

GHG EMISSIONS, WATER PRODUCTIVITY AND YIELD PATTERNS IN THE RICE–WHEAT PRODUCTION SYSTEM OF PUNJAB, PAKISTAN

ÉMISSIONS DE GES, PRODUCTIVITÉ DE L'EAU ET PROFILS DE RENDEMENT DANS LE SYSTÈME DE PRODUCTION RIZ–BLÉ DU PENDINGJAB, AU PAKISTAN

Dr. Abdul Qayyum¹, and Dr. Mirza Waseem Abbas²

ABSTRACT

Using Crop Reporting Service (CRS) datasets for 2024–25, this study evaluates greenhouse gas (GHG) emissions, water productivity and yield performance in Punjab's rice–wheat production system. GHG emissions were estimated using the IPCC Tier I methodology. Rice was identified as the largest agricultural emitter (6.839 million t CO₂-eq) because of flooded irrigation practices, while wheat contributed 2.985 million t CO₂-eq despite occupying the largest cultivated area. Water productivity analysis showed that rice, cotton and sugarcane exert substantial pressure on groundwater resources, whereas maize, pulses, potatoes and fodder crops demonstrated higher water-use efficiency. The study highlights the value of CRS area-frame sampling, digital surveys and crop-cut experiments for climate reporting and agricultural planning. Results support crop diversification, water-efficient irrigation and climate-smart agricultural policies in Punjab.

Keywords: Water productivity; Yield patterns; Rice–wheat production system; Digital surveys; Climate-smart agricultural policies.

RÉSUMÉ

À partir des jeux de données du Crop Reporting Service (CRS) pour 2024–2025, cette étude évalue les émissions de gaz à effet de serre (GES), la productivité de l'eau et les performances de rendement dans le système de production riz–blé du Pendjab. Les émissions de GES ont été estimées selon la méthodologie de niveau 1 du GIEC. Le riz a été identifié comme la principale source d'émissions agricoles (6,839 millions de t éq. CO₂) en raison des pratiques d'irrigation par submersion, tandis que le blé a contribué à hauteur de 2,985 millions de t éq. CO₂, bien qu'il occupe la plus grande superficie cultivée. L'analyse de la productivité de l'eau a montré que le riz, le coton et la canne à sucre exercent une forte pression sur les ressources en eaux souterraines, tandis que le maïs, les légumineuses à graines, la pomme de terre et les cultures fourragères présentent une meilleure efficacité d'utilisation de l'eau. L'étude souligne l'intérêt de l'échantillonnage sur base aréolaire, des enquêtes numériques et des expériences de coupe des récoltes réalisés par le CRS pour l'établissement de rapports climatiques et la planification agricole. Les résultats plaident en faveur de la diversification des cultures, d'une irrigation économe en eau et de politiques d'agriculture intelligente face au climat au Pendjab.

Mots clés : Productivité de l'eau; Profils de rendement; Système de production riz–blé; Enquêtes numériques; Politiques d'agriculture intelligente face au climat.

INTRODUCTION

Agriculture forms the backbone of food security, employment, and rural livelihoods in Punjab, Pakistan, which is the country's largest agricultural province in terms of cultivated area, production,

1 Director General, Crop Reporting Service, Agriculture Department, Government of the Punjab, Pakistan.

2 Deputy Director, Crop Reporting Service, Agriculture Department, Government of the Punjab, Pakistan. Email: wazeem.mirza@gmail.com

and contribution to national food supplies. Punjab accounts for approximately 31 million acres (about 12.5 million hectares) of cultivated land, representing the most intensively farmed landscape in Pakistan. The province is predominantly irrigated, relying heavily on an extensive canal network supplemented by widespread groundwater extraction through tube wells. While this irrigation infrastructure underpins high crop production, it also makes Punjab particularly vulnerable to water stress, climate variability, and climate-induced natural disasters.

The dominance of the rice-wheat cropping system, supported by intensive irrigation, high fertilizer use, and increasing groundwater dependence, has amplified concerns regarding greenhouse gas (GHG) emissions, aquifer depletion, and the long-term sustainability of agricultural production. These challenges are further compounded by Punjab's growing exposure to extreme climatic events. The province has witnessed two major flood disasters in recent years most notably the catastrophic floods of 2022 and another severe flood event in 2025 both of which caused extensive crop losses, damaged irrigation infrastructure, and disrupted farming livelihoods. Such events underscore the urgency of re-evaluating agricultural systems through the combined lens of climate mitigation, water productivity, and resilience.

This study presents a comprehensive, data-driven assessment of crop-wise GHG emissions, water productivity, and yield patterns across Punjab for the agricultural year 2024-25. The analysis is based on high-resolution, field-verified datasets generated by the Crop Reporting Service (CRS), Punjab, which operates one of the most extensive and statistically robust agricultural data collection systems in South Asia. By integrating crop acreage, yield estimates derived from scientifically designed crop cut experiments, irrigation practices, groundwater dependency, cost of production surveys, growers' perceptions, and annual loss and damage assessments, the study provides a holistic evaluation of the environmental footprint of Punjab's major crops, with particular emphasis on the rice-wheat production system.

