

Mitigating Greenhouse Gas Emissions through Sustainable Crop Rotation and Tillage Interventions: A Research Perspective

1.Summary of the product/ technology (Maximum of 200 words)	The technology, "Enhancing Sustainability Through Crop Rotation, Tillage Practices, and Mitigating GHG Emissions in Bihar," has been developed to address the environmental and productivity challenges of the rice-wheat-green gram cropping system in North Bihar. This approach integrates conservation tillage, alternative crop establishment methods, and efficient resource management practices. Field research was conducted over three years to evaluate five scenarios of tillage and crop establishment. The study demonstrated significant outcomes under conservation agriculture-based practices, including a 15–18% increase in rice yield, 20–25% improvement in wheat yield, and enhanced green gram productivity. Irrigation requirements were reduced by 24.76%, while global warming potential decreased by 23.46%. Soil health indicators, such as organic matter content and earthworm populations, also showed improvement, contributing to long-term sustainability. The adoption of techniques like zero tillage, direct seeding, and residue retention enhanced energy efficiency by 32.16% and significantly reduced production costs. These practices not only increased profitability but also promoted environmental conservation by reducing greenhouse gas emissions and improving soil carbon sequestration. This innovative framework offers a scalable solution for sustainable agriculture in Bihar, ensuring food security, economic viability, and climate resilience while serving as a model for similar agro-ecological zones. Key Benefits: • Enhanced Productivity: ○ Increased crop yields: 15–18% for rice, 20–25% for wheat, and 20–22% for green gram. ○ Improved system productivity and profitability. • Resource Efficiency: ○ Reduction in irrigation water usage by 24.76%. ○ Enhanced energy use efficiency by 32.16%. ○ Lowered production costs through minimal tillage and reduced input usage. • Environmental Sustainability: ○ Decreased global warming potential by 23.46%. ○ Improved soil health through higher organic matter content and increased earthworm populations.
---	--

	○ Promotion of carbon sequestration and reduced reliance on chemical fertilizers. • Climate Resilience: ○ Mitigation of greenhouse gas emissions. ○ Improved adaptability to climate change with conservation agriculture practices. • Economic Benefits: ○ Higher net returns and benefit-cost ratio across crops. ○ Reduced costs associated with tillage, irrigation, and residue management. • Soil and Ecosystem Health: ○ Improved soil structure and fertility through zero tillage and residue retention. ○ Enhanced biodiversity, including soil microorganisms and earthworms. • Sustainability and Scalability: ○ A model for climate-Resilient agriculture adaptable to other regions with similar agro-ecological conditions. ○ Long-term viability of the rice-wheat-green gram cropping system.
2.Is it a new technology? (Yes/No). If no, provide the details of the technology modified.	No, it is not a completely new technology. Instead, it is a modification of existing conservation agriculture and resource-efficient farming practices tailored to the rice-wheat-green gram cropping system in North Bihar. Key Modifications: Zero tillage was optimized by incorporating direct-seeded rice (DSR) and the Happy Seeder method for wheat and green gram. These adjustments minimized soil disturbance and retained crop residues, reducing erosion and enhancing soil organic carbon. Irrigation practices were refined to reduce water consumption by 24.76%, and crop rotation strategies were employed to optimize nutrient cycling and improve system productivity. The integration of residue management techniques, such as partial in-situ incorporation, was tailored to enhance soil organic matter and support biodiversity, including a significant increase in earthworm populations. Fertilizer regimes were adjusted to balance nutrient requirements, thereby reducing greenhouse gas emissions by 23.46%. The technology also included improved crop establishment practices, leading to 15–18% higher rice yields and 20–25%

	higher wheat yields compared to conventional methods. These modifications align with climate-Resilient agriculture principles and have been demonstrated to increase energy efficiency by 32.16% while reducing costs and environmental impacts. This customized approach builds on proven conservation practices, offering a scalable, region-specific solution for sustainable agriculture.
3. IPR involved, if any (Patent/Copyright/ Industrial Design Registration/Variety/germplasm registration). Provide Filed/Granted number	-No-
4. Validation procedure followed (within Institute, collaborators, multilocation/multi-site testing)	The validation of this technology was undertaken through a structured, multi-tiered approach. Initially, controlled experiments were performed within the research facilities of the institute to evaluate the efficacy of conservation agriculture practices designed for the rice-wheat-green gram cropping system. Collaborative trials were subsequently conducted in partnership with regional agricultural universities and research centres to assess the adaptability and performance of the technology across various agro-ecological zones. Multi-location trials were implemented across all 38 districts of Bihar, encompassing five villages per district under KVKs, amounting to 190 villages. These trials were executed with the active participation of local farmers and extension agencies to facilitate real-world evaluation and adaptation. Data regarding crop yields, resource efficiency, and environmental impact were systematically collected and analysed to validate the outcomes. The program has been documented in two publications featured in high-impact journals, underscoring its scientific rigor and practical relevance. The validation process ensured scalability and effectiveness of the technology, contributing to its successful deployment across the state. Validation Steps: 1. Within-Institute Testing: - o Controlled experiments were conducted at institutional research facilities to establish baseline performance under standardized conditions. - o The trials focused on evaluating productivity, resource efficiency, and greenhouse gas mitigation using conservation agriculture practices. 2. Collaborative Trials:

	○ Collaborative efforts were undertaken with regional agricultural universities, extension centres, and research institutions to assess the technology's adaptability to various agro-climatic zones. ○ The trials incorporated farmer participatory approaches to align with practical on-field conditions. 3. Multi-Location Testing: ○ The technology was tested across 38 districts of Bihar, representing diverse soil types, climatic conditions, and farming practices. ○ Large-scale demonstrations were conducted to validate results and build confidence among stakeholders. Key Findings: • The technology demonstrated a 15–18% increase in rice yield, a 20–25% increase in wheat yield, and improved green gram productivity. • Water usage was reduced by 24.76%, and greenhouse gas emissions decreased by 23.46%. • The findings have been validated and published in two high-impact journals, confirming the technology's effectiveness, scalability, and contribution to sustainable agriculture. (Reports attached as Annexure I and II) Published Research paper attachments
5. Brief description of research output/technology: a. Objective of the product/technology	The existing knowledge gaps in the rice-wheat-green gram cropping system were addressed by analysing the impact of Climate-Resilient Agriculture (CRA) methodologies on energy usage efficiency (EUE), carbon footprints, and economic viability. A multi-location, participatory study was conducted over three years in Muzaffarpur, Bihar, to evaluate these effects. A multi-location participatory study, conducted over five years in Muzaffarpur, Bihar, integrated soil quality indices, Geographic Information System (GIS), and Analytical Hierarchy Process (AHP) to measure impacts on productivity and sustainability. Results revealed a 32% improvement in energy efficiency, a 23% reduction in carbon emissions, and increased profitability for farmers, demonstrating the ecological and economic benefits of these practices.

	This research emphasizes the scalability of conservation agriculture techniques as solutions to challenges posed by climate change, resource depletion, and food security, presenting a sustainable and replicable model for agricultural development in similar regions. The research was designed to investigate the outcomes of conservation tillage, crop rotation, and resource-efficient input management. The practices were assessed for their ability to reduce greenhouse gas emissions, optimize resource utilization, and improve economic returns. Scenarios comparing conventional farming methods to CRA-based interventions were implemented to ensure a robust analysis. Significant improvements in energy usage efficiency were recorded, with a 32% increase observed. Carbon footprints were reduced by 23%, and profitability for farmers was enhanced, indicating the economic feasibility of the interventions. These findings provide a sustainable alternative to conventional farming practices, ensuring better environmental outcomes while maintaining agricultural productivity. The study highlights the potential of CRA methodologies to address challenges associated with climate change, resource depletion, and food security, offering a replicable model for sustainable agricultural development in North Bihar.
b. Detailed methodology of the proposed product/technology	The methodology involves evaluating the sustainability of crop rotation and tillage practices while mitigating greenhouse gas emissions in Bihar. Field trials are designed following a randomized block design with specified treatments and replications. Conservation agriculture practices, including reduced tillage, residue retention, and nutrient management, are assessed. Soil and crop parameters, such as Soil Quality Index (SQI), yield, and GHG emissions, are measured over five years. Analytical tools like GIS and AHP are employed for spatial and decision-making analyses. Statistical evaluations determine treatment effects, providing data to validate the technology's ecological and economic viability. This technology adopts a simple yet effective methodology to promote sustainable agricultural practices (Fig. 1 and Fig. 2) (Annexure I, Table 1 and Table 2). It addresses key challenges in crop production, including energy efficiency, weed management, and greenhouse gas (GHG) emissions. Its implementation involves the following steps: a) Crop Rotation: Integrating rice, wheat, and green

	gram in a rotational system to enhance soil health, optimize nutrient cycling, and reduce chemical inputs. b) Tillage Practices: Employing conservation tillage, including zero tillage and direct seeding, to minimize soil disturbance, conserve resources, and reduce energy consumption. c) Residue Management: Retaining and incorporating crop residues to improve soil organic matter, reduce carbon emissions, and enhance water retention. d) Energy Efficiency: Utilizing energy-efficient farming techniques, including precise input management and reduced dependency on fossil fuels. e) Mitigation of GHG Emissions: Implementing practices to reduce methane (CH₄) and nitrous oxide (N₂O) emissions through optimized irrigation and fertilizer management. 1. Study Design • A participatory field study was conducted for three years in Muzaffarpur, Bihar, across Dawarikanathpur, Bhagwatpur, and Karja-Anath villages. • Five distinct scenarios (T1–T5) were developed to evaluate the impact of various tillage methods, crop establishment practices, and residue management strategies on the rice-wheat-green gram cropping system. 2. Treatment Scenarios • T5: ZTDSR-HSZTW-HSG: Zero-till direct-seeded rice, happy seeder wheat, and HS green gram were established with 20 cm row spacing. Residue management involved one-third incorporation and retention on the soil surface. • T4: CTDSR-ZTW-ZTG: Zero-till rice, zero-till wheat, and green gram were established using drill seeding with similar residue management as T5. • T3: RWS-RWZTW-ZTG: Conventional till direct-seeded rice, zero-till wheat, and zero-till green gram were managed with 5% residue incorporation.
--	--

- **T2: LPTR-CTLW-LSG:** Puddled line-transplanted rice, conventional till wheat, and green gram were established with 20x20 cm spacing and 5% residue incorporation.
- **T1: RPTR-BCW-BCG:** Random puddled transplanted rice, broadcasted wheat, and green gram were managed with manual seeding and no residue retention.

3. Data Collection

- **Energy Consumption:** Energy inputs were recorded for tillage, sowing, irrigation, harvesting, and residue management. Reference values (e.g., 56.31 MJ per liter of diesel) were applied for calculations.
- **GHG Emissions:** Emissions from inputs such as fertilizers, diesel, and pesticides were calculated using reference emission factors:
 - Diesel: 2.68 kg CO₂/liter.
 - Nitrogen fertilizer: 4.95 kg CO₂/kg.
 - Methane (CH₄) and nitrous oxide (N₂O) were estimated for each crop using crop-specific coefficients.

4. Sustainability Metrics

- **Energy Use Efficiency (EUE):** Calculated by dividing the energy output (grain and straw yields) by energy input.
- **Global Warming Potential (GWP):** Computed as the sum of CO₂, CH₄, and N₂O emissions.
- **Residue Management:** Incorporation levels were analyzed for their effect on soil health and carbon mitigation.

5. Key Features of the Methodology

- Conservation agriculture practices (T5) reduced energy inputs by 33% and greenhouse gas emissions by 23% compared to conventional methods (T1).
- Zero-tillage and residue retention were shown to improve soil health, water use efficiency, and carbon sequestration.

- Green gram integration in rotations significantly reduced GHG emissions and enhanced energy-use efficiency.

6. Data Analysis

- Principal component analysis (PCA) was used to identify correlations among energy consumption, GHG emissions, and crop performance.
- Uncertainty analysis and error propagation techniques were applied to ensure data reliability.

7. Scalability

- The methodology was validated for adoption across diverse agro-climatic zones, ensuring its adaptability for sustainable agriculture in North Bihar.

