# INTEGRATION OF REMOTELY SENSED DATA INTO CROP MODEL TO ADAPT CLIMATE CHANGE IN AGRICULTURE SECTOR IN PAKISTAN

**By**
**Hamza Saeed**
**Registration No. 00000328836**

**Supervisor**
**Prof. Dr. Muhammad Fahim Khokhar**

**Institute of Environmental Science & Engineering**
**School of Civil & Environmental Engineering**
**National University of Sciences & Technology**
**Islamabad, Pakistan**
**2024**

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**Submitted by**

**Mr. Hamza Saeed**

Has been found satisfactory for partial fulfillment of the requirements of the degree of Master of Science in Environmental Sciences.

Supervisor: ..............................

Professor

Dr. Muhammad Fahim Khokhar

IESE, SCEE, NUST

GEC Member: ..............................

Dr. Muhammad Arshad

Professor

IESE, SCEE, NUST

GEC Member: ..............................

Dr. Muhammad Ansar Farooq

Associate Professor

IESE, SCEE, NUST

GEC Member: ..............................

Dr. Ahmad Khan

Post-Doctoral Associate Researcher

University of Maryland, USA

# Acceptance Certificate

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Supervisor: ..........................
Prof. Dr. Muhammad Fahim Khokhar
Dated: 23-09-2024

Dr. Hassan Anwe
Assistant Profess
HoD Environmental Engineeri
SCEE (IESE), NU
H-12 Islamab

Head of Department: ..........................

Dated: 24.09.24

Associate Dean: ..........................
PROF DR MUHAMMAD ARSHAD
Associate Dean SCEE (IESE)
NUST H-12, Islamabad

Dated: 24.09.2024

Principal & Dean SCEE: ..........
PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Dated: 25 SEP 2024

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Student Name: …… Mr. Hamza Saeed……

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Signature of Supervisor: ……….

Dr. Muhammad Fahim Khokhar
Tenured Professor
Environmental Sciences
SCEE (IESE) NUST Islamabad

# DEDICATION

*This research is dedicated to the loving memory of my late mother, whose unwavering love, wisdom, and strength continue to guide me every day. To my family, for their constant support and encouragement, and to my dearest friends, whose belief in me has been a source of immense motivation throughout this journey.*

# ACKNOWLEDGEMENTS

To the highest God be all the glory, for great things He has done. I am deeply grateful for His abundant provisions, protection, and support throughout my life.

I would like to express my sincere gratitude to my supervisor, Dr. Muhammad Fahim Khokhar, for his continuous guidance, valuable suggestions, constructive criticism, and encouragement. His insights and feedback have significantly shaped both the research and the writing of this thesis. I am profoundly thankful for the time he has invested in me and for his unwavering support in improving my work.

I am also deeply indebted to my GEC members, Dr. Muhammad Arshad, Dr. Muhammad Ansar, and Dr. Ahmad Khan, for taking time out of their busy schedules to attend my progress reviews. Their beneficial suggestions, constructive feedback, and encouragement were pivotal in refining both the research methodology and the thesis.

I extend my heartfelt thanks to the Asian Development Bank for providing ground-truthing data, which was essential for the analysis of my research.

I am forever grateful to my family for their endless love, support, and sacrifices throughout this journey. I also want to express my special thanks to Ms. Aneeqa Wazir for her invaluable assistance in GHG estimation. My appreciation also goes out to my dear friends Ahmad Saleem, Ebadat-ur-Rehman and Nameer Urfi for their unwavering encouragement and friendship.

Finally, I am thankful to all my friends, C-Cargo Group, and faculty at IESE for their support and guidance during this research.

Hamza Saeed

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AEZ | Agroecological Zones |
| APSIM | Agricultural Production Systems Simulator |
| AWD | Alternate Wetting and Drying |
| CAP | Conventional Agricultural Practices |
| CERES-Wheat | Crop Environment Resource Synthesis-Wheat |
| CF | Continuous Flooding |
| CF | Carbon Footprint |
| $CH_4$ | Methane |
| $CO_2$ | Carbon Dioxide |
| CRS | Crop Reporting Service |
| CRA | Climate-Resilient Agriculture |
| CSM-CROPGRO | Cropping Systems Model for Cotton |
| DSR | Direct Seeded Rice |
| DSSAT | Decision Support System for Agrotechnology Transfer |
| EF | Emission Factor |
| GCM | Global Circulation Models |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| IPCC | Intergovernmental Panel on Climate Change |
| LULC | Land Use Land Cover |
| MSI | MultiSpectral Instrument |
| $N_2O$ | Nitrous Oxide |
| NDVI | Normalized Difference Vegetation Index |

| | |
|---|---|
| NIR | Near-Infrared |
| PRECIS | Providing Regional Climates for Impact Studies |
| PAE | Potential Application Efficiency |
| RCM | Regional Climate Models |
| RCP | Representative Concentration Pathway |
| RF | Random Forest |
| RGP | Rice Growth Period |
| SCY | Seed Cotton Yield |
| TMAX | Maximum Temperature |
| TMIN | Minimum Temperature |
| WP | Water Productivity |

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# ABSTRACT

This comprehensive study investigates the efficacy and impacts of climate-smart agricultural practices in Punjab, Pakistan, focusing on rice-wheat and cotton-wheat cropping systems as a meta-analysis. The research employed a multi-faceted approach, combining field studies, economic analyses to evaluate various climate-smart practices and their potential for enhancing agricultural sustainability in the region.

The study examined five key climate-smart practices: Alternate Wetting and Drying (AWD) and Direct Seeded Rice (DSR) for rice cultivation, Zero Tillage for wheat, ridge sowing for cotton, and raised bed planting for wheat. Each practice was evaluated for its agronomic performance, resource use efficiency, economic viability, and environmental impact.

Results demonstrated that AWD in rice cultivation led to water savings of 15-25% and reduced methane emissions by 30-70% compared to conventional flooding practices. Economic analysis revealed a 7% increase in net profit for AWD. DSR showed even more promising economic outcomes, with a 15% increase in total revenue and a 32% increase in net profit, accompanied by significant reductions in water use and labor requirements.

Zero Tillage wheat demonstrated substantial benefits, including a 24% increase in net profit and improved soil health. In the wheat-cotton cropping system, ridge sown cotton and raised bed wheat both showed improvements in water use efficiency and yield potential, with economic analyses indicating increases in net profit of 22% and 24% respectively.

The study also employed advanced remote sensing techniques, utilizing a Random Forest algorithm to estimate rice crop areas in Punjab. This method yielded a total rice area estimate of 2,703,586 hectares, which was 3.79% higher than official estimates from the Crop Reporting Service. The spatial resolution and accuracy of this approach enabled detailed, district-level analysis of rice cultivation patterns. Based on the crop area estimations, the study quantified GHG emissions from rice cultivation. Total $CH_4$ emissions were estimated at 252.79 Gg, with significant variations observed across districts. This analysis provides crucial data for targeting emission reduction strategies in high-emission areas.

Finally, the research modelled optimal sowing dates for wheat under changing climate, considering temperature increases of 1°C and 1.5°C. Results indicated that delayed sowing dates, ranging from 6 to 14 days depending on the location and temperature increase scenario,

could help to maintain or improve wheat yields under warming conditions. This finding highlights the importance of adaptive management strategies for climate change.

Comprehensive approach of this research, combining field-level practices with landscape-scale analysis and future climate modeling, provides a robust framework for understanding and addressing the complex challenges facing Punjab's agricultural sector. The findings offer valuable insights for policymakers, agricultural extension services, and farmers, emphasizing the potential of climate-smart practices to simultaneously enhance productivity, resource efficiency, and environmental sustainability. Furthermore, the study underscores the importance of location-specific recommendations and the integration of advanced technologies in agricultural planning and management under changing climatic conditions.

# CHAPTER 1

# 1. INTRODUCTION

Pakistan's economy is heavily reliant on agriculture, placing it among the top ten agricultural producers worldwide. The country is a leading producer of wheat, cotton, sugarcane, and rice, ranking thirteenth globally in rice production. These major crops contribute 6.5% to the nation's Gross Domestic Product (GDP), while minor crops add an additional 2.3% (Fahad & Wang, 2020). Furthermore, the agricultural sector employs approximately 43% of the national workforce (World Bank Statistics, 2021).

Despite efforts to boost agricultural productivity, Pakistan faces significant food insecurity. The World Food Program (2009) reports that over 48% of the population experiences food insecurity, with an estimated 41.4 million people suffering from undernourishment. Consequently, agriculture plays a crucial role in addressing food security concerns and improving socioeconomic well-being in the country. Pakistan also grapples with serious challenges posed by climate change and air pollution, which adversely affect public health and have been linked to a decrease in average life expectancy.

Climate is defined as the average weather conditions over an extended period, including factors such as air temperature, precipitation, atmospheric pressure, humidity, wind patterns, sunshine intensity, and cloud cover. Significant alterations in these weather patterns compared to historical observations are referred to as climate change.

The natural equilibrium of the climate is maintained by local ecosystems and global cycles of carbon, water, and nitrogen. The carbon cycle involves a series of geological, physical, chemical, and biochemical processes that regulate the distribution of carbon among Earth's systems.

Globally, the Earth's total carbon is estimated to be about 75,045,250 gigatons (Gt), distributed across various reservoirs. The lithosphere contains approximately 99.94% of this carbon, the hydrosphere 0.0005%, the biosphere 0.0000255%, fossil fuels 0.000055%, and the atmosphere 0.0000095%. Specifically, the biosphere holds around 2,000 Gt (2 teratons) of carbon, which is a minute fraction of the global carbon reserves.

Carbon dioxide ($CO_2$) emissions from natural processes like respiration and human activities such as fossil fuel combustion are partially absorbed by the oceans; the remainder accumulates in the atmosphere. Humans emit approximately 2.63 Gt of $CO_2$ annually through respiration alone. This calculation is based on an average exhalation rate of 0.058 grams per breath, with an average of 12 breaths per minute, across a global population of 7.2 billion people.

The lithosphere and hydrosphere are significant carbon reservoirs, containing about 75 petatons (Pt) and 38 teratons (Tt) of carbon, respectively (Majeed et al., 2021; Raza et al., 2019). The lithosphere sequesters carbon through processes like burial and sedimentation and releases it via volcanic eruptions and human extraction activities. The hydrosphere exchanges carbon by absorbing and releasing $CO_2$ and methane ($CH_4$), playing a vital role in the global carbon cycle.

## 1.1. Climate Change Impact on Agriculture Sector in Pakistan:

Climate change is expected to increase the vulnerability of agricultural sector by increasing temperature, changes in rainfall patterns, and increased frequency of extreme weather events in Pakistan. Climate change is projected to worsen in the upcoming future. In the Punjab province of Pakistan, there have been projections of increased minimum and maximum temperature for both *Kharif* and *Rabi* seasons. In *Kharif* season, the average maximum temperature and average minimum temperature is predicted to rise by 1–3.3 ◦C and 2–3 ◦C; while in rabi, it is projected to increase by 2.1–3.5 ◦C and 2–3 ◦C, respectively, in simulations done for the future mid-century (2040–2069) (Malhi et al., 2021). Projections indicate significant regional variations in rainfall, particularly during the Kharif season, with anticipated increases of 25–35%, while rainfall changes during the Rabi season are expected to be minimal (Malhi et al., 2021). Temperature trends in Punjab, India, are also projected to shift, with both minimum and maximum temperatures rising by the middle and end of the 21st century, as estimated by the PRECIS (Providing Regional Climates for Impact Studies) model. Furthermore, the likelihood of extreme weather events, such as heatwaves from March to June and frost during December and January, is expected to increase (Malhi et al., 2021).

In China, extreme fluctuations in weather patterns—particularly in temperature and precipitation—are also predicted to become more frequent and intense with an additional 0.5°C of global warming. However, if global temperature increases are kept below 1.5°C, the severity and frequency of these extremes may be mitigated (Ali & Erenstein, 2017; Aryal et al., 2020).

These projections highlight the growing impact of climate change on regional weather patterns. The anticipated rise of temperature extremes & erratic rainfall underscore the need for proactive measures to mitigate the consequences of climate change on agriculture and ecosystems. Limiting global warming remains a critical factor in reducing the intensity of future climate extremes.

Projected changes are expected to have a negative impact on crops in Pakistan, especially in arid to semi-arid regions. South Asian countries are particularly vulnerable to the impacts of climate change due to their large populations, many of whom rely on agriculture-based rural economies. More population living a poverty life creates serious challenges for their social, economic, and ecological systems (Fahad & Wang, 2020). The World Bank's South Asia Climate Change Strategy echoes these concerns, highlighting that the poorest communities in the region are likely to bear the brunt of climate change. This is largely due to their exposure to unfavorable geographic conditions, limited resources, and reliance on climate-sensitive livelihoods, making them disproportionately susceptible to the impacts of a changing climate.

## 1.2. Adaptation to Climate Change in Agriculture:

Adaptation to climate change involves actions aimed at reducing vulnerability and enhancing the resilience of systems, making adaptive capacity a critical factor in determining the actual impacts of climate change. This is particularly important in South Asian agriculture for several reasons: (1) agriculture remains a primary source of livelihood for a large portion of the population; (2) much of the farming is rain-fed, leaving it highly vulnerable to extreme weather conditions; (3) farms are often small and fragmented—typically less than 2-3 hectares—limiting farmers' capacity to adapt; (4) growing populations and rapid economic growth have increased pressure on land and water resources, driven by the demand for alternative farming practices; (5) inadequate institutions and policies to address climate risks in agriculture further exacerbate the issue; (6) underdeveloped risk and insurance markets hinder the promotion of climate adaptation strategies; and (7) there is a pressing need to sustain local food security, especially for poor and small-scale farmers, as climate-induced fluctuations drive up food prices (Abid et al., 2019).

Crop diversification—both spatially (replacing one crop with another) and temporally (altering crop rotations or cropping systems)—offers a practical and cost-effective strategy for enhancing agricultural resilience under changing climatic conditions. Additionally, diversification helps mitigate the impacts of climate change by reducing the likelihood of pest outbreaks and limiting pathogen transmission, which may increase due to greater climate variability. For instance, integrating disease-resistant rice varieties with susceptible ones over large areas resulted in an 89% increase in yields and a 94% reduction in fungal blast disease compared to monoculture systems (Khan et al., 2020).

By embracing diversified cropping practices, farmers can better buffer against climatic stresses, making their agricultural systems more robust and sustainable in the face of climate change. This approach also aids in adapting to increased water stress. For example, the rice–wheat system in South Asia is highly water-intensive, requiring approximately 1.9 cubic meters of water per kilogram of output, making it more vulnerable to rising temperatures that elevate irrigation needs. Replacing this system with less water-intensive cropping systems, such as maize–wheat, can enhance adaptation to water scarcity. Similarly, promoting neglected and underutilized species within diversified production systems offers additional opportunities for climate change adaptation, particularly in mountainous regions where initiatives like constructing new irrigation schemes can be beneficial (Aryal et al., 2020).

## 1.3. Climate Resilient Agricultural (CRA) Practices:

Climate Resilient Agriculture (CRA) is an alternate approach to conventional agricultural practices. CRA improves the utility of natural resources, and ensures resilient agricultural productivity, and reduces GHG emissions. The adverse effects of climate variability on agriculture can be significantly mitigated by adopting climate-resilient agricultural (CRA) practices and technologies, either individually or in combination. In cotton production, implementing CRA strategies can increases yields, improve capital efficiency, increases income, and minimize the harmful impacts of climate change.

Studies from both developed and developing countries, including India, have shown that even simple adaptations of CRA can lead to increased agricultural productivity and higher farm incomes (Jamil et al., 2021). This highlights that modifying cropping patterns and planting dates, along with adopting new agricultural and water-saving technologies, can significantly enhance agricultural productivity and profitability.

Similarly, numerous empirical studies have demonstrated that applying CRA practices and technologies boosts crop yields, enhances resource use efficiency, increases net farm income, and reduces greenhouse gas emissions (Abid et al., 2019). In Pakistan, research has found that implementing new agricultural practices and adapting to climate change significantly influence agricultural productivity, farm income, and resource use efficiency.

Moreover, researchers have noted that groundwater quality varies across different farms and regions in Pakistan, significantly impacting agricultural productivity, farm income, and the livelihoods of rural households (Imran et al., 2018). Farmers in Pakistan are increasingly adopting water-smart, energy-smart, carbon-smart, and knowledge-smart CRA practices and technologies to enhance their resilience to climate change.

## 1.4. Expected Outcomes of the Study:

This study is aimed at establishing a robust comparison of climate resilient agriculture and conventional agricultural practices based on the available secondary data and their impact on yield of crops. This would also include having a thorough analysis of various cropping systems that may hold a significant impact on the average yield based on the climate resilient agricultural practices with minimum use of water and fertilizers, and zero tillage applied to the fields saving a large amount of expenses and overall emissions. Also, the amount of GHG emissions added to the atmosphere through rice crop in conventional method will also be observed. Climate change has great impacts over the cropping seasons in different areas around the globe. This study also aims to understand the relationship between climate change and significant shifts in the sowing dates and overall cropping periods of regional and seasonal crops under changing climate conditions. By examining how climate change affects agricultural timelines, we seek to provide insights that can help adapt crop management practices to evolving environmental challenges.

## 1.5. Objectives:

The objectives of the study are as follows:

**i.** Comparison of climate resilient agricultural practices with conventional practices under the parameters of water saving and cost efficiency.

**ii.** Crop area estimation of rice crop using random forest algorithm and GHGs Estimation using IPCC default emission factors.

**iii.** Identifying suitable sowing dates for Wheat crop to attain optimum yield with respect to future climate shift scenarios.

# CHAPTER 2

# 2. LITERATURE REVIEW

## 2.1. Previous Studies on Agricultural Practices in Pakistan:

Akbar et al., (2016) evaluated conventional surface irrigation systems in Pakistan and found poor irrigation efficiencies across thirteen fields. Application efficiency ranged from 41% to 82%, with furrow beds showing the highest efficiency. Simulation modeling suggested potential improvements in efficiency up to 94%, 87%, and 96% for level basin, border, and furrow bed systems, respectively, by optimizing field dimensions. A study conducted by Watto & Mugera, (2019) investigated wheat farming efficiency and irrigation water use in Pakistan using meta frontier data envelopment analysis. Results indicated improvements in technical and irrigation water use efficiency among surveyed farms. Tube-well owners and water buyers showed average technical efficiencies of 82% and 77%, respectively, while irrigation water use efficiencies average at 66% and 65%, respectively. Latif et al. (2016) recognized the inefficiencies of traditional surface irrigation methods and emphasized the critical need to adopt pressurized irrigation systems like drip irrigation to enhance water use efficiency.

Ashfaq et al., (2015) studied factors contributing to low water productivity (WP) in different cropping areas of Punjab, Pakistan. Findings from 230 farmer interviews highlighted concerns over water, energy, and fertilizer shortages affecting WP. Field experiments have demonstrated that drip irrigation markedly enhances water productivity for wheat, achieving 2.26 kilograms per cubic meter while conserving 40% more water compared to conventional irrigation methods. Khokhar et al., (2010) investigated the impact of different irrigation levels on the growth and yield of various wheat genotypes in Sindh, Pakistan. The number of irrigations did not significantly affect plant height, but it did influence spike length, grain number, and grain yield. Overall, applying five irrigations at various wheat growth stages resulted in improved spike length, grain number, and grain yield.

Khan et al., (2009) reported that wheat grain yield was highest (3448 kg/ha) with water application depths of 30–45 cm and lowest in fields with depths exceeding 45 cm. On-farm application efficiencies ranged from 22% to 93%, emphasizing the need for optimal water management practices to maximize wheat yield in spate irrigation systems. Asif et al., (2019) reported that bed sowing resulted in the highest grain yield and water productivity compared to flat and ridge sowing methods in Potohar region which also led to substantial savings in irrigation time due to reduced water losses.

Munir et al., (2007) evaluated Resource Conserving Technologies (RCTs) like laser land leveling, zero-tillage, bed furrow irrigation, and crop residue management in Punjab, Pakistan, focusing on wheat-rice cultivation. Findings indicated significant water use efficiency gains (20% with laser leveling), substantial resource savings (up to 78% in fuel with zero-tillage), and improved soil health (enhanced microbial populations with zero-tillage). Muneer et al., (2022) evaluated the performance of subsurface drip irrigation (SDI) compared to surface drip and gravity irrigation methods for maize cultivation in Faisalabad, Pakistan. Trials conducted over two years indicated that SDI at a depth of 0.15 m gives the high grain yield and water productivity. The study reported that SDI at shallow depths can optimize water use efficiency and crop yields in semi-arid regions of Pakistan.

Fatima & Yasmin, (2016) conducted a meta-analysis of research papers from 1971 to 2014 to assess the efficiency of Pakistan's farm sector. Three models were used to analyse methodological, crop-specific, and regional influences on Mean Technical Efficiency Scores (MTES). The overall technical efficiency was found to be 73%, indicating room for improvement in Pakistan's farm sector. Naheed & Mahmood., (2021.) discussed the variations in water requirements across regions and emphasized the role of post-monsoon soil moisture and winter rainfall in meeting the initial water demand for wheat. Successful wheat cultivation depends on maintaining soil moisture levels at approximately 50% of crop evapotranspiration.

Jamil et al. (2021) conducted a study involving 350 cotton farmers in Punjab, Pakistan, to evaluate the adoption of Climate-Smart Agriculture (CSA) practices. Their findings suggest that embracing CSA practices can reduce the harmful impacts of climate change on cotton crops by enhancing profitability. They emphasize the importance of removing barriers to adoption through effective information dissemination and enforcement of regulations to ensure broader implementation.