Greenhouse gas emissions were estimated using the Intergovernmental Panel on Climate Change (IPCC) Tier I methodology, converting methane (CH₄) and nitrous oxide (N₂O) emissions into carbon dioxide equivalents (CO₂-eq) using standardized emission factors and global warming potentials. The results reveal substantial variation in emission intensity across crops, irrigation regimes, and production systems. Rice cultivation emerges as the largest contributor to agricultural GHG emissions in Punjab, accounting for approximately 6.84 million tons of CO₂-eq. This high emission burden is primarily driven by continuously flooded irrigation practices that create anaerobic soil conditions conducive to methane generation. Non-basmati rice exhibits the highest per-acre emission intensity, followed closely by basmati rice, reflecting longer inundation periods and varietal differences. In contrast, wheat, despite occupying the largest cultivated area in the province, generates comparatively lower emissions per acre, resulting in a total contribution of 2.99 million tons of CO₂-eq.

Beyond emissions, the study evaluates water productivity by linking crop yields with irrigation volumes and sources of water supply. The findings highlight pronounced inefficiencies in water use, particularly for rice, cotton, and sugarcane, where extensive groundwater abstraction does not translate proportionately into higher yields. Rice alone consumes the largest share of agricultural water in Punjab and exhibits extremely low water productivity, placing a disproportionate burden on already stressed aquifers. Cotton and sugarcane further exacerbate water stress due to their high absolute water requirements. In contrast, maize, pulses, potatoes, and fodder crops demonstrate significantly higher water-use efficiency, producing greater output per unit of water applied and offering viable pathways for crop diversification and climate resilience.

A key strength of this research lies in its methodological rigor. The use of CRS's area frame sampling, geo-referenced digital surveys, multi-tier validation mechanisms, and crop cut experiments ensures high data reliability and spatial granularity. This framework enables credible crop-wise emission and water productivity estimates at tehsil, district, and provincial scales, supporting integration into national climate reporting mechanisms such as Biennial Transparency Reports, Nationally Determined Contributions, and emerging Measurement, Reporting, and Verification systems. Overall, the study

emphasizes that Punjab's agricultural sustainability challenges stem not only from scale, but from cropping choices, irrigation practices, and exposure to climate extremes, highlighting the need for water- and emission-efficient, climate-resilient agricultural planning.

Climate change poses a severe threat to global agriculture, particularly in regions heavily dependent on groundwater and monsoon variability. South Asia, and Pakistan specifically, are experiencing a convergence of climatic and resource crises, declining water availability, increasing temperatures, and greenhouse gas (GHG) emissions from agriculture. Wheat and rice, which dominate Punjab's cropping system, are central to both national food security and environmental stress.

The agriculture sector contributes nearly 27% of Pakistan's total GHG emissions (Government of Pakistan, 2021), primarily through methane (CH₄) from flooded rice fields and nitrous oxide (N₂O) from fertilizer use. These emissions are compounded by inefficient irrigation practices, excessive groundwater pumping, and poor water productivity. Recent studies (e.g., [FAO, 2022](#)) highlight that Pakistan's water productivity for staple crops remains among the lowest in Asia, with rice requiring over 2,500-3,000 liters of water per kg of yield.

Punjab, as the country's agrarian hub, faces frequent heat stress and rising temperatures, declining groundwater levels (WRI, 2022), and increasing irrigation demand (Shafeeque & Bibi, 2023). Given these challenges, it is critical to conduct a spatially granular analysis of crop area, yield, water productivity, and GHG emissions. This study leverages district- and division-level data for rice and wheat in Punjab to quantify environmental burdens and identify high-impact zones for climate-smart interventions.

Literature Review

Agricultural activities significantly contribute to global greenhouse gas emissions, especially in regions where rice and wheat are primary crops (FAO, 2021). In developing countries like Pakistan, the agriculture sector plays a dual role contributing to food security and serving as a major emitter of greenhouse gases (GHGs). Punjab, being the breadbasket of Pakistan, has intensive wheat and rice cultivation. These two crops, covering a substantial portion of the cultivated area, release a considerable amount of methane (CH₄) and nitrous oxide (N₂O) during their cultivation, especially from flooded rice fields and nitrogen fertilizer applications in wheat (Ali et al., 2022).

This research paper aims to estimate the GHG emissions from wheat and rice crops in Punjab using the Tier 1 approach specified by the IPCC. By leveraging data from the Crop Reporting Service (CRS), the study provides a localized estimation of GHGs, thus bridging the gap in region-specific emission inventories. This analysis is critical for creating informed policies that can guide the reduction of GHG emissions in the agricultural sector.

Previous studies on agricultural sustainability in South Asia have emphasized the need for data-driven decision-making at sub-national levels. Pathak et al. (2010) demonstrated the significant contribution of rice-wheat systems to India and Pakistan's agricultural emissions. Similarly, Wassmann et al. (2009) identified alternate wetting and drying (AWD) as a key technique to reduce methane from paddy fields. In Pakistan, Ali et al. (2020) used FAO AquaCrop models to show regional variation in wheat water productivity, highlighting severe inefficiencies in southern Punjab.