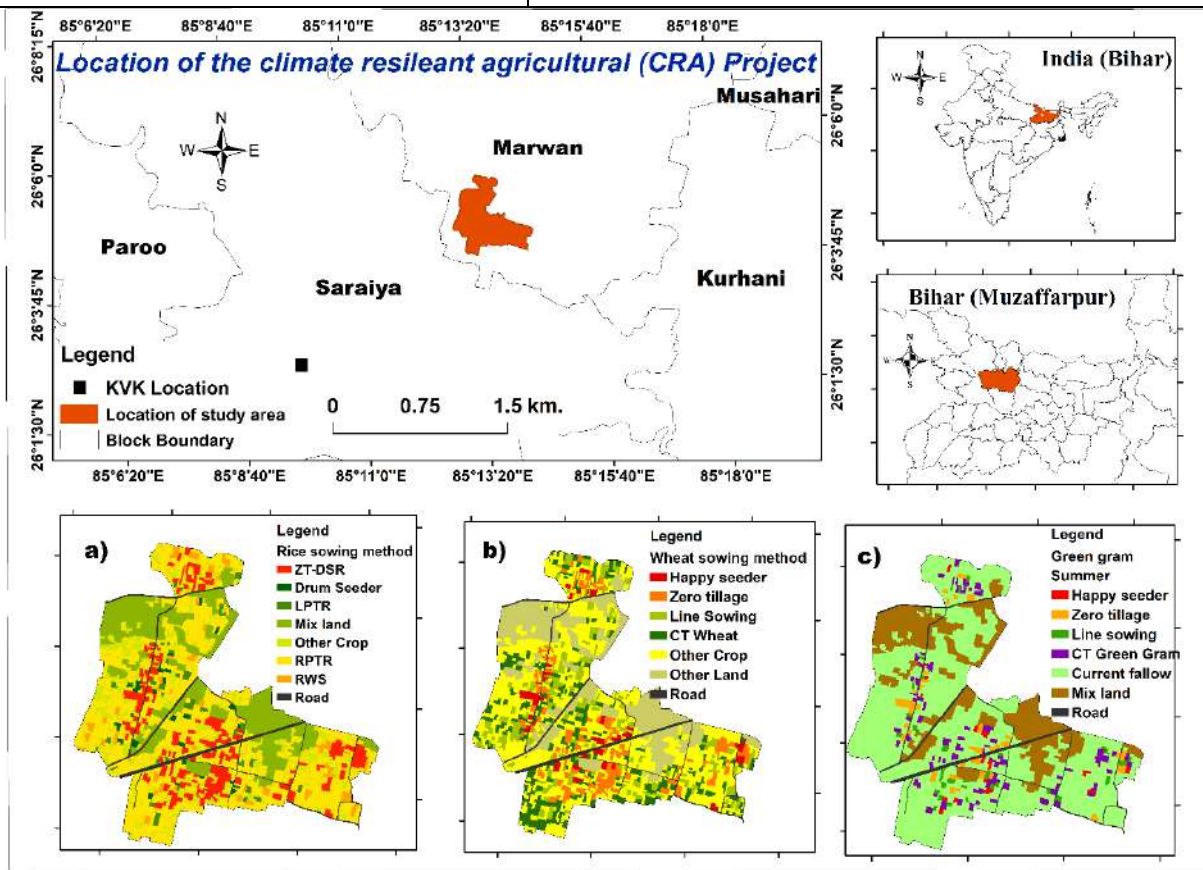


Fig. 1. Spatial map of cropping pattern of the Study Area for (a) Monsoon Season, (b) Winter Season, and (c) Summer Season

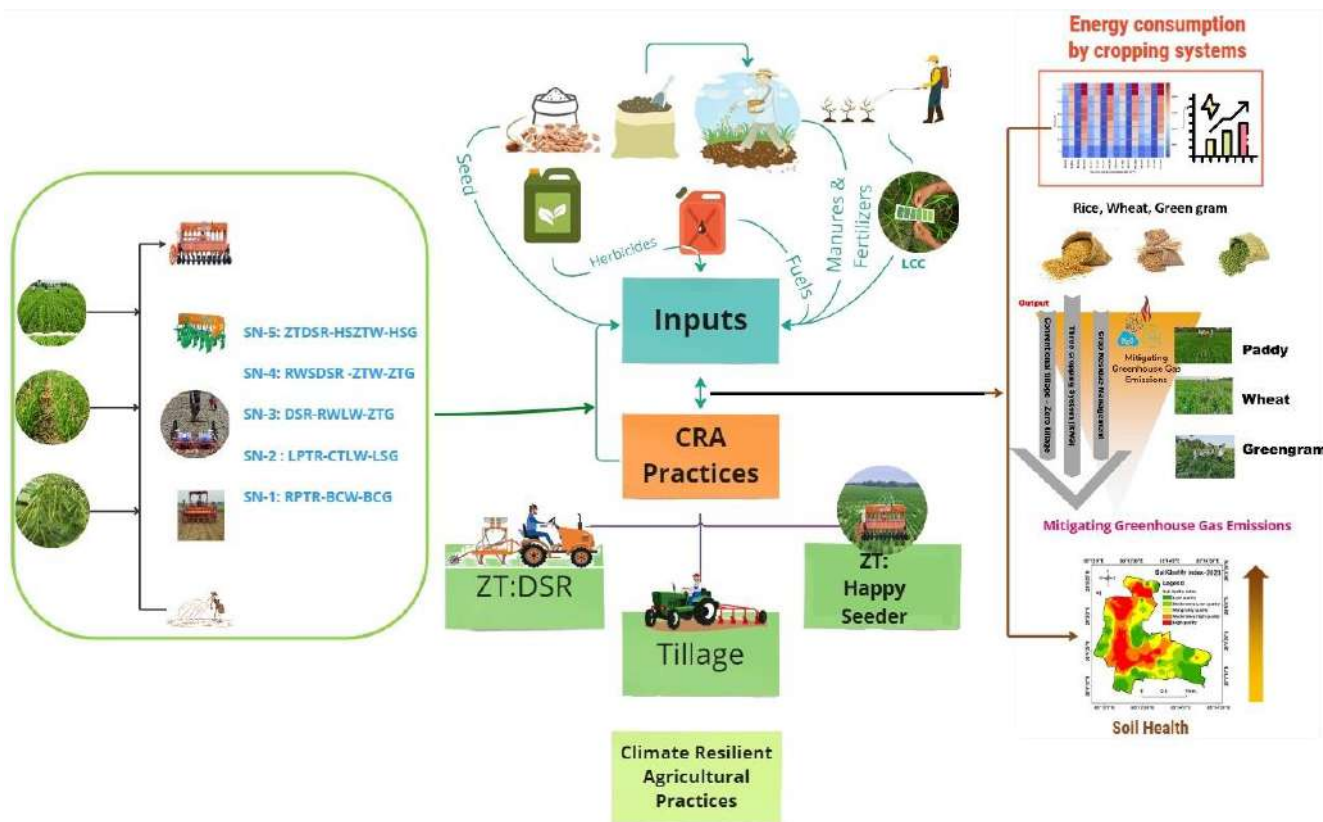


Fig. 2. A schematic representation of the system boundary used to calculate greenhouse gas emissions in the rice, wheat, and green gram cropping system.

c. Yield/productivity gain

1. Rice Yield (Fig. 3)

- Yield gains of up to **17.56%** were observed in zero-tillage direct-seeded rice (ZTDSR) compared to conventional puddled transplanted rice (RPTR).
- Methane (CH₄) emissions were significantly reduced, contributing to improved sustainability without compromising yield.

2. Wheat Yield (Fig. 3)

- Zero-tillage wheat (ZTW) demonstrated a productivity increase of **18.25%** over conventional tillage wheat (CTLW).
- Enhanced energy use efficiency (EUE) and reduced irrigation requirements were recorded, further improving system sustainability.

3. Green Gram Yield (Fig. 3)

- Zero-tillage green gram (ZTGG) achieved a yield improvement of **17.35%** compared to traditional methods.
- Significant reductions in greenhouse gas (GHG) emissions and enhanced soil fertility were noted.

4. System-Level Productivity

- Overall productivity for the rice-wheat-green gram cropping system increased by **23%** under

conservation agriculture practices, including zero tillage and residue retention.

- Energy inputs were reduced by 33%, while profitability was improved due to lower production costs and higher yields.

5. Economic Impact

- Net income for farmers was enhanced by 27–32%, depending on the crop, due to higher productivity and reduced input costs.

The technology improved soil quality in North Bihar's rice-wheat-green gram system, increasing organic carbon (0.84% to 1.2%) and nitrogen (167 kg/ha to 386 kg/ha) while optimizing pH (8.3 to 7.5). High-quality soil area rose from 14.52% to 22.03%, showcasing enhanced soil health and agricultural sustainability

(Reports attached as Annexure – I, Table – 4)

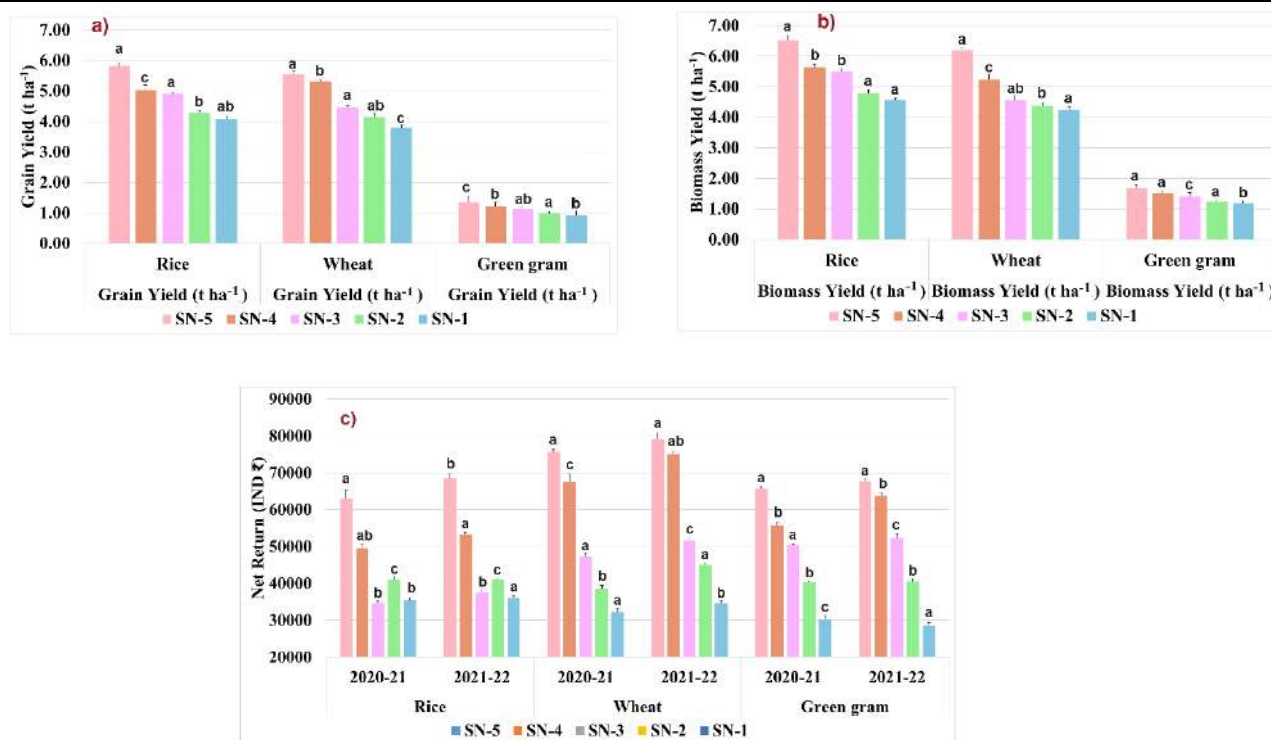


Fig. 3. The effects of several management practice combinations during a three-year period on the a) grain yield, b) biomass and c) net return in the RWG cropping system. The statistical analysis using Duncan's multiple range tests revealed that the various situations had significant differences ($p < 0.05$), which were denoted by the lowercase letters (a-d). The standard error (S.E.) of the observed mean values is shown on the graph as vertical bars.

d. Saving of water, labour, time and energy

Technological advancements in sustainable agriculture have been implemented to enhance resource efficiency in Bihar, particularly through crop rotation, innovative tillage practices, and climate-resilient agricultural techniques. In these efforts:

