries due to numerous economic and social factors. To delineate the current pollution generated from crop residue burning in Punjab, Pakistan, a detailed study was conducted based on district-level crop production data from 2020 to 2024. The extraction of agricultural land was gathered from the European Space Agency/Climate Change Initiative (ESA/CCI), and the active fire count data were acquired from the VIIRS 375 m FIRMS standard active fire product. Air quality parameters, including CO and CH4, were assessed using Sentinel 5SP Tropomi. It was determined from the results that approximately 27% of the burned area increased from the years 2020-2021, accounting for a rapid increase from 31,984.15 sq km to 40,651.86 sq km, correlated with high CO and CH4 concentrations in 2021 and 2024, respectively, whereas a 17% decline occurred from the years 2022 to 2023, accounting for a decrease from 37,008.54 sq km to 33,710.85 sq km. However, it increased again by approximately 5.9% from 2023 to 2024 (33,710.85 sq km to 35,691.10 sq km). Using GEE, our study demonstrates the application of satellite data to map agricultural residue burning, and this information can provide valuable insights for policy formulation and managing crop residue practices.

Keywords: Crop Residue Burning, Google Earth Engine, Burned Area, Moderate Resolution Imaging Spectro Radiometer, Sentinel 5P

Introduction:

One of the most prevalent agricultural practices worldwide, especially in developing countries, is crop residue burning, where farmers set fire to the leftover biomass after harvest to clear fields, primarily in preparation for the next planting season [1]. Burning of agricultural waste is the second largest source after forest fires, accounting for 25% of the total biomass burned across the globe [2] as shown in Figure 1. It is regarded as one of the largest contributors to biomass burning globally, accounting for 10% of the total global annual fire incidents [3]. It is estimated that 90% of wildfires are attributed to forest removal activities involving crop residue burning, mostly in the regions of Africa, Asia, and Amazonia [4]. It ranks as the fourth-largest type of biomass burning and has raised significant concerns due to its substantial emissions of black carbon and organic carbon. The global population reached 8 billion in 2022 and is projected to rise to 9 billion by 2050 [5], further increasing food demand in developing countries. This has led to significant pressure on agricultural activities to meet the pressing needs of the population [6]. Ending hunger is the second most prioritized goal of the United Nations Sustainable Development Goals (SDG 2) [5]. The continuous demand for food has compelled farmers to adopt residue burning, a practice that ultimately disrupts the ecological balance of the agroecosystem. This excessive agricultural production has led to increased waste generation, contributing to environmental pollution [7]. These tropical regions include Northern Australia, Southeast Asia, South Africa, and South America [2].

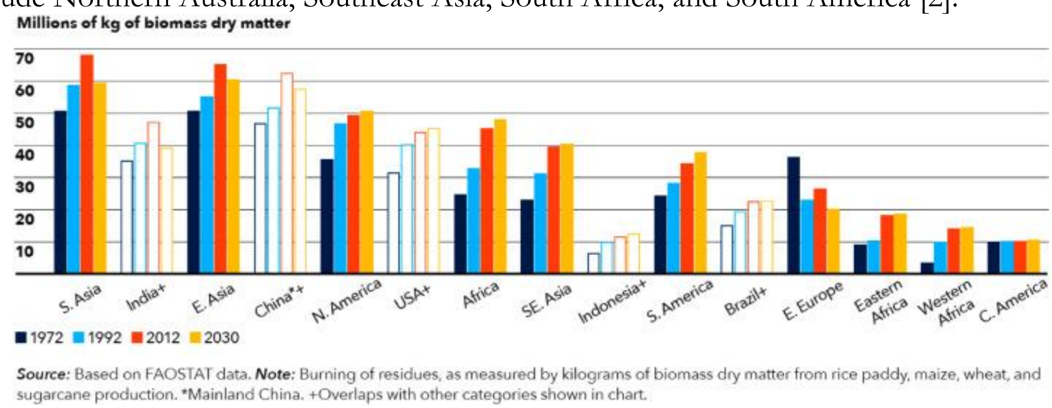

Figure 1. Showing Millions of Kg of Biomass dry matter worldwide perspective

Three types of biomass burning occur in the Asian region, including agricultural crop residue burning (34%), forest fires (45%), and grassland burning (20%) [8]. The global contribution of Asian countries to biomass burning includes China (25%), Indonesia (13%), and India (18%), while Myanmar contributes (8%). In South Asian countries, particularly India and China, more than 80 tons of agricultural residues are burnt annually [9]. China is among the top producers of crop residue, generating 600–800 Tg annually, of which 20–30% is directly burned in the fields [10]. In Asia, it is estimated that an average of 730 Tg of biomass is burned annually worldwide, of which 250 Tg originates from agricultural residue burning. [1]. In 2019, statistics revealed that approximately 458×10^6 tons of crop residue were burned globally, resulting in emissions of 1,238 kt of methane (CH_4) and 32 kt of nitrous oxide (N_2O). [11]. Although it is the cheapest and quickest method for residue removal, crop residue burning contributes to severe environmental and health problems, particularly through the degradation of air quality [12]. The present study aims to provide a comprehensive , high-resolution inventory of current pollutant emissions from crop residue burning in all districts of Punjab. These pollutants include CO, N_2O, and CH_4.