Despite these efforts, there remains a gap in integrating localized crop data with GHG estimations and water productivity analysis. Current provincial estimates are often too coarse for targeted interventions. Previous studies have highlighted the importance of integrating field-based agricultural datasets with GIS and remote sensing technologies to improve the spatial granularity of crop monitoring, water productivity assessment, irrigation performance evaluation, and environmental reporting. In Pakistan, Khan et al. (2021) demonstrated that the combined use of remote sensing and GIS provides reliable near real-time information on crop water deficits and irrigation adequacy, supporting evidence-based agricultural and water management decisions. This study builds on such frameworks by combining official Crop Reporting Service (CRS) data with standard emission factors to

produce a detailed profile of emissions, water productivity, and yield gaps for Punjab's wheat and rice systems.

Previous research has extensively analysed the GHG emissions from various agricultural systems, particularly rice and wheat. Methane emissions from rice cultivation have been identified as a significant contributor to global CH₄ levels (EPA, 2020). A study by Pathak et al. (2018) analysed emissions from rice paddies in South Asia and highlighted how water management practices could mitigate these emissions.

In the context of Punjab, the research by Hussain et al. (2021) emphasized the role of rice and wheat in contributing to regional GHG levels. However, there is a scarcity of studies utilizing CRS data to calculate emissions accurately. This study fills this gap by using crop-specific emission factors from the IPCC guidelines and combining them with CRS data.

METHODOLOGY

This study employed a quantitative, Tehsil, District & Division level analysis using primary and administrative datasets to estimate greenhouse gas emissions, crop productivity, and water productivity for wheat and rice crops in Punjab, Pakistan. The methodological framework integrates field-generated data collected by the **Crop Reporting Service (CRS)** with secondary data sources for emissions and water estimation using standard IPCC and FAO protocols.

Data Collection Framework of the Crop Reporting Service

The Crop Reporting Service operates an extensive ground-truthing network based on area frame sampling methodology, systematically covering the agricultural landscape of Punjab. For crop acreage and yield estimation, CRS utilizes 5,500 permanent sample segments, each covering 150 acres. These segments are randomly selected across the province with the goal of maintaining spatial representativeness and crop diversity. At least one sample segment is established per Union Council (UC), with a maximum of four segments per UC, depending on the UC's geographic size and crop density. The CRS employs a ground-based Area Frame Sampling approach that statistically represents the entire province of Punjab. Over 5,500 segments, each comprising 150 acres, are distributed across all 2,600 Union Councils (UCs), ensuring spatial diversity and crop representation. This approach aligns with international best practices and is consistent with frameworks used by the USDA's National Agricultural Statistics Service and the FAO's Global Strategy to Improve Agricultural and Rural Statistics, making it statistically rigorous and globally benchmarked.

Each land parcel within a segment is geo-referenced using digital mapping and GPS tools. Field enumerators physically visit every land parcel within the selected segment during active cropping seasons. During each visit, enumerators record comprehensive, parcel-level information that includes but not limited to:

- Land parcel coordinates
- Parcel size (area in acres or kanals)
- Ownership and cultivator status (owner, tenant, or shared)
- Crop(s) sown (including intercropping and multiple cropping)
- Crop variety or hybrid
- Area under each crop or land use (e.g., vegetables, orchards, flowers, fallow)
- Built-up area (if any)
- Irrigation type and visible crop health

This data collection process is conducted **four times a year**, aligned with Punjab's two major cropping seasons:

- **Rabi Season:** Two enumerations (early and final)
- **Kharif Season:** Two enumerations (early and final)

The use of this dual-phase enumeration helps capture the dynamics of crop growth, sowing planning and management, and final standing crop areas. The high-frequency observations also enable correction of any discrepancies between initial and final cropping patterns. This high-frequency model is effective for minimizing reporting errors and ensuring that early estimations are refined by real-time updates a process similar to the **European Union's Land Use/Cover Area Frame Survey (LUCAS)** method. Upon collection, data is digitally recorded in a tablet-based system or a digital register by the enumerator and then transmitted electronically to the CRS Data Cell for centralized processing. The incoming data passes through multiple layers of verification at the **tehsil, district, and divisional** levels. Each layer of review checks for inconsistencies, anomalies, and classification errors, using both internal thresholds and comparisons with past trends.

Multi-tier Data Validation and Supervision

Once these accurate surveys are done, the data is transmitted electronically to the CRS Data Cell, which is the designated unit for analyzing all field-generated data. The data validation framework works across **three tiers of administrative verification**:

1. **Tehsil Level:** The enumerator collects the data, which is initially reviewed by the **Tehsil Officer (TO)**. The TO typically accompanies the enumerator in the field and performs on-the-spot verification. Any discrepancies or missing information are immediately corrected in the field.
2. **District Level:** The verified data from the tehsil is then sent to the **District Officer (DO)**, who oversees 3 to 5 tehsils within the district. The DO randomly visits segments for ground-truthing, checks sample data entries, and validates them. Corrections, if necessary, are made at this level.
3. **Divisional Level:** Once cleared at the district level, the data is transmitted to the **Divisional Officer**, who supervises one of the ten administrative divisions in Punjab. The Divisional Officer undertakes a final level of scrutiny and validation, including monitoring and reporting on data integrity across districts.