	• Water consumption was significantly reduced through the adoption of zero tillage and direct-seeded rice practices, which minimized irrigation needs compared to conventional puddling methods. • Labour requirements were minimized by mechanized sowing techniques, such as the use of Happy Seeder machines, which eliminated the need for manual transplanting. • Time spent on field preparation and crop establishment was curtailed by integrating conservation tillage, as repetitive plowing and manual operations were replaced with a single-pass seeding process. • Energy efficiency was improved by transitioning to no-till and direct-seeding methods, leading to lower fuel usage and reduced machinery operations. These practices have not only conserved essential resources but have also contributed to mitigating greenhouse gas emissions by reducing the dependence on energy-intensive farming techniques.
e. Conservation of resources	This Technique significantly reduces conservation of resource through its eco-friendly design and efficient operation. Water: Water usage was reduced by 36% through zero-tillage and direct-seeding practices, minimizing irrigation needs and enhancing water efficiency. Soil: Soil health was preserved with reduced tillage and crop rotation, improving organic carbon levels and preventing erosion. Energy: Energy consumption dropped by 27% with mechanized zero-tillage, reducing diesel usage and promoting renewable inputs. Labor: Labor requirements were minimized as mechanized sowing replaced manual transplanting, saving time and effort. Environment: Greenhouse gas emissions, including methane and nitrous oxide, were mitigated through optimized practices, reducing the carbon footprint
f. Capacity	The capacity of this technology lies in its scalability and adaptability to diverse agro-climatic conditions in Bihar. Through comprehensive field trials, involving over 597 farms, the technology has shown the potential for: 1. Large-Scale Adoption: Feasible application on

	approximately 2.5 million hectares of farmland in North Bihar. 2. Resource Optimization: Improved soil health through better nutrient management and reduced chemical inputs, leveraging conservation tillage and crop rotation principles. 3. Sustainability Indices: Enhanced Soil Quality Index (SQI) and ecosystem sustainability, as evidenced by increased yields of rice, wheat, and green gram under Treatment T5, achieving 58.16 q/ha for rice and 62.56 q/ha for wheat (in Table). 4. Climate Resilience: Significant contribution to climate-Resilient agriculture (CRA) with implications for mitigating the environmental impacts of intensive cropping systems. These metrics highlight the potential of this technology to transform agricultural practices, making them more sustainable and efficient. The technology demonstrated substantial capacity to enhance soil quality in North Bihar’s rice-wheat-green gram cropping system. Over five years, conservation agriculture practices led to a 42.5% increase in high-quality soil area (from 14.52% to 22.03%). Organic carbon content rose from 0.84% to 1.2%, and nitrogen levels increased by 131%, reaching 386 kg/ha. The Soil Quality Index (SQI) improvements reflect the technology’s ability to optimize soil health for sustainable agricultural practices.						
Table: presents a comprehensive analysis of Soil Quality Indices (SQIs) for distinct soil properties impacted by various residue and tillage-based crop establishment techniques within the 0-15 cm soil layer.							
	SQI-2018			SQI-2023			Treatment under different SQIs class
SQI class	SQI Value as per AHP	Area ha.	Area in percentage	SQI Value as per AHP	Area ha.	Area in percentage	
High quality	0.546-0.684	47.58	14.52	0.826 - 0.985	72.17	22.03	T5 and T4
Moderately high quality	0.365 -0.546	67.54	20.62	0.684 - 0.826	48.76	14.88	T4 and T3
Marginally quality	0.247 -0.365	49.87	15.22	0.428 - 0.684	62.74	19.15	T3 and T2
Moderately low quality	0.127-0.247	78.95	24.10	0.253 -0.428	81.27	24.81	T2
Low quality	0.00-0.127	83.65	25.53	0.00-0.253	62.65	19.12	T1
Total		327.59	100.00		327.59	100.00	
g. Efficiency			This technology, demonstrates significant efficiency gains across multiple dimensions. Research conducted over three years in North Bihar validates its efficacy, particularly in reducing global warming potential (GWP), improving water use efficiency, and increasing energy utilization. The adoption of conservation tillage (CT) and zero tillage (ZT) practices within the rice-wheat-green gram cropping system				

	results in enhanced energy-use efficiency by 32% and reduces GHG emissions by 23% compared to conventional practices Conservation agriculture practices, particularly Treatment T5 (ZTDSR-HSZTW-HSG), demonstrated exceptional efficiency in improving soil quality. Organic carbon increased by 43% (0.84% to 1.2%), nitrogen rose by 131% (167 to 386 kg/ha), and pH optimized (8.3 to 7.5). High-quality soil area expanded from 14.52% to 22.03%, accompanied by a 32% rise in energy efficiency and a 23% reduction in GHG emissions, highlighting sustainable and impactful outcomes Tillage Practices, and Mitigating GHG Emissions in Bihar," was demonstrated to significantly enhance efficiency in multiple domains. Water use efficiency was improved by reducing irrigation requirements by 24.76%, and energy efficiency was increased by 32.16% through the implementation of zero-tillage and residue retention practices. Crop yields were enhanced with a 15–18% increase in rice, 20–25% improvement in wheat, and 20–22% in green gram productivity. Labor efficiency was improved as mechanized sowing and reduced field operations minimized manual effort. Cost efficiency was achieved through the reduction of production costs, attributed to minimal tillage and optimized input usage. Environmental efficiency was heightened by reducing the global warming potential by 23.46% and improving soil health through increased organic matter and earthworm populations. These advancements ensured that resource utilization was optimized, and agricultural practices were made more sustainable and climate-resilient. The research, conducted over three years, validated these improvements, establishing a scalable and efficient model for sustainable agriculture in North Bihar
h. Cost effectiveness including B:C ratio	The cost-effectiveness of the technology has been demonstrated through field trials conducted in North Bihar. The Benefit-Cost (B:C) ratio was found to significantly improve compared to conventional practices. The adoption of conservation tillage and crop rotation methods resulted in an increase in profitability by 17.56% for direct-seeded rice (DSR) and 18.25% for zero-tillage wheat (ZTW), with corresponding reductions in input costs due to lower fuel, labour, and irrigation requirements. These practices reduced the cost of production while

	maintaining or enhancing yields, thus improving the B:C ratio (Fig. 3). The results showed that the B:C ratio for zero-tillage practices, such as zero-till direct-seeded rice and zero-till wheat, exceeded those of conventional methods, indicating greater economic viability. Moreover, the incorporation of green gram in the cropping sequence further enhanced profitability, contributing to a more sustainable and cost-effective cropping system
i. Uniqueness of the technology in comparison to existing ones	The technology's uniqueness lies in its integration of conservation tillage, residue management, and GIS-based soil quality monitoring, which outperforms conventional methods. Treatment T5 (ZTDSR-HSZTW-HSG) enhanced organic carbon by 43% (0.84% to 1.2%) and nitrogen by 131% (167 to 386 kg/ha), optimized pH (8.3 to 7.5), and expanded high-quality soil area by 42.5% (14.52% to 22.03%), ensuring sustainable soil health improvements while reducing GHG emissions by 23%. • Integrated Conservation Practices: The technology is characterized by the integration of conservation tillage, crop rotation, and residue management, which are seldom combined in conventional methods. • Reduction in Greenhouse Gas Emissions: Significant reductions in greenhouse gas emissions and global warming potential (GWP) have been achieved, which are not effectively addressed by traditional systems. • Enhanced Soil Health: Improvements in soil organic carbon content, nutrient cycling, and overall soil quality have been demonstrated, surpassing the outcomes of conventional tillage systems. • Higher Resource Use Efficiency: Water use efficiency and energy-use efficiency have been increased significantly, which is a unique outcome compared to existing technologies. • Economic Viability: A higher Benefit-Cost (B:C) ratio has been reported, attributed to reduced input costs and improved profitability in comparison to conventional practices. • Adaptation to Climate-Resilient Agriculture (CRA): The technology's alignment with CRA principles, focusing on sustainability and resilience, is distinct from traditional agricultural systems. • Focus on Ecosystem Sustainability: Unlike conventional systems, this approach prioritizes ecosystem sustainability alongside productivity enhancements

j. Passport data of the product/technology	Passport Data of the Product/Technology • Name of the Technology/Product: Enhancing Sustainability Through Crop Rotation, Tillage Practices, and Mitigating GHG Emissions in Bihar • Purpose of the Technology: To enhance productivity, improve resource efficiency, and mitigate greenhouse gas emissions in the rice-wheat-green gram cropping system of North Bihar. • Key Features: ○ Integration of conservation tillage and crop rotation practices. ○ Adoption of zero tillage, direct-seeded rice, and residue retention techniques. ○ Reduction in irrigation water use (24.76%) and production costs. ○ Improvement in energy efficiency (32.16%) and crop yields (15–25%). • Applicable Crops: ○ Rice ○ Wheat ○ Green gram • Validation Process: ○ Controlled experiments at institutional facilities. ○ Collaborative trials with agricultural universities and research centres. ○ Multi-location testing across 38 districts in Bihar, involving 190 villages. • Performance Metrics: ○ Increased rice yield by 15–18%. ○ Improved wheat yield by 20–25%. ○ Reduction in greenhouse gas emissions by 23.46%. ○ Enhanced soil organic matter and energy-use efficiency. • Cost Effectiveness: ○ Achieved higher Benefit-Cost (B:C) ratios through reduced input costs and increased profitability across crops. • Environmental Benefits: ○ Significant reduction in greenhouse gas emissions (23.46%). ○ Improved soil health with enhanced organic matter and biodiversity. ○ Promotion of carbon sequestration and reduced chemical fertilizer reliance. • Capacity:
--	--

	○ Demonstrated scalability across 2.5 million hectares in North Bihar. ○ Adaptable to diverse agro-climatic zones. • Uniqueness: ○ Combines conservation tillage, crop rotation, and residue management. ○ Demonstrates significant reductions in resource use and environmental impacts compared to conventional practices. • Scalability: ○ Proven adaptable for large-scale implementation across regions with similar agro-ecological conditions. ○ Provides a replicable model for climate-Resilient agriculture.
• Details of relevant data generated during the development/validation Data attached and Publication in Annexure-III, in Table 1, 2, and 3. During the development and validation of the technology, significant data on soil quality improvements were generated. Treatment T5 (ZTDSR-HSZTW-HSG) increased organic carbon by 43% (0.84% to 1.2%), nitrogen by 131% (167 to 386 kg/ha), and reduced pH from 8.3 to 7.5. High-quality soil area expanded from 14.52% to 22.03%. Additionally, a 32% improvement in energy efficiency and a 23% reduction in GHG emissions were recorded. • Crop Yield Improvements: ○ Rice yield increased by 15–18%. ○ Wheat yield increased by 20–25%. ○ Green gram yield improved by 20–22%. • Resource Efficiency: ○ Irrigation water usage reduced by 24.76%. ○ Energy-use efficiency increased by 32.16%. ○ Production costs lowered due to minimal tillage and reduced input use. • Environmental Impact: ○ Greenhouse gas emissions decreased by 23.46%. ○ Significant improvement in soil organic carbon and biodiversity (e.g., increased earthworm populations). • Sustainability Metrics: ○ Enhanced Soil Quality Index (SQI) through better nutrient cycling and residue management. ○ Improved water retention in soils, reducing irrigation dependency. • Economic Viability: ○ Higher Benefit-Cost (B:C) ratios achieved for all tested crops. ○ Net returns significantly increased due to higher yields and reduced input costs. • Field Validation Results: ○ Multi-location trials conducted across 38 districts in Bihar, covering 190 villages under CRA project. ○ Data from farmer-participatory trials demonstrated real-world applicability and benefits.	

- **Climate Resilience:**
 - Reduced methane (CH₄) and nitrous oxide (N₂O) emissions.
 - Improved adaptability to changing climate conditions through conservation agriculture practices.
- **Comparative Performance:**
 - Conservation agriculture practices (e.g., zero tillage and residue retention) outperformed conventional methods in productivity, resource efficiency, and environmental sustainability.
- **Data Analysis and Validation:**
 - Principal Component Analysis (PCA) used to identify correlations among energy use, emissions, and crop performance.
 - Uncertainty analysis ensured data reliability and robustness.
- **Publications and Documentation:**
 - Key findings validated and published in high-impact journals, ensuring scientific rigor and practical relevance.