Similarly, Imran et al. (2018) reported that cotton farmers are adopting various CSA practices—such as water-smart, energy-smart, carbon-smart, and knowledge-smart strategies—to mitigate the effects of climate change. These practices contribute to increased resilience and sustainability in cotton production under changing climatic conditions. Results show higher yield, uniform germination, and financial returns with CSA adoption. Imran et al., (2022) reported that CSA adopters had higher economic benefits and improved resource use efficiencies, particularly in the cotton-wheat cropping system. The study concluded that adopting water-smart practices of CSA can increase profits, save inputs like water, and enhance production.

## 2.2. Rice-Wheat Cropping System:

### 2.2.1. Alternate Wetting & Drying vs. Conventional Flooding

Rice is a semi-aquatic crop that requires waterlogged conditions in the root zone for optimal growth. To achieve this, farmers commonly puddle the soil before transplanting seedlings, which helps control deep drainage losses. However, this practice can be detrimental to the soil's physical, chemical, and biological health (Akbar et al., 2023). According to Ishfaq et al., (2020) conventional flooded rice production (CF) exacerbates global warming and water scarcity issues by requiring excessive water and contributing to GHG emissions and heavy metal accumulation. Alternate wetting and drying (AWD), an intermittent irrigation method, emerges as a promising, water-saving, and eco-friendly alternative. Hussain et al., (2021) suggested that alternate wetting and drying with maximum water productivity and continuous flooding with maximum benefit-cost ratio could be more efficient approaches compared to aerobic rice.

A meta-analysis conducted by Carrijo et al., (2017) assessed the impact of alternate wetting and drying (AWD) irrigation on rice yields and water use compared to continuous flooding (CF). It found that while AWD decreased yields by 5.4% overall, under Mild AWD conditions, yields were not significantly reduced. Severe AWD led to yield losses of 22.6%. Akbar et al., (2023) examined the effects of different irrigation methods on the yield and water productivity of the rice variety PK 1121. They compared traditional flooding with puddling (CF), alternate wetting and drying (AWD), and responsive drip irrigation (RDI) to assess which method offers the best performance in terms of crop yield and efficient water use. Results showed that while RDI required significantly less irrigation (76% less than CF) and had higher water productivity (249% higher than CF), it also had a yield trade-off of 18%. AWD, on the other hand, showed less water saving (32% less than CF) but yielded 4% more than CF, resulting in a 52% higher water productivity compared to CF. Farooq et al., (2020) examined the impact of alternate wetting and drying (AWD) cycles on soil nutrient availability and maize production, emphasizing integrated nutrient management for sustainability. Conducted over repeated experiments, they find that all fertilizer treatments significantly increase soil nutrients and maize yield, particularly under 14-day AWD cycles. This showed that integrating crop straw and inorganic fertilizers with AWD irrigation shows promising results for sustainable maize production.

A study conducted by Abid et al., (2022) examined nitrogen (N) fertilization strategies in rice cultivation under alternate wetting and drying (AWD) irrigation versus conventional permanent flooding (PF). Comparing two improved nutrient management practices — nutrient management by pig manure (NMPM) and nutrient management by organic slow-release fertilizer (NMSR)—to farmer's fertilizer practice (FFP), it finds that AWD significantly increases grain yield compared to PF. Both NMPM and NMSR outperform FFP, with NMPM showing the most promise in stimulating nitrifier and denitrifier gene abundance and promoting rice production while minimizing environmental impact.

Field experiments showed that UB and NPK significantly reduced N losses and improved grain yields and NUE under both AWD and CSW, with larger benefits observed under AWD. They further suggested that AWD combined with FDP can enhance water and fertilizer use efficiencies in rice cultivation. Ullah et al., (2018) examined the effects of integrated nutrient management, cultivation method, and variety on lowland rice under alternate wetting and drying (AWD) irrigation. They suggested that using 50% NPK and 50% FYM could be a favourable option under AWD, though outcomes may vary with varieties and cultivation methods. Wakeel et al., (2017) suggested that potash fertilization can enhance yield and adaptability of aerobic basmati rice production, emphasizing the need for precise potash recommendations for both aerobic and flooded production systems.

### 2.2.2. Direct Seeded Rice

Bista, (2018) reviewed integrated cultivation technologies associated with DSR, discussing its advantages, constraints, and potential as the future of rice cultivation in Nepal. According to this study, direct-seeded rice (DSR) offers significant benefits, including a 50% reduction in water use, a 60% decrease in labour costs, and a 5-10% increase in productivity. DSR also contributes to lower methane emissions, addressing global warming concerns. However, blast disease and root-knot nematodes pose significant challenges. According to Iqbal, (2014) close planting patterns in direct-seeded rice have been proven to enhance growth and productivity by optimizing the utilization of environmental and soil resources. Additionally, this method effectively suppresses weed infestation, a significant factor known to reduce the quality and yield of aerobic rice. According to Nawaz et al., (2016), no-till (NT) wheat experiences poor stand establishment when sown after both direct-seeded aerobic rice and puddled transplanted flooded rice systems. However, the study found that seed priming techniques significantly improved the uniformity and speed of wheat emergence, with osmopriming being the most effective method.

A field study in Punjab, Pakistan compared traditional transplanted rice (TPR) with dry direct seeded rice (DDSR) across two years. DDSR consistently yielded higher (13–18%) and required less water (8–12%) compared to TPR. According to Ishfaq et al. (2020), implementing alternate wetting and drying (AWD) irrigation under dry direct-seeded rice (DDSR) conditions significantly reduced water input by 27–29% compared to continuous flooding. This method not only conserved water but also improved yield and water productivity. Specifically, the combination of DDSR with AWD using the Chenab Basmati-2016 rice variety achieved the highest yields of 6.6 and 6.7 tons per hectare, along with increased profitability. According to a study conducted by Rehman et al., (2015) DSR-AWD with MLE or $CaCl2$ priming exhibited the highest tillering rate, tiller count, yields, harvest index, grain quality, benefit-cost ratio, and water productivity.

Shaheen et al. (2017) evaluated the technical efficiency of conventional and direct rice farming methods in Punjab, Pakistan, with the goal of identifying factors that affect rice output. Their research indicated that direct seeding is more profitable and efficient for farmers engaged in dry rice cultivation. The study further suggested that by improving management practices, rice output could increase by 14% without the need for additional inputs, emphasizing the crucial role of efficient farming techniques in rice production.

Building on this, Nawaz et al. (2017) found that wheat grown after dry-seeded aerobic rice (DSAR) exhibited better performance and enhanced soil properties. This makes the combination of DSAR followed by no-till wheat (NTW) the optimal choice for sustaining productivity and boosting net profits in rice-wheat cropping systems.

Additionally, Muhammad et al. (2016) conducted a two-year field study assessing five different weed control measures in direct-seeded rice (DSR), providing valuable insights into effective weed management practices for this cultivation method. Hand weeding resulted in the highest crop yield, while tine cultivation offered effective and economical weed control. Overall, weed management methods significantly influenced crop growth, grain yield, and grain quality in DSR. A study in Bangladesh evaluated weed competitiveness of rice cultivars and seeding rates in DSR. Results showed that under weed-free conditions, inbred cultivars yielded best at moderate seeding rates, while hybrids performed well at lower rates. In weedy conditions, higher seeding rates compensated for yield losses, with hybrids showing greater weed competitiveness (Ahmed et al., 2021).

### 2.2.3. Zero Tillage Wheat

Shahzad et al., (2016) reported that cotton and wheat under zero tillage (ZT) exhibited the highest weed diversity, while sorghum-wheat under DT had the lowest. The study aimed to assess the impact of different tillage implements on wheat growth and yield in District Toba Tek Singh showed that MRP (mouldboard plough, rotavator, planking) (Treatment-4) resulted in the highest germination rate, grains per spike, tillers per square meter, grain yield, and benefit-cost ratio compared to other tillage practices. Specifically, MRP yielded 4439.7 kg/ha of grain with a Cost-benefit proportion of 3.41. Therefore, MRP is recommended for use in the cotton-wheat zone of Pakistan following cotton harvesting (Khan et al., 2017).

Ali et al., (2016) reported that zero tillage significantly improved plant height, tillers per square meter, spike length, 1000 kernel weight, and overall grain yield compared to conventional tillage. Additionally, wheat plants grown with a row spacing of 15 cm exhibited higher tillers per square meter, biomass accumulation, and grain yield compared to wider row spacing options. Hussain et al., (2020) reported that zero tillage resulted in 13% higher wheat and 9% higher mung bean yields, better germination, and reduced production costs by Rs. 6236 per hectare. According to Akhtar & Rasool, (2020), data from 150 farmers revealed that ZT farmers used more seed, but fewer irrigations compared to conventional farmers. Conventional farmers spent more on inputs like fertilizer, irrigation, and chemicals, resulting in higher variable costs. Additionally, they required more labor due to the heavy investment in conventional tillage.

Sharif et al., (2018) showed that zero tillage (ZT) without residue return resulted in significantly lower yields. Gross margins were highest with residue retention under RT, followed by MT and CT, while ZT without residue return had the lowest gross margin. Minhas et al., (2023) examined the impact of tillage and cropping systems on soil properties, weed infestation, and wheat yield. Conventional tillage (CT) led to better soil conditions and higher wheat productivity, while zero tillage (ZT) resulted in increased weed infestation but lower wheat yields. Mungbean-wheat cropping systems improved soil health and wheat productivity, while sorghum-wheat cropping reduced weed infestation.

## 2.3. Cotton-Wheat Cropping System

### 2.3.1. Ridge Sown Cotton

Shahzad et al., (2017) examined the effects of sowing method and planting density on weed infestation, crop characteristics, yield, and fiber quality of cotton. Ridge sowing reduced weed density by 25%, while bed sowing increased sympodial branches, bolls per plant, lint yield, seed index, and seed cotton yield compared to flat sowing. Bed sowing with lower planting density was found most effective for enhancing crop morphology, yield, and yield-related traits. A series of six experiments conducted across three locations in Punjab, Pakistan, sought to enhance seed cotton yield and water use efficiency by exploring different cotton planting methods.

Khan et al., (2015) compared the performance of cotton under different tillage methods—zero tillage, reduced tillage, and conventional tillage—and various intra-row spacings of 15.0, 22.5, 30.0, and 37.5 cm. Optimal results were observed with a 22.5 cm intra-row spacing under reduced tillage, indicating its potential as an effective alternative to conventional tillage for improving cotton yield, earliness, and quality while also benefiting soil health.

In their study, Bakhsh et al., (2018) demonstrated significant advantages of bed planting over conventional flat sowing. For wheat, bed planting led to higher germination rates, more tillers, and increased dry matter weight. In cotton, it resulted in taller plants and more bolls per plant. For rice, bed planting produced higher tiller numbers and grain yields. Additionally, bed planting conserved substantial amounts of irrigation water and enhanced water productivity across all three crops.

A study conducted at the Nuclear Institute of Agriculture in Pakistan evaluated different cotton varieties under two planting dates to assess their performance. Results showed that cotton sown on April 1st yielded higher compared to May 1st sowing. Among the varieties, NIA-88 exhibited the highest seed cotton yield and boll retention percentage. Additionally, planting date influenced various traits such as the number of bolls per plant, sympodial branches, ginning out turn percentage, seed index, and staple length (Deho, 2023). Deep tillage resulted in higher seed cotton yields compared to conventional tillage, with bed sowing showing the highest yield-contributing traits. Deep tillage combined with bed sowing yielded the maximum net returns. Soil bulk density was lower under deep tillage systems (Irfan et al., 2020).

### 2.3.2. Raised Bed Wheat

Traditional flat planting of wheat in Pakistan leads to inefficient nitrogen use, low water efficiency, and soil surface issues. In contrast, bed planting improves fertilizer efficiency and yield. A study by Majeed et al., (2015) found that wheat planted on beds with 120 kg ha−1 nitrogen produced 15.06% higher yield compared to flat planting at the same nitrogen rate. Hashimi et al., (2019) reported that raised bed planting increased grain yield by 21%, with improvements in various yield-related parameters. Economic analysis revealed that raised bed planting methods resulted in higher net income compared to flat line and ridge-line sowing methods. Ansari et al., (2019) indicated that soil-moisture-based treatments led to significantly higher wheat grain yields compared to climatic-based treatments. Additionally, in-season Normalized Difference Vegetation Index (NDVI) measurements proved effective in accurately estimating wheat grain yield potential, providing valuable insights for crop management.

Chauhdary et al., (2016) compared three seed rates (100, 130, and 160 kg/ha) and three sowing methods (broadcasting, drill sowing, bed planting) for wheat cultivation. Results showed that bed planting with a seed rate of 160 kg/ha yielded the highest grain yield, water productivity, and agronomic parameters. Bed planting also saved 35% water compared to broadcasting. They further recommended sowing wheat at a seed rate of 160 kg/ha using bed planting techniques to enhance yield and water productivity in the semi-arid region of Faisalabad, Pakistan. A study comparing flooding and raised bed irrigation systems for wheat cultivation was conducted in Jaffarabad, Balochistan, Pakistan. The raised bed irrigation system resulted in 17.2% higher yield (1656 kg/acre) compared to flooding irrigation (1368 kg/acre). Additionally, the raised bed system showed efficient water usage, helping to control waterlogging and salinity in the area (Jamali & Laghari, 2019). Yigezu et al., (2021) suggested that embracing raised bed (RB) can address various socioeconomic, biophysical, and environmental challenges associated with irrigation in Egypt and similar countries.

A study conducted by Akbar et al., (2016) reported that raised-bed irrigation outperformed conventional, with 50.73% higher water saving, 54.37% greater water productivity, and 24.65% higher yield. This suggests raised-bed irrigation as favourable for achieving higher yield and water productivity while conserving water in similar soils. Akbar et al., (2017) investigated irrigation management on Narrow Beds (NB) and Wide Beds (WB) in the Indus Basin. Results showed that WB had better application efficiency and distribution uniformity compared to NB. Simulation modelling suggested that achieving over 90% Potential Application Efficiency (PAE) is feasible by improving operational practices and field design.

This study highlights the potential for enhancing irrigation efficiency on raised beds without significant infrastructure changes or increased costs.

## 2.4. Greenhouse Gases Emissions

Kashyap & Agarwal, (2021) revealed significant variations in the carbon footprint among different zones and farm sizes. Notably, large farms demonstrated a 39% lower carbon footprint per ton of rice compared to small farms, indicating that farm size delineates a crucial role in the environmental impact of rice production. Key contributors to CF were residue burning, methane emissions, and fertilizer use, with nitrogen fertilizer identified as a major hotspot for mitigation.

According to Xiaoyuan et al. (2010), introducing at least one drainage period during the growing season in rice fields that are typically kept continuously flooded can reduce methane ($CH_4$) emissions by approximately 4.1 teragrams per year (Tg/yr). Additionally, globally applying rice straw during the off-season whenever feasible could lead to a further reduction of $CH_4$ emissions by another 4.1 Tg/yr.

In a separate study, Kumar and Nandini (2016) employed the IPCC Tier 1 methodology for the Agriculture and forest sector to estimate GHG emissions from flooded rice paddy fields. Their analysis revealed that methane emissions from rice fields were 1.255 gigagrams (Gg), equivalent to 31.364 Gg of $CO_2$ equivalent ($CO_2e$), in 1990–1991. By 2012–2013, these emissions had decreased to 0.269 Gg (6.725 Gg $CO_2e$). This indicates an overall reduction of 21.44% in methane emissions from rice paddies over the past two and a half decades.

Behzad et al., (2019) indicated 5128 kg/ha of wet biomass generated during the Rice Growth Period (RGP), with a corresponding dry biomass estimate of 2564 kg/ha (2.82 ton/ha). However, these estimates appeared exaggerated compared to field estimates of 1.83 ton/ha. Wang et al., (2018) indicated that $CH_4$ fluxes were closely linked to various factors such as organic amendments, water regime, soil properties, and agroecological conditions. The global default emission factor (EF) was estimated at 1.19 kg $CH_4$/ha/day, with variations across regions, with lower EFs observed in South Asia and North America.

According to Begum et al., (2019), AWD significantly reduced $CH_4$ emissions compared to continuous flooding (CF) while maintaining similar yield levels. Additionally, AWD was found to be cost-effective and yielded lower yield-scaled emissions intensity compared to CF, with integrated management further enhancing these benefits. Aliyu et al., (2019) analysed 151 nitrous oxide ($N_2O$) emission factor (EF) values from agricultural fields across China to understand variations based on climate and soil types. It found that the EF of synthetic nitrogen (N) fertilizer differed significantly among six climatic zones, with factors like precipitation and soil pH influencing EFs. Shang et al., (2020) compared nitrous oxide ($N_2O$) emission factors (EFs) derived from year-round measurements versus those based only on the crop-growing season. Analysis of 123 DEFs from 21 studies globally showed that EFs from year-round data are significantly higher, particularly for vegetables.

Arunrat & Pumijumnong, (2017) investigated the impact of land management practices on greenhouse gas (GHG) emissions and rice productivity. It revealed an increase in soil organic carbon sequestration rate (SOCSR) alongside rice yield. The net global warming potential (GWP) varied across sites, with the highest value at 5180 kg $CO_2$eq/ha/year and an average of 3100 kg $CO_2$eq/ha/year. They suggested that avoiding rice residue burning can reduce GHG emissions. Wang et al., (2023) examined greenhouse gas (GHG) emissions from rice production and consumption across 227 countries over 32 years. The study found a significant increase in trade volume, contributing to a reduction in global GHG emissions by an average of 56.3Mt per year.

Gangopadhyay et al. (2022) evaluated the carbon emissions associated with different rice cultivation practices to understand their impact on greenhouse gas emissions and carbon sequestration. The study compared conventional farming methods, the System of Rice Intensification (SRI), and zero-tillage (ZTL). The researchers discovered that fertilizer application significantly affected the global warming potential (GWP) of these practices.

In another study, Brodt et al. (2014) analyzed the greenhouse gas emissions involved in producing one kilogram of rice in California using life cycle assessment methods. They found that the 100-year global warming potential was 1.47 kg $CO_2$-equivalent per kilogram of milled rice, with field emissions accounting for 69% of the total. This highlights the significant contribution of field practices to the overall GHG emissions in rice production.

Nikolaisen et al. (2023) reviewed methane emissions from rice paddies, focusing on factors such as water management regimes and soil texture. They developed a new generalized additive model (GAM) to estimate emission factors (EFs), which outperformed existing models by showing greater sensitivity to management practices in both tropical and temperate regions. The study provided baseline emission factors at global, regional, and national levels, emphasizing the need to consider variations in water management when estimating methane emissions from rice cultivation.

## 2.5. Remote Sensing & Machine Learning Algorithms

Sudarmanian et al., (2017) focused on methane emissions from rice cultivation using SAR satellite data. Methane emission rates, based on IPCC factors, ranged from 37.4 to 45.74 kg/ha for the flooding period. The total methane emission from Tiruchirapalli district during the Samba season in 2015-16 was estimated to be 1.57Gg. Pazhanivelan & Kaliaperumal, (2019) estimated methane emissions from rice cultivation in Thiruvarur district using SAR-based mapping and IPCC emission factors. The methane emission rate ranged from 35.88 to 41.49 kg/ha, depending on the duration of flooding. The total methane emission for the district during the samba season of 2017-18 was estimated at 1.32 Gg.

Yang et al., (2021) developed a method using Sentinel-1A to accurately estimate the area of rice. Results showed high accuracy in rice mapping and transplanting date retrieval. The method outperformed traditional approaches, offering valuable insights into rice phenology distribution. Potapov et al., (2022) analysed global cropland changes from 2003 to 2019 using satellite data. Cropland area increased by 9%, with Africa and South America leading expansion. However, 49% of new cropland replaced natural vegetation, posing sustainability challenges. According to Khan et al., (2016), utilizing Landsat satellite imagery for wheat mapping in Punjab achieved an overall accuracy of 76%. However, the method exhibited a wheat commission error of 38% and a wheat omission error of 30%. The estimated wheat area from the Landsat data was 6.13 million hectares, which closely matched the field-based sample estimate of 6.96 ± 2.15 million hectares and the official figure reported by the Punjab Crop Reporting Service (CRS) of 6.77 million hectares.

A study in Australia developed methods for mapping croplands across large areas using spectral matching techniques and an Automated Cropland Classification Algorithm (ACCA). Using MODIS satellite data from 2000-2015 and training the ACCA algorithm with a 2014 reference, the study achieved 89.4% overall agreement across six classes. These results accurately depicted Australian cropland dynamics, aiding in food security analysis (Teluguntla et al., 2017). Khan et al., (2021) showcased the effectiveness of using time-series Landsat data for wheat area mapping. By integrating current season maps with previous season wheat data, the study developed a rapid and accurate mapping model. By employing a classification-tree algorithm, the method produced wheat maps with accuracy comparable to traditional supervised classification techniques. However, an analysis of pixel counts from 2013 to 2017 showed slight overestimations when compared to official estimates. Among various estimation approaches, stratified random and simple random sampling coupled with regression yielded the smallest standard errors. A study conducted by Ali et al., (2021) utilized Sentinel-2 satellite data to map rice cultivation areas and predicted yields in the Kafr El-Sheikh governorate, covering 3240 hectares. Using multitemporal NDVI, a supervised classification method achieved 95% accuracy. Yield prediction, based on an empirical model incorporating NDVI and LAI calculated from SEBAL, showed a ±6.76% MPAE for LAI and ±6.53% for yield, indicating its suitability for estimating rice area and yield well before harvest in the northern Nile delta.

Torbick et al. (2017) conducted a study that combined multiscale satellite imagery with a process-based biogeochemical model to map greenhouse gas (GHG) emissions from rice cultivation in Vietnam's Red River Delta. They trained a random forest classifier using field observations and surveys to accurately map the extent of rice fields. Subsequent time-series analysis provided geospatial information on crop calendars, hydroperiods, and cropping intensity. The findings revealed that in 2015, the rice cultivation area covered 583,470 hectares with a total harvested area of 1,078,783 hectares. Total methane emissions for the delta were estimated at 345.4 million kilograms of $CH_4$-C, equivalent to 11.5 million tonnes of $CO_2$e.

