Carbon Footprint Assessment of Precision Nutrient Management in Rice-Based Cropping Systems Using Life Cycle Assessment (LCA)

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ABSTRACT
Background: Rice farming is a significant source of greenhouse gases from agriculture, especially methane and nitrous oxide. Precision nutrient management could solve these problems through nitrogen efficacy and reduced emissions, but it needs more investigation into its potential advantages for sustainability.
Objectives: This study evaluated the impacts of alternative nutrient management practices on carbon footprint, energy use and environmental impacts in irrigated rice-based systems using Life Cycle Assessment (LCA).
Materials and Methods: The farmers' practice, site-specific nutrient management (SSNM), Nutrient Expert® and sensor-based variable-rate PNM treatments were compared in a two-year field experiment using a randomized complete block design. A cradle-to-farm-gate LCA was conducted according to ISO 14040/14044 standards for determining the greenhouse gas emissions, energy demand, acidification and eutrophication potential.
Results: Sensor-based PNM and Nutrient Expert® increased grain yield by 22% and 19%, respectively, and reduced carbon footprint by 38% and 27%, respectively, compared with farmers' practice. Lower emission intensity was partly driven by lower N 2 O emissions and improved nitrogen-use efficiency. The main environmental hotspots identified were fertilizer production and N2O emissions at field level.
Conclusion: Rice production can be more environmentally friendly without losing productivity or profit through precise management of nutrients. Digital decision-support tools and improved nutrient strategies can speed up the transition to sustainable, low-carbon rice-based agriculture.

Keywords: Carbon footprint, Life Cycle Assessment, precision nutrient management, rice-based cropping systems, greenhouse gas mitigation, nitrogen-use efficiency, climate-smart agriculture, sustainable intensification

1. Introduction
1.1. Global Importance of Rice-Based Cropping Systems
More than half of the world's population depends on rice-based cropping systems, such as rice-wheat, rice-rice and rice-rice-legume sequences, for food security (Buresh *et al*., 2010; Peng *et al*., 2010) [8, 11]. These systems are grown on more than 160 million ha in Asia, sub-Saharan Africa and Latin America (Buresh *et al*., 2010) [8]. These systems are more than a staple calorie source; they are the bedrock of rural livelihoods, employment and cultural identity in many smallholder-dominated economies (Peng *et al*., 2010) [11]. However, the hydrological and management conditions that make rice uniquely productive under flooded culture - prolonged soil saturation, high input intensity, and multiple cropping per year - also make rice-based systems disproportionately important to agricultural greenhouse gas (GHG) budgets, creating an urgent need to reconcile continued productivity growth with climate mitigation commitments (IPCC, 2021; Linquist *et al*., 2012; Yan *et al*., 2009) [4, 5, 6].

1.2. Agricultural Greenhouse Gas Emissions
Agriculture, forestry and land-use change together contribute a substantial proportion of anthropogenic GHG emissions (IPCC, 2021) [4]. Crop and livestock production alone constitute a large share of global non-CO2 emissions, mainly as methane (CH4) and nitrous oxide (N2O) (IPCC, 2019; IPCC, 2021) [3, 4]. In crop agriculture, flooded rice cultivation is often mentioned as a major single-crop source of CH4, whereas the use of nitrogenous fertilizers in all cereal systems is the primary driver of direct and indirect N2O emissions (Yan *et al*., 2009; Pittelkow *et al*., 2013) [6, 7]. Upstream processes such as fertilizer and pesticide manufacture, fuel combustion in irrigation pumps and farm machinery, and transportation of inputs, add another level of embodied carbon, which is often excluded from field-level emission inventories but is necessary for a complete life-cycle accounting of the carbon footprint of rice production (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015) [1, 2, 21].

1.3. Climate Change Impacts on Rice Production
Rice production is both a victim and a culprit of climate change (IPCC, 2021) [4]. The principal producing areas will see reductions in rice yields and increased variability in those yields from the projected impacts of climate change, including higher average temperatures, shifts in monsoon timing, more frequent intense rainfall events and droughts, and salt-water intrusion into

coastal deltas due to rising sea levels (IPCC, 2021) [4]. High temperatures at night in particular have been associated with spikelet sterility and reduced grain filling, while erratic precipitation alters the precise water management on which flooded rice culture depends (IPCC, 2021) [4]. This feedback loop means climate change erodes the system that contributes to its cause, strengthening the case for mitigation strategies that do not compromise and, ideally, improve productivity and resilience.

1.4. Methane Emissions from Paddy Fields

Rice farming leads to anthropogenic emissions of methane as a result of methanogen activity, especially when it comes to soils flooded over an extended period and resulting into anaerobic fermentation (Yan *et al*., 2009; Sander *et al*., 2014) [6, 22]. Determinants of methane emissions include the type and schedule of organic amendments used manipulation of soil redox potential as well as the quantities of root exudates produced by different rice strains (Yan *et al*., 2009; Sander *et al*., 2014; Islam *et al*., 2020) [6, 22, 12].

1.5. Nitrous Oxide Emissions

Nitrous oxide is generated as a result of coupled nitrification-denitrification processes that are sensitive to soil moisture, the presence of mineral nitrogen, and the timing of drainage in the case of flooded systems (IPCC, 2019; Sander *et al*., 2014) [3, 22]. Due to the fact that paddy soils cycle between anaerobic and aerobic phases, particularly in the case of AWD or mid-season drainage, they can generate high amounts of Nitrous oxide during these transition periods, making the importance of timing in the application of water for irrigation (Sander *et al*., 2014; Islam *et al*., 2020) [22, 12]. If excessive Nitrogen is applied at the wrong time, then it can be left in the soil profile at times when the crop does not need it so much, which means that precision, not just the amount of nutrient applied is paramount in the determination of the GHG emission potential (Peng *et al*., 2010; Chivenge *et al*., 2021; Pittelkow *et al*., 2013) [11, 10, 7].

1.6. Carbon Dioxide Emissions

CO2 fluxes or releases from flooded paddy soils may be justifiable as climate-neutral over short periods since they represent the recycling of carbon produced by the most recent photosynthesis (IPCC, 2019) [3]. However, the reality is that rice-based systems involve something much bigger than simply CO2 emissions out of flooded paddy fields (Mohammadi *et al*., 2015; Roy *et al*., 2021) [21, 14]. The biggest part of life-cycle CO2 emissions in rice-based systems comes from the combustion or burning of fossil fuels, which occurs during various irrigation activities and also during land preparation for planting rice, harvesting and even during transportation (ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 21, 14]. These invisible emissions of CO2, actually sometimes accounted up to the volume of rice produced, make this topic very interesting for further exploration and calculations (Mohammadi *et al*., 2015; Cheng *et al*., 2011) [21, 17].