Proposed stakeholders

1. **Farmers**
 - Small and marginal farmers adopting sustainable practices in rice-wheat-green gram cropping systems.
 - Large-scale farmers aiming to reduce costs and environmental impacts.
2. **Agricultural Institutions and Research Bodies**
 - Krishi Vigyan Kendras (KVKs) for technology dissemination and farmer training.
 - ICAR-Agricultural Technology Application Research Institute (ATARI), Patna, for regional adaptation and monitoring.
 - Dr. Rajendra Prasad Central Agricultural University, Pusa, for research collaboration and validation.
3. **Government and Policy Makers**
 - Department of Agriculture, Bihar, for promoting climate-resilient agriculture through policy frameworks.
 - National Innovations in Climate Resilient Agriculture (NICRA) for integrating this technology into broader CRA programs.
4. **Extension Agencies**
 - State and district-level agricultural extension services for large-scale demonstrations and capacity building.
 - NGOs focused on sustainable agriculture and environmental conservation.
5. **Agri-Tech Companies**
 - Organizations involved in producing and supplying tools for zero tillage, direct seeding, and residue management.

	○ Companies offering precision agriculture solutions for optimizing inputs like water and fertilizers. 6. Environmental Organizations ○ Agencies working on reducing greenhouse gas emissions and promoting carbon sequestration in agriculture. 7. Financial Institutions ○ Banks and microfinance organizations providing credit facilities for farmers to adopt conservation agriculture technologies. 8. Educational Institutions ○ Universities and agricultural colleges for research, curriculum integration, and capacity building in climate-Resilient agriculture. 9. International Organizations ○ Organizations like FAO and UNDP for promoting the technology as a model for sustainable agriculture in similar agro-ecological zones globally. 10. Farm Input Suppliers ○ Fertilizer, seed, and irrigation equipment providers supporting the technology's implementation.
Commercial potential, if any	This technology offers significant commercial potential due to its scalability, adaptability, and cost-effectiveness. Key aspects of its commercial viability include: 1. Scalable Adoption: ○ Can be implemented across 2.5 million hectares in North Bihar and similar agro-ecological zones. ○ Proven adaptability to diverse farming conditions, ensuring widespread utility. 2. Cost Savings for Farmers: ○ Reduction in production costs due to minimal tillage and optimized input usage. ○ Increased profitability through higher Benefit-Cost (B:C) ratios across all crops. 3. Market Demand: ○ Addresses growing demand for sustainable agriculture solutions. ○ Provides an effective model for reducing greenhouse gas emissions in agriculture. 4. Opportunities for Agri-Tech Companies: ○ Commercial production and sale of zero-till seeders, residue management equipment, and precision farming tools.

	- Development of advisory services and apps for farmers to monitor energy efficiency and environmental impact. 5. Environmental Incentives: - Aligns with carbon credit programs by reducing greenhouse gas emissions (23.46%). - Supports national and international climate goals, attracting government and NGO funding. 6. Economic Benefits for Stakeholders: - Potential for collaboration with private firms to market the technology and its components. - Boosts income for local service providers engaged in tillage, irrigation, and residue management operations. 7. Sustainability Appeal: - Appeals to consumers demanding climate-Resilient and eco-friendly farming products. - Can be integrated into branding for sustainably grown agricultural produce, enhancing marketability. 8. Global Replication: - Suitable for adoption in other regions with similar cropping systems and agro-climatic conditions, expanding its market reach. This technology not only offers a sustainable solution for enhancing productivity and reducing environmental impacts but also opens pathways for commercialization through partnerships with agricultural equipment manufacturers, input suppliers, and financial institutions.
Publications/photos/video clipping, if any	- Kumar, Tarun, Madhu Sudan Kundu, and Ratnesh Kumar Jha. "Impact of crop rotation and tillage operations on mitigating greenhouse gas emissions and evaluation of sustainability index in rice-wheat-green gram cropping system of north Bihar." <i>Journal of Environmental Management</i> 366 (2024): 121689. Published, NAAS rating – 15.70. - Adarsh, Anupam, Tarun Kumar, Kajol Kumari, Rajnesh Singh, Madhu Sudan Kundu, Ratnesh Kumar Jha, Jitendra Prasad, Anupma Kumari, Tej Pratap, and Ravindra Kumar Tiwari. "Enhancing Sustainability and Productivity of Rice-Wheat-Green Gram Cropping System through Alternative Tillage and Crop Establishment Approaches in North-Bihar." <i>International Journal of Plant Production</i> (2024): 1-15. Published NAAS rating – 8.50. - Tarun Kumar, Madhu Sudan Kundu, Santosh Kumar Gupta, and Ratnesh Kumar Jha (2024) Sustainable

	Tillage and Residue Management for Enhanced Soil Health and Productivity in North Bihar's Rice-Wheat-Green Gram System, Environment, Development and Sustainability. Accepted for publication, NAAS rating – 10.50. List of publication, photos/ video clips enclosed - Annexure II)
Any other information not covered above	NA

ANNEXURE I

Table 1 An overview of the different scenarios and their respective notations and management protocols will be provided.

Scenarios	Tillage			Crop establishment			Residue management				
	Paddy	Wheat	Green gram	Rice			Wheat	Green gram	Paddy	Wheat	Green gram
				Transplanting /Seeding	Seedling age	Spacing (cm)					
T5: ZTDSR-HSZTW-HSG	Zero-till direct seeded rice	Happy seeder wheat	HS greengram	DSR: Zero-till	Drill seeding	20 cm row spacing	Happy seeder	Happy seeder	One-third Incorporated	One-third retained on soil surface	Full Incorporated
T4: CTDSR-ZTW-ZTG	Rice-wheat seeder: Cultivator: 2 passes (dry tillage: DT) Rotavator: 1 pass Dry tillage: DT),	Zero tillage wheat	ZT greengram	DSR: Zero-till	Drill seeding	20 cm row spacing	Zero-till	Zero-till	One-third Incorporated	One-third retained on soil surface	Full Incorporated
T3: RWS-RWZTW-ZTG	Drum Seeder: Conventional till direct seeded rice (CTDSR)	Zero tillage wheat	ZT greengram	Rice-wheat seeder	-	20 cm row spacing	Rice-wheat seeder	Zero-till	5 % Incorporated	5 % Incorporated	Full Incorporated
T2 : LPTR-CTLW-LSG	Puddled line transplanted rice (LPTR)-	Conventional tillage line sown wheat (CTLW)	Conventional tillage line sown ZT: greengram	Broadcasting	21-25 days	20 x 20	Line sowing: 20 cm	Zero-till	5 % Incorporated	5 % Incorporated	Full Incorporated
T1: RPTR-BCW-BCG	Random puddled transplanted rice (RPTR)	Broadcasted wheat: Cultivator: 2 passe, Rotavator: 1 pass	Broadcasted: 1 pass Rotavator	Manual	21-25 days	Random	Broad-casting	Broad-casting	5 % Incorporated	5 % Incorporated	Nil

Table 2 shows the various crop management strategies performed under different circumstances within the rice-wheat-green gram cropping systems. The scenarios are marked as SN-1 through SN-5, and they incorporate diverse combinations of crop rotation, tillage methods, seed kinds, fertilizer application, and irrigation approaches. For a full explanation of each scenario, go to Table 4.

Management practices	Cropping system	SN-5	SN-4	SN-3	SN-2	SN-1
Field preparation	Rice	ZTDSR	CTDSR: (Same as SN-2)	RWS - (Same as SN-2)	LPTR - (Cultivator: 2 passes (dry tillage: DT) Rotavator: 1 pass Dry tillage: DT)	RPTR - (Cultivator: 2 passes (dry tillage: DT) Rotavator: 1 pass Dry tillage: DT, Rotavator: 1 pass wet tillage: WT)
	Wheat	HSZTW	ZTW	RWZTW - (Same as SN-2)	CTLW - (Same as SN-1)	BCW - (Cultivator: 2 passes (dry tillage: DT) Rotavator: 1 pass Dry tillage: DT)
	Green gram	HSG	ZTG	ZTG	LSG - (Same as SN-1)	BCG - (Cultivator: 2 passes (dry tillage: DT) Rotavator: 1 pass Dry tillage: DT)
Seed rate (kg ha ⁻¹)	Rice	20	20	20	25	25
	wheat	100	100	100	120	120
	Green gram	20	20	20	25	25
Crop geometry	Rice					
	Wheat	22–20 cm	22–20 cm	22–20 cm	22–20 cm	Random geometry
	Green gram					
Fertilizer (N:P:K) in kg ha ⁻¹	Rice	Rice-140:60:40;	Rice-140:60:40;	Rice-150:60:60;	Rice-160:60:60;	Rice-160:60:60;
	Wheat	Wheat-120:60:40	Wheat- 120:60:40	Wheat- 150:60:40	Wheat- 160:60:40	Wheat- 160:60:40
	Green gram	GG-20:30:20	GG-20:40:30	GG-20:40:40	GG-20:40:40	GG-20:40:40
Water management	Rice	4 Irrigations	4 Irrigation	5 Irrigations	5 Irrigations	5 Irrigations
	Wheat	3 Irrigations	3 Irrigations	4 Irrigations	4 Irrigations	4 Irrigations
	Green gram	-	1 Irrigations	1 Irrigations	1 Irrigations	1 Irrigations

Table 3 The energy equivalents and greenhouse gas emission factors for different agronomic inputs in various agricultural activities kg CO₂ eq. per unit of input. (Babu et. al. 2020; Jat et. al. 2021; Mishra et. al. 2021; Islam et. al., 2022; Zhang et. al., 2023).

Sr. No.	Inputs	Unit	Energy equivalent (MJ Unit ⁻¹)	Unit	Emission factor (kg CO ₂ eq. per unit of input)	Unit	N ₂ O	CH ₄
1	Human labour	Man-hour	1.96	h	0.7			
2	Diesel	Liter	56.31	Liter	2.68	g/liter	0.7	5.2
3	Nitrogen (N)	Kg.	66.14	N (kg)	4.95	g/kg.	11.5	3.7
4	Phosphorus (P ₂ O ₅)	Kg.	22.44	P (kg)	0.73	g/kg.	0.29	1.8
5	Potassium (K ₂ O)	Kg.	11.15	K (kg)	0.545	g/kg.	0.002	1.1
6	GWP CO ₂ equivalence factor	-	-	-	1		310	21
7	Herbicides, insecticides and pesticides	Kg.	120.56	Herbicides (kg a.i. ⁻¹)	24.2			
8	Irrigation water	cum	1.02	-	-			
9	wheat seed	kg.	14.7	kg.	0.58			
10	Maize	kg.	14.7	kg.	1.93			
11	Mustard	kg.	22.72	kg.	1.22			
12	Lentil/Green gram	kg.	23.8	kg.	0.43			
13	Tractor	Kg.	93.61	Mj	0.71			
	Farm machinery	Kg.	62.7	Hr	3.32			
14	Output							
15	Wheat seed	kg.	14.7	kg.	0.58			
16	Maize	kg.	14.7	kg.	1.93			
17	Mustard	kg.	22.72	kg.	1.22			
18	Lentil/Green gram	kg.	23.8	kg.	0.43			

Table 4 The energy use patterns assessed in (MJ ha⁻¹) for different management approaches in rice, wheat, and green gram agriculture, averaged over a three-year period. SN-5, SN-4, SN-3, SN-2, and SN-1 reflect distinct management situations in rice, wheat, and green gram agriculture, respectively. The acronyms used in the scenarios reflect particular techniques performed in each circumstance. The values highlighted with distinct uppercase letters (a-d) show significant differences across scenarios at a significance level of $p < 0.05$.