In another study, Wang et al. (2021) utilized the DNDC model to estimate methane emissions from Chinese rice fields in 2012. They reported emissions totaling 8.20 teragrams of $CH_4$ per year, with significant variations across different cropping systems. The highest emissions originated from Agro-Ecological Zones (AEZ) 7 and 6, primarily due to double-cropping rice fields in AEZ 7 and single-cropping rice fields in AEZ 6.

Gumma et al. (2022) focused on creating three essential cropland products for South Asia using remote sensing data. The first product differentiated between irrigated and rainfed croplands using Landsat data at a 30-meter resolution on the Google Earth Engine (GEE) platform. The second product identified major crop types by employing MODIS data at a 250-meter resolution. The third product assessed cropping intensity, also utilizing MODIS 250-meter data. Accuracy assessments showed overall accuracies ranging from 79.8% to 85.3%, with producer's accuracies between 67% and 88%. By leveraging advanced satellite data and machine learning algorithms, these products serve as indispensable tools for assessing, modeling, and monitoring food and water security in South Asia. They play a crucial role in supporting sustainable resource management and addressing the pressing challenges faced by the region.

## 2.6. Previous Studies on Crop Modelling Approaches

Jabeen et al., (2022) examined wheat grain yield and water use efficiency (WUE) under limited irrigation in arid and semi-arid regions of Pakistan. Using DSSAT simulation, various irrigation levels were assessed, revealing significant impacts on yield and water consumption. While higher irrigation levels in semi-arid sites decreased WUE and yield, the optimal level for semi-arid regions was found to be 50% less water, resulting in improved yield and WUE. Hussain et al., (2020a) investigated the uncertainty in simulating climate change impacts on wheat production by comparing outputs from multiple climate (GCMs from CMIP5) and crop models (CERES-Wheat, DSSAT-Nwheat, CROPSIM-Wheat, and APSIM-Wheat). Fahad et al., (2019) integrated remotely sensed soil moisture data with the CERES-Wheat model to estimate wheat yield in the Faisalabad district. Calibration showed good agreement with observed grain yield, and regional validation demonstrated accuracy across 25 farms. The estimated regional yield ranged from 1500 to 3593 kg/ha, with a mean of 2979 kg/ha, slightly higher than presented by the Crop Reporting Service (CRS), Punjab.

Yasin et al., (2022) used multiple models to assess future climate impacts on maize grown in semi-arid regions. Three models were calibrated and evaluated, with five selected GCMs predicting temperature increases during the maize growing season. Among the models, CERES-Maize and APSIM-Maize performed well, while CSM-IXIM-Maize excelled in growth parameters and yield. Hussain et al., (2020) employed future climate scenarios (2040–2069) under RCP 8.5 and categorized them into five climatic conditions based on temperature and rainfall changes. Results indicated that Faisalabad and Layyah experienced a 2–3°C temperature increase, with Faisalabad becoming drier and Layyah wetter. Wheat yields varied based on sowing dates and climatic conditions, but agronomic and breeding options mitigated climate change impacts, increasing yields by 20%. The DSSAT-wheat and APSIM-Wheat models showed differing sensitivity to temperature changes.

Using APSIM and 33 GCMs, Collins & Chenu, (2021) evaluated sowing date adjustments and cultivar selection to combat abiotic stresses. Results indicated shifting sowing dates earlier and planting early maturing cultivars can boost yield and reduce stress effects, maintaining grain filling periods. Overall, the study suggested that proper adaptation strategies, combined with $CO_2$ fertilization, can reduce the frequency of severe stress events, and increase national wheat yield by 4.6%, with reduced risk of crop failure in most areas. Both crop models predicted reduced wheat yield under future scenarios. Hussain et al., (2021) utilized well-calibrated CERES-wheat within DSSAT to forecast grain yield under future climate scenarios projected by 29 global circulation models (GCMs) under RCP 8.5. Results reported a substantial increase in average seasonal temperatures and a notable reduction in grain yield, by 35% in the arid region.

Four wheat simulation models were tested using field experiments in two different climatic regions of Punjab, Pakistan. While the models performed well for early, optimum, and late sowing dates, they struggled to accurately simulate yields for very late planting dates, especially under high temperatures during grain filling. The study further suggested that all models require enhancement in simulating maximum leaf area index, with APSIM-Wheat particularly struggling to simulate days to maturity for very late planting dates (Hussain et al., 2018). Awan et al., (2021) calibrated and validated a cotton model using climate and crop data from Bahawalpur and Khanewal. The Cotton model within the DSSAT framework was utilized to simulate climate future scenarios under RCP 4.5 and 8.5 using five GCMs. Results revealed a substantial reduction in seed cotton yield (SCY) under both RCPs, with the hot/wet climate scenario showing the most significant impact. Simulations suggested that increasing nitrogen application and plant population, along with planting 15 days earlier and implementing water and nitrogen management practices (fertigation), could help mitigate yield losses.

# CHAPTER 3

# 3. METHODOLOGY

## 3.1. Study Design for Comparison of climate resilient agricultural practices with conventional practices under the parameters of water saving and cost efficiency

This study conducts a comparative analysis to evaluate the effectiveness of climate-resilient agricultural practices (CRAP) against conventional agricultural practices (CAP), focusing on water conservation and cost efficiency. The research specifically examines the rice-wheat and cotton-wheat cropping systems that are prevalent in Pakistan.

### 1. Data Collection

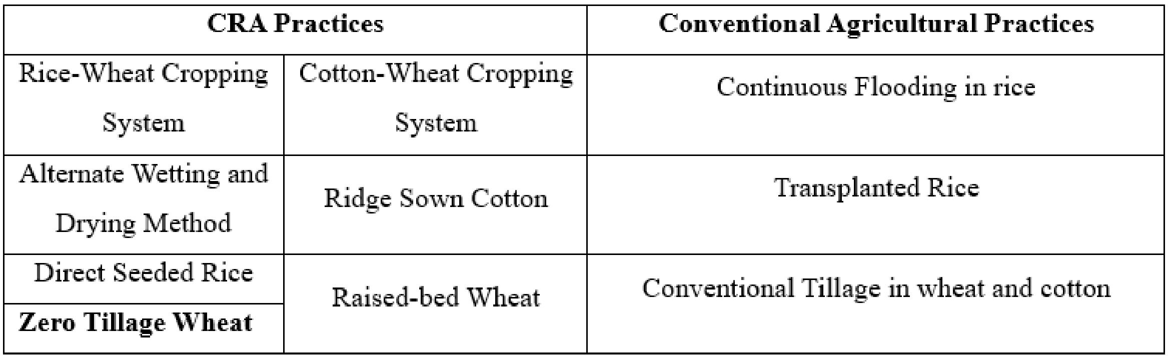
Data for this study is sourced from a combination of literature reviews. Literature review data was extracted from peer-reviewed articles, government reports, and existing agricultural studies conducted between 2015 and 2023.

### 2. Parameters of Study

The specific parameters analyzed in this study include:

i. **Water Saving:** Measured by the percentage reduction in water use compared to conventional practices.

ii. **Cost Efficiency:** Evaluated through the analysis of total costs, net profits, and benefit-cost ratios of agricultural practices.



| **CRA Practices** | | **Conventional Agricultural Practices** |
|---|---|---|
| Rice-Wheat Cropping System | Cotton-Wheat Cropping System | Continuous Flooding in rice |
| Alternate Wetting and Drying Method | Ridge Sown Cotton | Transplanted Rice |
| Direct Seeded Rice | Raised-bed Wheat | Conventional Tillage in wheat and cotton |
| **Zero Tillage Wheat** | | |

*Table 1: Comparison of Climate Resilient Agricultural Practices with Conventional Practices*

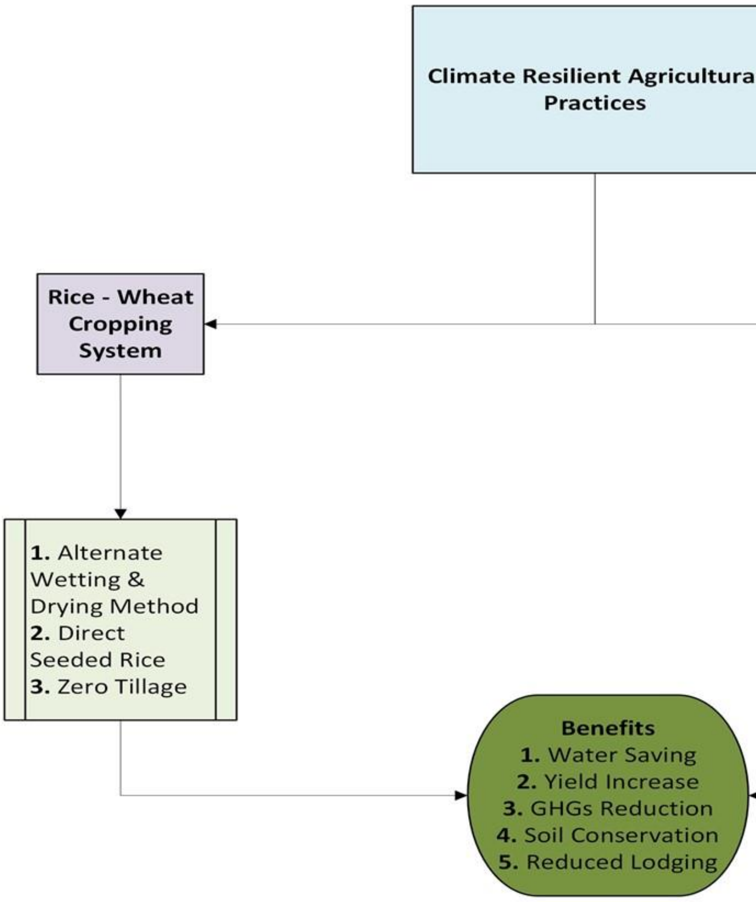


*Figure 1: Flowchart of Objective-1 Methodology*

## 3.2. Study design for crop area estimation of rice crop using random forest algorithm and GHGs Estimation using IPCC default emission factors

The accurate estimation of agricultural crop areas using satellite imagery and the quantification of greenhouse gas (GHG) emissions are crucial for understanding environmental impacts and aiding in sustainable agricultural planning. This methodology section outlines the detailed processes involved in estimating the rice crop area in Punjab, Pakistan, using machine learning techniques on Sentinel-2 imagery and subsequent GHG emission estimations using Intergovernmental Panel on Climate Change (IPCC) default emission factors.

## 1. Data Acquisition and Preprocessing

Satellite Imagery The research utilizes Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A data, which provides atmospherically corrected surface reflectance. The study period spans the Kharif cropping season, aligning with the rice growing period in Punjab.

Ground Truthing Data Ground truth data, essential for training and validating the classification model, was obtained from the Asian Development Bank's data portal. This dataset includes geolocated crop data, where rice is coded as '1' and non-rice crops as '2'.

NDVI Calculation The Normalized Difference Vegetation Index (NDVI) is calculated from the Sentinel-2 imagery to assess vegetation health and is defined as:

$$\text{NDVI} = \frac{(NIR-RED)(NIR+RED)}{(NIR+RED)(NIR-RED)}$$

where NIR represents the near-infrared band, and RED denotes the red band in the satellite data. The Normalized Difference Vegetation Index (NDVI) values range from -1 to 1, indicating various levels of vegetation biomass and health (Rouse et al., 1973).

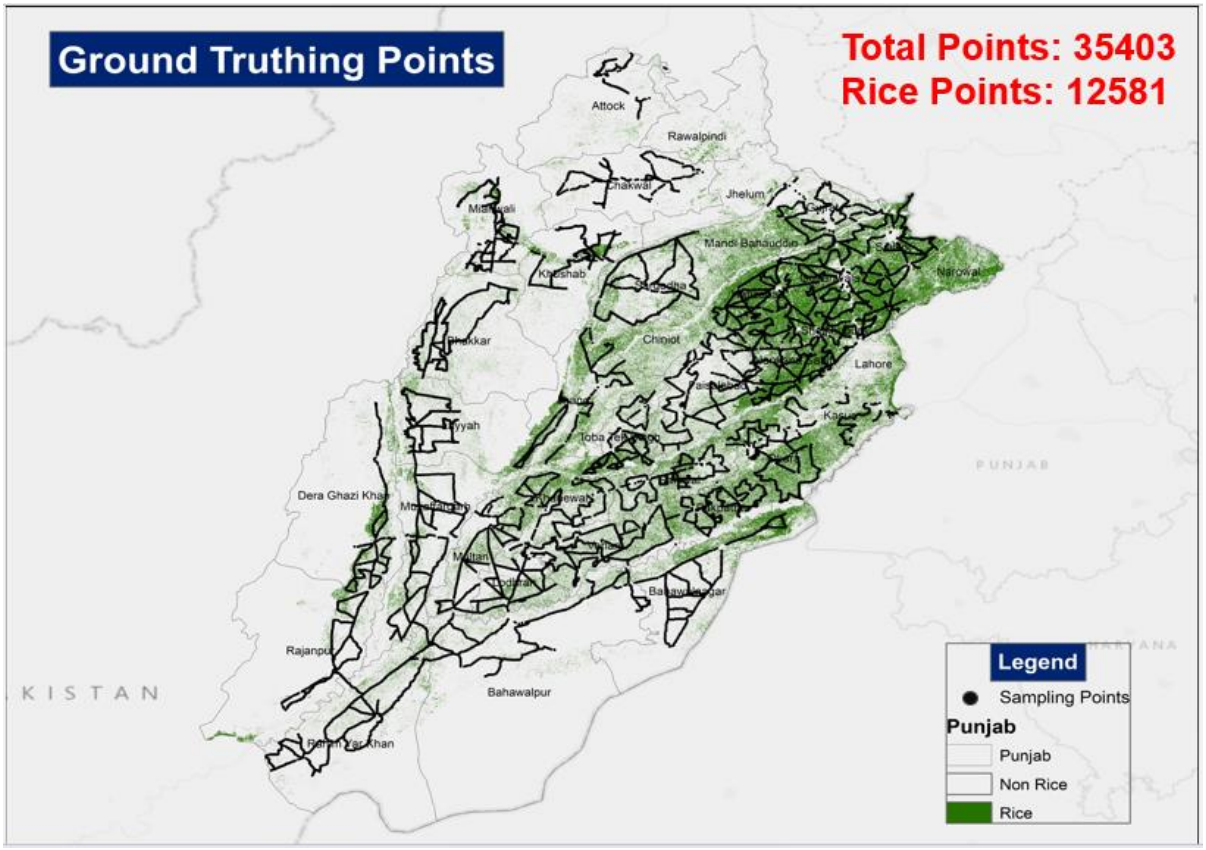


*Figure 2: Ground Truthing Points of Kharif Season*

## 2. Random Forest Classification

A random forest algorithm, implemented using Google Earth Engine's ee.Classifier.smileRandomForest() method, is employed to classify the satellite images into rice and non-rice crops based on NDVI values and other spectral signatures. Parameters for the classifier, such as the number of trees and max nodes, are optimized based on preliminary trials Khan et al., (2016).

Validation of the classification model is conducted using a subset of the ground truth data. Accuracy assessment metrics are derived through the creation of a confusion matrix, which includes calculations for overall accuracy, user accuracy, producer accuracy, and the Kappa coefficient. The mathematical representations are as follows:

### 3. Overall Accuracy

The overall accuracy of a classifier is calculated by adding the number of correct estimation and then dividing by the sunned predictions. This is represented as:

$$\text{Overall Accuracy} = \frac{\sum_{i=1}^{k} xii}{N}$$

Where:

- $xii$ is the number of correct predictions for class $ii$ (true positives for class $ii$),
- $N$ is the total number of predictions,
- $k$ is the number of classes.

### 4. User Accuracy (Precision)

Precision for each class is calculated by dividing the number of true positives by the total number of instances predicted as positive for that class, which includes both true positivesand false positives. It is expressed using the following formula

$$\text{User Accuracy (Precision)} = \frac{xii}{\sum_{j=1}^{k} xji}$$

Where:

- $xji$ is the number of instances classified as class $ii$ that are actually class $jj$.

### 5. Producer Accuracy (Recall)

Recall for each class is calculated by dividing the number of true positives by the total number of actual positives for that class, which includes both true positives and false negatives. The formula is represented as:

$$\text{Producer Accuracy (Recall)} = \frac{xii}{\sum_{j=1}^{k} xij}$$

Where:

- $xij$ is the number of instances that are actually class $ii$ but predicted as class $jj$.

## 6. Kappa Coefficient

The Kappa coefficient is a statistical measure used to evaluate the level of agreement between two raters for categorical items. Unlike simple percent agreement calculations, it provides a more robust assessment by accounting for the agreement that could occur by chance.

$$\text{Kappa Coefficient} = \frac{N\sum_{i=1}^{k} xii - \sum_{i=1}^{k}(\sum_{j=1}^{k} xji \ \sum_{j=1}^{k} xij)}{N2 - \sum_{i=1}^{k}(\sum_{j=1}^{k} xji \ \sum_{j=1}^{k} xij)}$$

Where:

- $N$ is the total number of observations,
- $xii$, $xji$, and $xij$ are as previously defined,
- $k$ is the number of categories.

These formulas collectively help evaluate different aspects of the accuracy and reliability of classification systems.

Finally the results were compared with the Crop Reporting Services department of Punjab.

## 7. GHG Emissions Estimation

### i. Methane Emissions

Using the area of rice fields classified by the random forest model, $CH_4$ emissions are estimate using the IPCC default emission factor for rice paddies in the specific region:

$$CH_4 \text{ emissions} = \text{Area(rice)} \times EF\,CH_4$$

### ii. Carbon Dioxide and Nitrous Oxide Emissions

Emissions from the application of fertilizers are calculated by:

$$CO_2 \text{ or } N_2O \text{ emissions} = \text{Area(rice)} \times \text{Fertilizer rate} \times EF\,CO_2/N_2O$$

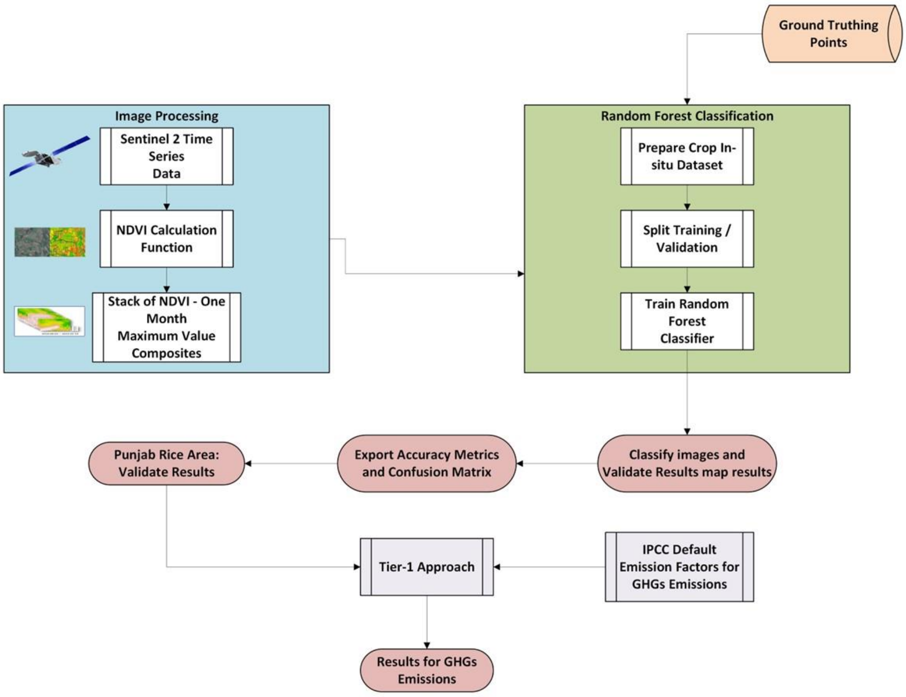


*Figure 3: Flowchart of Objective-2 Methodology*

## 3.3. Study design for Identifying suitable sowing dates for crops for optimum yield with respect to future climate shift scenarios

The methodology presented here is designed to identify the optimal sowing dates for wheat crops in the Multan, Nankana Sahib, and Sialkot districts of Pakistan to maximize yield in the context of anticipated climate shifts. This study integrates climate projections, crop modeling using the Decision Support System for Agrotechnology Transfer (DSSAT), and field data to develop adaptation strategies that mitigate the impacts of changing climate on wheat.

### 1. Study Area

The research focuses on three districts of Punjab, Pakistan:

- Multan – Southern Punjab
- Nankana Sahib – Northeast Punjab
- Sialkot – North Punjab

These regions are characterized by their distinct climatic patterns and agricultural practices, making them ideal for studying the impacts of climate variability on wheat.

### 2. Data Collection

### i. Weather Data

Historical and projected weather data from 1981 to 2022 have been obtained from NASA's POWER dataset, which provides solar and meteorological data tailored for agricultural and renewable energy applications (Stackhouse et al., 2018).

### ii. Soil Data

Soil characteristics are crucial for crop modeling and have been sourced from the ISRIC soil files for Pakistan. This dataset provides detailed information on soil profiles essential for simulating crop growth conditions (Batjes, 2016).

### iii. Crop Management Data

Data regarding planting dates, irrigation practices, fertilizer application, and other management practices have been collected through a phone call based survey of local farmers. This information is vital for accurately configuring the DSSAT model to reflect local agricultural practices. Crop management data of 15 farmers was collected, 5 farmers from each district. The number of farmers is limited due to mobility and logistic constraints.

### iv. Genotype Data

Genotypic data for the wheat varieties cultivated in the study area were collected from peer-reviewed literature. This data includes information on growth cycles, biomass accumulation, and yield potential necessary for the DSSAT model.