1.7. Carbon Neutrality, Sustainable Intensification, and Climate-Smart Rice Production

Carbon neutrality in rice farming can be achieved by addressing three main issues simultaneously (IPCC, 2019; Roy *et al*., 2021) [3, 14]. Firstly, there is a need to reduce methane (CH4) and nitrous oxide (N2O) emissions from the fields (Yan *et al*., 2009; Pittelkow *et al*., 2013; Sander *et al*., 2014) [6, 7, 22]. Next, it is essential to decrease the amount of carbon in the purchased agricultural inputs (ISO, 2006; Mohammadi *et al*., 2015) [1, 21]. Finally, there will also be a need to enhance the soil organic carbon in the farmer's farmland through residue retention and the application of the correct ratio of nutrients (Cheng *et al*., 2011; Nayak *et al*., 2015) [17, 18]. Sustainable intensification addresses the challenge of increased agricultural yield without expanding cultivated land through increased output per hectare among other means (Chen *et al*., 2014) [15]. In such a case, climate-smart agriculture takes into account the productivity, adaptation, and mitigation (IPCC, 2021; Chivenge *et al*., 2021) [4, 10]. Precision nutrient management does lie between the two concepts above as it can help in decreasing the emissions while improving grain yields of rice farmers (Peng *et al*., 2010; Pampolino *et al*., 2012; Chivenge *et al*., 2021) [11, 9, 10].

2. Precision Nutrient Management in Rice-Based Systems

2.1. Definition and Principles

Precision nutrient management (PNM) refers to the practice of supplying crop nutrients in the right amount, form, timing, and placement to match spatially and temporally variable crop demand, in contrast to blanket fertilizer recommendations applied uniformly across fields and seasons (Peng *et al*., 2010; Pampolino *et al*., 2012) [11, 9]. The underlying principle is the '4R' stewardship framework - right source, right rate, right time, right place - which seeks to align nutrient supply with plant uptake curves so that the surplus mineral nitrogen available for gaseous loss or leaching is minimized while yield-limiting deficiencies are avoided (Peng *et al*., 2010; Chivenge *et al*., 2021) [11, 10]. In rice, where nitrogen-use efficiency (NUE) under conventional practice is frequently below 40%, this alignment carries particularly large agronomic and environmental leverage (Peng *et al*., 2010; Chivenge *et al*., 2021) [11, 10].

2.2. Site-Specific Nutrient Management (SSNM)

Site-specific nutrient management is a field-specific approach in which fertilizer nitrogen, phosphorus, and potassium rates are derived from the difference between the nutrient requirement of a targeted yield and the indigenous nutrient supply of the specific field, often estimated using omission-plot techniques or simplified proxies such as leaf color charts (Buresh *et al*., 2010; Peng *et al*., 2010) [8, 11]. By tailoring rates to field-level soil fertility status rather than regional averages, SSNM typically reduces total nitrogen application relative to farmers' practice while maintaining or increasing yield, translating directly into lower N2O emission potential and reduced embodied carbon from fertilizer manufacture (Peng *et al*., 2010; Chen *et al*., 2014; Zhang *et al*., 2013) [11, 15, 19].

2.3. The Nutrient Expert® Approach

Nutrient Expert® is a computer- or smartphone-based decision-support tool that operationalizes SSNM principles by combining a structured farmer interview on field history, crop establishment method, and residue management with algorithms that estimate attainable yield, indigenous nutrient supply, and nutrient-use efficiency to generate a field-specific fertilizer schedule within minutes (Pampolino *et al*., 2012; Buresh *et al*., 2010) [9, 8]. Field evaluations across South and Southeast Asia have generally reported that Nutrient Expert®-based recommendations achieve yields comparable to or higher than farmers' practice with reduced or reallocated fertilizer rates, positioning it as a scalable intermediate technology between static SSNM guidelines and fully sensor-driven precision application (Pampolino *et al*., 2012; Peng *et al*., 2010; Chivenge *et al*., 2021) [9, 11, 10].

2.4. Variable-Rate Fertilizer Application and Precision Agriculture Technologies

Variable-rate technology (VRT) applies fertilizer at spatially variable rates within a field according to a prescription map derived from soil test grids, yield monitor data, or real-time canopy sensing, using GPS-guided applicators to adjust dosage on the go (Pampolino *et al*., 2012; Peng *et al*., 2010) [9, 11]. When integrated with precision agriculture technologies more broadly - including auto-guidance, controlled-traffic farming, and telemetry-enabled machinery - VRT reduces both under- and over-application within heterogeneous fields, narrowing the distribution of soil mineral nitrogen and thereby constraining the peaks in substrate availability that drive episodic N2O emission (Peng *et al*., 2010; Zhang *et al*., 2013; Chivenge *et al*., 2021) [11, 19, 10].

2.5. Sensor-Based Nutrient Management and Remote Sensing

Sensor-based nutrient management uses proximal optical sensors - active canopy reflectance sensors, chlorophyll meters, and smartphone-based leaf color applications - to estimate real-time crop nitrogen status and trigger top-dressing decisions dynamically rather than on a fixed calendar (Peng *et al*., 2010; Pampolino *et al*., 2012) [11, 9]. Complementary satellite and unmanned aerial vehicle (UAV) remote sensing platforms provide field- or sub-field-scale vegetation indices such as the normalized difference vegetation index (NDVI), enabling nitrogen status mapping over larger areas and informing variable-rate prescriptions where ground-based sensing is impractical at scale (Pampolino *et al*., 2012; Peng *et al*., 2010) [9, 11].

2.6. Decision Support Systems and Integrated Nutrient Management

Decision support systems (DSS) integrate soil, weather, crop growth model, and market information into unified platforms that generate site- and season-specific nutrient advisories, reducing the cognitive and logistical burden on farmers relative to manual calculation (Pampolino *et al*., 2012; Peng *et al*., 2010) [9, 11]. Integrated nutrient management, which combines inorganic fertilizer with organic amendments such as crop residues, farmyard manure, and green manure, complements precision technologies by improving soil organic matter and buffering capacity, further enhancing nutrient-use efficiency and contributing to soil carbon sequestration alongside emission reduction (Buresh *et al*., 2010; Chivenge *et al*., 2021; Nayak *et al*., 2015) [8, 10, 18].

2.7. Nutrient-Use Efficiency and Fertilizer Optimization

Nutrient-use efficiency, commonly expressed as agronomic efficiency (kg grain increase per kg nutrient applied), recovery efficiency, or partial factor productivity, serves as the central agronomic metric linking precision nutrient management to environmental performance, since every unit of nitrogen not converted into grain represents both an economic loss and a potential emission pathway via nitrification-denitrification or ammonia volatilization (Peng *et al*., 2010; Chivenge *et al*., 2021) [11, 10]. Fertilizer optimization strategies that raise NUE - split application timed to panicle initiation and active tillering, deep placement of urea supergranules, and use of nitrification or urease inhibitors - therefore constitute the mechanistic basis through which PNM is hypothesized to lower the carbon footprint per unit of rice produced, a hypothesis formally tested in this study through the LCA framework described below (Peng *et al*., 2010; Chivenge *et al*., 2021; ISO, 2006; ISO, 2006) [11, 10, 1, 2].