This **three-tier review process** (Tehsil → District → Division) backed by **GPS-referenced mapping, digital registers, and tablet-based data capture**. This ensures data integrity and minimizes human error. Internal consistency is maintained via automated checks at the CRS Data Cell, a method comparable to systems implemented by **Statistics Canada** and the **US Census of Agriculture**, confirming adherence to globally recognized data verification standards.

After conformity is established across all three tiers, the data reaches the **central CRS Data Cell in Lahore**, where final anomaly detection and consistency checks are performed. If any outliers or abnormal trends are detected, the data is reverted to the respective field enumerator, repeating the same verification chain.

Data Analysis and Acreage Estimation

Once fully validated, the cleaned dataset is transmitted to the **Director in charge of the respective crops**. The Director conducts comprehensive analytical procedures including:

- Time-series comparison (current vs previous year)
- Five-year historical trend analysis
- Descriptive statistics (mean, variance)
- Spatial distribution patterns using coordinates

- Cross-verification with auxiliary data sources (e.g., weather, satellite imagery)

The output includes detailed district-wise and division-wise acreage estimates based on the first and second enumeration rounds in each season. In addition to yield forecasting, the analysis provides insight into standing crop conditions, emerging trends in sown area, and overall crop performance.

A crop-wise dashboard system is also maintained, which dynamically segregates crops by their geo-referenced coordinates. This enables real-time visualization and analytics, allowing users to isolate, view, or extract data for specific crops, regions, or time frames based on mapped survey coordinates.

These accurate estimates, once finalized at the CRS Head Office, are submitted for approval to the Provincial Coordination Committee (PCC), which is chaired by the Chairman of the Planning and Development Board, Punjab. Upon formal approval, these estimates are officially notified and disseminated to relevant institutions including the Pakistan Bureau of Statistics (PBS), Punjab Bureau of Statistics (BoS), published on the CRS website, and shared with other provincial and federal stakeholders.

These official estimates provide a comprehensive picture of the total cultivated area for each crop, including information on the crop variety, seed type, sowing method, and location coordinates. Following the release of these estimates, additional data extraction and analysis is enabled via the dashboard, which offers detailed filters for crop-wise, variety-wise, farmer-specific, and district-level information. The dashboard also facilitates comparisons through year-on-year analysis, historical trend assessments, and regional comparisons.

Field-Level Validation, Digital Girdawari, and Crop Cut Experiments

Once data arrives at the CRS Data Cell, a final layer of scrutiny is applied. If anomalies, discrepancies, or inconsistencies are identified at this stage, a validation and correction team may be deputed directly from the CRS Headquarters to the field. This counter-verification process ensures that all Standard Operating Procedures (SOPs) and the protocols outlined in the official instruction manual were properly adhered to. These inspections are initiated either by the Director concerned or by a special team constituted by the Director General of CRS, particularly in instances where significant errors or doubts are flagged. This final tier of inspection provides institutional assurance that field-collected data truly reflects the on-ground situation.

Digital Girdawari Register

During the initial field survey, enumerators digitally record the crop information for each land parcel within a given segment into a standardized Digital Girdawari Register, a foundational dataset structured similarly to an Excel spreadsheet. This digital register includes a comprehensive list of all possible crops grown in the respective season (Rabi or Kharif) and is populated in real-time during the field enumeration process.

The data entered is subject to multi-tier verification at the Tehsil, District, and Divisional levels. Furthermore, Directors of specific crops may also conduct spot-checks for re-verification. A key integrity feature built into the Digital Girdawari system is its automated area validation check: if the total cultivated area, built-up area, and land parcel areas within a segment do not align with the known geographical parameters, the system halts the enumerator from proceeding to the next segment until corrections are made.

Jinswar: Segment-Wise Crop Summary

Based on the finalized Digital Girdawari entries, an automated report known as Jinswar is generated. Jinswar provides a consolidated snapshot of the entire segment, listing each crop along with its cumulative cultivated area across all relevant land parcels. For instance, if a segment contains 1,000

land parcels and 700 are under wheat cultivation, with a total area of 80 acres, the Jinswar will indicate 80 acres for wheat. This report is vital for ensuring internal consistency and provides a succinct summary for crop-level analysis and segment-level validations.

Integration into CRS Dashboard

Upon validation, the data including the Digital Girdawari and Jinswar reports is transmitted to the CRS digital dashboard. The dashboard compiles data across approximately 5,500 segments and allows users to perform complex queries such as crop-wise, variety-wise, district-wise, or farmer-specific analyses. Temporal and spatial analytics, such as historical trend evaluations and inter-seasonal comparisons, are also supported. The CRS dashboard consolidates data from 5,500 segments and supports geo-spatial analytics, temporal trend analysis, and farmer/crop-specific filters. This interactive and transparent platform reflects global standards of open-data access and data-driven agricultural governance, akin to platforms run by GeoStat (Georgia) and Agri-Food Data Canada. The dashboard also assists with early warning, climate resilience, and disaster recovery planning.

Enumerators input all crop-specific and parcel-level data into the Digital Girdawari Register, which operates with automated validation to ensure area consistency. Subsequently, Jinswar reports are generated to consolidate crop summaries per segment. These tools function similarly to digital land records systems employed in technologically advanced agricultural economies like Australia and the Netherlands, supporting systematic segment-level aggregation of crop data for analysis and policy.