Scenarios	Field operations			Agronomic inputs				Labor		Harvesting & threshing	Transportation
	Tillage	Puddling	Sowing/ transplanting	Seed	Fertilizers	Pesticides	Irrigation	Weeding	Input application		
Paddy											
SN-5	0.00	0.00	438.34	235.20	9729.20 ^a	330.00	13056.00 ^a	15.68	150.92 ^a	1128.31	353.40
SN-4	1860.26	836.42	575.41	264.60	9729.20 ^a	330.00	13056.00 ^a	15.68	156.80 ^a	1128.31	353.40
SN-3	1937.29	0.00	630.12	264.60	11713.40 ^b	390.00	13056.00 ^a	19.60	176.40 ^b	1128.31	353.40
SN-2	2008.92	936.34	825.80	294.00	12374.80 ^c	420.00	20400.00 ^b	25.48	180.32 ^c	1128.31	353.40
SN-1	2096.08	955.37	851.73	323.40	12374.80 ^c	450.00	20400.00 ^b	35.28	186.20 ^c	1128.31	353.40
Green Gram											
SN-5	0	-	535	294	2438.78 ^a	210	1467.87 ^a	3.92	113.68 ^a	728.635	315.62
SN-4	0	-	535	294	2438.98 ^a	210	1738.40 ^b	3.92	115.64 ^b	728.635	315.62
SN-3	0	-	538	307	2496.56 ^b	239	1849.56 ^c	4.35	118.36 ^b	728.635	315.62
SN-2	2268.45	-	565	323	2551.15 ^c	270	1958.90 ^c	5.88	125.44 ^c	728.635	315.62
SN-1	2366.88	-	450	367	2551.17 ^c	300	2191.17 ^d	7.84	129.36 ^c	728.635	315.62
Wheat											
SN-5	0.00	-	686.60	1323.00	9729.20 ^a	330.00	2895.07 ^a	3.92	103.88 ^a	871.12	325.24
SN-4	0.00	-	678.78	1323.00	9729.20 ^a	330.00	3099.08 ^b	3.92	105.84 ^a	871.12	325.24
SN-3	1536.48	-	837.81	1470.00	11052.54 ^b	390.00	3490.53 ^c	5.88	111.72 ^b	871.12	325.24
SN-2	1668.79	-	820.17	1617.00	11184.28 ^c	420.00	3777.82 ^d	7.84	117.60 ^c	871.12	325.24
SN-1	1733.54	-	846.74	1764.00	11713.40 ^d	420.00	3807.67 ^d	9.80	119.56 ^c	871.12	325.24

Table 5 Effect of crop establishment techniques and tillage on energy metrics in the rice-wheat-green gram system (2020–2023). The values highlighted with distinct uppercase letters (a-d) show significant differences across scenarios at a significance level of $p < 0.05$.

Scenarios	Total energy input (MJ ha ⁻¹)			Energy output (MJ ha ⁻¹)			Net energy (MJ ha ⁻¹)		
	Rice	Wheat	Green gram	Rice	Wheat	Green gram	Rice	Wheat	Green gram
SN-1	20289.64 ^c	15794.91 ^c	6435.40 ^{cd}	210063.79 ^c	157481.19 ^d	41157.09 ^c	204881.95 ^c	141686.28 ^c	34721.69 ^c
SN-2	22222.13 ^c	15866.98 ^{cd}	6650.77 ^c	191288.40 ^{cd}	151212.63 ^{cd}	36741.77 ^d	181138.04 ^c	135345.66 ^b	30091.00 ^{cb}
SN-3	23608.74 ^d	18768.79 ^d	7754.55 ^d	167551.15 ^d	122248.30 ^d	34194.47 ^c	152651.31 ^{cd}	103479.51 ^c	26439.92 ^d
SN-4	26021.98 ^a	19247.21 ^a	8042.99 ^a	150157.83 ^b	113362.47 ^a	29676.05 ^a	129751.85 ^c	94115.27 ^{ab}	21633.06 ^{ab}
SN-5	26356.07 ^a	19990.53 ^a	8032.18 ^a	139095.41 ^a	102751.11 ^a	31689.63 ^{ab}	116928.59 ^a	82760.58 ^a	23657.45 ^a
Scenarios	Energy use efficiency (MJ ha ⁻¹)			Grain energy productivity (MJ ha ⁻¹)			Specific energy (MJ ha ⁻¹)		
	Rice	Wheat	Green gram	Rice	Wheat	Green gram	Rice	Wheat	Green gram
SN-1c	10.35 ^c	9.97 ^c	6.40 ^c	0.29 ^c	0.35 ^c	0.21 ^c	3.51 ^c	2.85 ^c	4.72 ^c
SN-2	8.61 ^{cd}	9.53 ^d	5.52 ^{cd}	0.23 ^c	0.33 ^{cd}	0.18 ^d	4.45 ^d	3.14 ^{cd}	5.52 ^c
SN-3	7.10 ^{cd}	6.51 ^d	4.41 ^d	0.21 ^d	0.24 ^d	0.15 ^d	4.87 ^c	4.23 ^c	6.88 ^{cd}
SN-4	5.77 ^{ab}	5.89 ^{ab}	3.69 ^a	0.16 ^a	0.21 ^{ab}	0.12 ^{ab}	6.12 ^a	4.67 ^a	7.65 ^b
SN-5	5.28 ^a	5.14 ^a	3.95 ^a	0.15 ^a	0.19 ^a	0.11 ^a	6.58 ^a	5.27 ^a	8.21 ^a

Table 6 The rice-wheat-green gram cropping system's total energy intake (in MJ ha⁻¹), broken down into direct, indirect, renewable, and non-renewable sources. The statistical significance shown by individual capital letters (a–d) indicates differences between circumstances at a significance level of $p < 0.05$.

Scenarios	Total Direct Energy			Total Indirect Energy		
	Rice	Wheat	Green gram	Rice	Wheat	Green gram
SN-1	6591.40 ^d	5434.71 ^d	4711.08 ^d	10703.83 ^c	12363.46 ^d	3924.16 ^d
SN-2	8852.75 ^d	5469.33 ^{cd}	4926.45 ^c	10590.28 ^{cd}	12363.46 ^{cd}	3924.16 ^{cd}
SN-3	8394.12 ^c	6841.35 ^c	5828.63 ^c	12634.48 ^c	13893.26 ^c	4125.76 ^c
SN-4	9799.49 ^a	7010.48 ^{ab}	6042.97 ^{ab}	13355.28 ^b	14202.54 ^b	4199.86 ^a
SN-5	10015.87 ^a	7077.69 ^a	6210.00 ^a	13414.68 ^a	14878.66 ^a	4248.56 ^a

Scenarios	Total Renewable energy			Total Non-Renewable energy		
	Rice	Wheat	Green gram	Rice	Wheat	Green gram
SN-1	2944.95 ^d	1956.98 ^d	731.40 ^d	14369.88 ^d	13837.94 ^d	4722.75 ^d
SN-2	3075.09 ^{cd}	1996.38 ^{cd}	733.36 ^d	16387.53 ^c	13870.60 ^d	4936.16 ^{cd}
SN-3	3100.18 ^c	2170.82 ^c	772.56 ^c	17953.89 ^c	16597.97 ^c	6000.74 ^c
SN-4	3301.75 ^{ab}	2308.02 ^a	822.54 ^{ab}	19878.49 ^a	16939.19 ^b	6239.20 ^b
SN-5	3334.60 ^a	2458.94 ^a	889.56 ^a	20127.31 ^a	17531.59 ^a	6357.65 ^a

Table 7 Rice, wheat, and green gramme cropping systems are assessed for their potential to contribute to global warming in kg CO₂ equivalent per hectare (due to diesel, power, fertilizers, herbicides, methane, and nitrous oxide) in Table 4 during three years (2020–2023).

Scenarios	Crop	Deisel	N	P ₂ O ₅	K ₂ O	Pesticides in Liter (kg)	Total CO ₂	Methane (CH ₄)	Nitrous oxide (N ₂ O)	Total GWP
SN-5	Rice	252.99	693.00	43.80	21.80	66.55	1078.14	1156.88	71.88	2611.70
	Wheat	222.44	594.00	43.80	21.80	66.55	948.59	0.00	63.3	2128.67
	Green gram	132.66	123.75	25.55	0.00	42.35	324.31	0.00	36.1	570.16
	Total						2351.04	1156.88	171.28	5310.53
SN-4	Rice	407.39	693.00	43.80	21.80	66.55	1232.54	1256.46	112.20	2855.70
	Wheat	233.16	594.00	43.80	21.80	66.55	959.31	0.00	66.12	2139.39
	Green gram	147.27	123.75	25.55	0.00	42.35	338.92	0.00	39.92	584.77
	Total						2530.77	1256.46	218.22	5579.86
SN-3	Rice	382.97	742.50	43.80	21.80	78.65	1269.72	1446.08	106.13	2991.22
	Wheat	295.20	668.25	43.80	21.80	78.65	1107.70	0.00	82.76	2435.29
	Green Gram	141.64	123.75	25.55	0.00	42.35	333.29	0.00	38.45	579.14
	Total						2710.71	1446.08	227.33	6005.65
SN-2	Rice	524.78	792.00	43.80	21.80	84.70	1467.08	1758.23	143.47	3398.92
	Wheat	351.62	668.25	43.80	21.80	84.70	1170.17	0.00	97.49	2497.76
	Green Gram	184.25	123.75	29.20	0.00	54.45	391.65	0.00	49.68	637.50
	Total						3028.90	1758.23	290.63	6534.18
SN-1	Rice	532.19	792.00	43.80	21.80	90.75	1480.54	1772.61	145.41	3412.38
	Wheat	358.24	693.00	43.80	21.80	84.70	1201.54	0.00	99.37	2578.30
	Green Gram	195.51	123.75	29.20	0.00	60.50	408.96	0.00	52.62	654.81
	Total						3091.04	1772.61	297.39	6645.49

Table 8 presents a comprehensive analysis of Soil Quality Indices (SQIs) for distinct soil properties impacted by various residue and tillage-based crop establishment techniques within the 0-15 cm soil layer.

SQI class	SQI-2018			SQI-2023			Treatment under different SQIs class
	SQI Value as per AHP	Area ha.	Area in percentage	SQI Value as per AHP	Area ha.	Area in percentage	
High quality	0.546-0.684	47.58	14.52	0.826 - 0.985	72.17	22.03	T5 and T4
Moderately high quality	0.365 -0.546	67.54	20.62	0.684 - 0.826	48.76	14.88	T4 and T3
Marginally quality	0.247 -0.365	49.87	15.22	0.428 - 0.684	62.74	19.15	T3 and T2
Moderately low quality	0.127-0.247	78.95	24.10	0.253 -0.428	81.27	24.81	T2
Low quality	0.00-0.127	83.65	25.53	0.00-0.253	62.65	19.12	T1
Total		327.59	100.00		327.59	100.00	

**Complete SQI framework encompassing these three soil property characteristics
will give a more accurate depiction of soil health, resulting to enhanced
productivity and sustainability**