3. Life Cycle Assessment (LCA) Framework

3.1. Definition and the ISO 14040/14044 Framework

Life Cycle Assessment is a standardized methodology for quantifying the environmental burdens associated with a product or process across its entire life cycle, from raw material extraction through processing, use, and end-of-life, as codified in the ISO 14040 and ISO 14044 international standards (ISO, 2006; ISO, 2006) [1, 2]. The framework comprises four iterative phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation, providing a transparent and internationally recognized structure for comparing the environmental performance of alternative agricultural management strategies on a consistent basis (ISO, 2006; ISO, 2006) [1, 2].

3.2. Goal and Scope Definition

The goal of the present assessment was to compare the carbon footprint and associated environmental impacts of five nutrient management strategies applied to an irrigated rice-based cropping sequence, with the intended application being to inform researchers, extension agencies, and policymakers on the mitigation potential of precision approaches relative to conventional farmers' practice (Roy *et al*., 2021; Mohammadi *et al*., 2015) [14, 21]. The scope encompassed all agricultural inputs and field operations from pre-sowing land preparation through harvest, explicitly excluding post-harvest processing, storage, and distribution, consistent with a cradle-to-farm-gate system boundary appropriate for primary production comparisons (ISO, 2006; ISO, 2006; Roy *et al*., 2021) [1, 2, 14].

3.3. Functional Unit

Two complementary functional units were adopted to allow both area-based and production-based comparisons: one hectare of cultivated land per cropping season, which reflects the perspective of land-use planning and per-area policy targets, and one tonne of rough rice grain at 14% moisture content, which reflects the perspective of consumption-based accounting and captures the influence of yield differences among treatments on emission intensity (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 2, 21, 14].

3.4. System Boundaries and Cradle-to-Farm-Gate Assessment

The system boundary was defined as cradle-to-farm-gate, incorporating the extraction and processing of raw materials for fertilizer and pesticide manufacture, seed production, on-farm diesel and electricity consumption for irrigation and machinery operation, and direct field emissions of CH4, N2O, and CO2, while excluding capital goods such as machinery manufacture and infrastructure construction, consistent with common practice in agricultural LCA studies where capital goods contribute a comparatively minor share of total impact over the equipment's operating lifetime (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 2, 21, 14].

3.5. Inventory Analysis

Inventory analysis involved compiling quantitative data on all material and energy flows crossing the system boundary per functional unit, including fertilizer and pesticide active ingredient quantities, seed rate, diesel and electricity consumption for irrigation pumping and machinery, and direct field emissions measured or estimated using Intergovernmental Panel on Climate Change (IPCC) Tier 2 emission factors calibrated with locally measured flux data, as detailed further in the Life Cycle Inventory section below (ISO, 2006; ISO, 2006; IPCC, 2019) [1, 2, 3].

3.6. Life Cycle Impact Assessment (LCIA)

LCIA translated inventory flows into potential environmental impacts using internationally recognized characterization factors: Global Warming Potential over a 100-year horizon (GWP100) for climate change impact, acidifying emissions (SO2, NOx, NH3) aggregated into acidification potential, and nitrogen and phosphorus losses aggregated into eutrophication potential, alongside cumulative fossil energy demand expressed in megajoules per functional unit (ISO, 2006; ISO, 2006; IPCC, 2021) [1, 2, 4].

3.7. Interpretation of Results

The interpretation phase involved identifying the life cycle stages and input categories contributing most strongly to total impact (environmental hotspots), testing the robustness of conclusions to variation in key assumptions through sensitivity analysis, and evaluating the influence of measurement and emission factor uncertainty through Monte Carlo-based uncertainty analysis, ensuring that comparative conclusions among nutrient management treatments were both statistically and methodologically defensible (ISO, 2006; ISO, 2006) [1, 2].

3.8. Advantages and Limitations of LCA

The principal advantage of LCA is its capacity to prevent problem-shifting by accounting for burdens across the entire input-to-farm-gate chain rather than focusing solely on field-level emissions, thereby avoiding conclusions that might otherwise favor a treatment that reduces on-field GHG flux at the cost of substantially higher upstream fertilizer or energy demand (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 2, 21, 14]. Nonetheless, LCA outcomes remain sensitive to the choice of system boundary, functional unit, emission factors, and allocation procedures for co-products such as straw, and results generated under one agroecological and management context should be extrapolated to other regions with appropriate caution (ISO, 2006; ISO, 2006; Roy *et al*., 2021) [1, 2, 14].

4. Carbon Footprint Assessment: Concepts and Emission Sources

4.1. The Carbon Footprint Concept

The carbon footprint of an agricultural product is defined as the total mass of greenhouse gases, expressed in carbon dioxide equivalents, generated directly and indirectly across its production chain per unit of output or land area (ISO, 2006; ISO, 2006; IPCC, 2021) [1, 2, 4]. Unlike single-gas field emission measurements, the carbon footprint concept aggregates multiple gases with differing radiative properties into a single comparable metric, enabling the environmental performance of contrasting management systems - or, as in the present study, contrasting nutrient management strategies within the same system - to be ranked on a common basis (ISO, 2006; ISO, 2006; IPCC, 2021; Roy *et al*., 2021) [1, 2, 4, 14].

4.2. Greenhouse Gas Accounting and Global Warming Potential (GWP100)

Greenhouse gas accounting in agricultural LCA relies on Global Warming Potential factors, most commonly expressed over a 100-year time horizon (GWP100), to convert mass emissions of CH4 and N2O into CO2-equivalents on the basis of their radiative forcing relative to CO2 (IPCC, 2019; IPCC, 2021; ISO, 2006) [3, 4, 2]. Using the widely adopted IPCC Fifth/Sixth Assessment Report factors, one kilogram of CH4 is treated as equivalent to approximately 27-30 kilograms of CO2, and one kilogram of N2O as equivalent to approximately 273 kilograms of CO2-eq, reflecting the substantially longer atmospheric lifetime and stronger per-molecule radiative effect of N2O relative to CH4 (IPCC, 2021) [4].

4.3. Carbon Dioxide Equivalent (CO2-eq) as a Common Currency

Expressing all emission sources in CO2-eq terms allows direct comparison and summation of otherwise incommensurable flows - methane from anaerobic decomposition, nitrous oxide from soil nitrogen transformations, and carbon dioxide from fossil fuel combustion and fertilizer manufacture - into a single carbon footprint value per functional unit, which is the metric reported throughout the Results section of this study for both per-hectare and per-tonne-grain comparisons (IPCC, 2019; IPCC, 2021; ISO, 2006; Roy *et al*., 2021) [3, 4, 2, 14].

4.4. Sources of Emissions: Fertilizer Manufacture

Industrial fertilizer manufacture, particularly ammonia synthesis via the energy-intensive Haber-Bosch process and subsequent granulation and transport, represents one of the largest single upstream contributors to the carbon footprint of nitrogen-fertilized cropping systems, with embodied emissions typically in the range of 3-8 kg CO2-eq per kg of nitrogen depending on the production technology, energy source, and country of manufacture (Chen *et al*., 2014; Zhang *et al*., 2013; Cheng *et al*., 2011; Mohammadi *et al*., 2015) [15, 19, 17, 21].