Novelty Statement:

Although many studies have explored primary and secondary data collection regarding crop production estimates in Punjab, none have assessed the district-wise profile of secondary information (panel data) with specific reference to spatial variation in cropland patterns, particularly due to the issue of crop residue burning and its impact on air quality. The results will be insightful for policymakers to design mitigation strategies in a region that is highly vulnerable to atmospheric pollution. This research seeks to address these gaps by integrating geospatial analysis to provide a holistic understanding of agricultural residue burning practices in Punjab, Pakistan. Comparing our work with pioneering previous studies of a similar nature, the novelty emphasizes spatial and temporal trends and variations in recent years with detailed district-level data using MODIS fire data. As mentioned above, the present work fills the gap in knowledge and estimation of air pollutant concentrations due to crop residue burning in selected districts of Punjab, Pakistan.

Research Objectives:

Extract agricultural zones and determine land utilization statistics of Punjab.

Analyze spatio-temporal patterns of agricultural fires that occurred in a selected period.

Quantify the emission of greenhouse gases and their contribution to regional air pollution.

Materials and Methods:

Study Area:

The primary focus of this research is Punjab (shown in Figure 2), 31.1704° N, 72.7097° E, which contributes 53% to Pakistan's agricultural GDP [13]. It produces about 74% of the country's cereals, with major crops including rice, wheat, maize, cotton, and pulses. Punjab is mainly divided into five agroclimatic zones , known as the cotton-wheat zone, mixed cropping zone, wheat-rice zone, arid zone, and low crop intensity zone [14]. As rice is the most significant contributor during the Kharif season, which starts in June and ends in October, the wheat-rice cropping zone is the most important region for the cultivation of crops [4]. As discussed earlier by various studies and literature, open field burning is the most common method utilized by farmers for crop residue management, and they also use it for domestic cooking. Further reports indicate that in mixed-cropping regions where rice, wheat, and sugarcane are cultivated, the majority of crop residue is managed through burning [15]. Consequently, this province is also responsible for widespread crop residue burning, which has resulted in severe health and environmental consequences [3]. This study was mainly conducted in the Punjab districts to demonstrate the rate of burning, selected from the rice-wheat, mixed cropping, and cotton-wheat zones, and its impact on ambient air quality, shown in Figure 3. Data acquisition and the methodological framework are well explained in Figure 4 below.

The cropping zones of Punjab Province are illustrated in Figure 3 below. Kasur, Lahore, Nankana Sahib, Hafizabad, Narowal, and Sialkot are the dominant wheat-rice cropping zones. Mixed cropping zones are dominant in Jhang, Faisalabad, Sargodha, and Khushab, while cotton-wheat zones are predominantly occupied by Southern Punjab, including Rahim Yar Khan, Bahawalpur, Lodhran, Vehari, Khanewal, Bahawalnagar, and Sahiwal. Low-intensity crop zones and dry areas are occupied by Dera Ghazi Khan, Layyah, Bhakkar, Mianwali, Attock, and Chakwal.

Extraction of the Agricultural Area:

Land utilization statistics were gathered from the Punjab Development Statistics Report 2024. The data regarding Kharif and Rabi crop production were collected from the Directorate of Agriculture, Crop Reporting Service, Punjab**, ** Lahore, and the Agricultural Division, Bureau of Statistics, Punjab**, ** Lahore. The agricultural zones were extracted**, as mentioned in Figure 4 above**, using the ESA Land Use Land Cover product in Google Earth Engine [16]. The European Space Agency/World Cover 10 m product provides data on global land cover at 10 m resolution based on Sentinel 1 and Sentinel 2 data.