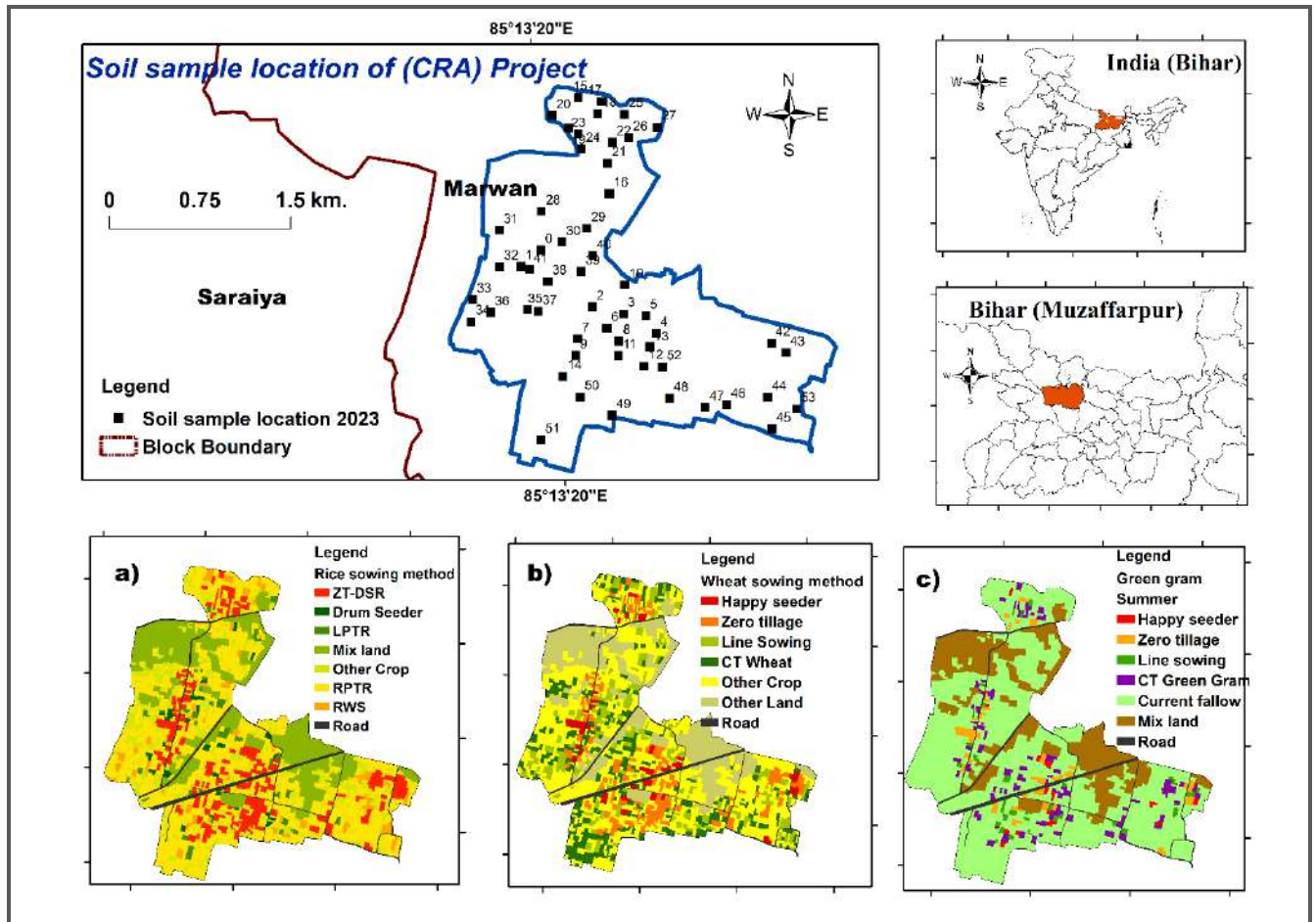


Fig. 1: Experimental location map of Dawarikanathpur, Bhagwatpur, and Karja Anath village, Madwan block, Muzaffarpur, showing different tillage-based establishment of crops and residue management strategies during a) Kharif season, b) Rabi season, and c) Summer season.

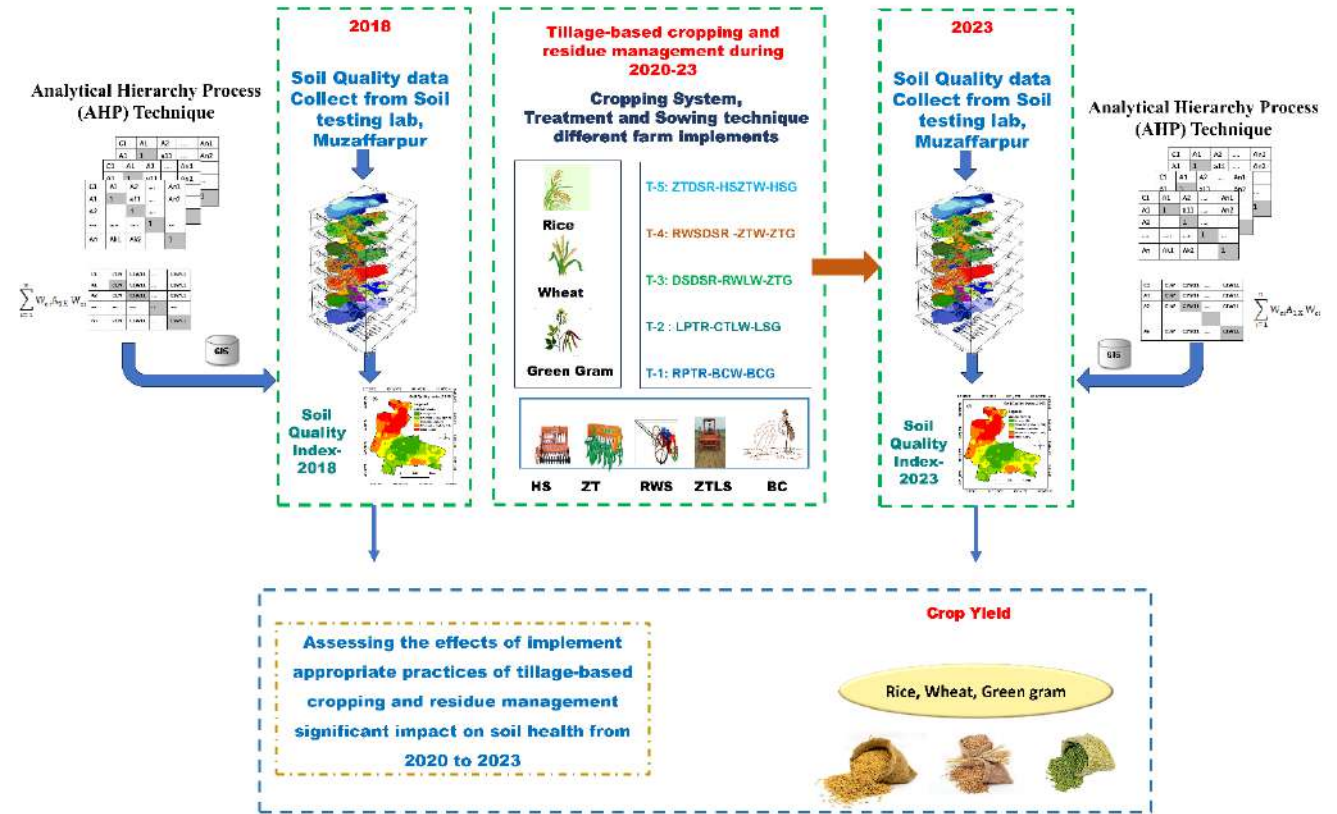
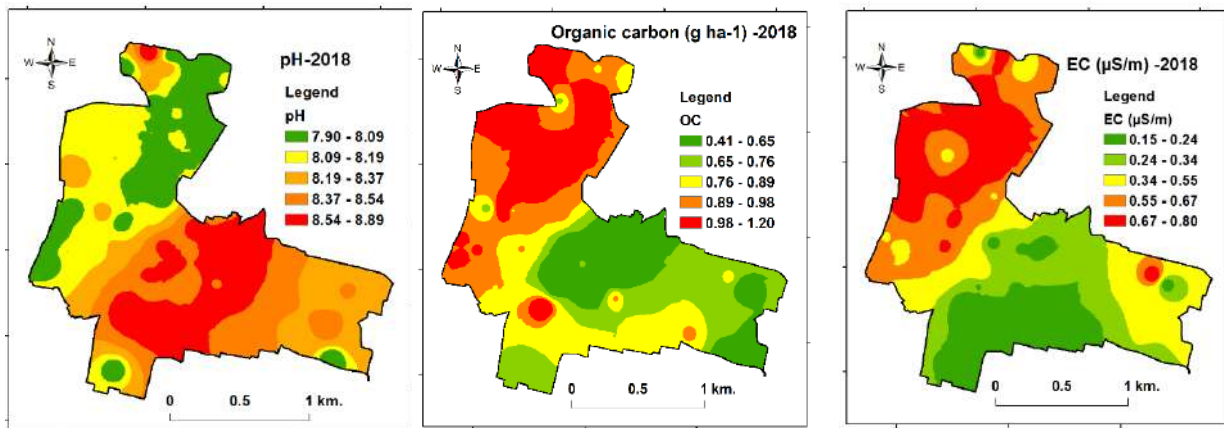


Fig. 2: Overview of the treatments, tillage methods, crop establishment practices, and crop residue management practices implemented in the RWG cropping system.



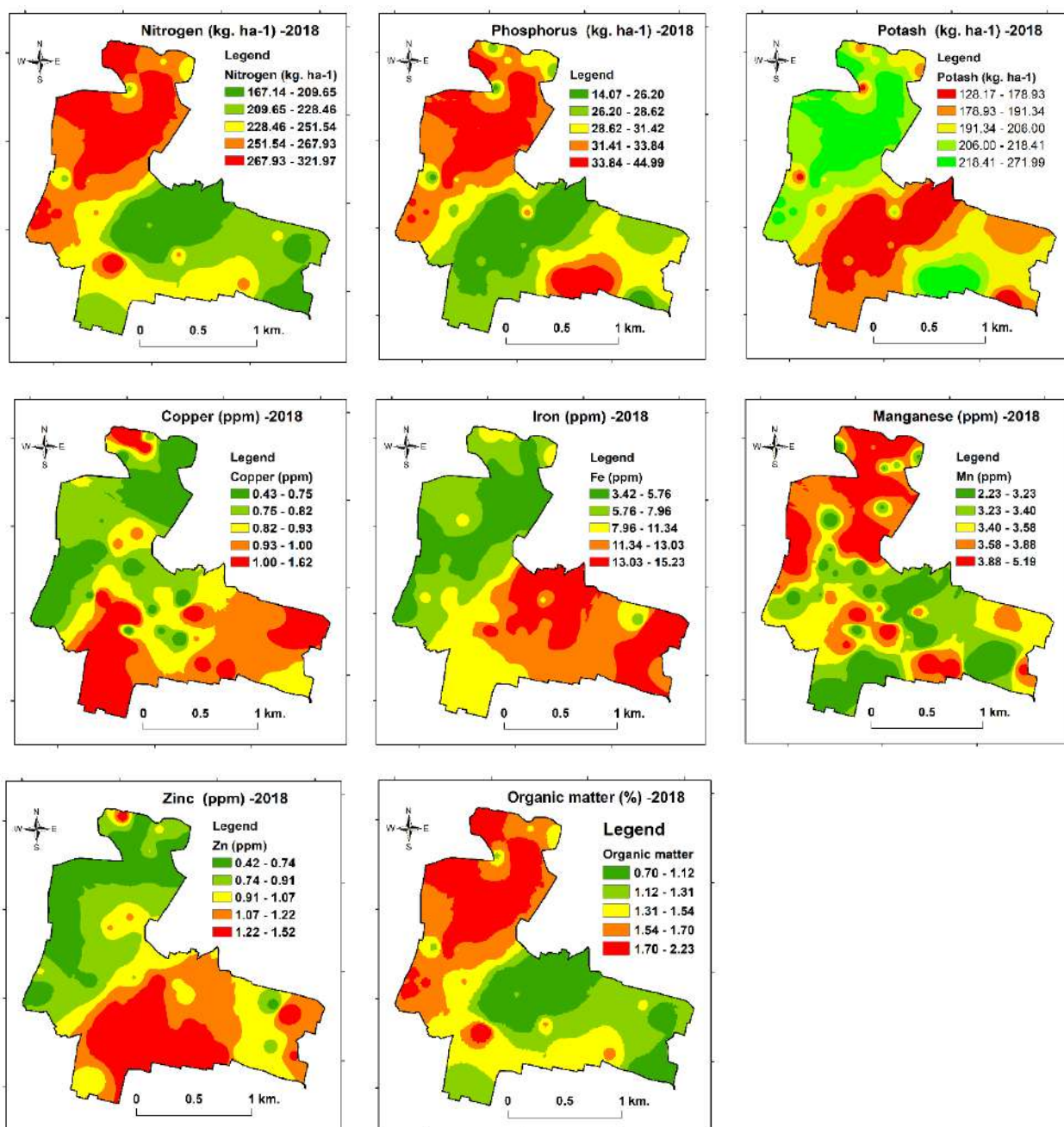
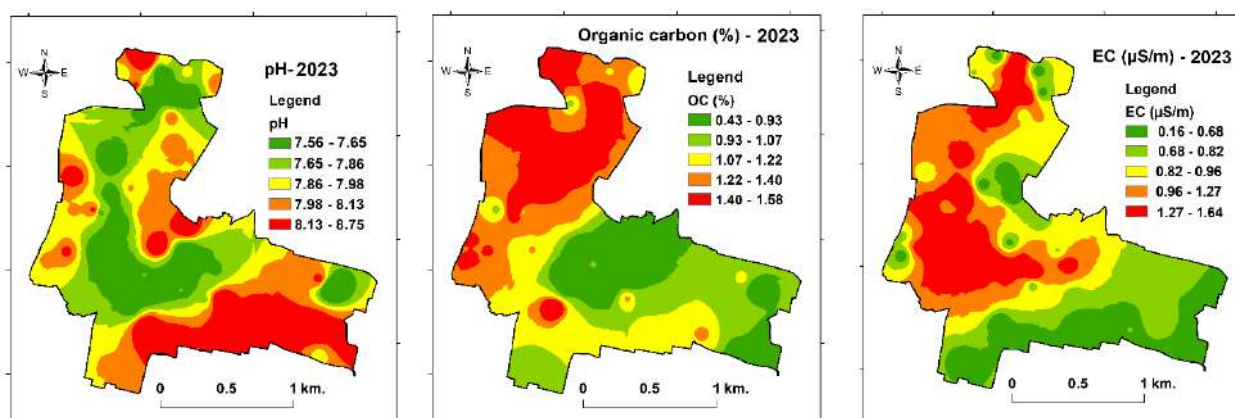


Fig. 3 Spatial distribution maps of selected soil quality parameters in the 0–15 cm soil layers during 2018.