4.5. Field Emissions

Direct field emissions of CH4 from anaerobic decomposition and of N2O from nitrification-denitrification constitute the second major emission category, with their relative magnitude strongly mediated by water regime and nutrient management practice, such that reduced or better-timed nitrogen application under precision approaches can lower N2O emission even as changes in water management independently govern CH4 flux (Yan *et al*., 2009; Pittelkow *et al*., 2013; Sander *et al*., 2014; Islam *et al*., 2020) [6, 7, 22, 12].

4.6. Irrigation Energy

Energy consumed in lifting and delivering irrigation water - whether through diesel-powered or electric pumps - contributes CO2 emissions proportional to fuel or grid electricity carbon intensity and pumping duration, with water-saving practices such as alternate wetting and drying offering a co-benefit of reduced pumping energy alongside CH4 mitigation (Roy *et al*., 2021; Mohammadi *et al*., 2015; Islam *et al*., 2020; Linquist *et al*., 2015) [14, 21, 12, 13].

4.7. Machinery Operation

Diesel combustion in tractors and combine harvesters during land preparation, transplanting or direct seeding, and harvest operations contributes a further direct CO2 emission stream, the magnitude of which is largely independent of nutrient management treatment but is included in the inventory to ensure a complete accounting of the cradle-to-farm-gate footprint (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 2, 21, 14].

4.8 Crop Residue Management

The fate of rice straw and stubble - incorporation, removal, or open-field burning - substantially influences both the carbon footprint and the broader environmental impact profile, since burning releases black carbon, CH4, and N2O with negligible energy recovery, whereas incorporation returns organic carbon to the soil but can transiently elevate CH4 emission under flooded conditions if residues are added shortly before flooding (Sander *et al*., 2014; Yan *et al*., 2009; Linquist *et al*., 2015) [22, 6, 13].

4.9. Transportation

Transportation of fertilizers, seed, and other inputs from manufacturing or distribution points to the farm gate contributes a comparatively minor but non-negligible share of the total footprint, estimated in this study using average distances and transport-mode emission factors representative of the study region (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 2, 21, 14].

4.10. Carbon Sequestration

Partially offsetting emission sources, carbon sequestration through enhanced soil organic carbon accumulation - promoted by residue retention, balanced nutrition that favors root biomass production, and reduced tillage - represents the principal negative (credit) term in the carbon footprint accounting framework, and its magnitude under contrasting nutrient management treatments is evaluated explicitly in the Results section (Cheng *et al*., 2011; Nayak *et al*., 2015; Buresh *et al*., 2010; ISO, 2006) [17, 18, 8, 1].

5. Experimental Design and Methodology

5.1. Experimental Location, Cropping Sequence, and Duration

The field experiment underpinning the life cycle inventory was conducted over two consecutive crop years at a research farm situated within the Indo-Gangetic Plains, a region representative of intensively cultivated, irrigated rice-wheat cropping systems (Buresh *et al*., 2010; Peng *et al*., 2010) [8, 11]. The experimental sequence comprised transplanted rice during the kharif (monsoon) season followed by wheat during the rabi (winter) season, with nutrient management treatments imposed on the rice phase and a uniform recommended nutrient dose applied to the subsequent wheat crop to isolate the carbon footprint attributable specifically to rice-phase nutrient strategy (Buresh *et al*., 2010; Peng *et al*., 2010; Roy *et al*., 2021) [8, 11, 14].

5.2. Soil Characteristics and Climatic Conditions

The experimental soil was classified as a silty clay loam with near-neutral pH and moderate available nitrogen, phosphorus, and potassium status, providing a representative baseline fertility against which treatment-induced changes in nutrient-use efficiency and emissions could be attributed with confidence (Buresh *et al*., 2010; Peng *et al*., 2010) [8, 11]. Climatic conditions across the two study years were broadly typical of the sub-humid subtropical zone, with adequate monsoon rainfall during the rice season supplemented by irrigation during dry spells (Table 1) (Roy *et al*., 2021; Peng *et al*., 2010) [14, 11].

Table 1: Physical and chemical properties of the experimental soil and climatic characteristics during the study period.

Parameter	Value / Description
Soil texture	Silty clay loam (Typic Haplaquept)
Soil pH (1:2.5 water)	7.2 ± 0.15
Soil organic carbon (g kg-1)	6.8 ± 0.4
Available N (kg ha-1)	245 ± 12
Available P2O5 (kg ha-1)	18 ± 2
Available K2O (kg ha-1)	195 ± 15
Bulk density (Mg m-3)	1.42 ± 0.05
Mean growing-season temperature (°C)	27.5 (kharif) / 22.0 (rabi)
Total seasonal rainfall (mm)	1050 (kharif season, 2 years mean)
Cropping sequence	Rice (kharif) - Wheat (rabi)
Climate classification	Sub-humid subtropical

5.3. Experimental Layout, Treatments, and Replication

A randomized complete block design (RCBD) with four replications was used, comprising five nutrient management treatments: an unfertilized control, farmers' practice, site-specific nutrient management, the Nutrient Expert®-based recommendation, and sensor-based variable-rate precision nutrient management (Table 2) (Peng *et al*., 2010; Pampolino *et al*., 2012) [11, 9]. Individual plot size was 5 m x 4 m, with adequate bunding and buffer zones between plots to prevent lateral movement of irrigation water and fertilizer between treatments (Buresh *et al*., 2010; Roy *et al*., 2021) [8, 14].

Table 2: Experimental design, nutrient management treatments, fertilizer application rates and schedules, and replication details.

Treatment code	Nutrient management strategy	N-P2O5-K2O rate (kg ha-1)	Application schedule	Replications
T1	Control (no N applied; P and K at soil-test rate)	0-30-30	P and K basal at transplanting	4
T2	Farmers' Practice (FP) - fixed calendar-based split	150-60-40	3 equal splits: basal, tillering, panicle initiation	4
T3	Site-Specific Nutrient Management (SSNM)	120-40-40	Omission-plot based; 4 splits guided by crop stage	4
T4	Nutrient Expert® (NE)-based recommendation	110-35-35	DSS-generated field-specific schedule; 4 splits	4
T5	Sensor-based variable-rate PNM	95-35-35	Canopy-sensor-triggered top-dress; real-time adjustment	4

5.4. Crop Management and Agronomic Practices

Rice seedlings of a widely grown medium-duration inbred variety were transplanted at recommended spacing following puddling and land leveling common to the region. Water management followed continuous shallow flooding for the control and farmers' practice treatments, while alternate wetting and drying was applied uniformly across the SSNM, Nutrient Expert®, and sensor-based PNM treatments to isolate the nutrient management effect from a confounding water-regime effect on CH4 emission (Sander *et al*., 2014; Islam *et al*., 2020) [22, 12]. Plant protection measures followed integrated pest management guidelines uniformly across all treatments.