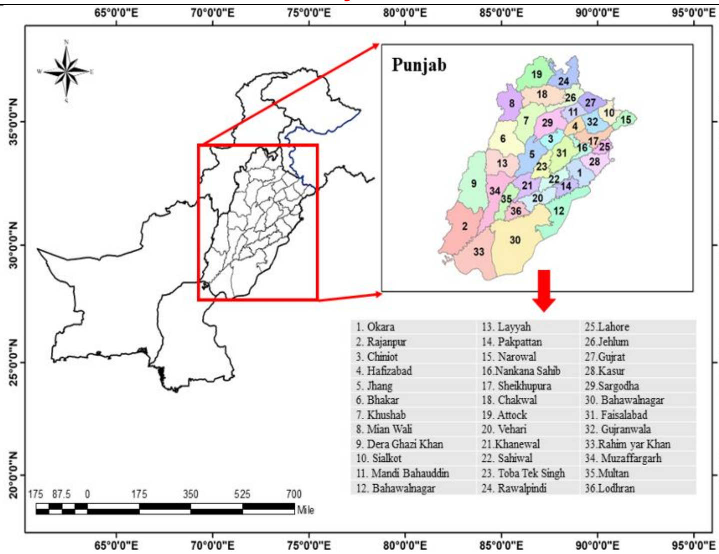

Figure 2. Location Map of the Study Area

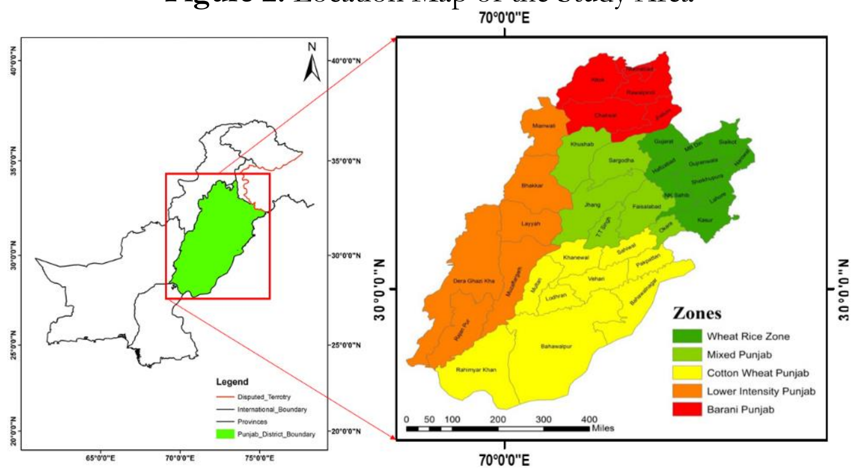

Figure 3. Showing the Cropping Zones in Punjab, Pakistan

Data Acquisition and Processing:

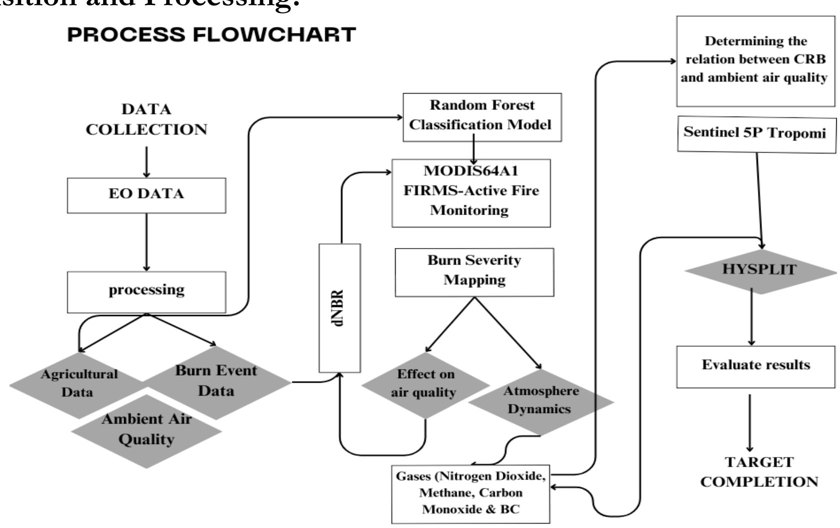

Figure 4. Methodological framework

ODIS Thermal Anomalies and VIIRS Fire Count Analysis:

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor is onboard two satellite platforms, Terra and Aqua. Its wavelength ranges from visible to infrared spectra, and the satellite records the DN value. These values can help in estimating atmospheric radiance, reflectance, or brightness temperature. Potential fire pixels are gathered from the 4, 11, and 12 μm wavelengths. In the present study, active fire count data were obtained from the VIIRS 375 m FIRMS standard active fire product (https://firms.modaps.eosdis.nasa.gov/). Due to its high spatial resolution, this dataset is widely used for fire management, as it can detect active fire zones of even low intensity [17].

Determining Air Quality:

Air pollutant data (carbon monoxide, nitrous oxide, and methane) concentrations over Punjab were analyzed during the Rabi (wheat) and the Kharif (rice) seasons. Sentinel 5P was used to determine the air quality parameters. Concurrently, data were collected over Punjab districts to study the impacts of the transported air pollutants released from CRB activities. A brief description of all the datasets is provided in Table 1 below.

Table 1. Showing Datasets Used in the Study

Data Acquisition	Product	Spatial Resolution	Use
ESA LULC	ESA/World Cover/v200	10 m	Extraction of the agricultural zones
MODIS Thermal Anomalies	MOD14/MYD14 Fire	500m	To determine the burned area
VIIRS Active Fires	"NASA/LANCE/SNPP_VIIRS/C2"	375m	Active Fires
Sentinel 5P(CO)	"COPERNICUS/S5P/NRTI/L3_CO"	1113.2 meters	Carbon monoxide concentration
(N_2O)	"COPERNICUS/S5P/NRTI/L3_N2O"	1113.2 meters	Nitrous oxide concentration
(CH_4)	"COPERNICUS/S5P/NRTI/L3_CH4"	1113.2 meters	Methane Concentration

Data Preprocessing and Calibration:

All data preprocessing and calibration were done on the Google Earth Engine platform. To minimize false positives, such as cloud cover and sun glints**, the images were filtered by date and spatially by the study area. Quality masking was performed, where the qa value of the pixels < 0.5 was removed to obtain a clear picture. For accurate tropospheric measurements, pixels with a cloud fraction < 30% were masked.

Results and Discussion:

The land utilization statistics of Punjab are summarized in the crop calendar (Table 2). Wheat and barley are the primary Rabi crops, sown during October–November and harvested in March–April. In contrast, rice, maize, and cotton dominate the Kharif season, being sown in June–July and harvested in September–October, as illustrated in Table 2 and Figure 5.

Table 2. Land Utilization Statistics of Punjab,2024

	Reported Area	Total Cultivated Area	Net sown	Current Fallow	Total Cropped Area	Kharif	Rabi
The Punjab	17538	12,532	10785	1747	17058	7235	9823

Area in 1000 hectares [18]

Source: Punjab Development Statistics,2024:

The total reported area of Punjab is 17,538,000 hectares according to 2020 statistics**, as** mentioned in Table 3. Punjab is the second-largest province of Pakistan, contributing approximately 30% of the country's total land area, which spans about 20.63 million hectares (20,630,000 hectares). Of this, nearly 72% is available for cropping. Punjab's total cropped area was about 16.68 million hectares , reported in the year 2020, which is equal to 166,800 sq km, where wheat was cropped on 40% of the land, rice (12.8%), and cotton (11.5%) [18].