Yield Estimation via Crop Cut Experiments

Following acreage verification, the next critical phase is crop yield estimation through scientifically designed Crop Cut Experiments (CCEs). Based on the Digital Girdawari and Jinswar data, the enumerator generates crop-wise lists of all land parcels cultivated with specific crops. These lists are system-generated, and each land parcel is assigned a random number for unbiased selection.

The enumerator then conducts CCEs by visiting the randomly selected land parcels and, in coordination with the landowner or cultivator, establishes experimental plots according to a strict SOP. The experimental plot size is fixed at 8 feet × 6 feet, and its location within the land parcel is determined using a randomized instruction from a pre-defined reference table based on the assigned random number. The enumerator harvests two plots for each crop.

At the selected site, the enumerator and a helper manually harvest the crop within the plot. Two types of weights are measured:

1. **Total biomass weight** – including straw and grains.
2. **Grain weight** – extracted post-threshing.

By subtracting the grain weight from the total biomass, the residue weight is calculated, which is critical for estimating fodder availability and potential stubble burning. This residue data also contributes to broader environmental assessments, such as greenhouse gas emissions (GHG) and residue management planning.

This method is internationally validated and widely used by FAO, Indian Ministry of Agriculture, and CGIAR institutions for accurate, field-based yield measurement. Each plot (8 × 6 feet) is harvested and weighed for both total biomass and grain output, ensuring realistic estimates reflective of field conditions. The use of random number-based selection of plots adds objectivity and statistical reliability.

Each land parcel requires **two independent crop cut experiments**, randomly located to ensure representativeness. All results are entered into yield estimation form i.e. **Form 6A** (for grain crops), which captures extensive metadata including:

- Farmer's name, CNIC, contact number
- Sowing and harvesting dates
- Seed type (certified/un-certified)
- Fertilizer and pesticide usage
- Irrigation method and water source (canal/tubewell)
- Threshing method

Separate versions of yield estimation forms are used for orchards and cotton crops due to their specific harvesting methods. These forms are digitally transmitted through the same validation chain (Tehsil → District → Division → Data Cell) before final analysis.

Advanced Analytics and Use of Yield Data

After final validation, the data is handed over to the Director in charge of the respective crop. Comprehensive statistical and econometric analyses are conducted at multiple levels to estimate average **yield and production** by tehsil, district, and division. The cleaned yield data also supports:

- GHG emission estimation using standardized emission factors
- Water productivity analysis to determine how much water was used per unit of output
- Seed and input efficiency assessments

Ultimately, this robust, multi-stage process ensures that CRS estimates are scientifically credible, policy-relevant, and transparently generated. These outputs inform strategic agricultural planning, crop forecasting, climate change assessments, and national-level reporting such as the Biennial Transparency Reports (BTR) and Pakistan Climate Prosperity Plan (PCCP). CRS's approach is not only statistically valid but also internationally aligned with methodologies endorsed by the Intergovernmental Panel on Climate Change (IPCC) and FAO's GHG protocols. The integration of crop residue data from CCEs helps estimate GHG emissions, a step toward meeting Paris Agreement and SDG 13 targets. The full process from field data to final estimates follows principles of transparency, accountability, and reproducibility, core to global statistical governance.

Cost of Production Survey

Following the completion of acreage surveys and dissemination of estimates, CRS undertakes the second critical task: the **Cost of Production Survey**. This component is vital for understanding the **economic viability and input cost structure** of crop cultivation from the farmer's perspective.

For the cost of production survey, CRS field enumerators engage in **structured interviews with approximately 20 farmers** within or adjacent to the sampled segments. Farmers are selected from the local area to ensure representativeness and contextual accuracy. The enumerators gather detailed information on all input components associated with cultivation, including:

- Cost of land preparation (e.g., tractor use, laser leveling)
- Seed type and treatment costs
- Fertilizer usage (quantities and cost of DAP, Urea, etc.)
- Pesticides and weedicides
- Labor wages for sowing, irrigation, and harvesting
- Water usage (canal water, tubewell pumping, fuel or electricity)
- Land rent or tenancy agreements
- Harvesting, threshing, and post-harvest handling

The collected cost data is then aggregated and analyzed to develop a standardized cost of production estimate for each crop, which serves as a vital input for policy formulation, crop profitability analysis, and price support mechanisms. This also supports the provincial and federal government in price fixing, crop procurement policies, and future agro-economic planning.

Methodology for Estimating GHG Emissions under Tier I Using Farm-Level Data

This study adopts the Tier I methodology prescribed by the Intergovernmental Panel on Climate Change (IPCC, 2006 Guidelines) for estimating greenhouse gas (GHG) emissions from agricultural crop production systems. Tier I Approach and GHG Overview: This study employs the IPCC Tier I methodology (IPCC, 2006) to estimate greenhouse gases, methane (CH₄) and nitrous oxide (N₂O) from rice, wheat, and cotton systems in Pakistan. The approach uses default emission factors (EFs) and activity data to generate national-level estimates in regions lacking Tier II/Tier III models. Global warming potentials (GWPs: CH₄ = 25; N₂O = 298) are applied to convert emissions into CO₂-equivalent units (Ahmed et al., 2022; Qian et al., 2023).