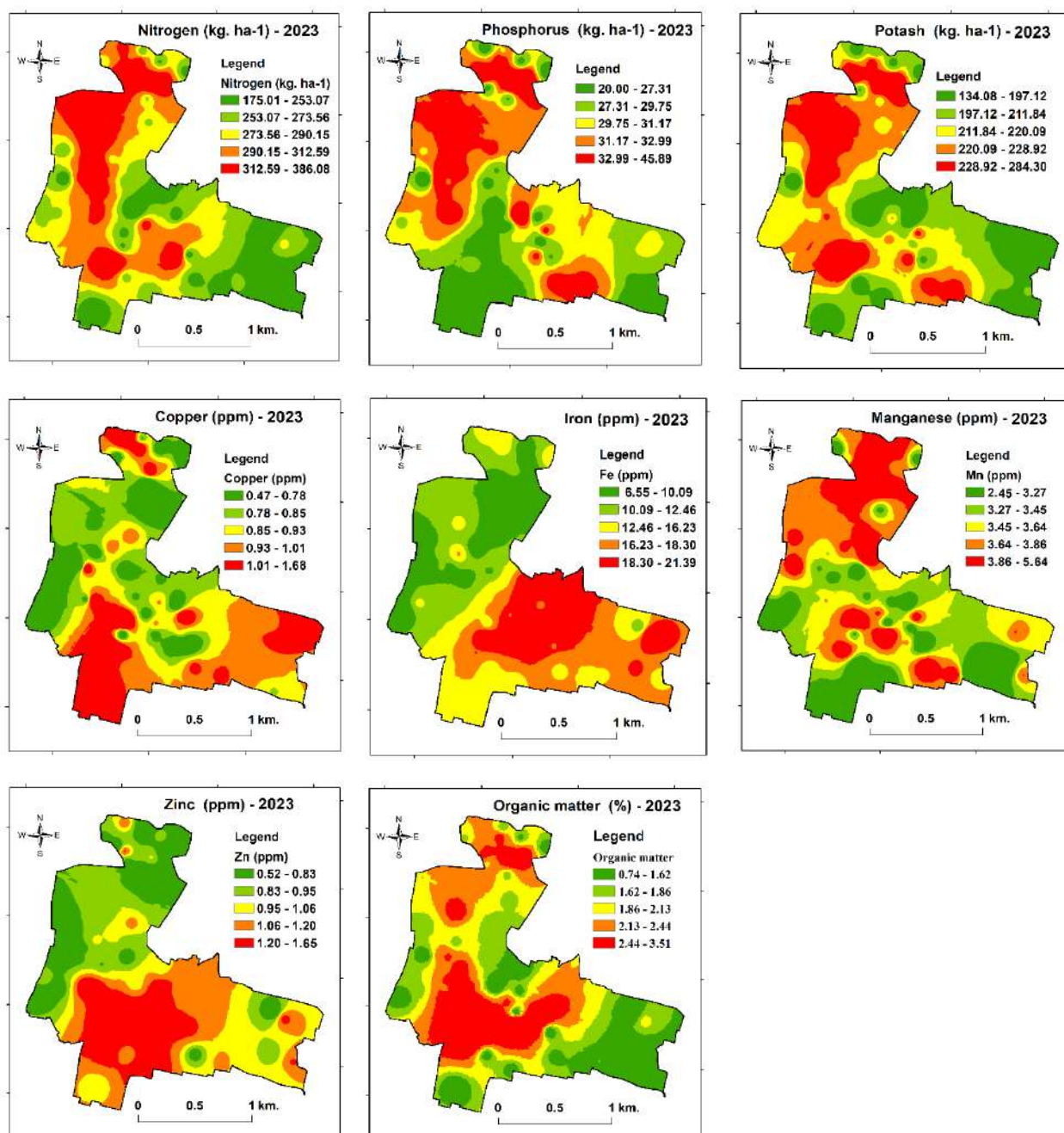


Fig. 4 Spatial distribution of selected soil quality parameters for rice-wheat-green gram cropping system's 0–15 cm of soil depth during 2023, showcasing the impact of different treatments on soil characteristics.

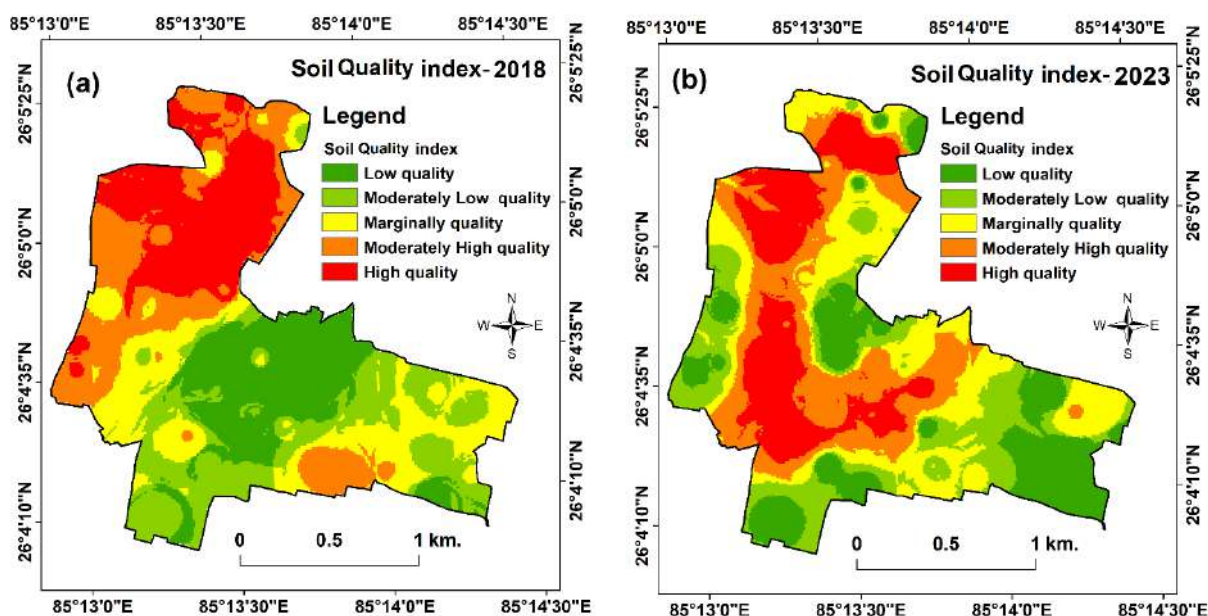


Fig. 5 The geographical distribution pattern of Soil Quality Indices (SQIs) for different soil qualities in the top 0-15 cm soil layer. The SQIs are impacted by various residue and tillage-based crop establishment treatments. The chart displays the distribution pattern for both the year a) for 2018 and b) for 2023.

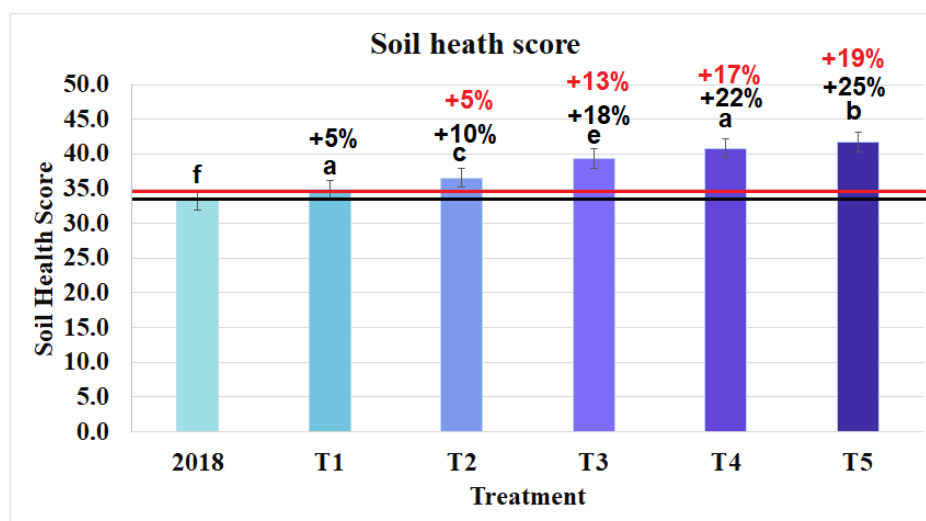


Fig. 6 The Soil Health Assessment (SHA) for various rotation regimes. The Analytical Hierarchy Process (AHP) was used to calculate the eigenvalues of eleven essential soil properties, including pH, EC, OC, N, P, K, Zn, Cu, Fe, Mn, and OM. Each of these variables was standardized as an independent contributor to the total soil health score. A one-way ANOVA with two-sided and post-hoc tests was undertaken to examine the significance across different treatments. In the illustration, distinct lowercase letters represent statistically different sets of crop rotations with a significance threshold of $P < 0.05$. The red dashed line with red percentages is the baseline of the T1: RPTR-BCW-BCG rotation, whereas the black dashed line with black percentages represents the baseline of 2018.

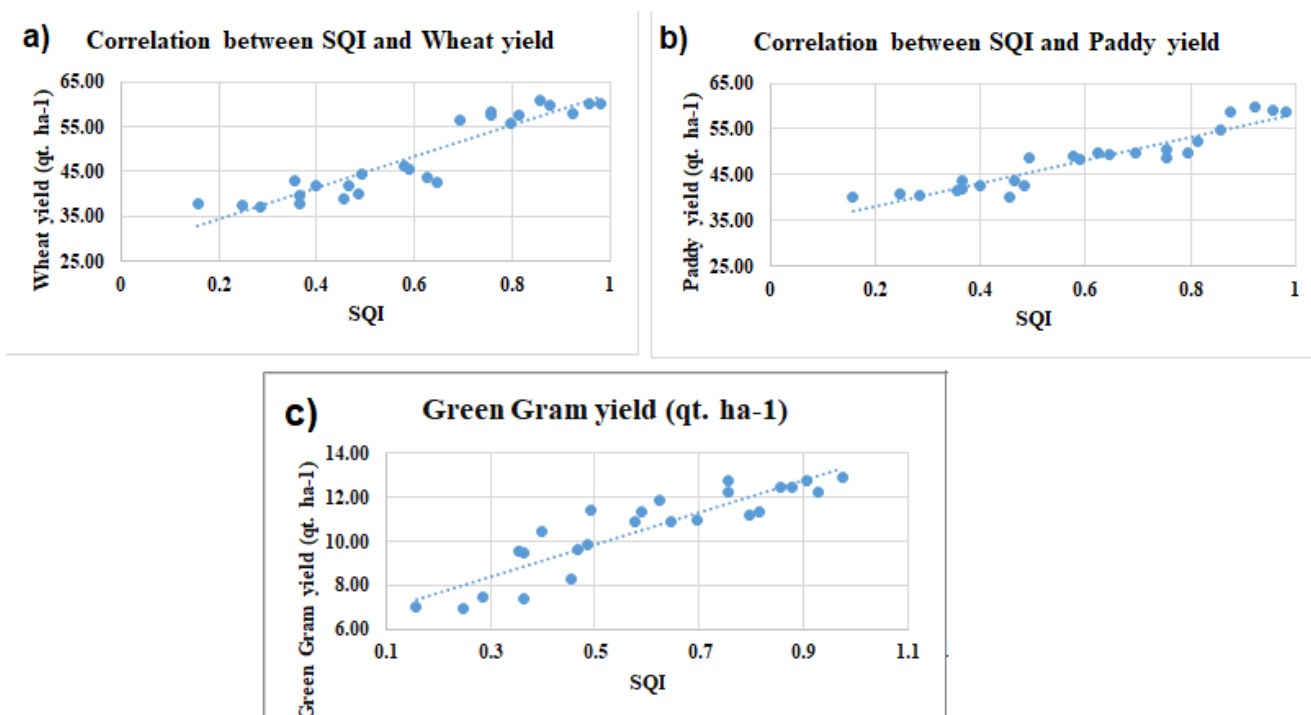


Fig. 7 The correlation between the soil quality index (SQI) in 2023 and the yield of the rice-wheat-green gram cropping system at the soil depth of 0-15 cm.