Table 3. Showing the total cropped Area in all the districts of Punjab, Pakistan

Sr. No.	Division / District	Reported Area	TOTAL CROPPED LAND	KHARIF	RABI
	THE PUNJAB	**17538**	**17058**	**7235**	**9823**
	BAHAWALPUR DIVN.	**2161**	**2488**	**1196**	**1292**
1	BAHAWALPUR	622	728	331	397
2	BAHAWALNAGAR	746	973	436	537
3	RAHIM YAR KHAN	793	787	429	358
	D.G. KHAN DIVN.	**3157**	**2258**	**931**	**1327**
1	DERA GHAZI KHAN	936	486	211	275
2	LAYYAH	628	657	214	443
3	MUZAFFARGARH	831	629	276	353
4	RAJANPUR	762	486	230	256
	FAISALABAD DIVN.	**1791**	**2043**	**887**	**1156**
1	FAISALABAD	584	657	310	347
2	CHINIOT	263	269	114	155
3	JHANG	618	721	278	443
4	TOBA TEK SINGH	326	396	185	211
	GUJRANWALA DIVN.	**1733**	**2168**	**997**	**1171**
1	GUJRANWALA	367	577	286	291
2	GUJRAT	321	309	118	191
3	HAFIZABAD	235	337	168	169
4	MANDI BAHA-UD-DIN	270	304	134	170
5	NAROWAL	235	222	92	130
6	SIALKOT	305	419	199	220
	LAHORE DIVN.	**1170**	**1490**	**702**	**788**
1	LAHORE	180	153	70	83
2	KASUR	395	472	218	254
3	NANKANA SAHIB	222	306	142	164
4	SHEIKHUPURA	373	559	272	287
	MULTAN DIVN.	**1524**	**2081**	**974**	**1107**
1	MULTAN	378	419	185	234
2	KHANEWAL	427	578	262	316
3	LODHRAN	281	445	228	217
4	VEHARI	438	639	299	340
	RAWALPINDI DIVN.	**2243**	**814**	**165**	**649**
1	RAWALPINDI	526	191	31	160
2	ATTOCK	692	244	36	208
3	CHAKWAL	669	268	76	192
4	JHELUM	356	111	22	89
	SAHIWAL DIVN.	**1032**	**1434**	**691**	**743**
1	SAHIWAL	320	412	192	220
2	OKARA	439	594	288	306
3	PAKPATTAN	273	428	211	217
	SARGODHA DIVN.	**2634**	**2243**	**690**	**1553**

1	SARGODHA	590	561	231	330
2	BHAKKAR	813	838	208	630
3	KHUSHAB	654	429	96	333
4	MIANWALI	577	415	155	260
	ISLAMABAD	**93**	**39**	**2**	**37**

Source: Bureau of Statistics, Punjab, Lahore:

The key insights derived from Table 1 reveal that Punjab agriculture is Rabi dominant, with 58% of its cultivation, while the Kharif season covers 42%. The highest cropland areas were Sargodha (2,243,000 hectares) and Bahawalpur (2,488,000 hectares), respectively.

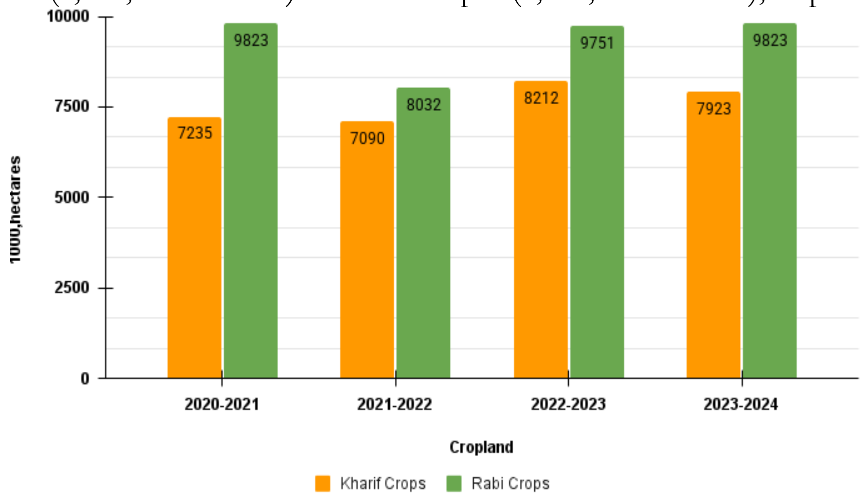

Figure 5. Showing Rabi and Kharif Crop Production in Punjab

Further details of total Rabi and Kharif crop production are mentioned in detail in Figure 6 below. Overall statistics reveal that in 2020**,** the total agricultural area reported was 17,058,000 hectares, followed by 15,112,000, 17,074,000, 17,936,000, and 17,746,000 hectares in 2021, 2022, 2023, and 2024, respectively. The high-intensity agricultural zones in terms of the top five major districts of Punjab were found to be Bahawalnagar**, occupying approximately 973,000** hectares of the total cropland area with the key major crops of wheat, cotton, and gram, followed by Rahim Yar Khan, Muzaffargarh, Sahiwal**,** and Okara**, occupying a total cropland of 787,000**, 629,000, 412,000, and 594,000 hectares**, respectively**. The lowest cropland regions were found to be Islamabad, Jhelum, and Narowal with 39,000, 111,000, and 222,000 hectares**, respectively**, as shown in Figure 6 below.