The farm-level data collected by the Crop Reporting Service (CRS) Punjab provides disaggregated activity data essential for Tier I estimations. The key variables extracted from CRS surveys include cropped area (hectares), yield (tons/ha), fertilizer usage (kg/ha), water application method (flooded vs. non-flooded), type and quantity of organic amendments (e.g., manure or compost), residue management practices (e.g., burning or incorporation), and cropping patterns. For rice, information on the extent of continuously flooded fields and duration of flooding is critical for estimating methane emissions. For wheat and cotton, synthetic nitrogen fertilizer application rates and crop residue practices are the main variables influencing nitrous oxide emissions. Rice methane emissions are calculated using default South Asia seasonal EF ($\approx 0.85 \text{ kg CH}_4 \text{ ha}^{-1} \text{ day}^{-1}$) under continuously flooded conditions without amendments (Islam et al., 2020; Qian et al., 2023). The IPCC equation used is
$$\text{CH}_{4\text{rice}} = \sum \text{EF}_i \times T_i \times A_i \times 10^{-6}$$

where EF is the emission factor for each water regime or amendment class, T is season length, and A is the area. The mitigation potential of AWD or early-season drainage can lower methane by 70-85% (Islam et al., 2020)

Nitrous oxide emissions from wheat and cotton fields are computed using default EFs: 0.01 kg N₂O-N per kg N applied for direct N₂O from fertilizer, and 0.005 kg N₂O-N per kg N from residue incorporation, as per IPCC (2006). This aligns with findings that semi-arid Pakistani wheat systems heavily emit N₂O when urea is used, though biochar amendments can reduce emissions by 27–35% (Dawar et al., 2021)

The Tier I approach, though conservative and generalized, enables quantification of GHG emissions at the district or provincial scale when integrated with CRS-generated farm-level data. For this study, all relevant variables were aggregated to the crop-season level and emissions were calculated on a per hectare and total emission basis (t CO₂e) using global warming potential (GWP) values: CH₄ = 25, N₂O = 298, as per the IPCC Fourth Assessment Report (AR4), unless updated GWPs were used. All calculations were standardized to metric tons of CO₂ equivalent (t CO₂e) to allow comparability across gases and cropping systems.

RESULTS AND DISCUSSION

By leveraging the CRS's reliable, ground-based data collection and applying the IPCC Tier I emission factors, this methodology provides a consistent and replicable approach to assess the environmental impact of rice, wheat, and cotton production systems in Pakistan. While the Tier I method lacks the specificity of Tier II or III models, it offers a practical and scientifically robust basis for preliminary national inventories, mitigation planning, and future integration into **climate-smart agriculture policies** and **MRV (Measurement, Reporting, and Verification)** systems for Pakistan's commitments under the **UNFCCC**.

Based on the data collected every season for all crops, GHG emissions from Rice & Wheat crops were estimated under Tier-I approach. The GHG estimation is as follows in Table 1 & 2:

The table presents **estimated greenhouse gas (GHG) emissions from major crops in Punjab for the year 2024–25**, highlighting significant variation across crop types, cultivated area, and irrigation practices. **Rice (all categories combined)** emerges as the **largest contributor**, accounting for **6.839 million tons of CO₂ emissions**, primarily due to flooded irrigation practices and higher per-acre emission intensity. Within rice, **non-basmati varieties show the highest emissions per acre (1,071 kg/acre)**, followed closely by basmati rice, reflecting methane emissions associated with prolonged inundation.

Wheat, despite having the **largest cultivated area (16.25 million acres)**, shows comparatively lower emissions per acre, contributing **2.985 million tons of CO₂**, indicating relatively efficient emission performance under Punjab's agronomic conditions. **Sugarcane**, cultivated on a smaller area, contributes **0.617 million tons of CO₂**, while **fodder (kharif)** accounts for **0.600 million tons**, reflecting lower emission intensity but wide spatial coverage. Overall, irrigated agriculture is the dominant source of emissions, underscoring the strong linkage between water-intensive cropping patterns and agricultural GHG emissions.

Table 1: Carbon Emission Major Crops

Amount of Carbon Emission from Major Crops, Punjab 2024-25							
Crops	Area (000 acres)	CO ₂ (Carbon) Emission (million tons)			CO ₂ (Carbon) Emission (Kg/acre)		
		Irrigated	Un- irrigated	Total	Irrigated	Un- irrigated	Total
Wheat	16,252	2.928	0.057	2.985	203	45	187
Sugarcane	2,018	0.617		0.617	3.3		3.3
Rice (Bas)	2,029	5.026		5.026	1,002		1,002
Rice (Non-Bas)	685	1.813		1.813	1,071		1,071
Rice (All)	2,714	6.839		6.839	1,020		1,020
Fodder (Kharif)	4,552	0.600		0.600	132	16.8	1,020
Source: Crop Reporting Service, Agriculture Department, Punjab Technically Assisted by Asian Development Bank (ADB)							

These GHG emission estimates are based on comprehensive data collected by the Crop Reporting Service (CRS), Punjab, through regular seasonal surveys. The estimations utilize verified information on acreage, yield estimation, cost of production, growers' opinions, and annual loss and damage assessments, collected for each crop and each season. The data were analyzed using standardized emission coefficients to quantify crop-wise carbon emissions, providing an evidence-based foundation for climate reporting, mitigation planning, and sustainable agricultural policy formulation. Amount of water Applied & Crop Productivity in Punjab are given in Table 2.