## 3. Crop Modeling with DSSAT

The DSSAT model, specifically the CERES-Wheat model, is used to simulate the growth and yield of wheat under varying climatic and management scenarios (Jones et al., 2003). The model is calibrated using the collected genotype, soil, and management data to reflect the specific conditions of the study areas. Seasonal Analysis file was generated with extension ".SNX". Fifteen seasonal files were generated each having the crop management practices of their own farmer, Weather data was acquired from NASA Power, including the parameters of Minimum temperature, maximum temperature, precipitation and solar radiation. Model was simulated for 40 years of period starting from 1982-2022.

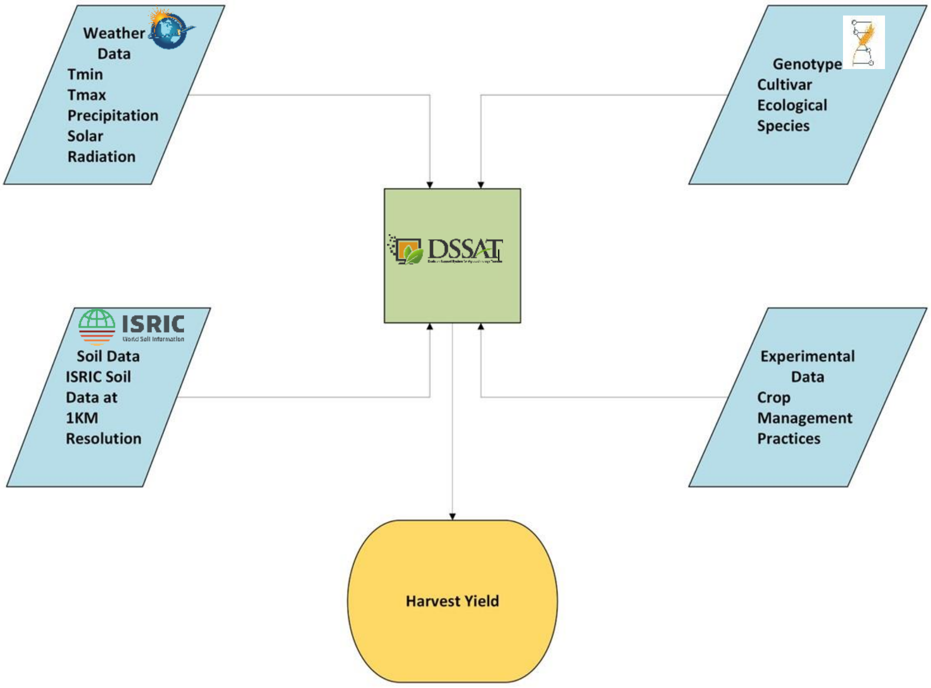


*Figure 4: Flowchart of Objective-3 Methodology*

### 3.3.4. Simulation Scenarios

i. **Baseline Scenario:** Using historical weather data to establish a reference yield for current sowing dates and practices.

ii. **Future Scenarios:** Simulations incorporate projected changes in temperature and precipitation to assess the impact on wheat yield. This projected change was acquired from peer reviewed research papers which state 2°C rise in temperature and 10% increase in precipitation based on Representative Concentration Pathways (RCPs) scenarios provided by the IPCC.

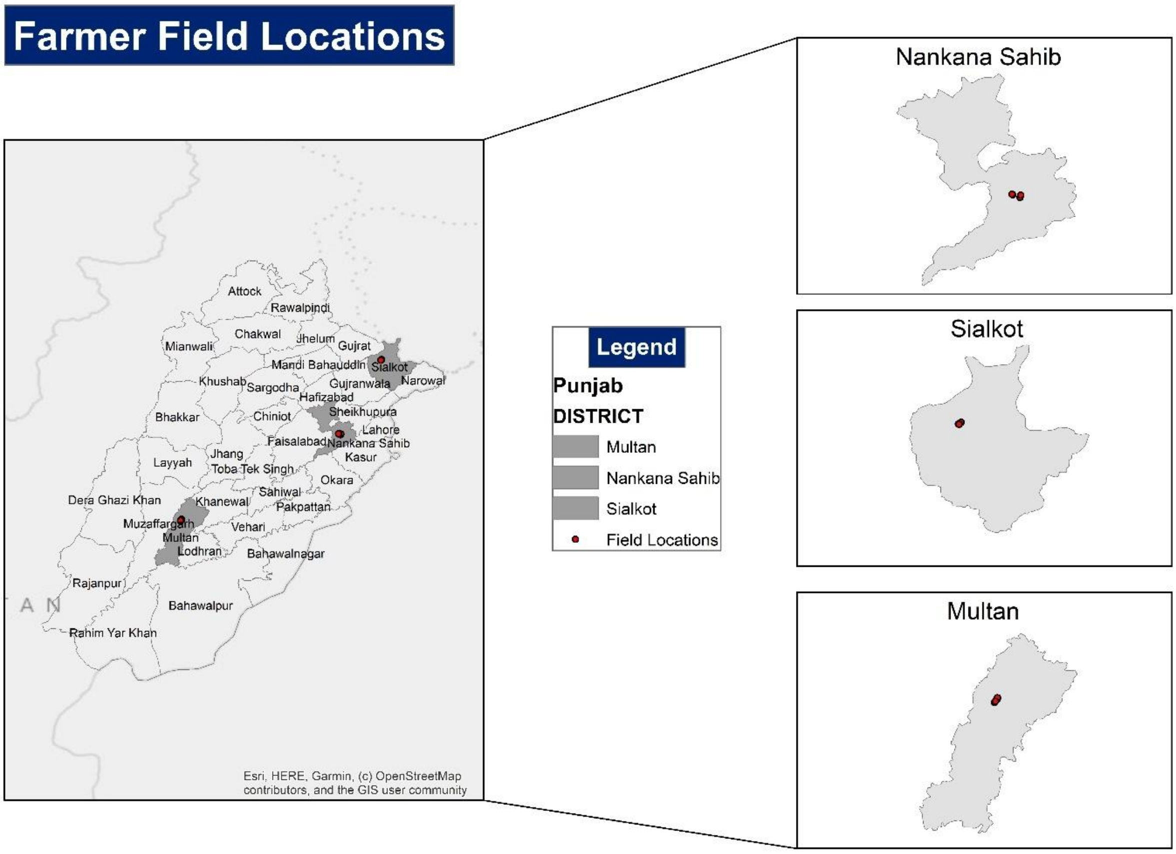


*Figure 5: Farmer Field Locations for Objective-3*

# CHAPTER 4

# 4. RESULTS

## 4.1. Rice-Wheat Cropping System

### 4.1.1. Alternate Wet-Dry Rice Production:

Alternate Wet-Dry (AWD) rice production, as conceptualized, is a strategic irrigation practice that alternates between flooding and drying periods in rice fields. This method is distinguished by its adaptability, with the duration of dry periods calibrated according to the crop development stage, soil type, and prevailing weather conditions, typically ranging from one to ten days. The essence of AWD lies in its water-efficient management, which not only ensures the rice crop's physiological needs are met but also optimizes water use, resulting in substantial water savings of 15-25% (IRRI, 2009).

The adoption of AWD practices translates into direct economic benefits for farmers, primarily through reduced water-related expenses, whether they be fees associated with water usage or costs incurred from pumping. Such savings are pivotal, especially in regions where water resources are scarce or where agricultural water usage significantly impacts farmers' operational costs. Moreover, AWD has a profound environmental impact, notably in its capacity to reduce methane emissions by 30-70%, depending on the specific AWD protocols implemented. This reduction in methane emissions is critical, considering the potent greenhouse effect of methane and its contribution to climate change (IRRI, 2009).

| | Conventional | CRA | %age change |
|---|---:|---:|---:|
| Total Revenue | 51,612 | 53,580 | 3.81% |
| Seed | 664 | 664 | |
| Fertilizer | 7,875 | 7,875 | |
| Machinery | 4,802 | 4,802 | |
| Other Variable costs | 2,407 | 2,407 | |
| Wages | 7,591 | 8,016 | |
| Fixed Costs | 7,718 | 5,790 | |
| Total Costs | 31,057 | 29,554 | -5% |
| Net Profit | 20,555 | 22,058 | 7% |

*Table 1: AWD vs Continuous Flooding*

Table 2 provides a quantitative comparison of the economic outcomes associated with rice cultivation under traditional methods versus those under the AWD system. Notably, the total revenue increased by 3.18%, indicating that the shift to AWD does not adversely affect the gross income from rice production. This stability in revenue is crucial, underscoring that water-saving practices do not compromise yield or market value.

The detailed cost analysis reveals a 5% reduction in total costs when transitioning to AWD practices, primarily driven by a notable decrease in fixed costs from 7,718 PKR to 5,790 PKR. This reduction suggests that AWD practices may lead to more efficient resource utilization and possibly lower investment in irrigation infrastructure or less dependency on continuous water supply systems. Conversely, wages show a slight increase, potentially reflecting the labor costs associated with managing the alternating wet and dry cycles, albeit this increase is offset by the overall reduction in other production costs.

The net profit analysis underscores the economic viability of AWD, with a 7% increase in net profit under the AWD system. This enhancement of profitability, in conjunction with the environmental benefits of reduced methane emissions, positions AWD as a sustainable and economically advantageous rice production strategy.

### 4.1.2. Direct Seeded Rice (DSR) Practice:

The DSR practice, which involves sowing seeds directly into the soil before the presence of soil moisture, marks a significant shift from conventional transplantation methods. DSR is beneficial for the regions which receive erratic rainfall leading to uncertainty in irrigation. The Government of Pakistan (2017) reports that DSR can lead to a 15-20% reduction in water usage and results in 20-25% higher plant populations compared to traditional transplantation, ultimately leading to enhanced productivity.

| | Conventional | CRA | %age change |
|---|---:|---:|---:|
| Total Revenue | 51,612 | 59,354 | 15% |
| Seed | 664 | 1,328 | |
| Fertilizer | 7,875 | 8,415 | |
| Machinery | 4,802 | 8,715 | |
| Other Variable costs | 2,407 | 1,411 | |
| Wages | 7,591 | 6,273 | |
| Fixed Costs | 7,719 | 6,175 | |
| Total Costs | 31,058 | 32,317 | 4% |
| Net Profit | 20,554 | 27,037 | 32% |

*Table 2: DSR vs Transplanting*

Table 3 presents a comparative analysis of the Direct Seed Rice Cropping System "with project" (implementation of DSR practice) versus "without project" (conventional practices). Key findings include:

i. **Total Revenue Increase:** The adoption of DSR practices led to a 15% increase in total revenue, highlighting the productivity benefits of DSR over conventional methods.
ii. **Investment in Seeds:** The cost associated with seeds doubled, reflecting the direct seeding approach's requirement for a higher seed rate.
iii. **Fertilizer and Machinery Costs:** Slight increases in fertilizer and machinery costs indicate the need for additional inputs and mechanization in DSR practices.
iv. **Reduction in Other Variable Costs and Wages:** Notably, other variable costs and wages decreased, suggesting that DSR can lead to labor savings and more efficient use of resources.
v. **Overall Cost and Net Profit:** While total costs saw a modest 4% increase, the net profit experienced a significant 32% boost with the adoption of DSR practices. This demonstrates the economic viability of DSR in enhancing farmer income through improved efficiency and productivity.

#### 4.1.3. Zero Tillage:

In the pursuit of sustainable agriculture and the betterment of rice-wheat farming systems, the adoption of zero-till wheat practice stands out as a transformative approach. This technique, characterized by the direct sowing of wheat seeds into untilled soil, leverages the residue moisture from the preceding rice harvest. Utilizing a zero-till seed drill, farmers can plant wheat amidst rice stubble without any prior land preparation, thereby streamlining the process into a single tractor operation.

i. **Cost Savings and Efficiency:** The zero-till method markedly reduces the need for extensive labor and machinery traditionally required for land preparation. This efficiency not only cuts down operational costs but also shortens the turnaround time between rice harvest and wheat sowing. Consequently, farmers can capitalize on optimal planting windows, enhancing wheat germination and establishment.
ii. **Soil and Water Stewardship:** By avoiding soil tillage, zero-till farming helps in preserving the soil structure and enhancing its health over time. The maintenance of soil integrity reduces erosion and improves water retention capabilities, which are crucial for crop sustenance. Moreover, the practice aids in incrementally enriching the

soil with organic matter, thanks to the undisturbed decomposition of rice stubble left in the field.

iii. **Climate Change Mitigation:** Traditional rice-wheat cropping systems often entail the burning of rice residue, contributing significantly to greenhouse gas emissions and air pollution. Zero-till wheat farming circumvents the need for stubble burning, directly addressing this environmental concern. By incorporating rice residues back into the earth, it fosters a carbon sequestration process, thereby mitigating the adverse impacts of agricultural practices on climate change.

iv. **Yield Enhancement and Economic Gains:** The adoption of zero-till practices has been empirically linked to increases in wheat yield. This uptick can be attributed to improved soil conditions, better moisture retention, and timely planting—all conducive factors for wheat growth. The resultant economic gains are substantial, as delineated by the comparative financial outcomes presented in Table 2.

| | Conventional | CRA | %age change |
|---|---:|---:|:---:|
| Total Revenue | 50,311 | 57,858 | 15% |
| Seed | 2,034 | 2,034 | |
| Fertilizer | 6,705 | 6,705 | |
| Machinery | 5,851 | 4,414 | |
| Wages | 3,995 | 3,995 | |
| Fixed Costs | 3,327 | 2,662 | |
| Total Costs | 21,912 | 19,810 | -10% |
| Net Profit | 28,399 | 38,048 | 34% |

*Table 3: Zero Tillage vs Deep Tillage*

Table 4: Economic Impact of Zero-till Wheat Practice meticulously illustrates the financial ramifications of adopting zero-till wheat farming. Here's a more detailed analysis:

Total Revenue: A notable increase of 15% in total revenue was observed for farms implementing zero-till practices. This uplift is indicative of higher yield potentials and, possibly, better-quality wheat grain, which can command higher market prices.

v. **Operational Costs:** The analysis showcases a strategic reduction in operational expenses, particularly in machinery costs, which decreased due to the diminished reliance on conventional tilling equipment. The overall cost savings of 10% underscore the economic efficiency of the zero-till approach.

vi. **Fixed Costs:** A reduction in fixed costs further accentuates the cost-effectiveness of zero-till wheat farming. By minimizing soil disturbance, there's less wear and tear on farming equipment, leading to lower maintenance and replacement expenses.

vii. **Net Profit:** Perhaps the most compelling outcome is the 34% surge in net profit for farms adopting zero-till practices. This significant enhancement in profitability is a direct testament to the method's ability to optimize resource use, reduce operational costs, and improve yield quality and quantity.

## 4.2. Cotton-Wheat Cropping System

### 4.2.1. Ridge Sown Cotton

Ridge Planning Cotton involves the strategic creation of ridges or raised beds, which fundamentally alters the irrigation dynamics within cotton fields. This innovative approach restricts surface irrigation to the furrows between the ridges or beds, substantially reducing water requirements by 20-30%. The efficiency gained through this targeted irrigation method directly translates into significant cost savings, particularly in groundwater-dependent regions, where water use fees or pumping costs can be curtailed by up to 40% (Government of Sindh, 2017; Majeed et al., 2015). Moreover, the structural advantage of raised beds facilitates enhanced nitrogen uptake efficiency, reported at an impressive 15-20%. This not only implies a more efficient utilization of fertilizers but also contributes to the overall health and growth vigor of the cotton plants. The agronomic benefits extend to crop productivity, with research indicating a productivity increase of up to 15% in raised bed wheat production and 10% for cotton planted on ridges. Such productivity gains are particularly pertinent in areas prone to waterlogging or localized flooding, where traditional flat planting methods would otherwise result in sub-optimal crop outcomes (Government of Sindh, 2017; Majeed et al., 2015).

| | Conventional | CRA | %age change |
|---|---|---|---|
| Total Revenue | 74,250 | 81,675 | 15% |
| Seed | 1,328 | 1,328 | |
| Fertilizer | 16,026 | 16,026 | |
| Machinery | 5,636 | 7,036 | |
| Wages | 15,194 | 16,193 | |
| Fixed Costs | 7,719 | 6,561 | |

| | | | |
|---|---|---|---|
| Total Costs | 45,903 | 47,144 | 3% |
| Net Profit | 28,347 | 34,531 | 22% |

*Table 4: Ridge Sown Cotton VS Flat Sown Cotton*

Table 5 encapsulates the economic impact of adopting ridge sowing in cotton cultivation, contrasting the outcomes with and without the project's implementation:

i. **Total Revenue Increase:** The transition to ridge sowing manifests in a notable 15% increase in total revenue, rising from 74,250 units to 81,675 units. This uplift in revenue underscores the enhanced productivity and, potentially, the quality improvements attributable to ridge sowing practices.

ii. **Cost Implications:** Despite the static costs for seeds and fertilizers, machinery and wage expenses witnessed marginal increases, indicative of the initial investments and labor required for ridge construction and maintenance. However, the overall total costs saw a modest increase of 3%, from 45,903 units to 47,144 units.

iii. **Net Profit Growth:** Crucially, the net profit realized a significant 22% surge, from 28,347 units to 34,531 units. This underlines the economic viability of ridge sowing cotton, where the incremental costs are comfortably outweighed by the revenue gains, resulting in a substantial net benefit to the cultivators.

### 4.2.2. Raised Bed Planting of Wheat:

Raised bed planting offers numerous agronomic benefits, contributing to its widespread adoption among wheat farmers. The method allows for optimal plant spacing and density, leading to better plant stands and reduced lodging. This spatial arrangement not only enhances the physiological efficiency of wheat plants but also improves water management by facilitating targeted irrigation, which is particularly beneficial in arid and semi-arid regions where water scarcity is a prevalent challenge. Moreover, the raised bed structure provides an excellent opportunity for pre-planting weed control, either through pre-irrigation measures or mechanical means, thus reducing reliance on herbicides and making manual weeding and rouging more manageable (Govt. of Sindh, 2017; Majeed, 2015; PCRWR).

The adoption of raised bed planting has been associated with significant economic returns and yield improvements. Yield increases of 15-30% have been observed, alongside water savings of 20-50%. Such efficiency gains not only enhance the sustainability of wheat production but also translate into substantial economic benefits for farmers, with reports indicating up to a 29% increase in economic returns from adopting this new system. The rationale behind these improvements includes lower wheat seed rates due to precise sowing, enhanced irrigation management, and improved weed control measures (Govt. of Sindh, 2017; Majeed, 2015; PCRWR).

|  | Conventional | CRA | %age change |
|---|---|---|---|
| Total Revenue | 50,311 | 57,857 | 15% |
| Seed | 2,034 | 2,034 |  |
| Fertilizer | 6,705 | 6,705 |  |
| Machinery | 5,851 | 7,285 |  |
| Wages | 3,995 | 3,995 |  |
| Fixed Costs | 3,327 | 2,661 |  |
| Total Costs | 21,912 | 22,680 | 4% |
| Net Profit | 28,399 | 35,177 | 24% |

*Table 5: Raised-bed Wheat Planting vs Broadcasting*

Table 6 shows a comparative analysis illustrating the economic impact of adopting raised bed planting for wheat cultivation:

i. **Revenue Increase:** The transition to raised bed planting results in a 15% increase in total revenue, from 50,311 units without the project to 57,857 units with the project implementation. This revenue uplift reflects the yield enhancement attributable to the practice.

ii. **Cost Implications:** Despite unchanged costs for seeds and fertilizers, there is a noticeable increase in machinery costs, which may reflect the initial investment in bed planting equipment. However, the overall total costs witness a modest increase of 4%, from 21,912 units to 22,680 units.

iii. **Net Profit Growth:** The net profit showcases a significant 24% increase, underscoring the economic viability of raised bed planting in wheat cultivation, from 28,399 units to 35,177 units.

## 4.3. Rice Crop Area Estimation

The Random Forest algorithm was applied to estimate the rice crop area in Punjab, Pakistan for the 2023-24 growing season. The results obtained using the Random Forest algorithm were compared with estimates from the Crop Reporting Service (CRS). The detailed comparison is shown in Table.

The Random Forest algorithm, utilizing Sentinel-2 imagery and ground truth data, estimated a total rice crop area of 2,703,586 hectares, which was slightly higher than the CRS estimate of 2,604,858 hectares. The remote sensing rice area is 3.79% more than the CRS Punjab rice area.

### 4.3.1. Greenhouse Gas (GHG) Emissions Estimation

The GHG emissions were estimated based on the rice crop area estimated by the Random Forest algorithm. Methane ($CH_4$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$) emissions were quantified using IPCC default emission factors.

Key findings from the rice crop area estimation include:

The top five districts with the largest estimated rice areas according to the Random Forest algorithm were:

**i.** Gujranwala: 200,493 ha
**ii.** Okara: 170,383 ha
**iii.** Sheikhupura: 163,032 ha
**iv.** Jhang: 153,902 ha
**v.** Nankana Sahib: 146,585 ha

Some districts showed significant differences between CRS and Random Forest estimates. For example:

**i.** Gujranwala: CRS (261,134 ha) vs. Random Forest (200,493 ha)
**ii.** Sheikhupura: CRS (253,846 ha) vs. Random Forest (163,032 ha)
**iii.** Faisalabad: CRS (47,368 ha) vs. Random Forest (98,946 ha

Using the IPCC default emission factors, the study estimated methane ($CH_4$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$) emissions for each district based on the Random Forest area estimates.