Estimation of the Burned Area Statistics:

The highest burned area in Punjab was recorded in the year 2021 (40,651.86 sq km), demonstrating extreme fire activity with burned incidents possibly due to stubble burning activities and also due to climatic factors such as intense heat**, as** mentioned in Figure 7 and Table 4 below. The lowest burned area was recorded in the year 2023, mainly due to public awareness and policy intervention programs. In 2024, statistics indicate a 5.9% increase (35,691.10 sq km), reflecting a resurgence in fire activities. Over the five-year temporal period**, as** presented in Table 4, the burned area increased by approximately 27% between 2020 and 2021, rising from 31,984.15 sq km to 40,651.86 sq km. In contrast, a 17% decline was observed between 2022 and 2023, with the burned area decreasing from 37,008.54 sq km to 33,710.85 sq km. However, it increased again by approximately 5.9% from 2023 to 2024 (33,710.85 sq km to 35,691.10 sq km), as mentioned in Table 5 and Figure 7 below.

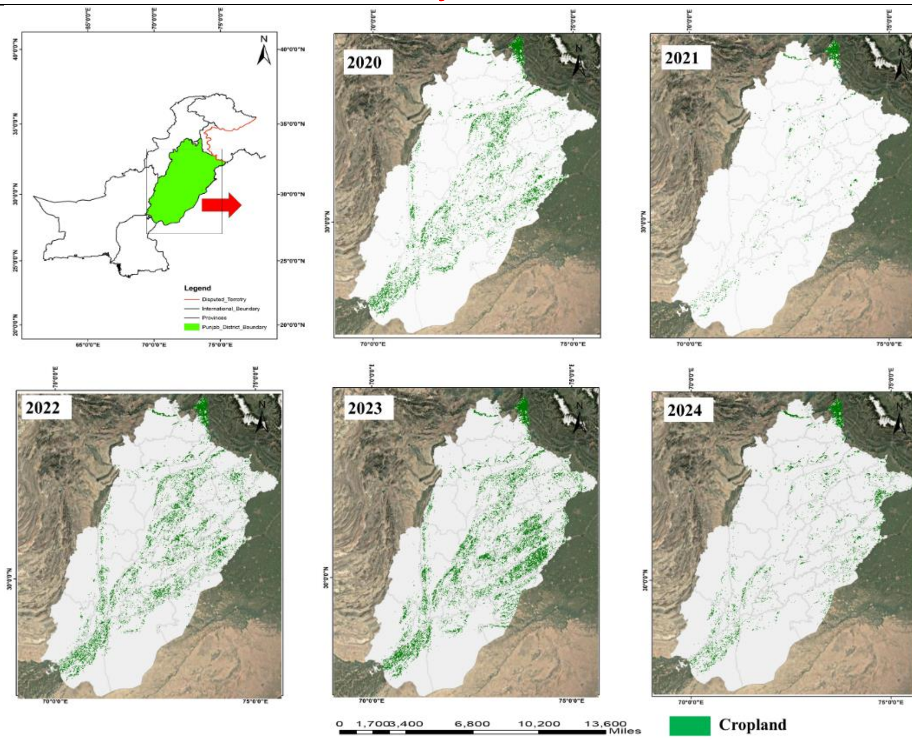

Figure 6. Showing the Extraction of the Agricultural zones in Punjab computed in the GEE platform from 2020-2024

Table 4. Showing the Total Burnt statistics of Punjab with the percentage of change detected in the selected temporal period

YEAR	Total Punjab Burnt Area Sq km	% CHANGE
2020	31984.15	-
2021	40651.86	27% increase
2022	37008.54	-
2023	33710.85	17% decrease
2024	35691.10	5.9% increase