Table 2: Water Productivity

Amount of Water Applied & Crops' Productivity, Punjab 2024-25						
Crops	Area (000 acres)	Production (000 tons bales)	Amount of Water Applied (MAF)			Remarks
			TW	Canal	Total	
Wheat	16,252	22,053	11.01 (74%)	3.91 (26%)	14.97	837 liter of water applied for 1 kg Wheat
Rice	6,707	6,030	19.59 (83%)	3.88 (17%)	23.47	4801 liter of water applied for 1 kg clean Rice
Cotton	3,221	3,838	3.94 (47%)	4.40 (53%)	8.34	5583 liter of water applied for 1 kg Phutti
Sugarcane	2,018	60,112	7.90 (69%)	3.50 (31%)	11.40	2463 liter of water applied for 1 kg Sugar (@9.5%)
Maize (A)	1,153	3,096	1.85 (66%)	0.96 (34%)	2.81	1120 liter of water applied for 1 kg Maize grain
Maize (S)	1,563	4,971	3.26 (70%)	1.46 (30%)	4.72	1171 liter of water applied for 1 kg Maize grain
Maize (A+S)	2,716	8,067	5.11 (68%)	2.42 (32%)	7.53	1151 liter of water applied for 1 kg Maize grain (A+S)
Moong	383	116	0.25 (71%)	0.10 (29%)	0.35	3741 liter of water applied for 1 kg Moong
Potato	921	9,813	1.76 (83%)	0.37 (17%)	2.14	269 liter of water applied for 1 kg Potato
Fodder (R)	3,639	127,336	6.06 (74%)	2.12 (26%)	8.26	80 liter of water applied for 1 kg Fodder(Rabi)
Fodder (K)	4,802	68,781	4.43 (65%)	2.41 (35%)	6.84	124 liter of water applied for 1 kg Fodder(kharif)
Fodder(R+K)	8,441	196,117	10.49 (69%)	4.53 (31%)	15.10	95 liter of water applied for 1 kg Fodder(Rabi+Kharif)

Source: Crop Reporting Service, Agriculture Deptt, Punjab

(Crop Delta of water calculated at each Tehsil level)

The data presents a comprehensive picture of crop-wise area, production, and water use in Punjab during 2024-25, highlighting stark differences in water intensity and productivity across major crops. Overall, the figures clearly demonstrate that water use does not translate proportionally into output, underscoring structural inefficiencies in cropping patterns under increasing water scarcity.

Wheat, the largest crop by area (16.25 million acres), consumed 14.97 MAF of water, with tube wells supplying nearly three-quarters of this requirement. Despite its scale, wheat shows moderate water efficiency, requiring 837 liters of water per kg, which is relatively low compared to several other major crops. This positions wheat as comparatively sustainable among staple crops, although its heavy reliance on groundwater raises long-term concerns for aquifer depletion.

Rice stands out as the most water-intensive crop in Punjab. Cultivated over 6.71 million acres, it consumed 23.47 MAF, the highest among all crops, with 83% drawn from tube wells. The water productivity is extremely low, with 4,801 liters required per kg of clean rice, clearly indicating that rice places a disproportionate burden on Punjab's water resources, especially groundwater. This reinforces long-standing concerns about rice cultivation in water-stressed regions.

Cotton and sugarcane further illustrate inefficiencies. Cotton required 5,583 liters per kg of phutti, while sugarcane required 2,463 liters per kg, despite sugarcane's long duration and high total water

demand (11.40 MAF). Although sugarcane shows relatively better per-kg efficiency than rice or cotton, its large absolute water footprint makes it problematic in canal-deficient and groundwater-dependent areas.

Maize, when analyzed across spring and autumn seasons, demonstrates comparatively better water productivity. Combined maize (A+S) used 7.53 MAF and required 1,151 liters per kg, substantially lower than rice, cotton, or sugarcane. This indicates maize's potential as a water-efficient alternative, especially in areas where rice dominates but water availability is declining.

Moong and potato emerge as **highly water-efficient crops**. Moong required only **374 liters per kg**, while potato required **269 liters per kg**, among the lowest in the dataset. Despite their smaller cultivated area, these crops deliver **high productivity per unit of water**, making them strong candidates for diversification strategies aimed at improving water productivity and farmer income.

Fodder crops collectively consume a **significant volume of water** due to their large area (over 8.4 million acres combined). However, their **water requirement per kg is extremely low** (80–124 liters/kg), reflecting high biomass output. While fodder crops are water-efficient in productivity terms, their expanding area still represents a substantial aggregate demand on water resources, particularly groundwater. Across nearly all crops, the data shows a **dominant dependence on tube wells**, typically supplying 65–83% of total water requirements. This reliance highlights the **structural stress on groundwater systems** and signals that current cropping patterns are **not aligned with sustainable water availability**, particularly in central and southern Punjab.