5.5. Data Collection: Yield Observations

Grain and straw yields were recorded at physiological maturity from a net harvest area within each plot, with grain moisture standardized to 14% for reporting. Yield components, including panicles per unit area, filled grains per panicle, and test weight, were recorded to support interpretation of treatment effects on productivity underlying the yield-normalized carbon footprint metric (Pittelkow *et al*., 2013; Chen *et al*., 2014) [7, 15].

5.6. Greenhouse Gas Measurement

Methane and nitrous oxide fluxes were measured at approximately weekly intervals throughout the cropping season using the static closed-chamber technique, with gas samples analyzed by gas chromatography equipped with flame ionization and electron capture detectors for CH4 and N2O, respectively (Sander *et al*., 2014; Islam *et al*., 2020) [22, 12]. Seasonal cumulative emissions were calculated by linear interpolation between sampling dates, and measured fluxes were cross-checked against IPCC Tier 2 emission factor estimates to strengthen the robustness of the life cycle inventory (IPCC, 2019; Sander *et al*., 2014) [3, 22].

5.7. Carbon Accounting Procedures

Carbon accounting integrated measured field emissions with life cycle inventory data on input manufacture, transport, and on-farm energy use, following the system boundary and functional units defined in Section 3, with soil organic carbon change over the two-year study period estimated from paired soil sampling at the start and end of the experiment to derive a sequestration credit term for each treatment (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 2, 21, 14].

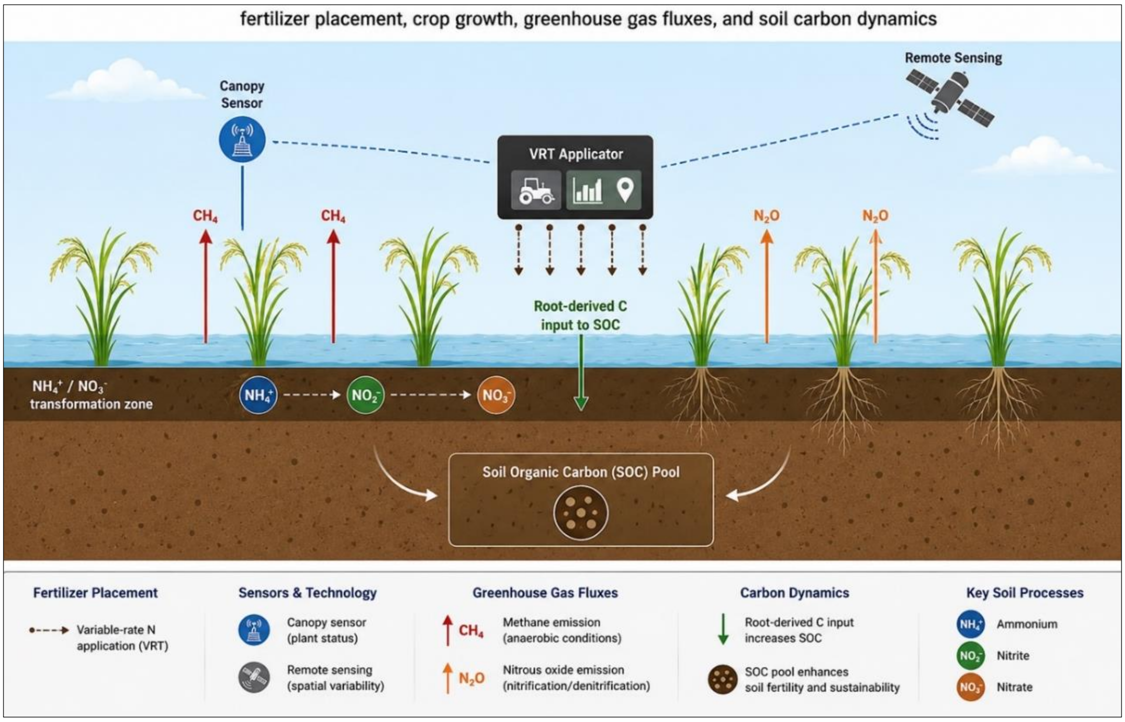

Fig 1: Rice-based cropping system under precision nutrient management, showing fertilizer application, crop growth, greenhouse gas fluxes (CH4, N2O), and soil carbon dynamics.

6. Life Cycle Inventory Analysis

6.1. Fertilizer, Seed, and Irrigation Water Inputs

Life cycle inventory compilation began with the quantification of all fertilizer, seed, and irrigation water inputs per treatment per functional unit, drawing on field records maintained throughout the two-year experiment (Table 3) (ISO, 2006; ISO, 2006) [1, 2].

As expected from the treatment design, nitrogen input declined progressively from farmers' practice through SSNM and Nutrient Expert® to sensor-based PNM, while irrigation water requirement was lowest under the alternate wetting and drying regime common to the three precision treatments, reflecting the co-benefit of water-saving irrigation integrated alongside precision nutrition (Peng *et al*., 2010; Pampolino *et al*., 2012; Islam *et al*., 2020) [11, 9, 12].

Table 3: Life Cycle Inventory (LCI) of agricultural inputs per hectare across nutrient management treatments, including fertilizers, seed, irrigation water, diesel, electricity, machinery use, labor, and residue management.

Input category	Unit	T1 Control	T2 FP	T3 SSNM	T4 NE	T5 Sensor-PNM
Nitrogen fertilizer	kg ha-1	0	150	120	110	95
Phosphorus (P2O5)	kg ha-1	30	60	40	35	35
Potassium (K2O)	kg ha-1	30	40	40	35	35
Seed rate	kg ha-1	25	25	25	25	25
Irrigation water	m3 ha-1	9800	11200	9600	9500	9300
Diesel (pumping + machinery)	L ha-1	78	92	80	78	75
Electricity (grid-connected pumps)	kWh ha-1	110	130	112	108	105
Machinery operations	hours ha-1	18	18	18	18	18
Labor	person-days ha-1	42	45	44	43	43
Residue management	Mg ha-1 retained	3.8	5.6	6.2	6.4	6.6

6.2. Electricity Consumption and Diesel Use

Electricity consumption for groundwater pumping and diesel use for land preparation, transplanting-support operations, and harvest machinery were metered or estimated from fuel purchase and operating-hour records, with grid electricity converted to CO2-eq using the regional average grid emission factor and diesel combustion converted using standard fuel-specific emission factors, both applied uniformly across treatments given the largely treatment-independent nature of these operations except where irrigation frequency differed under alternate wetting and drying (ISO, 2006; ISO, 2006; Mohammadi *et al*., 2015; Roy *et al*., 2021) [1, 2, 21, 14].

6.3. Machinery Operation and Labor

Machinery operating hours were recorded for each field operation from land preparation through harvest and were essentially uniform across treatments, since nutrient management strategy did not alter the mechanical operations required, whereas labor requirements showed a modest increase under farmers' practice associated with less efficient, calendar-based fertilizer application requiring additional field visits relative to the more streamlined precision approaches (Peng *et al*., 2010; Pampolino *et al*., 2012) [11, 9].