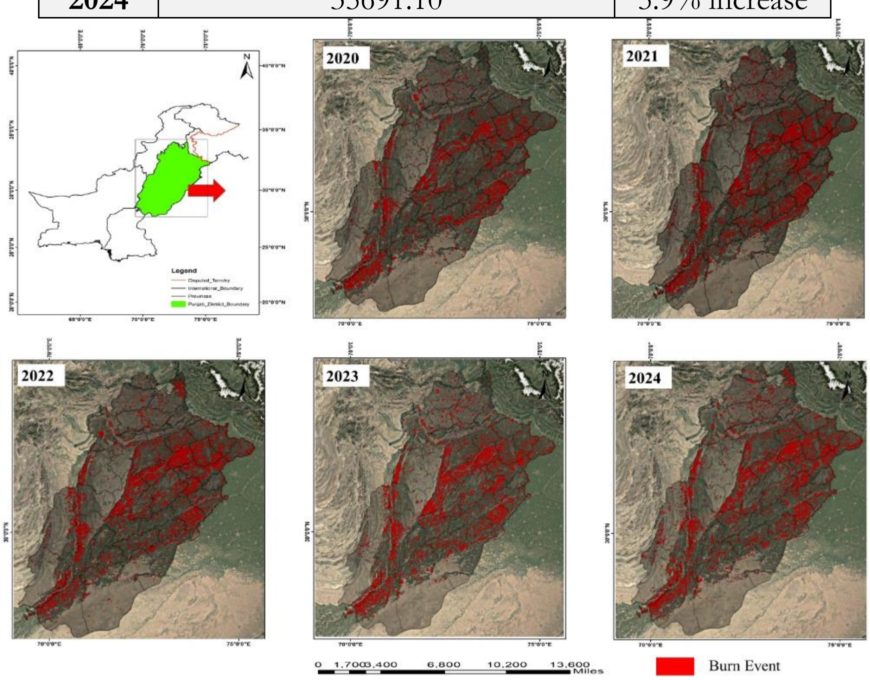

Figure 7. Showing Burned Area Estimation through MODIS Data

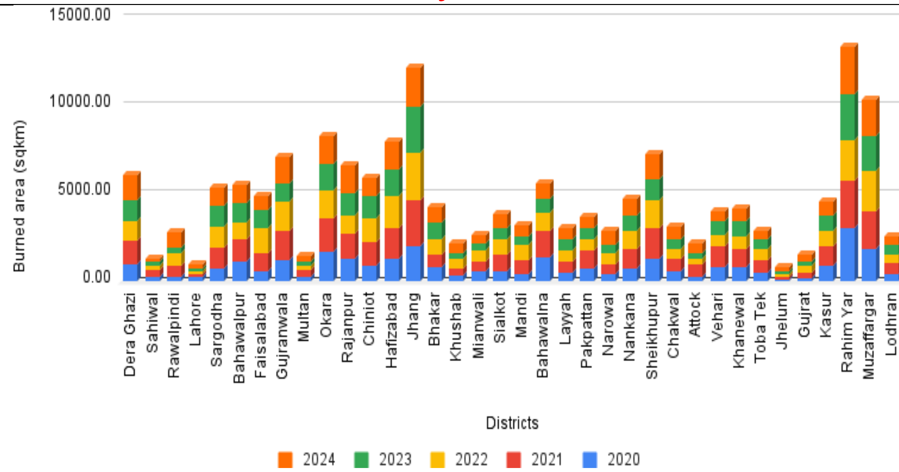

Figure 8. Showing the amount of area burned in the districts of Punjab

Overall trends from Figure 8 reveal a significantly high burn rate in the regions of Rahim Yar Khan**, which recorded an average burned area of approximately 2,669 km²/year**, followed by the district of Jhang (2,433 km²/year) and Muzaffargarh (2,067 km²/year), whereas the lowest burned districts were calculated to be Jhelum, which maintained the smallest burned area average, calculated to be 162 km²/year, followed by Lahore (191 km²/year) and Gujrat (300 km²/year).

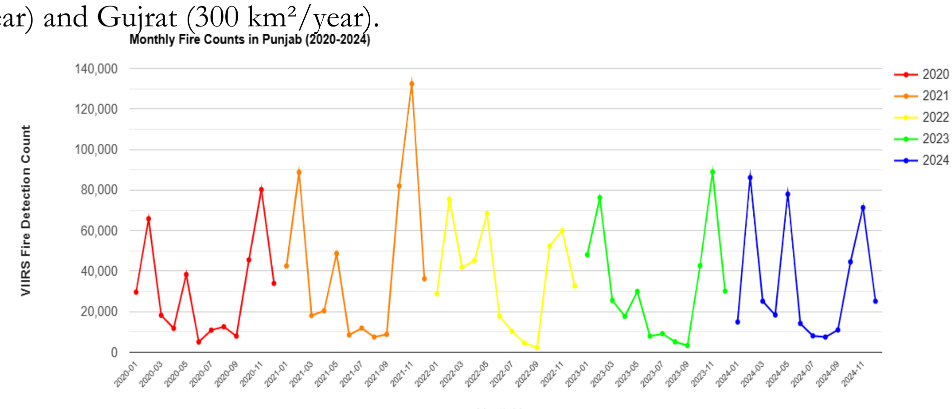

Figure 6. Monthly Fire Counts in Punjab

Yearly patterns reveal 2021 to be the peak year for burning crop residues, where 22 districts showed the maximum rate of burning in 2021, whereas the 2024 concentrations indicated critical and alarming situations where the burned data exceeded that in the regions of Rahim Yar Khan and Muzaffargarh districts. The key observations from Figure 8 reveal that the peak fire season consistently occurred during February (17 to 20%) and November (13 to 26%). Secondary peaks were also observed in May (ranging from 7% to 19%) and in October (11% to 16%), as shown in Tables 5 and 6. Table 5. Percentage of Fire Count Analysis in the Selected Time Period.