In summary, the analysis reveals that Punjab's agricultural water use is heavily skewed toward **water-intensive crops with low productivity**, especially rice and cotton, while **water-efficient crops occupy a smaller share of area**. The findings strongly support the need for **crop zoning, diversification, and water-productivity-based planning**, rather than area- or production-centric decision-making, to ensure long-term agricultural sustainability in the province.

CONCLUSION

This study demonstrates that Punjab's prevailing rice–wheat dominated agricultural system imposes a significant dual burden on climate and water resources. The integration of high-resolution, field-verified CRS data with IPCC Tier I emission methodologies reveals that rice cultivation is the principal driver of agricultural greenhouse gas emissions, primarily due to continuous flooding and high methane intensity, while wheat contributes substantially lower emissions per unit area despite its extensive footprint. The water productivity analysis further exposes deep structural inefficiencies, with water-intensive crops such as rice, cotton, and sugarcane consuming disproportionate volumes of groundwater relative to their output, thereby accelerating aquifer depletion under already stressed hydrological conditions. In contrast, maize, pulses, potatoes, and fodder crops demonstrate markedly superior water-use efficiency, highlighting their potential role in climate-resilient crop diversification strategies.

The findings strongly indicate that sustainability challenges in Punjab's agriculture are not merely a function of total water use or cultivated area, but of cropping choices, irrigation practices, and productivity outcomes. Reliance on tube wells across most crops reflects a systemic vulnerability that threatens long-term food security and environmental stability. By leveraging CRS's statistically rigorous area frame sampling, multi-tier validation, and crop cut experiments, this research establishes a credible foundation for sub-national greenhouse gas inventories, water-productivity benchmarking, and climate reporting. The study supports a transition toward water- and emission-sensitive planning, including crop zoning, adoption of alternate wetting and drying in rice, and policy incentives for climate-smart crops. Ultimately, aligning agricultural planning with water productivity and emission intensity rather than production volume alone is essential for ensuring Punjab's agricultural sustainability under climate change and for meeting Pakistan's national and international climate commitments.

REFERENCES

- Ali, M., A. Rehman, F. Munsif, M.T. Jan and H. Ahmad. 2017. Estimation of nitrous oxide emissions from wheat–maize cropping system using IPCC methodology. *J. Environ. Manage.* 202: 219–225.
- Ali, S., M. Hussain and R. Ahmed. 2022. Greenhouse gas emissions from agricultural practices in Punjab, Pakistan. *J. Environ. Manage.* 289: 112453.
- Dawar, K., M. Saeed, M. Farooqi and M. Latif. 2021. Biochar amendments reduce nitrous oxide emissions and improve nitrogen use efficiency in wheat under semi-arid conditions. *Sci. Rep.* 11(1): 1–9.
- FAO. 2021. Agricultural greenhouse gas emissions: Global estimates and mitigation options. Food and Agriculture Organization of the United Nations, Rome.
- Hussain, M., A. Qadir and M. Rasheed. 2021. Assessing the GHG emission impact of rice and wheat cultivation in South Asia. *Environ. Res. Lett.* 16(4): 044039.
- IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change, Geneva.
- Khan, N., S. Abbas and M. Ali. 2022. Precision agriculture: Mitigating greenhouse gas emissions from wheat cultivation in Punjab, Pakistan. *Agriculture.* 12(6): 834.
- Khan, M.J., M. Ashraf, M. Ahmad and M. Sultan. 2021. A paradigm of GIS and remote sensing for crop water deficit assessment in near real time to improve irrigation distribution plan. *Agric. Water Manage.* 243: 106443.
- Mishra, S., H. Pathak and J.K. Ladha. 2020. Impact of water management on methane emissions from rice fields. *Mitig. Adapt. Strateg. Glob. Change.* 25: 1001–1019.
- Myhre, G., D. Shindell, F.M. Bréon, W. Collins, J. Fuglestad, J. Huang and H. Zhang. 2013. Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis*. Cambridge University Press. pp. 659–740.
- Pathak, H., P.K. Aggarwal and A. Bhatia. 2011. Greenhouse gas emissions from Indian agriculture: Trends, mitigation and policy options. *Indian J. Agric. Sci.* 81(11): 1045–1056.
- Pathak, H., S. Singh and N. Jain. 2018. Greenhouse gas emissions from rice and wheat systems in South Asia. *Agric. Ecosyst. Environ.* 252: 54–61.
- Syed, T.H., N. Muhammad and M.A. Iqbal. 2020. Greenhouse gas inventory and mitigation options for Pakistan's agriculture sector. *Environ. Sci. Pollut. Res.* 27(34): 43134–43146.
- U.S. Environmental Protection Agency (EPA). 2020. Global greenhouse gas emissions from agricultural practices. U.S. Environmental Protection Agency, Washington, D.C.
- Yan, X., H. Akiyama, K. Yagi and H. Akimoto. 2009. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 IPCC Guidelines. *Global Biogeochem. Cycles.* 23(2).
- Yan, X., T. Ohara and H. Akimoto. 2005. Statistical modelling of global soil NO_x emissions. *Global Biogeochem. Cycles.* 19(3).