#### 4.3.1.1.Methane Emissions

The total estimated methane emissions from rice cultivation in Punjab were 252.79 Giga grams. The top five districts with the highest methane emissions were:

**i.** Gujranwala: 18.75 Gg
**ii.** Okara: 15.93 Gg
**iii.** Sheikhupura: 15.24 Gg
**iv.** Jhang: 14.39 Gg
**v.** Nankana Sahib: 13.71 Gg

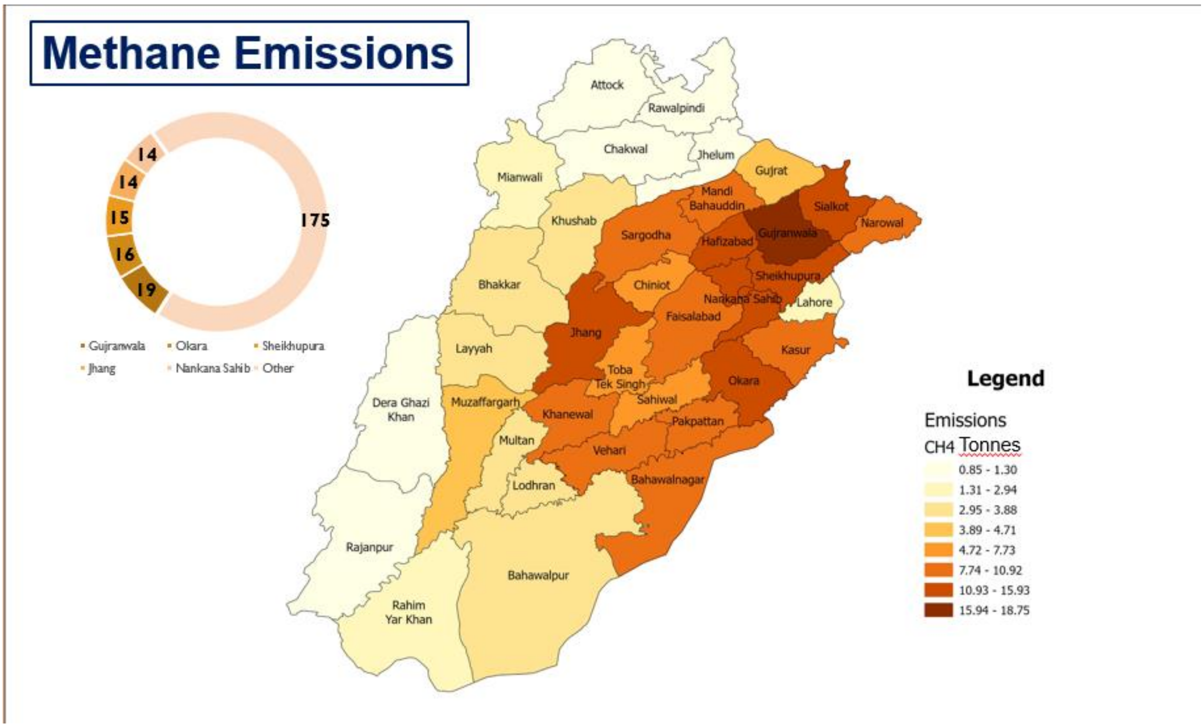


*Figure 6: Methane Emissions from Punjab Rice Fields*

#### 4.3.1.2.Nitrous Oxide Emissions

The total estimated nitrous oxide emissions were 1,001.68 Giga grams. The top five emitting districts were:

**i.** Gujranwala: 74.28 Gg
**ii.** Okara: 63.13 Gg
**iii.** Sheikhupura: 60.40 Gg
**iv.** Jhang: 57.02 Gg
**v.** Nankana Sahib: 54.31 Gg

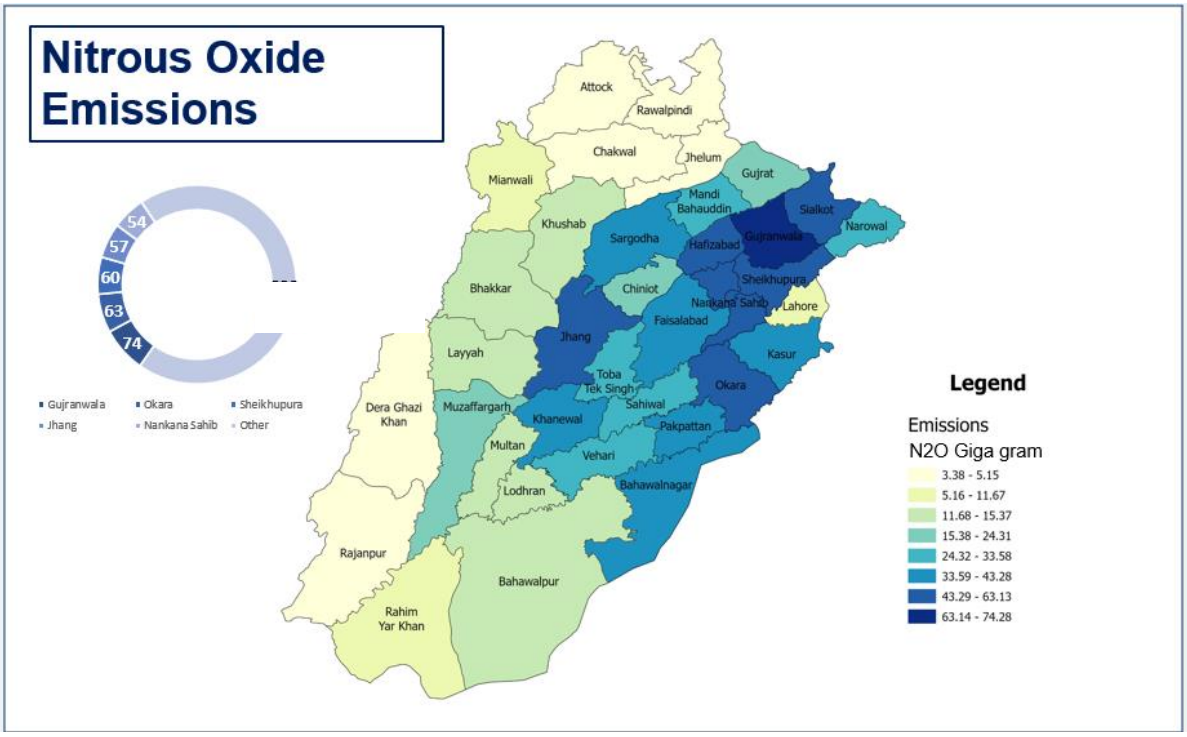


*Figure 7: Nitrous Oxide Emissions from Punjab Rice Fields*

### 4.3.1.3.Carbon Dioxide Emissions

The total estimated carbon dioxide emissions from rice cultivation were 428,495.85 tonnes. The top five emitting districts were:

**i.** Gujranwala: 31,776.47 tons
**ii.** Okara: 27,004.29 tons
**iii.** Sheikhupura: 25,839.21 tons
**iv.** Jhang: 24,392.18 tons
**v.** Nankana Sahib: 23,232.50 tons

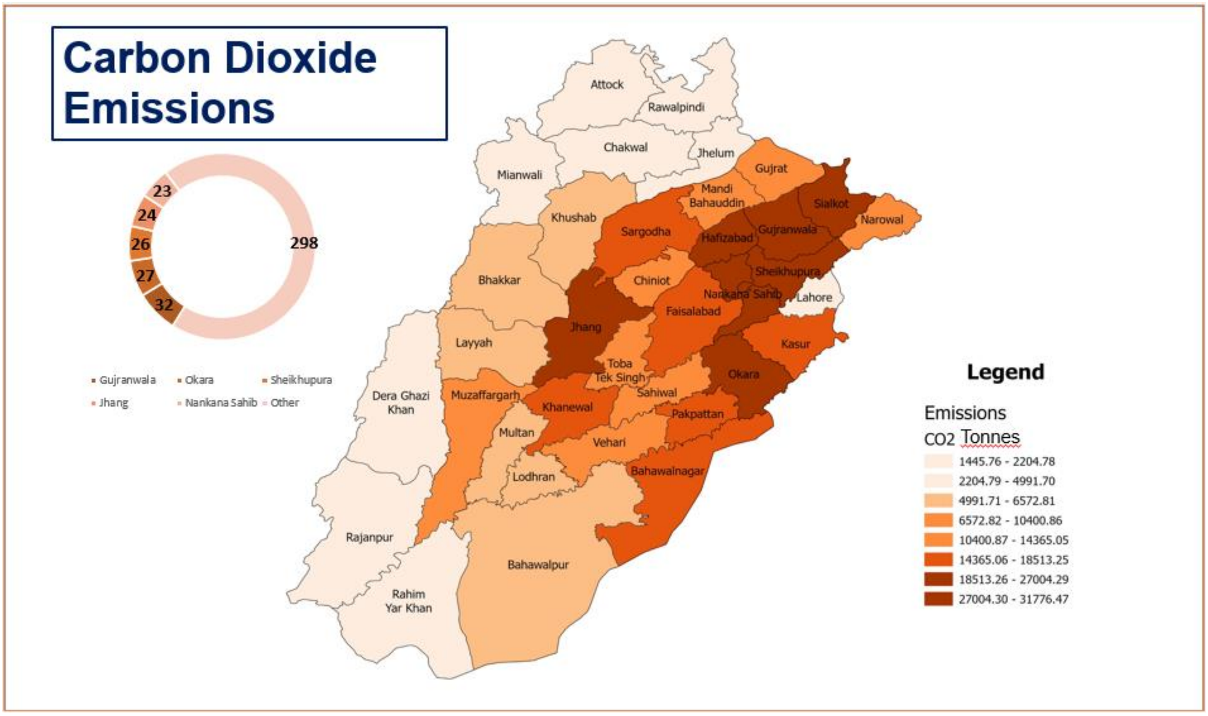


*Figure 8: Carbon Dioxide Emissions from Punjab Rice Fields*

These results highlight the spatial variability of rice cultivation and associated greenhouse gas emissions across Punjab, providing crucial information for targeted mitigation strategies and agricultural planning.

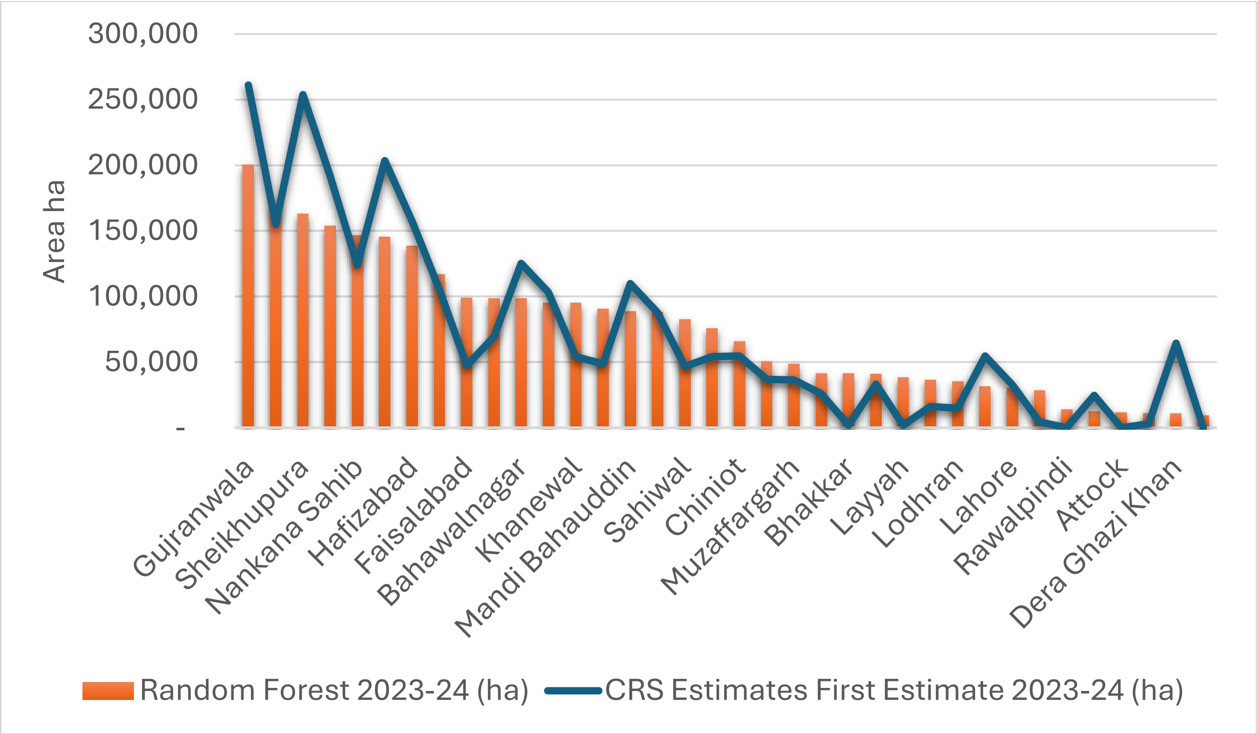


*Figure 9: District-Wise Remote Sensing Rice Estimated Area Vs Crop Reporting Services Area*

| Sr | Districts | CRS Estimates First Estimate 2023-24 (ha) | Random Forest 2023-24 (ha) | Methane Emissions (Giga gram) | Nitrous Oxide Emissions (Giga gram) | Carbon Dioxide Emissions (Tonnes) |
|---|---|---|---|---|---|---|
| 1. | Gujranwala | 261,134 | 200,493 | 18.75 | 74.28 | 31,776.47 |
| 2. | Okara | 155,061 | 170,383 | 15.93 | 63.13 | 27,004.29 |
| 3. | Sheikhupura | 253,846 | 163,032 | 15.24 | 60.40 | 25,839.21 |
| 4. | Jhang | 191,903 | 153,902 | 14.39 | 57.02 | 24,392.18 |
| 5. | Nankana Sahib | 123,887 | 146,585 | 13.71 | 54.31 | 23,232.50 |
| 6. | Sialkot | 203,644 | 145,347 | 13.59 | 53.85 | 23,036.29 |
| 7. | Hafizabad | 157,490 | 138,385 | 12.94 | 51.27 | 21,932.87 |
| 8. | Kasur | 105,668 | 116,809 | 10.92 | 43.28 | 18,513.25 |
| 9. | Faisalabad | 47,368 | 98,946 | 9.25 | 36.66 | 15,682.12 |
| 10. | Sargodha | 69,231 | 98,556 | 9.21 | 36.51 | 15,620.30 |
| 11. | Bahawalnagar | 125,101 | 98,507 | 9.21 | 36.50 | 15,612.54 |
| 12. | Pakpattan | 103,239 | 95,144 | 8.90 | 35.25 | 15,079.53 |
| 13. | Khanewal | 54,251 | 94,939 | 8.88 | 35.17 | 15,047.04 |
| 14. | Vehari | 48,583 | 90,636 | 8.47 | 33.58 | 14,365.05 |
| 15. | Mandi Bahauddin | 109,717 | 88,735 | 8.30 | 32.88 | 14,063.76 |
| 16. | Narowal | 87,854 | 88,388 | 8.26 | 32.75 | 14,008.76 |
| 17. | Sahiwal | 46,559 | 82,668 | 7.73 | 30.63 | 13,102.19 |
| 18. | Toba Tek Singh | 54,251 | 75,753 | 7.08 | 28.07 | 12,006.22 |
| 19. | Chiniot | 54,656 | 65,624 | 6.14 | 24.31 | 10,400.86 |
| 20. | Gujrat | 36,842 | 50,420 | 4.71 | 18.68 | 7,991.15 |
| 21. | Muzaffargarh | 36,437 | 48,682 | 4.55 | 18.04 | 7,715.69 |
| 22. | Khushab | 25,911 | 41,471 | 3.88 | 15.37 | 6,572.81 |
| 23. | Bhakkar | 2,024 | 41,165 | 3.85 | 15.25 | 6,524.31 |
| 24. | Multan | 33,198 | 40,827 | 3.82 | 15.13 | 6,470.74 |
| 25. | Layyah | 2,024 | 38,149 | 3.57 | 14.13 | 6,046.30 |
| 26. | Bahawalpur | 16,194 | 36,212 | 3.39 | 13.42 | 5,739.30 |
| 27. | Lodhran | 14,980 | 35,223 | 3.29 | 13.05 | 5,582.55 |
| 28. | Rahim Yar Khan | 54,656 | 31,495 | 2.94 | 11.67 | 4,991.70 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 29. | Lahore | 32,794 | 30,179 | 2.82 | 11.18 | 4,783.12 |
| 30. | Mianwali | 4,453 | 28,258 | 2.64 | 10.47 | 4,478.66 |
| 31. | Rawalpindi | - | 13,911 | 1.30 | 5.15 | 2,204.78 |
| 32. | Rajanpur | 24,696 | 12,373 | 1.16 | 4.58 | 1,961.02 |
| 33. | Attock | - | 11,625 | 1.09 | 4.31 | 1,842.47 |
| 34. | Jhelum | 2,834 | 10,918 | 1.02 | 4.05 | 1,730.41 |
| 35. | Dera Ghazi Khan | 64,372 | 10,724 | 1.00 | 3.97 | 1,699.66 |
| 36. | Chakwal | - | 9,122 | 0.85 | 3.38 | 1,445.76 |
| | Total | 2,604,858 | 2,703,586 | 252.79 | 1,001.68 | 428,495.85 |

*Table 6: Comparison of District-Wise Rice Area Estimates*

### 4.3.2. Accuracy of the Random Forest Algorithm

The confusion metrics of the Random Forest algorithm used for rice crop classification is shown in Table 8.

| Confusion Matrix | Accuracy |
|---|---|
| Overall Accuracy | 95% |
| Rice Producer Accuracy | 96% |
| Non-Rice Producer Accuracy | 92% |
| Rice User Accuracy | 96% |
| Non-Rice User Accuracy | 94% |

*Table 7: Confusion Matrix of Remote Sensing Rice Area Estimates of Punjab*

The overall accuracy of the Random Forest algorithm was 95%, with high producer and user accuracies for both rice and non-rice classifications. These metrics demonstrate the effectiveness of the Random Forest algorithm in accurately identifying rice crop areas.

## 4.4. Optimum Sowing Dates for Wheat Crop under Future Climate Scenarios

The purpose of this objective is to determine the optimum sowing date for wheat in Multan, Nankana Sahib, and Sialkot by analyzing the effects of varying sowing dates, temperature and precipitation changes on crop yield using the DSSAT model. The treatments included changes in temperature with a rise of 1.0°C and 1.5 °C combined with varying sowing dates ranging from 25 days earlier to 25 days later than the baseline sowing date.

| Treatment for 1.5 °C Rise | Treatment for Sowing Dates | Treatment for 1°C Rise | Treatment for 1°C and Precipitation Rise |
|---|---|---|---|
| Control | Control | Temp-1+Precip | Temp-1.5+Precip |
| Temp-1.5 - +25Day | +25Day | Temp-1+Precip+25 Day | Temp-1.5+Precip+25Day |
| Temp-1.5 - +20Day | +20Day | Temp-1+Precip+20 Day | Temp-1.5+Precip+20Day |
| Temp-1.5 - +18Day | +18Day | Temp-1+Precip+18 Day | Temp-1.5+Precip+18Day |
| Temp-1.5 - +16Day | +16Day | Temp-1+Precip+16 Day | Temp-1.5+Precip+16Day |
| Temp-1.5 - +14Day | +14Day | Temp-1+Precip+14 Day | Temp-1.5+Precip+14Day |
| Temp-1.5 - +12Day | +12Day | Temp-1+Precip+12 Day | Temp-1.5+Precip+12Day |
| Temp-1.5 - +10Day | +10Day | Temp-1+Precip+10 Day | Temp-1.5+Precip+10Day |
| Temp-1.5 - +8Day | +8Day | Temp-1+Precip+8 Day | Temp-1.5+Precip+8Day |
| Temp-1.5 - +6Day | +6Day | Temp-1+Precip+6 Day | Temp-1.5+Precip+6Day |
| Temp-1.5 - +4Day | +4Day | Temp-1+Precip+4 Day | Temp-1.5+Precip+4Day |
| Temp-1.5 - +2Day | +2Day | Temp-1+Precip+2 Day | Temp-1.5+Precip+2Day |

| | | | |
|---|---|---|---|
| Temp-1.5 - -2Day | -2Day | Temp-1+Precip-2 Day | Temp-1.5+Precip-2Day |
| Temp-1.5 - -4Day | -4Day | Temp-1+Precip-4 Day | Temp-1.5+Precip-4Day |
| Temp-1.5 - -6Day | -6Day | Temp-1+Precip-6 Day | Temp-1.5+Precip-6Day |
| Temp-1.5 - -8Day | -8Day | Temp-1+Precip-8 Day | Temp-1.5+Precip-8Day |
| Temp-1.5 - -10Day | -10Day | Temp-1+Precip-10 Day | Temp-1.5+Precip-10Day |
| Temp-1.5 - -12Day | -12Day | Temp-1+Precip-12 Day | Temp-1.5+Precip-12Day |
| Temp-1.5 - -14Day | -14Day | Temp-1+Precip-14 Day | Temp-1.5+Precip-14Day |
| Temp-1.5 - -16Day | -16Day | Temp-1+Precip-16 Day | Temp-1.5+Precip-16Day |
| Temp-1.5 - -18Day | -18Day | Temp-1+Precip-18 Day | Temp-1.5+Precip-18Day |
| Temp-1.5 - -20Day | -20Day | Temp-1+Precip-20 Day | Temp-1.5+Precip-20Day |
| Temp-1.5 - -25Day | -25Day | Temp-1+Precip-25 Day | Temp-1.5+Precip-25Day |

*Table 8: Treatments for Sowing Date Optimization of Wheat Crop in Punjab*

### 4.4.1. Effect of Temperature Rise and Sowing Date Shifts on Wheat Yield

The results of our simulations demonstrate a clear relationship between sowing dates, temperature changes, and wheat yield across the three study districts. As shown in the provided graphs, the optimal sowing dates varied depending on the magnitude of temperature increase and precipitation changes.

#### i. Multan District

In Multan, under a 1°C temperature rise scenario, the optimal sowing date shifted to approximately 10 days delayed than the current practice. This is indicated by the red marker on the graph, which shows the highest yield point. When considering a 1.5°C temperature increase, the optimal sowing date moved even delayed, to about 14 days before the current sowing-date.