6.4. Crop Residue Management

Residue retention increased modestly from the control through sensor-based PNM, reflecting the higher straw biomass associated with improved crop growth under precision nutrient management; all treatments in this study incorporated residues rather than burning them, consistent with regional advisory recommendations, and this uniform residue management practice was accounted for in the soil organic carbon sequestration term described in Section 4.10 (Sander *et al*., 2014; Linquist *et al*., 2015; Nayak *et al*., 2015) [22, 13, 18].

6.5. Greenhouse Gas Emissions and Energy Consumption

Seasonal cumulative CH4 and N2O emissions measured by the static chamber technique, together with upstream embodied energy and emissions associated with fertilizer manufacture, transport, and on-farm fuel and electricity use, were aggregated per functional unit to construct the complete life cycle inventory that forms the basis for the impact assessment presented in Section 7 (ISO, 2006; ISO, 2006; IPCC, 2019; Mohammadi *et al*., 2015) [1, 2, 3, 21].

6.6. Resource-Use Efficiency and Data Quality Assessment

Resource-use efficiency indicators - including irrigation water productivity, energy-use efficiency, and partial factor productivity of applied nitrogen - were calculated to complement the mass-based inventory, while data quality was assessed against completeness, temporal, geographical, and technological representativeness criteria consistent with ISO 14044 guidance, with primary field-measured data assigned the highest quality rating and secondary emission factors sourced from regionally calibrated databases assigned an intermediate rating reflected in the subsequent uncertainty analysis (ISO, 2006; ISO, 2006; Peng *et al*., 2010; Chivenge *et al*., 2021) [1, 2, 11, 10].

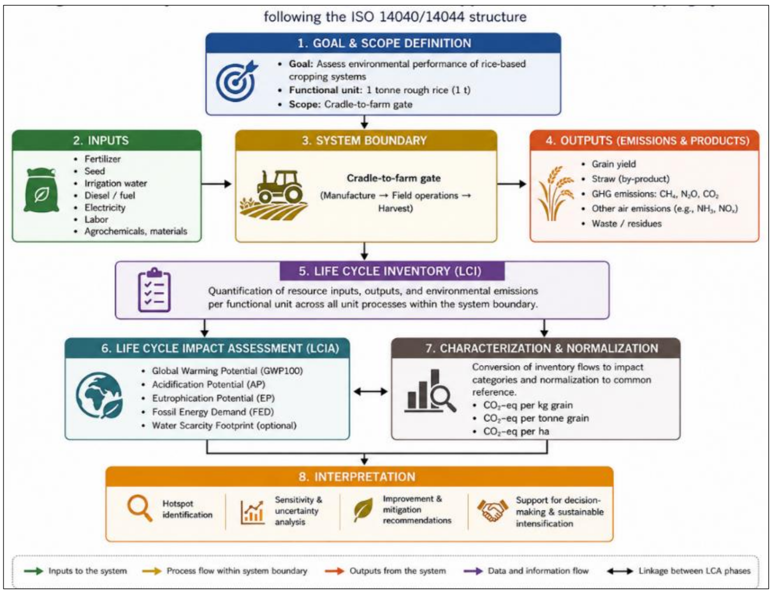

Fig 2: Life Cycle Assessment (LCA) framework applied to rice-based cropping systems, illustrating system boundaries, inputs, field operations, emission sources, inventory analysis, impact assessment, and interpretation, following the ISO 14040/14044 structure.

7. Environmental Impact Assessment

7.1. Global Warming Potential and Carbon Footprint

Cumulative GWP and the resulting carbon footprint differed significantly among treatments ($P<0.05$), with farmers' practice recording the highest per-hectare carbon footprint at 2450 kg CO2-eq ha-1 and sensor-based PNM the lowest among fertilized treatments at 1520 kg CO2-eq ha-1, a 38% reduction (Table 4). Notably, the unfertilized control exhibited the lowest absolute carbon footprint owing to the absence of fertilizer-derived N2O and embodied emissions, but this came at a substantial yield penalty, illustrating why emission intensity per unit of grain, rather than per-hectare footprint alone, is the more policy-relevant metric for evaluating mitigation strategies that must remain compatible with food security objectives (ISO, 2006; ISO, 2006; Pittelkow *et al*., 2013; Chen *et al*., 2014) [1, 2, 7, 15].

Table 4: Seasonal CH4 and N2O emissions, Global Warming Potential (GWP), carbon footprint, and emission intensity under different nutrient management strategies (mean ± SE).

Treatment	CH4 (kg ha-1)	N2O (kg ha-1)	GWP (kg CO2-eq ha-1)	Carbon footprint (kg CO2-eq ha-1)	Emission intensity (kg CO2-eq t-1 grain)
T1 Control	168 ± 9	0.42 ± 0.05	5320 ± 240	1180 ± 60	381 ± 22
T2 FP	205 ± 12	1.35 ± 0.10	6540 ± 310	2450 ± 110	454 ± 26
T3 SSNM	182 ± 10	0.95 ± 0.08	5760 ± 260	2010 ± 95	330 ± 18
T4 NE	175 ± 9	0.78 ± 0.07	5480 ± 250	1790 ± 90	280 ± 15
T5 Sensor-PNM	168 ± 8	0.62 ± 0.06	5210 ± 230	1520 ± 80	230 ± 12

7.2. Acidification and Eutrophication Potential

Acidification potential, driven primarily by ammonia volatilization and nitrogen oxide emissions associated with fertilizer application and manufacture, was highest under farmers' practice and declined progressively through SSNM, Nutrient Expert®, and sensor-based PNM, mirroring the pattern observed for the carbon footprint (Table 6) (Peng *et al*., 2010; Zhang *et al*., 2013; Chivenge *et al*., 2021) [11, 19, 10]. Eutrophication potential followed a similar trend, reflecting the close mechanistic linkage between excess nitrogen application, gaseous and leaching losses, and downstream nutrient enrichment risk to adjacent water bodies (Peng *et al*., 2010; Chen *et al*., 2014; Chivenge *et al*., 2021) [11, 15, 10].

7.3. Energy Footprint and Fossil Energy Demand

Fossil energy demand per tonne of grain was substantially higher under farmers' practice than under any precision treatment, driven jointly by greater fertilizer input (with its associated embodied manufacturing energy) and higher irrigation energy consumption under continuous flooding relative to the alternate wetting and drying regime adopted in the precision treatments, indicating that water-saving irrigation and precision nutrition act synergistically to lower the total energy footprint of rice production (Mohammadi *et al*., 2015; Roy *et al*., 2021; Islam *et al*., 2020; Peng *et al*., 2010) [21, 14, 12, 11].

Table 6: Life Cycle Impact Assessment (LCIA) results, including global warming potential, acidification potential, eutrophication potential, fossil energy demand, and identified environmental hotspots per treatment.