Table 5. Showing the percentage of the Monthly fire count in Punjab

Month	2020	2021	2022	2023	2024
January	8.26%	8.40%	6.55%	12.49%	3.69%
February	18.34%	17.51%	17.16%	19.81%	21.30%
March	5.08%	3.57%	9.53%	6.65%	6.22%
April	3.28%	4.03%	10.29%	4.59%	4.55%
May	10.68%	9.61%	15.56%	7.80%	19.28%
June	1.41%	1.68%	4.06%	2.06%	3.51%
July	3.04%	2.35%	2.35%	2.38%	2.00%
August	3.50%	1.48%	1.02%	1.33%	1.85%

September	2.21%	1.74%	0.50%	0.86%	2.72%
October	12.68%	16.18%	11.92%	11.09%	11.03%
November	22.35%	26.12%	13.65%	23.11%	17.64%
December	9.46%	7.15%	7.43%	7.84%	6.22%

Determining the Atmospheric Quality Parameters:

Average CO levels revealed the highest trend in the years 2021 and 2024, which demonstrated alarming levels exceeding 39 ppm in multiple districts, as shown in Figure 9 below. The highest concentration of CO in 2024 was recorded in the central districts of Punjab, including Sheikhupura, Nankana Sahib, and Faisalabad, with peak levels reaching 41.1 ppm.

In contrast, the lowest concentration, approximately 34.1 ppm, was observed in the districts of Rawalpindi, Chakwal, and Rajanpur. In 2021, Lahore reached its maximum concentration (42.505 ppm), whereas the minimum concentration was found in Rawalpindi (35.873 ppm). Incomplete burning processes release CO, CH_4, and BC emissions. The most significant were CO emissions in the regions of Muzaffargarh, Jafferabad, and Naushero districts. The study revealed that 16,084.04 Gg of pollutants were emitted from burning wheat, rice, cotton, and bagasse in Punjab and Sindh in the years 2006-2007, highlighting that wheat straw burning was the largest contributor to CO, CO_2, SO_2, and carbon emissions [19]. It was estimated that a total of 72% of total crop residue pollutants were emitted from wheat residue burning, followed by rice straw burning, which contributed to CH_4 (51%) and NH_3 (65%) in Sindh. The data, as illustrated in Figure 10, show elevated methane concentrations, which are particularly dominant in agricultural and urban zones. The statistics revealed that major Punjab agricultural districts like Bahawalpur, Okara, and Vehari have a higher concentration of methane**, mainly due to the stubble burning of rice cultivation**. Central districts, including Lahore, Faisalabad, and Gujranwala, also show higher concentrations due to vehicular emissions combined with stubble burning of crops.