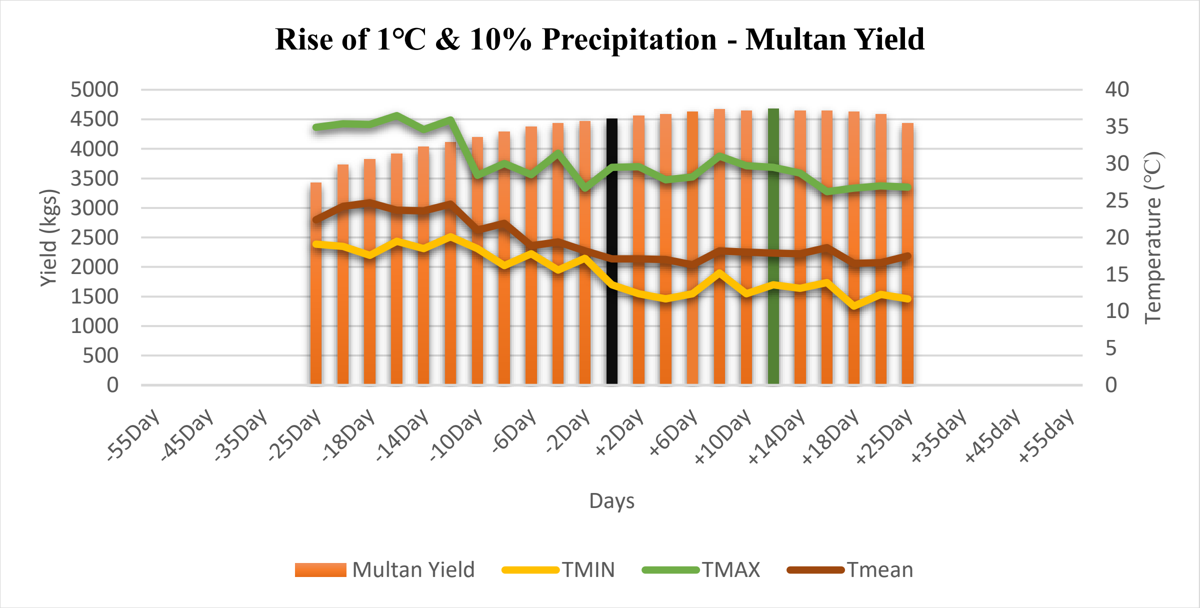


*Figure 10: Effect of 1°C & 10% Precipitation Rise in Multan*

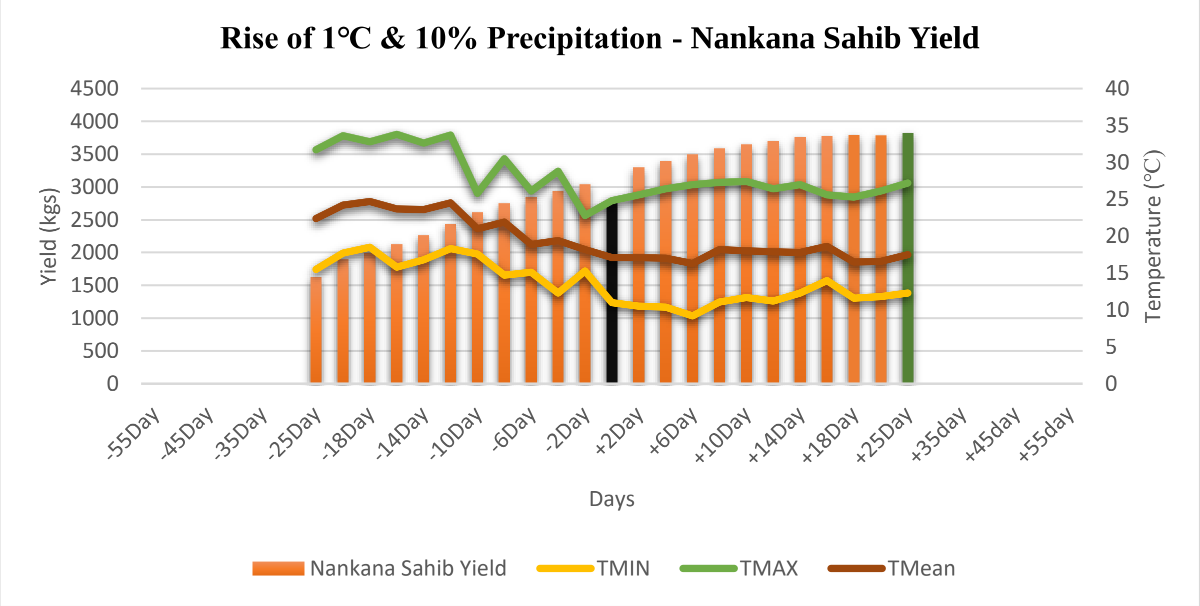


*Figure 11: Effect of 1°C & 10% Precipitation Rise in Nankana Sahib*

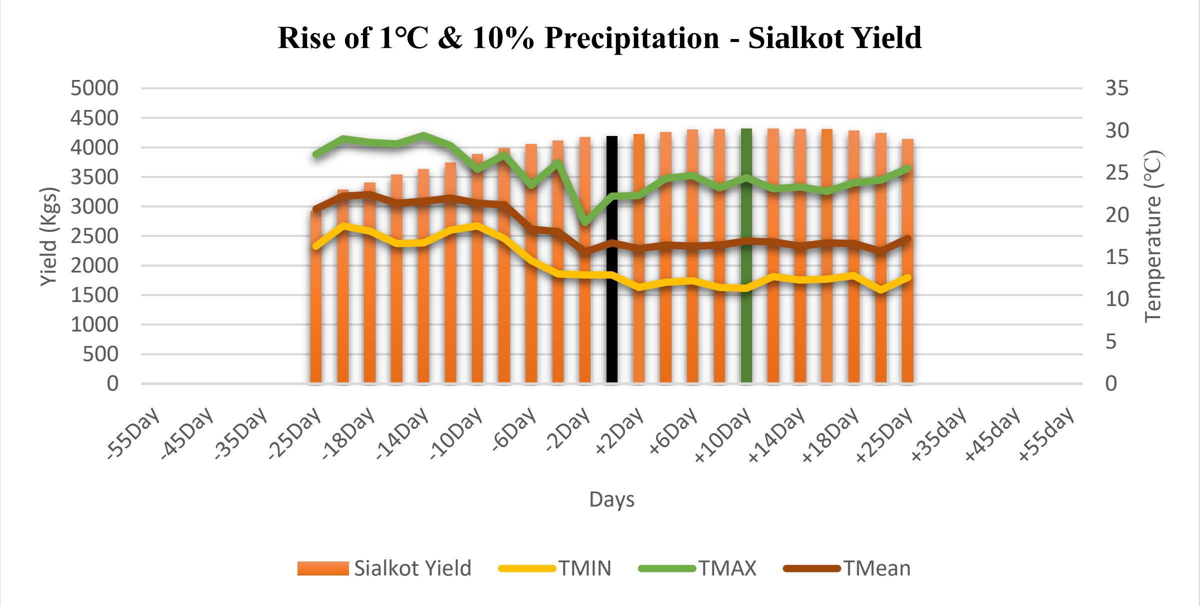


*Figure 12: Effect of 1°C & 10% Precipitation Rise in Sialkot*

These findings suggest that as temperatures rise, delayed sowing becomes more beneficial for wheat crops in Multan. This could be attributed to the crops taking advantage of cooler delayed-season temperatures and completing their growth cycle before the onset of extreme heat during the grain-filling stage.

### ii. Nankana Sahib District

The results for Nankana Sahib show a similar trend, but with some distinct differences. Under a 1°C temperature rise, the optimal sowing date was found to be about 25 days delayed than the baseline that was 4 November. For the 1.5°C increase scenario, the best yields were achieved when sowing occurred approximately 20 days delayed.

The smaller shift in optimal sowing dates compared to Multan could be due to Nankana Sahib's slightly different climatic conditions, possibly including higher rainfall or lower baseline temperatures.

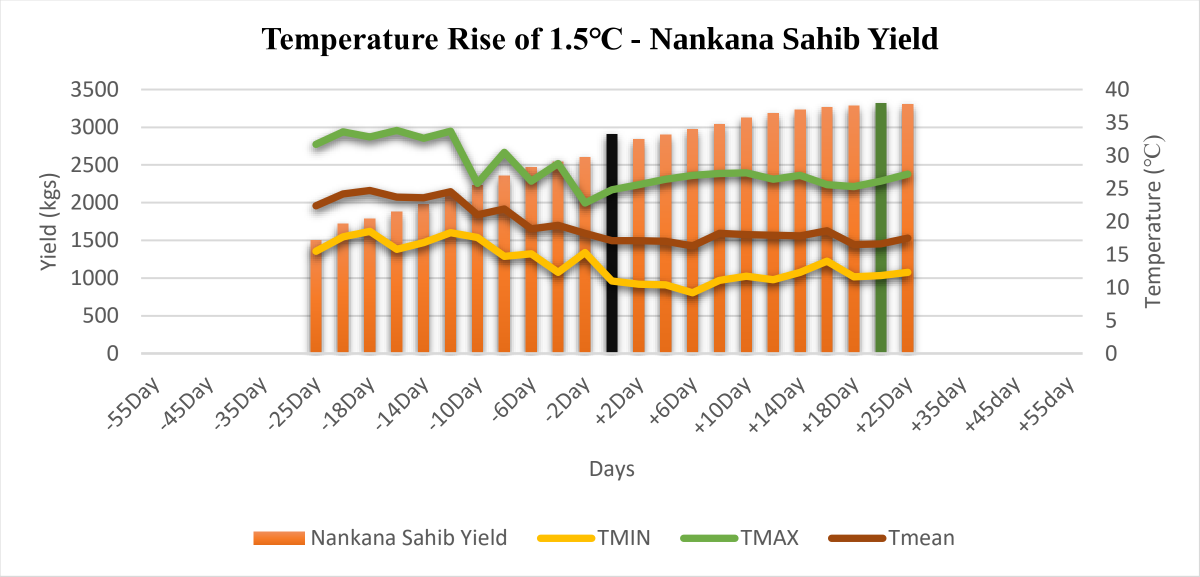


*Figure 13: Effect of 1.5℃ Rise in Nankana Sahib*

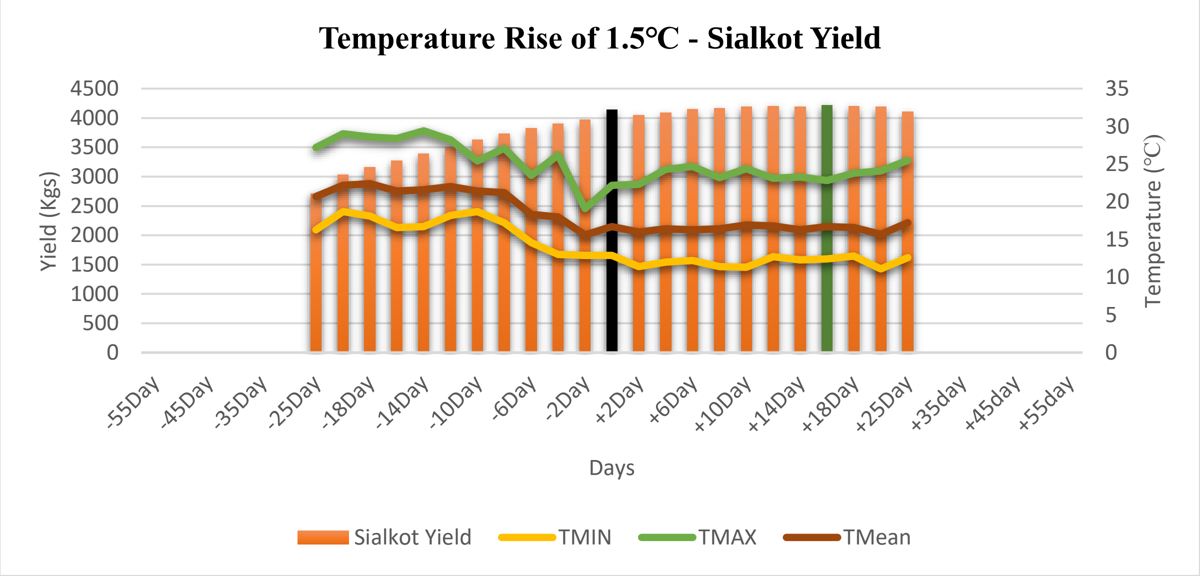


*Figure 14: Effect of 1.5℃ Rise in Sialkot*

### iii. Sialkot District

Sialkot exhibited the most conservative shift in optimal sowing dates among the three districts. For a 1°C temperature increase and 2mm precipitation rise, the best yields were obtained with a sowing date just 10 days delayed than current practices. In the 1.5°C scenario, the optimal sowing date moved to about 16 days delayed.

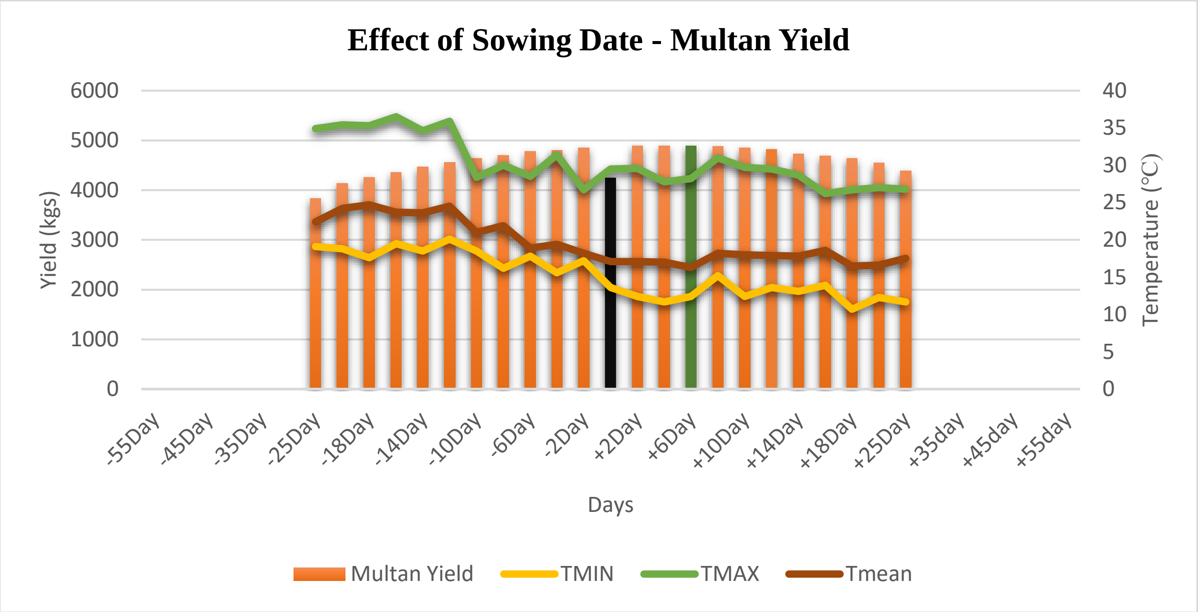


*Figure 15: Effect of Sowing Date on Yield in Multan*

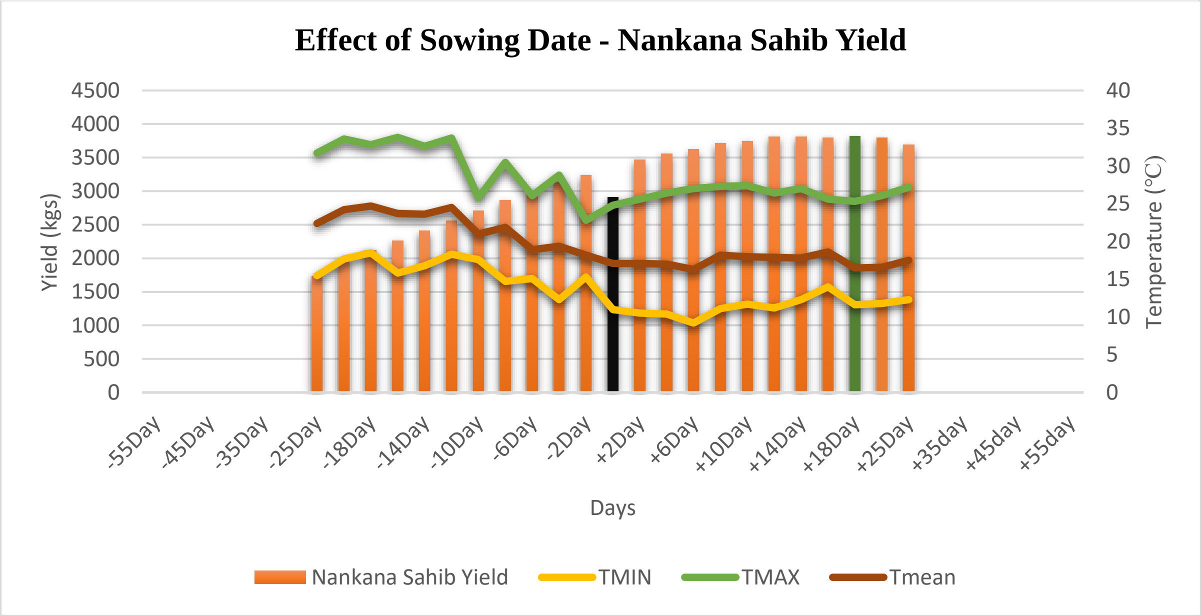


*Figure 16: Effect of Sowing Date on Yield in Nankana Sahib*

This more modest shift could be indicative of Sialkot's geographical location and its current climatic conditions, which may provide a longer suitable growing period for wheat.

### 4.4.2. Impact of Precipitation Changes

The study also considered scenarios with increased precipitation alongside temperature rises. Interestingly, the addition of 2mm more precipitation did not significantly alter the optimal sowing dates in any of the three districts. This suggests that temperature is the dominant factor influencing the ideal sowing time for wheat in these regions.

However, it's worth noting that increased precipitation did have a positive effect on overall yield across all sowing dates, as evidenced by the generally higher yield curves in the precipitation increase scenarios.