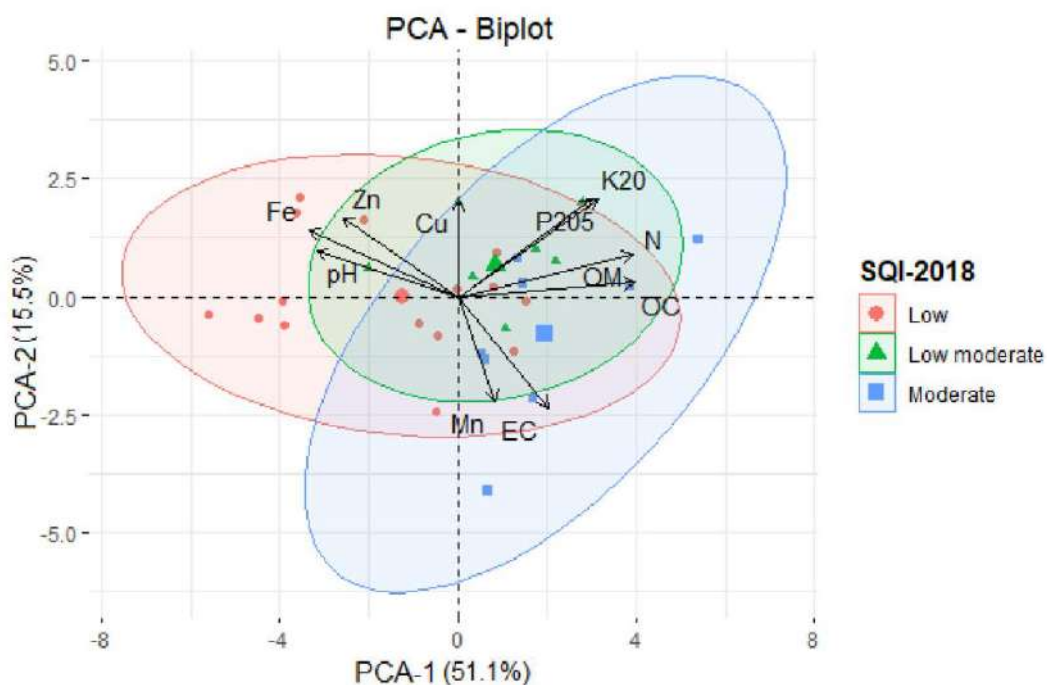


Fig. 8 Principal Component Analysis (PCA) results and biplots showing the scores (soil fertility indicators) represented by Soil Quality Index (SQI) categories: Low, Low Moderate, and Moderate. PCA-1 and PCA-2 represent the two principal components.

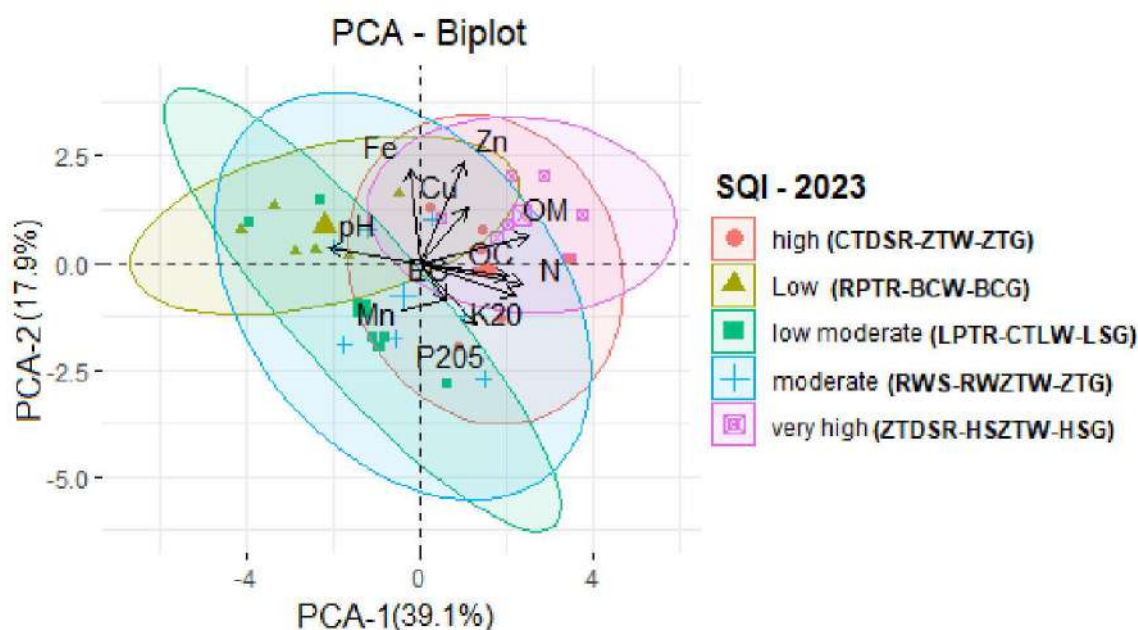


Fig. 9 Principal Component Analysis (PCA) results and biplots illustrating the scores (soil fertility indicators) categorized by Soil Quality Index (SQI) classes Low, Low Moderate, Moderate High, and Very High. The figure showed the significant effects of different implemented appropriate practises for tillage and residue management strategies on soil quality indicators. PCA-1 and PCA-2 represent the two principal components.

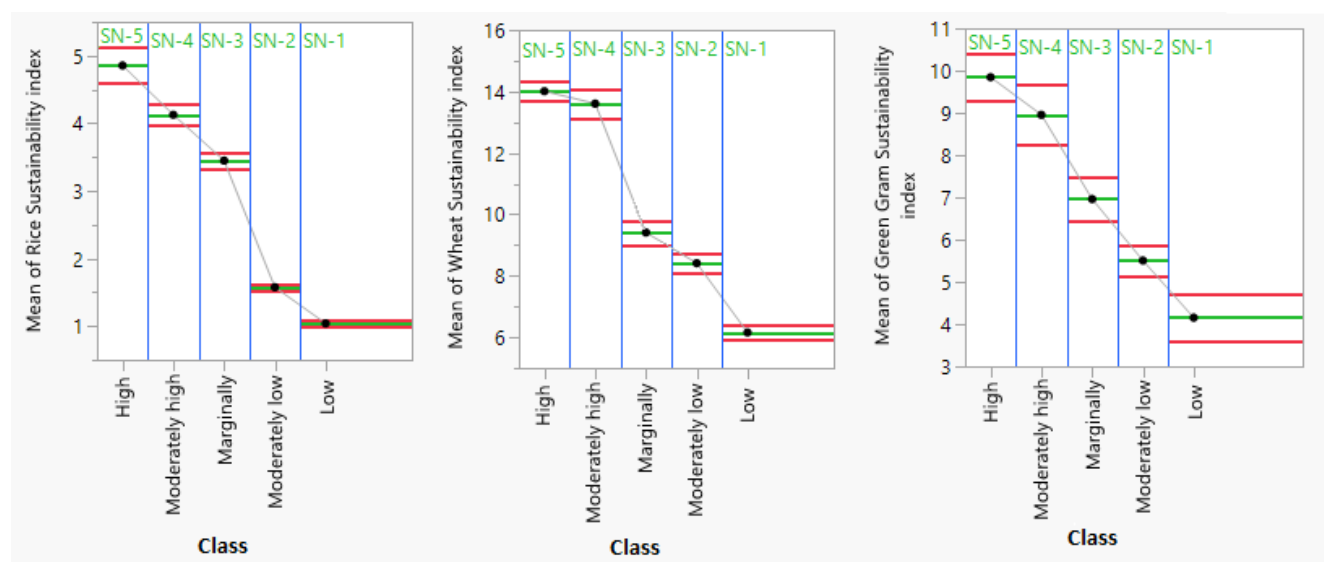


Fig. 10. Evaluation of the carbon ratio (kg C ha^{-1}) between input and output as well as the calculation of the sustainability index class (High to Low) for the rice, wheat, and green gram cropping system.

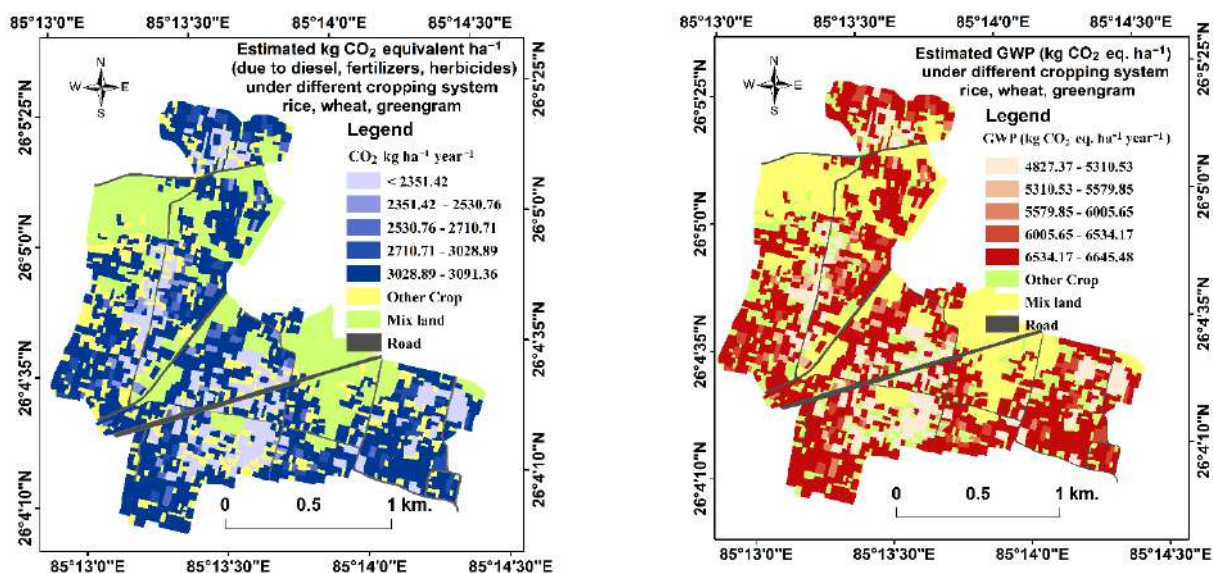


Fig. 11. Geographical distribution, a) kg CO₂ equivalent per hectare, due to the use of diesel, application of fertiliser, use of herbicides, emission of methane, and emission of nitrous oxide. b) Field-wise global warming potential of various farming systems, including rice, wheat, and green gram crop.

ANNEXURE II

	
ZT Green gram	Green gram crop residue management by happy seeder
	
DSR paddy field	Crop cutting (Field Day)
	
DSR paddy field	Use of “LCC” in paddy field for nutrient management

	
DSR technology used in sowing of paddy at Dwarikanathpur village.	Paddy sowing by “rice wheat seeder” DSR paddy
	
Crop cutting (Field Day)	Crop cutting (Field Day)
	
Zero Tillage wheat	Line sowing wheat



Crop cutting (Field Day)



Wheat sowing by Happy seeder (ZT)



Wheat sowing by Happy seeder (ZT)

ACKNOWLEDGEMENT:

The generous financial support from the Government of Bihar through the Climate Resilient Agriculture (CRA) initiative is sincerely appreciated. Gratitude is extended to Dr. P. S. Pandey Hon'ble Vice-Chancellor of Dr. Rajendra Prasad Central Agricultural University (RPCAU), Pusa, Bihar, for the leadership and support provided during this study. The invaluable guidance and collaboration facilitated by the Director of Research, RPCAU, were crucial in enabling the research efforts.

The unwavering support and provision of necessary facilities by RPCAU have been instrumental in the successful execution of this study. The progress and success of this work were made possible through the contributions and involvement of all stakeholders, for which sincere thanks are conveyed.