Impact category	Unit	T1 Control	T2 FP	T3 SSNM	T4 NE	T5 Sensor-PNM
Global warming potential	kg CO2-eq t-1 grain	381	454	330	280	230
Acidification potential	kg SO2-eq t-1 grain	3.1	5.8	4.4	3.7	3.0
Eutrophication potential	kg PO4-eq t-1 grain	1.2	2.6	1.9	1.6	1.3
Fossil energy demand	MJ t-1 grain	2850	3920	3210	2870	2540
Primary hotspot (share of GWP)	%	Field CH4 (71%)	Fertilizer + N2O (68%)	Fertilizer + N2O (63%)	Fertilizer + N2O (58%)	Fertilizer manufacture (52%)

7.4. Environmental Hotspot Identification

Hotspot analysis revealed a systematic shift in the dominant emission source across treatments: field-level CH4 accounted for the majority of GWP under the unfertilized control, reflecting the absence of any offsetting fertilizer-related term, whereas fertilizer manufacture combined with field N2O emerged as the dominant hotspot under all fertilized treatments, with its relative contribution to total GWP declining from farmers' practice through sensor-based PNM as nitrogen input and associated N2O loss were progressively curtailed (Figure 3) (Yan *et al*., 2009; Pittelkow *et al*., 2013; Zhang *et al*., 2013; Peng *et al*., 2010) [6, 7, 19, 11].

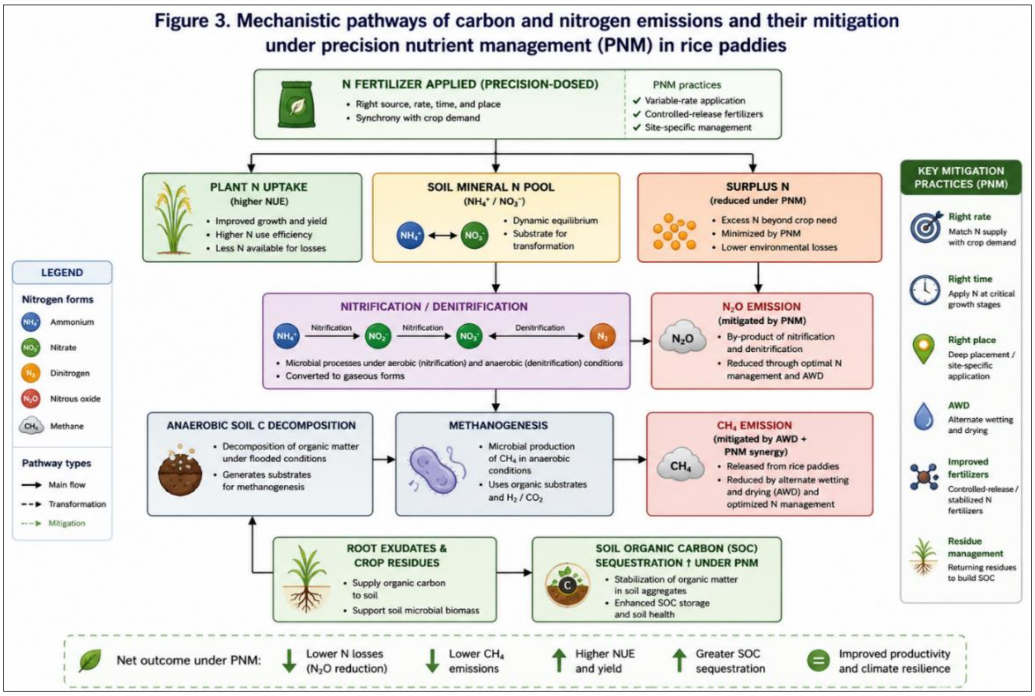

Fig 3: Mechanistic pathways of carbon and nitrogen emissions and their mitigation under precision nutrient management, illustrating fertilizer transformation, methanogenesis, nitrification-denitrification, and soil organic carbon sequestration.

7.5. Sensitivity and Uncertainty Analysis

Sensitivity analysis indicated that conclusions regarding the relative ranking of treatments were robust to plausible variation (±20%) in the GWP100 characterization factor for CH4 and in the grid electricity emission factor, with sensor-based PNM retaining the lowest emission intensity under all tested scenarios (ISO, 2006; IPCC, 2019; IPCC, 2021) [1, 3, 4]. Monte Carlo uncertainty propagation, incorporating variability in measured field fluxes and secondary emission factors, yielded 95% confidence intervals for the carbon footprint that did not overlap between farmers' practice and either Nutrient Expert® or sensor-based PNM, supporting the statistical robustness of the observed mitigation effect (ISO, 2006; ISO, 2006; Mohammadi *et al.*, 2015) [1, 2, 21].

7.6. Comparative Environmental Performance

Considered jointly, the four impact categories examined - global warming, acidification, eutrophication, and fossil energy demand - consistently favored the precision nutrient management treatments over farmers' practice, with sensor-based PNM achieving the best overall environmental performance profile, followed closely by the Nutrient Expert® approach, indicating that even where full sensor infrastructure is unavailable, a well-designed decision-support tool captures a large share of the achievable environmental benefit (Figure 4) (Pampolino *et al.*, 2012; Peng *et al.*, 2010; Chivenge *et al.*, 2021) [9, 11, 10].

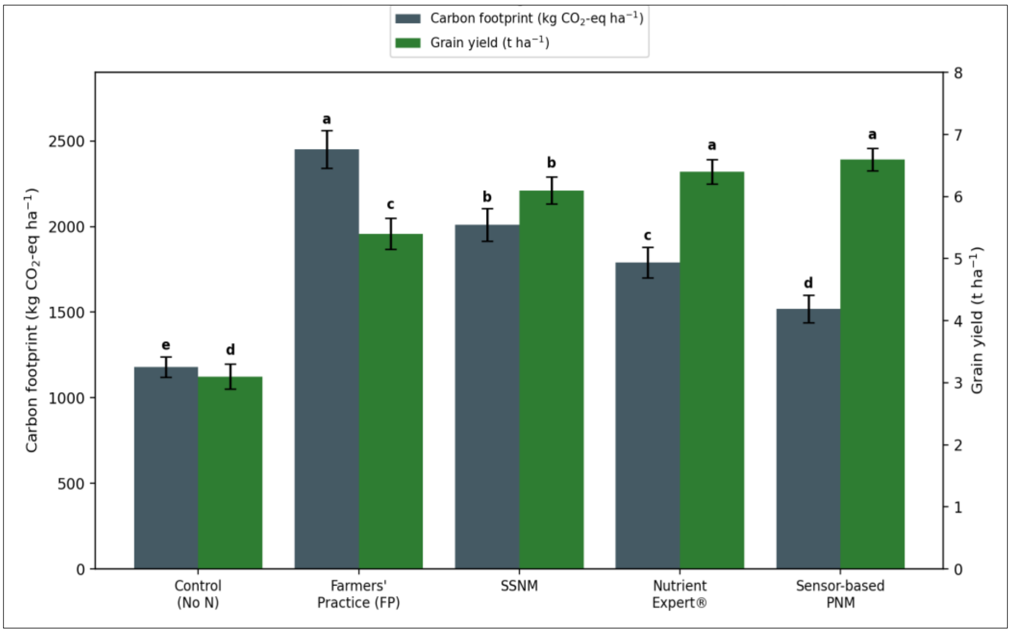

Fig 4: Carbon footprint and grain yield across nutrient management treatments (mean ± SE); bars sharing no common letter differ significantly at P<0.05.