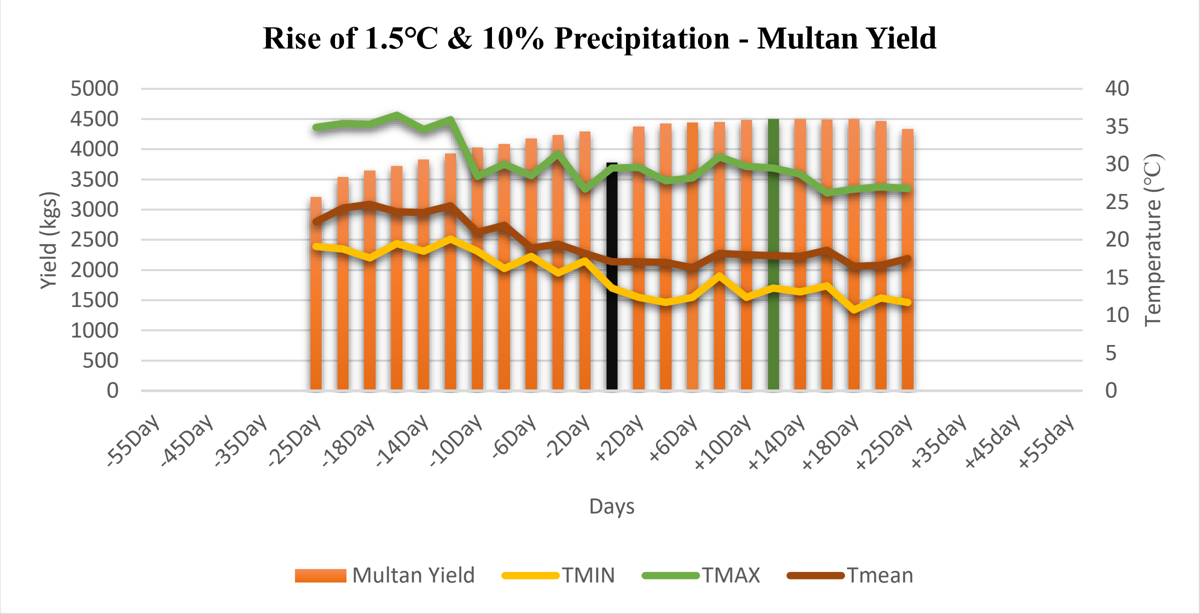


*Figure 17: Effect of Rise of 1.5°C & 10% Precipitation - Multan Yield*

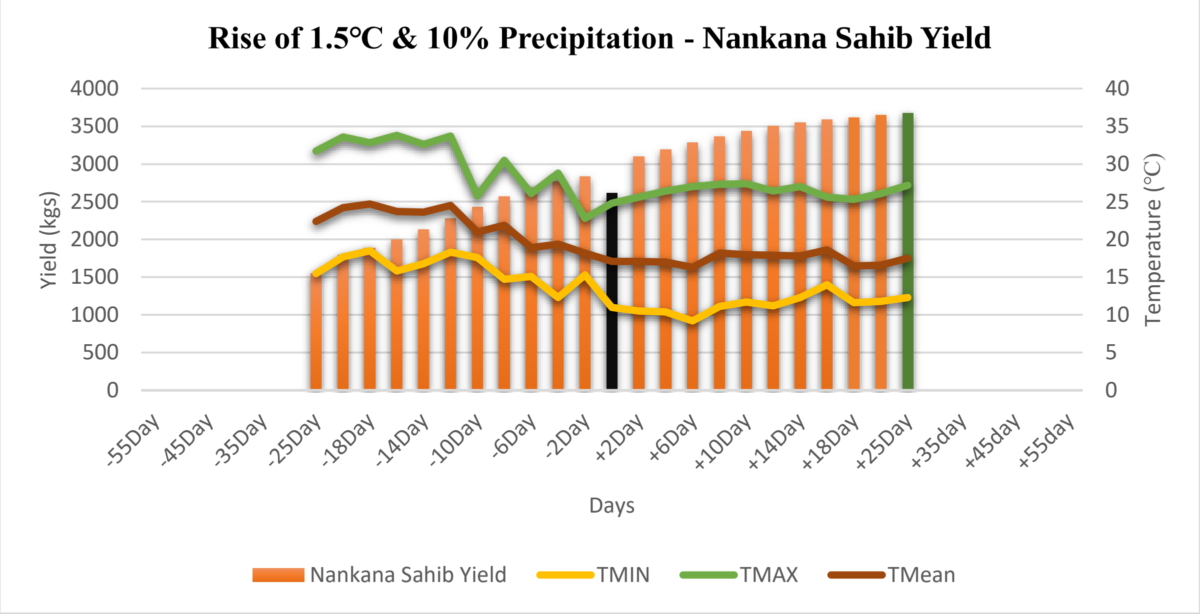


*Figure 18: Effect of Rise of 1.5℃ & 10% Precipitation - Nankana Sahib*

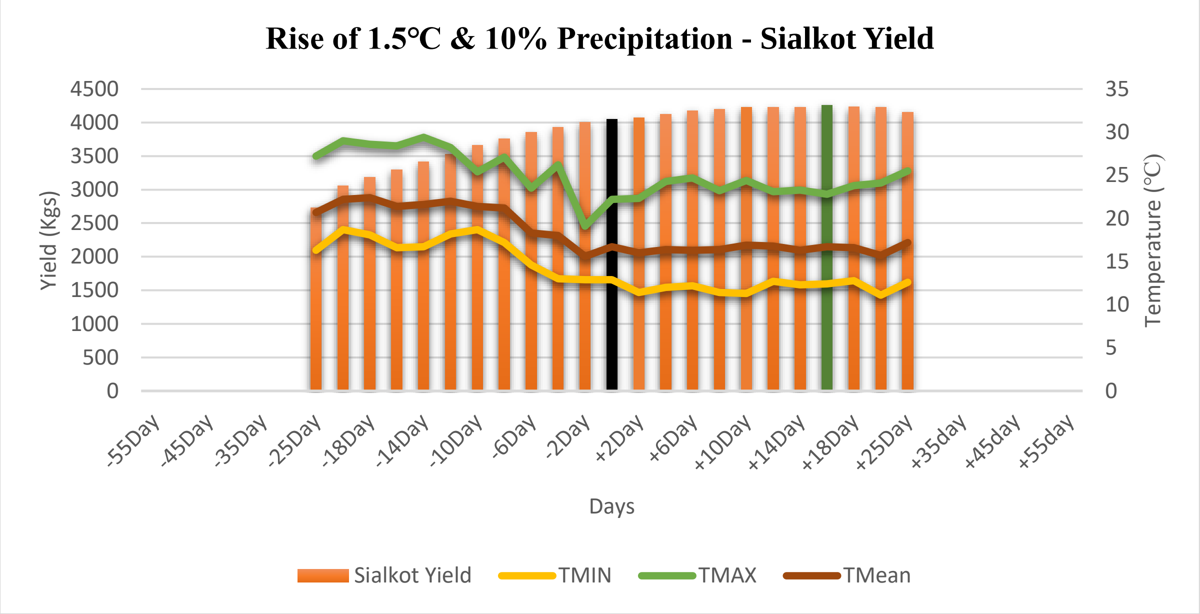


*Figure 19: Effect of Rise of 1.5℃ & 10% Precipitation - Sialkot Yield*

# CHAPTER 5

# 5. DISCUSSIONS

## 5.1. Rice-Wheat Cropping System

### 5.1.1. Alternate Wetting and Drying in Rice Cultivation

#### i. Comparative Superiority over Conventional Agriculture

Compared to traditional flooded rice cultivation, Alternate Wetting and Drying (AWD) offers a superior approach by significantly reducing water use while maintaining or even enhancing rice yields by 15%. This method, which involves periodic drying and re-flooding of rice fields, aligns closely with the physiological needs of the rice plant, optimizing water usage without compromising crop productivity (Bouman & Tuong, 2001).

#### ii. Irrigation and Fertilizer Savings

One of the primary benefits of AWD is its potential to conserve water by 15-20%. Studies have documented water savings of up to 30% compared to conventional flood irrigation practices, without adversely affecting yield (Lampayan et al., 2015). Furthermore, AWD can lead to improved nitrogen use efficiency, reducing the need for nitrogen fertilizers. The practice promotes better root growth and activity, enhancing the plants' ability to absorb nutrients more efficiently (Carrijo et al., 2017).

#### iii. Role in Sustaining the Environment

AWD plays a critical role in environmental sustainability by significantly reducing methane emissions from rice paddies by 20-30%, a substantial contributor to agricultural greenhouse gas emissions. By allowing oxygen to penetrate the soil during the drying phases, AWD inhibits methane production, which predominantly occurs under anaerobic conditions typical of continuously flooded fields (Bouman & Tuong, 2001; Lampayan et al., 2015). Additionally, the water savings associated with AWD contribute to the broader efforts of conserving freshwater resources, vital in regions experiencing water scarcity.

#### iv. Scalability and Ease of Adoption for Farmers

The scalability of AWD as a rice cultivation method is evidenced by its successful adoption across various rice-growing regions, from South Asia to Southeast Asia. The method's adaptability to different environmental and socio-economic conditions makes it a viable option for many farmers. Its ease of adoption is facilitated by the minimal changes required in farming practices and the availability of clear guidelines and field markers to manage the drying and re-watering cycles effectively (Lampayan et al., 2015; Carrijo et al., 2017). However, the transition to AWD may require initial training and support for farmers to optimize the practice's benefits fully.

### 5.1.2. Direct Seeded Rice

DSR offers a paradigm shift from traditional, water-intensive rice cultivation methods, presenting a sustainable solution to the pressing challenges of water scarcity, labor shortages, and the need for environmental conservation. Studies conducted in various regions, including Punjab, Pakistan, have demonstrated DSR's efficacy in reducing water usage by up to 30% while maintaining or enhancing yield compared to conventional transplanted rice (Nawaz et al., 2017; Awan et al., 2014). This significant water savings is attributed to DSR's avoidance of puddling and reduced evaporation losses, making it a cornerstone practice in water-scarce areas (Farooq et al., 2011; Bouman et al., 2007).

In addition to water conservation, DSR has been shown to lower greenhouse gas emissions, particularly methane, which is prevalent in flooded rice fields. DSR practice can help to cope climate change and ensure global sustainability (Farooq et al., 2011; Bouman et al., 2007). Economic benefits also accompany DSR adoption, with studies highlighting reduced labor and input costs leading to improved net returns for farmers (Nawaz et al., 2017; Iqbal et al., 2014). These benefits make DSR an economically viable option, encouraging broader adoption among rice farmers.

However, successful implementation of DSR requires addressing challenges such as effective weed management and the development of rice varieties suited for direct seeding. Weed competition in DSR systems can be significantly higher than in transplanted rice, necessitating integrated weed management strategies to ensure yield stability (Rao et al., 2007; Chauhan et al., 2011). Additionally, rice varieties with traits such as early vigor, resistance to lodging, and adaptability to variable water conditions are essential for maximizing the potential of DSR (Iqbal et al., 2014; Bouman et al., 2007).

Encouraging the adoption of DSR also involves extension services and policy support to address farmers' concerns and promote awareness of the practice's benefits. Research and development efforts must continue to refine DSR methodologies, develop suitable rice varieties, and devise effective weed control measures. Such integrated approaches will ensure that DSR remains a key component of climate-smart agricultural systems, offering a sustainable pathway for rice cultivation in the face of global environmental and socioeconomic challenges.

### 5.1.3. Zero Tillage Wheat:

#### i. Superiority over Conventional Agriculture Practices

Zero tillage (ZT) demonstrates significant advantages over conventional tillage by improving soil health, reducing erosion, and enhancing water infiltration. By leaving the soil undisturbed, ZT promotes a stable environment for microorganisms, which is essential for nutrient cycling and soil structure maintenance. Studies indicate that ZT can result in comparable or even improved wheat yields while substantially conserving soil and water resources (Khan et al., 2017).

#### ii. Benefits in Terms of Irrigation and Fertilizer Savings

One of the pivotal benefits of ZT is the conservation of water through improved soil moisture retention. The reduction in soil evaporation and increased water infiltration under ZT can lead to significant irrigation savings, crucial for sustainable agriculture in water-scarce regions. Moreover, the practice of leaving crop residues on the field surface contributes to enhanced soil organic matter and nutrient cycling, potentially reducing the reliance on synthetic fertilizers (Sharif et al., 2018).

#### iii. Role in Sustaining the Environment

ZT plays a critical role in environmental conservation by minimizing soil disturbance, which in turn reduces soil erosion and runoff, thereby protecting water bodies from sedimentation and pollution. Additionally, the carbon sequestration potential of ZT practices contributes to mitigating greenhouse gas emissions, aligning with global efforts to combat climate change (Ijaz & Ahmad, 2018).

#### iv. Scalability and Ease of Adoption for Farmers

The adoption of ZT practices is influenced by several factors, including access to suitable machinery, knowledge of ZT techniques, and initial costs. However, the long-term benefits, such as reduced labor and energy requirements, improved soil health, and potential yield advantages, make ZT an appealing option for farmers. Effective extension services and policy support are crucial in facilitating the transition to ZT and ensuring its scalability (Ahmad & Ijaz, 2018).

## 5.2. Cotton-Wheat Cropping System

### 5.2.1. Ridge Sown Cotton

The practice of ridge sowing cotton within the cotton and wheat cropping system offers numerous advantages over conventional agricultural practices. By employing this technique, farmers can achieve improved resource utilization, environmental sustainability, and potentially higher yields, making it a promising approach for modern agriculture.

#### i. Superiority over Conventional Agriculture:

Ridge sowing cotton has demonstrated its superiority over traditional flat sowing methods in several aspects. The raised bed geometry created by ridge sowing facilitates better aeration and drainage, promoting healthier root development and overall crop growth (Khaliq et al., 2014). Additionally, the furrows between ridges act as mini-reservoirs, allowing for more efficient water distribution and minimizing surface runoff (Fahong et al., 2004). These factors contribute to enhanced crop establishment, vigour, and ultimately, higher yield potential.

#### ii. Water and Fertilizer Efficiency:

Ridge sown cotton can significantly improve water efficiency. The furrow system created by ridge sowing allows for more targeted and efficient irrigation, resulting in water savings of up to 30% compared to conventional flat sowing methods (Chakraborty et al., 2008). Furthermore, the concentrated application of water and fertilizers in the furrows ensures better accessibility to the root zone, leading to improved nutrient uptake and fertilizer use efficiency (Lehrsch et al., 2000).

#### iii. Environmental Sustainability:

Ridge sowing cotton plays a pivotal role in promoting environmental sustainabilityAdditionally, the improved soil aeration and water management associated with ridge sowing can contribute to better soil health by minimizing waterlogging and soil compaction (Khaliq et al., 2014). Furthermore, the reduced water requirements and optimized fertilizer application may lead to lower greenhouse gas emissions associated with irrigation and fertilizer production processes (Houshyar et al., 2016).

#### iv. Scalability and Ease of Adoption:

The feasibility of adopting ridge sowing cotton varies depending on factors such as farm size, availability of specialized equipment, and labor requirements. For small-scale farmers with limited resources, the initial investment in equipment like ridge formers and specialized planters may pose a challenge (Govaerts et al., 2005). However, for larger farming operations, the potential water and fertilizer savings, as well as the yield benefits, could offset the initial costs over time. Additionally, the adoption of ridge sowing cotton may require specialized training and extension services to ensure proper implementation and maintenance of the ridges (Fahong et al., 2004).

### 5.2.2. Raised Bed Wheat

The practice of raised bed planting for wheat cultivation within the cotton and wheat cropping system has emerged as a promising alternative to conventional flat planting methods. This technique offers numerous benefits in terms of resource utilization, environmental sustainability, and yield enhancement, making it a viable approach for modern agricultural practices.

#### i. Superiority over Conventional Agriculture:

Raised bed planting for wheat has demonstrated its superiority over traditional flat planting methods in several aspects. The elevated bed geometry created by this technique promotes better soil aeration, drainage, and root development, leading to improved crop establishment and vigor (Jat et al., 2019). Additionally, the furrows between raised beds act as mini-reservoirs, facilitating more efficient water distribution and reducing surface runoff (Aryal et al., 2015). These factors contribute to higher yield potential and better resource utilization.

#### ii. Water and Fertilizer Efficiency:

One of the most significant advantages of raised bed planting for wheat is its potential for water conservation. The furrow irrigation system associated with raised beds allows for targeted and efficient water application, resulting in water savings of up to 25-35% compared to conventional flat planting methods (Zhao et al., 2017). Furthermore, the concentrated application of water and fertilizers in the furrows ensures better accessibility to the root zone, leading to improved nutrient uptake and fertilizer use efficiency (Aryal et al., 2015).

#### iii. Environmental Sustainability:

Raised bed planting for wheat plays a crucial role in promoting environmental sustainability. By reducing water consumption, this practice alleviates the strain on limited water resources, a critical consideration in semi-arid regions where wheat cultivation is prevalent. Additionally, the improved soil aeration and water management associated with raised bed planting can contribute to better soil health by minimizing waterlogging and soil compaction (Jat et al., 2019). Furthermore, the reduced water requirements and optimized fertilizer application may lead to lower greenhouse gas emissions associated with irrigation and fertilizer production processes (Sapkota et al., 2021).

### iv. Scalability and Ease of Adoption:

The feasibility of adopting raised bed planting for wheat varies depending on factors such as farm size, availability of specialized equipment, and labor requirements. For small-scale farmers with limited resources, the initial investment in equipment like bed formers and specialized planters may pose a challenge (Aryal et al., 2015). However, for larger farming operations, the potential water and fertilizer savings, as well as the yield benefits, could offset the initial costs over time. Additionally, the adoption of raised bed planting for wheat may require specialized training and extension services to ensure proper implementation and maintenance of the raised beds (Jat et al., 2019).

## 5.3. GHG Estimation from Paddy Rice

The comparison between the Crop Reporting Services (CRS) estimates and the Random Forest algorithm results reveals important insights into the potential advantages of machine learning techniques in agricultural monitoring. The overall higher estimate by the Random Forest algorithm (2,703,586 ha vs. 2,604,858 ha) suggests that this method may be capturing finer details of rice cultivation areas that traditional survey methods might overlook.

This finding aligns with recent studies that have demonstrated the superior performance of machine learning algorithms in crop area estimation. For instance, Zhao et al. (2022) reported that Random Forest-based estimations of crop areas in China were more accurate than traditional survey methods, with an overall accuracy of 91.5%. Similarly, Defourny et al. (2019) found that machine learning approaches, including Random Forest, outperformed conventional methods in mapping cropland extent across diverse agricultural landscapes in Africa.

The discrepancies observed between CRS and Random Forest estimates in certain districts (e.g., Gujranwala, Sheikhupura, Faisalabad) highlight the potential limitations of traditional survey methods and underscore the need for advanced remote sensing techniques in agricultural statistics. These differences may be attributed to factors such as the ability of Random Forest to capture small-scale farming practices, better discrimination between rice and other crops with similar spectral signatures, and the algorithm's robustness in handling complex landscape patterns.

### 5.3.1. Greenhouse Gas Emissions and Environmental Implications

The estimation of greenhouse gas emissions from rice cultivation provides critical information for understanding the environmental impact of this important crop in Punjab. The substantial methane emissions (252.79 Gg) highlight the significant contribution of rice farming to agricultural greenhouse gas emissions in the region.

These findings are consistent with other studies on rice-related emissions in South Asia. For example, Zhang et al. (2020) reported that rice cultivation in India contributed to approximately 3.5% of the country's total greenhouse gas emissions, with methane being the primary contributor. The spatial variability in emissions observed across districts in our study emphasizes the need for targeted mitigation strategies.

The high emissions from districts like Gujranwala, Okara, and Sheikhupura suggest that these areas should be prioritized for implementing emission reduction techniques. One **such** technique is Alternate Wetting and Drying (AWD), which has shown promise in reducing methane emissions from rice fields. According to a meta-analysis by Jiang et al. (2019), implementing alternate wetting and drying (AWD) irrigation methods can reduce methane emissions by approximately 35% compared to continuous flooding. Notably, this significant decrease in greenhouse gas emissions does not adversely affect crop yields, which remain largely unchanged.

### 5.3.2. Implications for Policy and Sustainable Agriculture

The detailed crop area and emissions data generated by this study have significant implications for agricultural policy and sustainable farming practices in Punjab. The accuracy of the Random Forest algorithm in estimating rice areas can inform more precise resource allocation, including water management and fertilizer application. This aligns with the findings of Lobell et al. (2020), who demonstrated that high-resolution crop mapping could improve water use efficiency in irrigation systems by up to 20%.

Furthermore, the emissions data provide a scientific basis for developing and implementing climate-smart agricultural policies. Policymakers can use this information to design targeted interventions, such as promoting AWD in high-emission districts or incentivizing the adoption of low-emission rice varieties. This approach is supported by recent research from Wassmann et al. (2019), who emphasized the importance of region-specific mitigation strategies in reducing greenhouse gas emissions from rice cultivation.

### 5.3.3. Future Research Directions

While this study provides valuable insights, it also points to several avenues for future research as below:

- **i.** Integration of socio-economic data with crop area estimates to better understand the drivers of spatial variability in rice cultivation and emissions.
- **ii.** Exploration of machine learning algorithms beyond Random Forest, such as deep learning approaches, for potentially improved accuracy in crop area estimation.
- **iii.** Long-term studies to assess the impact of climate change on rice cultivation patterns and associated emissions in Punjab.
- **iv.** Investigation of the potential for carbon sequestration in rice paddies as a mitigation strategy, building on recent work by Liu et al. (2021).

## 5.4. Optimum Sowing Dates for Wheat Crop under Future Climate Scenarios

Our findings align with several other studies conducted in similar agro-climatic zones. For instance, Hussain et al. (2018) reported that in South Punjab, earlier sowing dates became more favorable under climate change scenarios, this study included the experiments of sowing dates expanding from Nov-Mar. They found that sowing wheat in the month of November than traditional dates could help mitigate the negative impacts of rising temperatures.

Similarly, research conducted by Kumar et al. (2019) in the Indo-Gangetic plains—which have climatic conditions comparable to our study area—indicates that advancing wheat sowing dates by 5 to 10 days earlier than the traditional December schedule could enhance yields under projected climate change scenarios. This adjustment in planting time may help mitigate the adverse effects of climate variability on wheat production. Our results, showing optimal sowing dates 6-14 days delayed depending on the district and temperature scenario, are consistent with these findings.

However, our study provides more nuanced, location-specific recommendations. Unlike some previous studies that suggested a uniform shift in sowing dates across large regions, our district-level analysis reveals important local variations that should be considered in adaptation strategies.

The credibility of our results is supported by several factors:

i. **Robust Methodology:** The use of the DSSAT model, which has been extensively validated for wheat in various environments, lends strength to our simulations. The model's ability to integrate complex interactions between climate, soil, and crop management practices provides a comprehensive assessment of sowing date impacts.
ii. **Local Calibration:** By incorporating local soil data, farmer management practices, and district-specific weather data, we ensured that our simulations accurately reflected the conditions in each study area. This local calibration enhances the reliability and applicability of our results.
iii. **Consideration of Multiple Scenarios:** By simulating both 1°C and 1.5°C temperature rise scenarios, with and without precipitation increases, we've provided a range of potential outcomes. This approach acknowledges the uncertainty in climate projections and offers adaptive strategies for different possible futures.
iv. **Consistency with Physiological Understanding:** The trend towards delayed sowing dates as temperatures rise is consistent with our understanding of wheat physiology. Delayed sowing allows the crop to complete sensitive growth stages before the onset of high temperatures, which can negatively impact grain formation and filling.
v. **District-level Variations:** The differences in optimal sowing dates between districts reflect the importance of local conditions in determining adaptation strategies. This level of detail is a strength of our study, as it provides more targeted recommendations than broader regional analyses.

# CHAPTER 6

# 6. CONCLUSION AND RECOMMENDATIONS

This study on climate-smart agricultural practices in Punjab, Pakistan, has yielded several important conclusions. First, the adoption of practices such as AWD, DSR, Zero Tillage, ridge sowing, and raised bed planting can significantly improve resource use efficiency, particularly water conservation, while maintaining or enhancing crop yields. These practices also demonstrate potential for reducing greenhouse gas emissions, particularly methane from rice cultivation.

The economic analysis reveals that these climate-smart practices can lead to substantial increases in net profits for farmers, ranging from 15-30%. This economic viability is crucial for encouraging widespread adoption of these practices.

The use of advanced remote sensing techniques, along with the machine learning (Random Forest algorithm), proved effective in providing more detailed and potentially more accurate estimates of rice cultivated areas compared to traditional survey methods. This approach, combined with the subsequent greenhouse gas emissions estimations, offers a powerful tool for monitoring agricultural activities and their environmental impacts at a regional scale.

The modelling of optimal sowing dates for wheat under future climate scenarios highlights the importance of adaptive strategies in the wake of climate change. The study's findings suggest that delayed sowing dates, tailored to specific locations, could be an effective adaptation measure to mitigate the impacts of rising temperatures on wheat yields.

Overall, this research underscores the potential of climate-smart agricultural practices to address the dual challenges of food security and environmental sustainability in Punjab. The location-specific nature of many findings emphasizes the need for targeted, context-appropriate interventions rather than one-shoe-fits-all solutions.