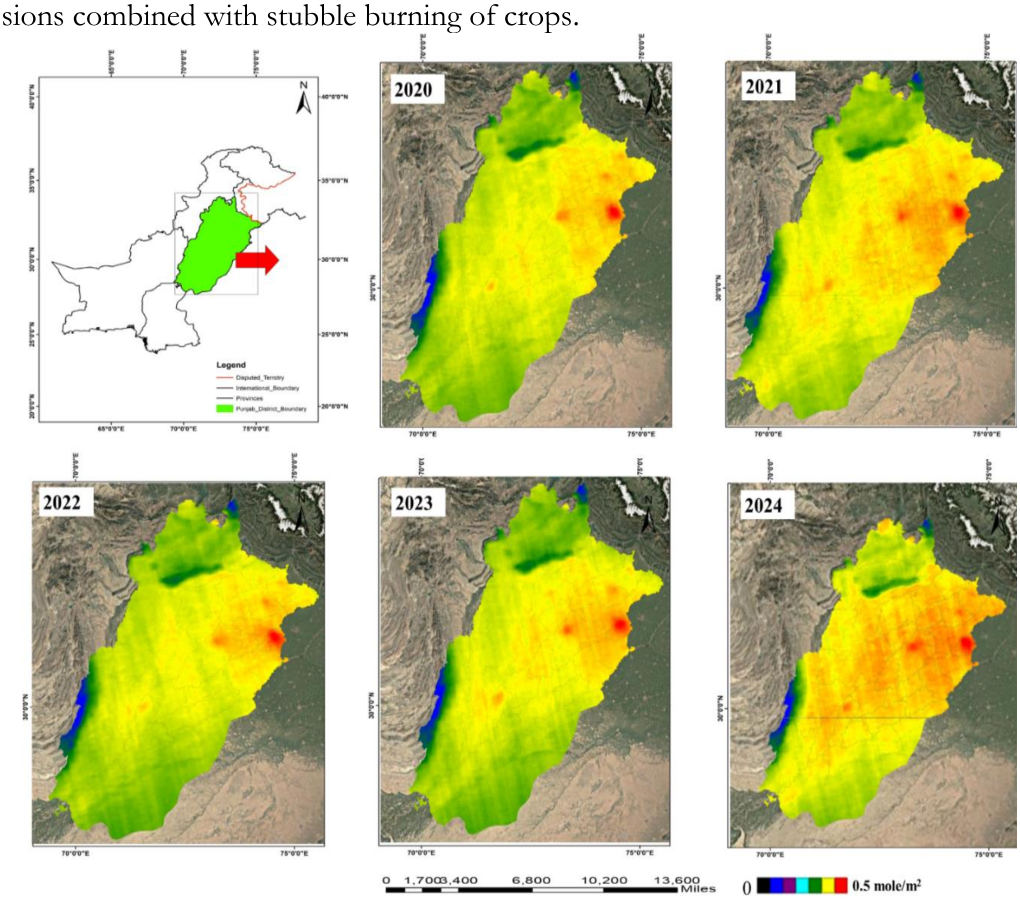

Figure 7. Showing spatial concentration of CO along the study Area

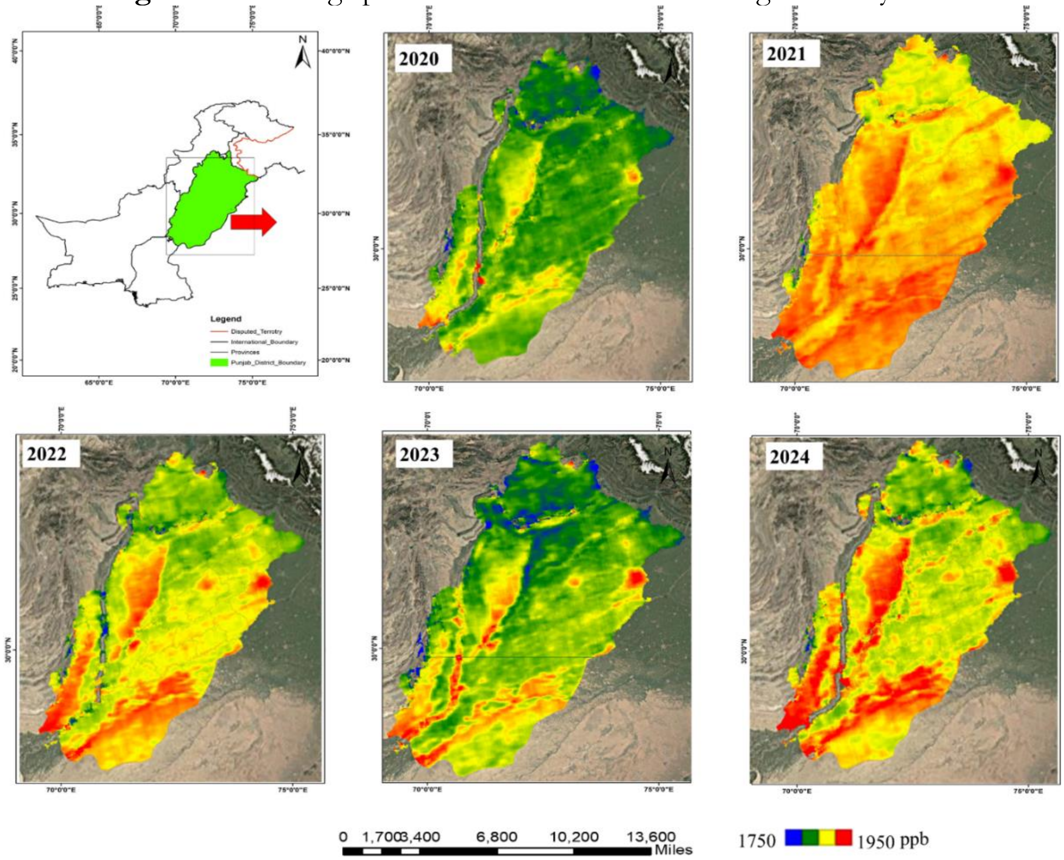

Figure 8. Showing spatial concentration of methane along the study Area

Discussion:

According to statistics presented by [20], the total cropland in Punjab occupies approximately 56.58%, followed by natural vegetation (23.05%). The findings are similar to those of [21] and [8]. The lowest cropland regions were found to be the Islamabad and Rawalpindi Divisions with (39,000 and 814,000 hectares, respectively). The results of selected air quality parameters are in line with the findings of [16] who also evaluated that CO emissions have increased by 40% at an average annual rate of about 2.7% from 1.16 Tg in 2000 to 1.63 Tg in 2014, increasing the emissions of CO2, CH4, NH3, SO2, and BC, ranging between 37% to 63% during the selected time period. The statistics from the findings presented by [22] revealed that most of the methane emissions were caused by cotton burning. Burning of maize residue caused the highest CH4 emissions (5,863.58 Gg) while wheat and barley caused the lowest emissions (2,129.40 Gg). The total emission from cotton burning was 4,437.98 Gg.

Table 5. Linking Burning Activity with Agricultural Practices

Months	Rabi Season (Rice Dominant	Linked to Agricultural Activity		Reference
November	13 to 26%	Post Rice harvest (Stubble burning)	Farmers clear the land for wheat sowing	[23]
February	17 to 21%	Pre-Wheat Harvest burning	For removal of weeds & leftover residues	[24]
March-April	3 to 10%	Less burning	Mechanized harvesting	[6]

	Kharif Season (Wheat Dominant)				
May	9.6%- 19%		Burning Rice straw for clearing land		[7]
October	11%- 16.18%		Post Rice harvest burning.		[25]
June-Sept	0% -4%		Low burning		

Conclusion:

It can be concluded from the key findings that**, overall**, Punjab cropland statistics reveal that in 2020, the total agricultural area reported was 17,058,000 hectares, which faced a significant decline to 15,112,000 in 2021. The top five major districts in terms of agricultural land were Bahawalnagar, Rahim Yar Khan, Muzaffargarh, Sahiwal, and Okara. Yearly patterns reveal 2021 to be the peak year for burning crop residues, where 22 districts showed the maximum rate of burning in 2021, with maximum burning occurring in high-cropland districts like Rahim Yar Khan (2,669 km^2), followed by Muzaffargarh (2,067 km^2/year). Monthly trend analysis revealed that the highest burning rate was recorded during the post-burning activity (November), particularly after the Rabi crop harvesting, and in February (pre-wheat harvest burning). Increased levels of selected GHGs (CO and CH4) also revealed elevated concentrations, particularly peaking in the years 2021 and 2024, respectively, with their increased concentration in the high-burning districts.

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