Future research should focus on temporal field trials to validate these findings, explore the integration of socio-economic factors in adoption patterns, and investigate the potential for scaling up these practices across diverse agro-ecological zones. Furthermore, the CRA practices for rice crop can help in reduction of GHGs emission which should be explored and tier-2 approach should be adopted. Moreover, these CRA practices have potential to help farmers in earning carbon credits, that is another field to be explored in this context.

Additionally, continued refinement of remote sensing and modelling techniques will be crucial for improving our ability to monitor and predict agricultural outcomes in a changing climate.

The insights gained from this study provide a strong scientific basis for policymakers, agricultural extension services, and farmers to make informed decisions about sustainable agricultural practices in the face of climate change. Implementing these climate-smart practices could significantly contribute to the resilience and sustainability of Punjab's agricultural sector, with potential applications to similar agro-climatic regions worldwide.

# 7. REFERENCES

Abid, A. A., Zhang, Q., Adil, M. F., Batool, I., Abbas, M., Hassan, Z., Khan, A. A., Castellano-Hinojosa, A., Zaidi, S. H. R., Di, H., & Abdeslsalam, N. R. (2022). Nitrogen optimization coupled with alternate wetting and drying practice enhances rhizospheric nitrifier and denitrifier abundance and rice productivity. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.927229

Ahmed, S., Jahangir Alam, M., Hossain, A., Mominul Islam, A. K. M., Awan, T. H., Soufan, W., Qahtan, A. A., Okla, M. K., & Sabagh, A. El. (2021). Interactive effect of weeding regimes, rice cultivars, and seeding rates influence the rice-weed competition under dry direct-seeded condition. *Sustainability (Switzerland)*, *13*(1), 1–15. https://doi.org/10.3390/su13010317

Akbar, G., Ahmad, M. M., Asif, M., Hassan, I., Hussain, Q., & Hamilton, G. (2016). Improved Soil Physical Properties, Yield and Water Productivity under Controlled Traffic, Raised-Bed Farming. *Sarhad Journal of Agriculture*, *32*(4), 325–333. https://doi.org/10.17582/journal.sja/2016.32.4.325.333

Akbar, G., Ahmad, M. M., & Khan, M. (2016). *Integrated Watershed Management View project Optimizing the irrigation efficiency of conventional surface irrigation systems in Pakistan View project*. https://www.researchgate.net/publication/312166102

Akbar, G., Islam, Z., Hameed, S., & Ahmad, B. (2023). *Water Resources and Irrigation Management v.12, n. 1-3*. 1–13. https://doi.org/10.19149/wrim.v12i1-3.2910

Akbar, G., Raine, S., McHugh, A. D., Hamilton, G., & Hussain, Q. (2017). Strategies to Improve the Irrigation Efficiency of Raised Beds on Small Farms. *Sarhad Journal of Agriculture*, *33*(4). https://doi.org/10.17582/journal.sja/2017/33.4.615.623

Akhtar, M. W., & Rasool, F. (2020). Investigating the impact of Zero Tillage on small farmer's wheat production and Income: A case of District Sialkot, Pakistan. *Journal of Arable Crops and Marketing*, *2*(2), 47–61. https://doi.org/10.33687/jacm.002.02.3193

Ali, A. M., Savin, I., Poddubskiy, A., Abouelghar, M., Saleh, N., Abutaleb, K., El-Shirbeny, M., & Dokukin, P. (2021). Integrated method for rice cultivation monitoring using Sentinel-2 data and Leaf Area Index. *Egyptian Journal of Remote Sensing and Space Science*, *24*(3), 431–441. https://doi.org/10.1016/j.ejrs.2020.06.007

Ali, S., Ibin-i Zamir, M. S., Farid, M., Farooq, M. A., Rizwan, M., Ahmad, R., & Hannan, F. (2016). Growth and yield response of wheat (Triticum aestivum L.) to tillage and row spacing in maize-wheat cropping system in semi-arid region. *EURASIAN JOURNAL OF SOIL SCIENCE (EJSS)*, *5*(1), 53. https://doi.org/10.18393/ejss.2016.1.053-061

Aliyu, G., Luo, J., Di, H. J., Lindsey, S., Liu, D., Yuan, J., Chen, Z., Lin, Y., He, T., Zaman, M., & Ding, W. (2019). Nitrous oxide emissions from China's croplands based on regional and crop-specific emission factors deviate from IPCC 2006 estimates. *Science of the Total Environment*, *669*, 547–558. https://doi.org/10.1016/j.scitotenv.2019.03.142

Amjad Shahzad, M., Ahmad Anjum, S., Zohaib, A., Ishfaq, M., & Ahmad Warraich, E. (2017). *EFFECT OF DIFFERENT SOWING METHODS AND PLANTING DENSITIES ON GROWTH, YIELD, FIBER QUALITY AND ECONOMIC EFFICACY OF COTTON Gossypium hirsutum Sowing Methods, Yield, Fiber Quality, Economic Efficacy*. https://cabidigitallibrary.org

Ansari, R., Jehanzeb Masud Cheema, M., Usman Liaqat, M., Ahmed, S., & Ihsan Ul Haq Khan, H. (2019). EVALUATION OF IRRIGATION SCHEDULING TECHNIQUES: A CASE STUDY OF WHEAT CROP SOWN OVER PERMANENT BEDS UNDER SEMI-ARID CONDITIONS. In *JOURNAL OF AGRICULTURE AND PLANT SCIENCES, JAPS* (Vol. 17, Issue 1).

Arshad Awan, Z., Khaliq, T., Masood Akhtar, M., Imran, A., Irfan, M., Jarrar Ahmed, M., & Ahmad, A. (2021). Building climate-resilient cotton production system for changing climate scenarios using the dssat model. *Sustainability (Switzerland)*, *13*(19). https://doi.org/10.3390/su131910495

Arunrat, N., & Pumijumnong, N. (2017). Practices for reducing greenhouse gas emissions from rice production in northeast Thailand. *Agriculture (Switzerland)*, *7*(1). https://doi.org/10.3390/agriculture7010004

Ashfaq, M., Ali, A., Rasool, G., & Haider, Z. (2015). Economic evaluation of different irrigation systems for wheat production in Improving groundwater management to enhance agriculture and farming livelihoods in Pakistan View project phytoremediation potential of Catharanthus roseus View project. In *PAA Article in Pakistan Journal of Agricultural Research*. http://www.pakjas.com.pk

Asif, M., Akbar, G., Khan, S. H., Islam, Z., & Kalwar, S. A. (2019). EFFECT OF SOWING METHODS ON WHEAT PRODUCTION IN POTOHAR, PAKISTAN. *Online) Pak. J. Agri., Agril. Engg., Vet. Sci*, *35*(2), 98–104. http://pjaaevs.sau.edu.pk/index.php/ojs

Begum, K., Kuhnert, M., Yeluripati, J. B., Ogle, S. M., Parton, W. J., Williams, S. A., Pan, G., Cheng, K., Ali, M. A., & Smith, P. (2019). Modelling greenhouse gas emissions and mitigation potentials in fertilized paddy rice fields in Bangladesh. *Geoderma*, *341*, 206–215. https://doi.org/10.1016/j.geoderma.2019.01.047

Behzad, A., Rafique, U., Qamar, M., Islam, B., Hameed, H. U., Basheer, M., Firdos, M., & Mahmood, S. A. (2019). Estimation of Net Primary Production of Rice Crop using CASA model in Nankana Sahib. *International Journal of*

*Agriculture & Sustainable Development*, *01*(01). https://doi.org/10.33411/ijasd/2019010103

Bista, B. (2018). Direct Seeded Rice: A New Technology for Enhanced Resource-Use Efficiency. *International Journal of Applied Sciences and Biotechnology*, *6*(3), 181–198. https://doi.org/10.3126/ijasbt.v6i3.21174

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, *203*, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Chauhdary, J. N., Khan, U. D., Shah, S. H. H., Shahid, M. A., & Arsalan, M. (2016). Effect of sowing methods and seed rates on wheat yield and water productivity. *Quality Assurance and Safety of Crops and Foods*, *8*(2), 267–272. https://doi.org/10.3920/QAS2015.0685

Collins, B., & Chenu, K. (2021). Improving productivity of Australian wheat by adapting sowing date and genotype phenology to future climate. *Climate Risk Management*, *32*. https://doi.org/10.1016/j.crm.2021.100300

Deho, Z. A. (2023). PLANTING DATES AFFECTS ON SEED COTTON YIELD AND CONTRIBUTED CHARACTERS OF COTTON ADVANCE LINES UNDER CHANGING CLIMATIC CONDITIONS OF TANDOJAM, SINDH PAKISTAN. *Pakistan Journal of Agriculture, Agricultural Engineering and Veterinary Sciences*, *39*(1), 10–15. https://doi.org/10.47432/2023.39.1.3

Fahad, M., Ahmad, I., Rehman, M., Waqas, M. M., & Gul, F. (2019). Regional Wheat Yield Estimation by Integration of Remotely Sensed Soil Moisture into a Crop Model. *Canadian Journal of Remote Sensing*, *45*(6), 770–781. https://doi.org/10.1080/07038992.2019.1692651

Farooq, N., Sarwar, G., Abbas, T., Bessely, L., Nadeem, M. A., Javaid, M. M., Matloob, A., Naseem, M., & Ikram, N. A. (2020). Effect of drying-rewetting durations in combination with synthetic fertilizers and crop residues on soil fertility and maize production. *Pakistan Journal of Botany*, *52*(6), 2051–2058. https://doi.org/10.30848/PJB2020-6(37)

Fatima, H., & Yasmin, B. (2016). EFFICIENCY AND PRODUCTIVITY ANALYSIS OF PAKISTAN’S FARM SECTOR: A META-ANALYSIS*. In *Pakistan J. Agric. Res* (Vol. 29, Issue 3).

Hussain, I., Aulakh, A. M., Sohail, M., Hussain, K., Ahmed, A., Hamid, A., & Imtiaz, M. (2020). Impact of Zero Tillage on Productivity of Traditional Mung Bean-Wheat Cropping System of Punjab, Pakistan. *Pakistan Journal of Agricultural Research*, *33*(4). https://doi.org/10.17582/journal.pjar/2020/33.4.896.904

Hussain, J., Khaliq, T., Ahmad, A., & Akhtar, J. (2018). Performance of four crop model for simulations of wheat phenology, leaf growth, biomass and yield across planting dates. *PLoS ONE*, *13*(6). https://doi.org/10.1371/journal.pone.0197546

Hussain, J., Khaliq, T., Asseng, S., Saeed, U., Ahmad, A., Ahmad, B., Ahmad, I., Fahad, M., Awais, M., Ullah, A., & Hoogenboom, G. (2020a). Climate change impacts and adaptations for wheat employing multiple climate and crop modelsin Pakistan. *Climatic Change*, *163*(1), 253–266. https://doi.org/10.1007/s10584-020-02855-7

Hussain, J., Khaliq, T., Asseng, S., Saeed, U., Ahmad, A., Ahmad, B., Ahmad, I., Fahad, M., Awais, M., Ullah, A., & Hoogenboom, G. (2020b). Climate change impacts and adaptations for wheat employing multiple climate and crop modelsin Pakistan. *Climatic Change*, *163*(1), 253–266. https://doi.org/10.1007/s10584-020-02855-7

Hussain, J., Khaliq, T., Ur Rahman, M. H., Ullah, A., Ahmed, I., Kumar Srivastava, A., Gaiser, T., & Ahmad, A. (2021). Effect of temperature on sowing dates of wheat under arid and semi-arid climatic regions and impact quantification of climate change through mechanistic modeling with evidence from field. *Atmosphere*, *12*(7). https://doi.org/10.3390/atmos12070927

Imran, M. A., Ali, A., Culas, R. J., Ashfaq, M., Baig, I. A., Nasir, S., & Hashmi, A. H. (2022). Sustainability and efficiency analysis w.r.t adoption of climate-smart agriculture (CSA) in Pakistan: a group-wise comparison of adopters and conventional farmers. *Environmental Science and Pollution Research*, *29*(13), 19337–19351. https://doi.org/10.1007/s11356-021-17181-3

Iqbal, M. A. (2014). Productivity and Quality of Direct Seeded Rice under Different Types of Mulches and Planting Patterns: A Review. *J. Agric. & Environ. Sci*, *14*(11), 1240–1247. https://doi.org/10.5829/idosi.aejaes.2014.14.11.12450

Irfan, M., Ali, H., Ahmad, S., Sattar, A., Areeb, A., Hussain, S., Shabbir, R. N., Sarwar, N., & Hussain, F. (2020). Various tillage systems and sowing methods affect growth and yield related characters of cotton. *Journal of Arable Crops and Marketing*, *2*(1), 09–19. https://doi.org/10.33687/jacm.002.01.3187

Ishfaq, M., Farooq, M., Zulfiqar, U., Hussain, S., Akbar, N., Nawaz, A., & Anjum, S. A. (2020). Alternate wetting and drying: A water-saving and ecofriendly rice production system. *Agricultural Water Management*, *241*. https://doi.org/10.1016/j.agwat.2020.106363

Jabeen, M., Rashid Ahmed, S., & Ahmed, M. (2022). Enhancing water use efficiency and grain yield of wheat by optimizing irrigation supply in arid and semi-arid regions of Pakistan. *Saudi Journal of Biological Sciences*, *29*(2), 878–885. https://doi.org/10.1016/j.sjbs.2021.10.018

Jamali, M. H., & Laghari, K. Q. (2019). *Comparison of Flooding and Raised Bed Irrigation Systems for Wheat Crop at Samoo (Village*. https://doi.org/10.4172/2168-9768.1000228

Kashyap, D., & Agarwal, T. (2021). Carbon footprint and water footprint of rice and wheat production in Punjab, India. *Agricultural Systems*, *186*. https://doi.org/10.1016/j.agsy.2020.102959

Khan, A., Hansen, M. C., Potapov, P., Adusei, B., Stehman, S. V., & Steininger, M. K. (2021). An operational automated mapping algorithm for in-season estimation of wheat area for Punjab, Pakistan. *International Journal of Remote Sensing*, *42*(10), 3833–3849. https://doi.org/10.1080/01431161.2021.1883200

Khan, M. J., Razzaq, A., Khattak, M. K., & Garcia, L. (2009). Effect of different pre-sowing water application depths on wheat yield under spate irrigation in Dera Ismael Khan District of Pakistan. *Agricultural Water Management*, *96*(10), 1467–1474. https://doi.org/10.1016/j.agwat.2009.05.001

Khokhar, B., Hussain, I., & Khokhar, Z. (2010). EFFECT OF DIFFERENT IRRIGATION FREQUIENCIES ON GROWTH AND YIELD OF DIFFERENT WHEAT GENOTYPES IN SINDH. In *Pakistan J. Agric. Res* (Vol. 23, Issue 4).

Majeed, A., Muhmood, A., Niaz, A., Javid, S., Ahmad, Z. A., Shah, S. S. H., & Shah, A. H. (2015). Bed planting of wheat (Triticum aestivum L.) improves nitrogen use efficiency and grain yield compared to flat planting. *Crop Journal*, *3*(2), 118–124. https://doi.org/10.1016/j.cj.2015.01.003

Malhi, G. S., Kaur, M., & Kaushik, P. (2021). Impact of climate change on agriculture and its mitigation strategies: A review. In *Sustainability (Switzerland)* (Vol. 13, Issue 3, pp. 1–21). MDPI. https://doi.org/10.3390/su13031318

Maqsod Hashimi, S., Afsana, N., & Ahmad Sarhadi, W. (2019). Study of Raised Bed Planting Method on Yield and Yield Components of Wheat in Kabul. *International Journal of Science and Research*, 2319–7064. https://doi.org/10.21275/SR201220172658

Minhas, W. A., Mumtaz, N., Ur-Rehman, H., Farooq, S., Farooq, M., Ali, H. M., & Hussain, M. (2023). Weed infestation and productivity of wheat crop sown in various cropping systems under conventional and conservation tillage. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1176738

Muneer, M. A., Arshad, M., Shahid, M. A., & Anwar-Ul-haq, M. (2022). Efficacy of subsurface and surface drip irrigation regarding water productivity and yield of maize. *Pakistan Journal of Agricultural Sciences*, *59*(1), 125–134. https://doi.org/10.21162/PAKJAS/22.239

Munir, A., Mann, R. A., & Ramzan, M. (2007). Improving the Sustainability of Wheat Production in Irrigated Areas of Punjab, Pakistan through Conservation Tillage Technology. *INTERNATIONAL JOURNAL OF AGRICULTURE &BIOLOGY*. http://www.fspublishers.org

Naheed, G., & Mahmood, A. (n.d.). Water Requirement of Wheat Crop in Pakistan. *Pakistan Journal of Meteorology*, *6*.

Pazhanivelan, S., & Kaliaperumal, R. (2019). *Estimation of methane emission from rice fields using satellite data in Thiruvarur district*. https://www.researchgate.net/publication/338223806

Potapov, P., Turubanova, S., Hansen, M. C., Tyukavina, A., Zalles, V., Khan, A., Song, X. P., Pickens, A., Shen, Q., & Cortez, J. (2022). Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nature Food*, *3*(1), 19–28. https://doi.org/10.1038/s43016-021-00429-z

Rehman, H. U., Kamran, M., Basra, S. M. A., Afzal, I., & Farooq, M. (2015). Influence of Seed Priming on Performance and Water Productivity of Direct Seeded Rice in Alternating Wetting and Drying. *Rice Science*, *22*(4), 189–196. https://doi.org/10.1016/j.rsci.2015.03.001

Shahzad, M., Farooq, M., & Hussain, M. (2016). Weed spectrum in different wheat-based cropping systems under conservation and conventional tillage practices in Punjab, Pakistan. *Soil and Tillage Research*, *163*, 71–79. https://doi.org/10.1016/j.still.2016.05.012

Shang, Z., Abdalla, M., Kuhnert, M., Albanito, F., Zhou, F., Xia, L., & Smith, P. (2020). Measurement of N2O emissions over the whole year is necessary for estimating reliable emission factors. *Environmental Pollution*, *259*. https://doi.org/10.1016/j.envpol.2019.113864

Sharif, M., Ijaz, S. S., Ansar, M., Ahmad, I., & Sadiq, S. A. (2018). Evaluation of Conservation Tillage System Performance for Rainfed Wheat Production in upland of Pakistan. *Pakistan Journal of Agricultural Research*, *31*(1). https://doi.org/10.17582/journal.pjar/2018/31.1.37.44

Sudarmanian, N. S., Pazhanivelan, S., & Ragunath, K. P. (2017). *Remote Sensing based Methane Emission from Rice Fields in Tiruchirapalli District* (Vol. 104, Issue 6).

Teluguntla, P., Thenkabail, P. S., Xiong, J., Gumma, M. K., Congalton, R. G., Oliphant, A., Poehnelt, J., Yadav, K., Rao, M., & Massey, R. (2017). Spectral matching techniques (SMTs) and automated cropland classification algorithms (ACCAs) for mapping croplands of Australia using MODIS 250-m time-series (2000–2015) data. *International Journal of Digital Earth*, *10*(9), 944–977. https://doi.org/10.1080/17538947.2016.1267269

Ullah, H., Mohammadi, A., & Datta, A. (2018). Growth, yield and water productivity of selected lowland Thai rice varieties under different cultivation methods and alternate wetting and drying irrigation. *Annals of Applied Biology*, *173*(3), 302–312. https://doi.org/10.1111/aab.12463

Wakeel, A., Rehman, H. U., Mubarak, M. U., Dar, A. I., & Farooq, M. (2017). Potash use in aerobic production system for basmati rice may expand its adaptability as an alternative to flooded rice production system 399 K fertilization for aerobic rice production. In *Journal of Soil Science and Plant Nutrition* (Vol. 17, Issue 2).

Wang, J., Akiyama, H., Yagi, K., & Yan, X. (2018). Controlling variables and emission factors of methane from global rice fields. *Atmospheric Chemistry and Physics*, *18*(14), 10419–10431. https://doi.org/10.5194/acp-18-10419-2018

Wang, X., Chang, X., Ma, L., Bai, J., Liang, M., & Yan, S. (2023). Global and regional trends in greenhouse gas emissions from rice production, trade, and consumption. *Environmental Impact Assessment Review*, *101*. https://doi.org/10.1016/j.eiar.2023.107141

Watto, M., & Mugera, A. (2019). Wheat farming system performance and irrigation efficiency in Pakistan: a bootstrapped metafrontier approach. *International Transactions in Operational Research*, *26*(2), 686–706. https://doi.org/10.1111/itor.12314

Yang, H., Pan, B., Li, N., Wang, W., Zhang, J., & Zhang, X. (2021). A systematic method for spatio-temporal phenology estimation of paddy rice using time series Sentinel-1 images. *Remote Sensing of Environment*, *259*. https://doi.org/10.1016/j.rse.2021.112394

Yasin, M., Ahmad, A., Khaliq, T., Habib-ur-Rahman, M., Niaz, S., Gaiser, T., Ghafoor, I., Hassan, H. S. ul, Qasim, M., & Hoogenboom, G. (2022). Climate change impact uncertainty assessment and adaptations for sustainable maize production using multi-crop and climate models. *Environmental Science and Pollution Research*, *29*(13), 18967–18988. https://doi.org/10.1007/s11356-021-17050-z

Yigezu, Y. A., Abbas, E., Swelam, A., Sabry, S. R. S., Moustafa, M. A., & Halila, H. (2021). Socioeconomic, biophysical, and environmental impacts of raised beds in irrigated wheat: A case study from Egypt. *Agricultural Water Management*, *249*. https://doi.org/10.1016/j.agwat.2021.106802

Zaman Khan, H., Atif Shabir, M., Akbar, N., Iqbal, A., Shahid, M., Shakoor, A., & Sohail, M. (2017). *Effect of Different Tillage Techniques on Productivity of Wheat (Triticum aestivum L.)*. http://www.jabsjournal.com/