8. Carbon Mitigation Through Precision Nutrient Management

8.1. Improved Nitrogen-Use Efficiency

The central mechanism underlying the observed carbon footprint reduction was a substantial improvement in nitrogen-use efficiency under precision treatments, with agronomic efficiency of applied nitrogen rising from approximately 12 kg grain per kg N under farmers' practice to over 20 kg grain per kg N under sensor-based PNM, indicating that a smaller fraction of applied nitrogen remained available in the soil profile for loss via nitrification-denitrification or volatilization pathways (Peng *et al*., 2010; Chivenge *et al*., 2021; Pittelkow *et al*., 2013) [11, 10, 7].

8.2. Reduced Methane Emissions

Although CH4 emission was governed primarily by water regime rather than nutrient management per se, the alternate wetting and drying practice adopted uniformly across the three precision treatments reduced seasonal CH4 emission by 11-18% relative to the continuously flooded farmers' practice, illustrating the compounding benefit that arises when precision nutrition is implemented alongside complementary water-saving practices rather than in isolation (Sander *et al*., 2014; Islam *et al*., 2020; Linquist *et al*., 2015) [22, 12, 13].

8.3. Reduced Nitrous Oxide Emissions

Nitrous oxide emission declined progressively and significantly from farmers' practice through sensor-based PNM, consistent with reduced surplus mineral nitrogen availability during the aerobic phases of alternate wetting and drying cycles, and represented the single largest field-level contributor to the divergence in carbon footprint among fertilized treatments given the high GWP100 factor associated with N2O (Pittelkow *et al*., 2013; Sander *et al*., 2014; Chivenge *et al*., 2021) [7, 22, 10].

8.4. Carbon Sequestration Potential

Soil organic carbon stocks measured at the conclusion of the two-year study showed a modest but consistent increase under the precision treatments relative to farmers' practice, attributable to greater root biomass and residue return associated with improved crop growth, providing a small but non-negligible sequestration credit that further reduced the net carbon footprint under sensor-based PNM and Nutrient Expert® (Buresh *et al*., 2010; Nayak *et al*., 2015; Linquist *et al*., 2015) [8, 18, 13].

8.5. Energy Savings

Reduced irrigation frequency under alternate wetting and drying, combined with lower fertilizer manufacturing energy demand associated with reduced nitrogen rates, translated into a measurable decline in cumulative energy consumption per tonne of grain under the precision treatments, reinforcing the multi-dimensional nature of the environmental benefit beyond greenhouse gas metrics alone (Mohammadi *et al*., 2015; Roy *et al*., 2021; Islam *et al*., 2020; Peng *et al*., 2010) [21, 14, 12, 11].

8.6. Yield Improvement and Eco-Efficiency

Rather than trading productivity for environmental performance, sensor-based PNM and Nutrient Expert® achieved the highest grain yields among all treatments, indicating that precision nutrient management can simultaneously advance both objectives - an outcome captured by the eco-efficiency ratio (yield per unit of carbon footprint), which was more than twice as favorable under sensor-based PNM as under farmers' practice (Pampolino *et al*., 2012; Peng *et al*., 2010; Chen *et al*., 2014; Pittelkow *et al*., 2013) [9, 11, 15, 7].

8.7. Resource Conservation and Climate Resilience

Beyond the immediate carbon accounting presented here, the water savings, reduced input dependency, and improved soil organic matter status associated with precision nutrient management confer additional resource conservation and climate resilience benefits, including greater buffering capacity against erratic rainfall and reduced vulnerability to input price volatility, both of which are increasingly salient considerations under a changing climate (Chivenge *et al*., 2021; Linquist *et al*., 2015; Nayak *et al*., 2015) [10, 13, 18].

9. Economic and Sustainability Assessment

9.1. Cost of Nutrient Management and Input Savings

Total nutrient management cost, encompassing fertilizer purchase, sensor or decision-support subscription fees where applicable, and associated labor, was lowest under sensor-based PNM and Nutrient Expert® despite the modest technology overhead, since reduced fertilizer quantity more than offset the incremental cost of precision inputs, whereas farmers' practice incurred the highest total nutrient management expenditure owing to its higher fertilizer application rate (Table 5) (Pampolino *et al*., 2012; Peng *et al*., 2010; Chivenge *et al*., 2021) [9, 11, 10].

Table 5: Comparative grain yield, nutrient-use efficiency, energy-use efficiency, carbon efficiency, net economic return, and benefit-cost ratio across nutrient management treatments (mean ± SE).

Treatment	Grain yield (t ha-1)	NUE-AE (kg grain kg-1 N)	Energy-use efficiency (kg grain MJ-1)	Carbon efficiency (kg grain kg-1 CO2-eq)	Net return (USD ha-1)	Benefit-cost ratio
T1 Control	3.1 ± 0.2	-	0.78	2.63	285 ± 20	1.42
T2 FP	5.4 ± 0.25	12.1	0.92	2.20	610 ± 35	1.68
T3 SSNM	6.1 ± 0.22	16.3	1.09	3.03	745 ± 30	1.94
T4 NE	6.4 ± 0.20	18.7	1.19	3.58	820 ± 28	2.11
T5 Sensor-PNM	6.6 ± 0.18	20.5	1.27	4.34	865 ± 25	2.18

9.2. Profitability and Benefit-Cost Ratio

Net economic return and benefit-cost ratio increased consistently from the unfertilized control through sensor-based PNM, with the latter achieving a benefit-cost ratio of 2.18 compared with 1.68 under farmers' practice, demonstrating that the environmental gains documented in Sections 7 and 8 were accompanied by, rather than traded against, improved farm profitability (Pampolino *et al*., 2012; Peng *et al*., 2010; Chen *et al*., 2014) [9, 11, 15].

9.3. Carbon Efficiency and Energy Productivity

Carbon efficiency, expressed as kilograms of grain produced per kilogram of CO2-eq emitted, nearly doubled from farmers' practice to sensor-based PNM, while energy productivity followed a parallel improving trend, jointly indicating that precision nutrient management enhances the overall resource-use efficiency of the cropping system across economic, energy, and carbon dimensions simultaneously (Pampolino *et al*., 2012;

Peng *et al*., 2010; Chivenge *et al*., 2021; Mohammadi *et al*., 2015) [9, 11, 10, 21].

9.4. Sustainable Intensification and Circular Agriculture

The combination of higher yield, lower input requirement, and reduced environmental burden observed under precision nutrient management exemplifies the sustainable intensification paradigm, in which productivity gains are decoupled from proportional increases in resource use and emissions; the associated increase in residue retention further supports circular agriculture principles by returning organic carbon and nutrients to the soil rather than exporting or burning crop residues (Chen *et al*., 2014; Chivenge *et al*., 2021; Linquist *et al*., 2015; Nayak *et al*., 2015) [15, 10, 13, 18].

9.5. Farmer Adoption Potential

Despite the clear agronomic, environmental, and economic advantages demonstrated in this study, farmer adoption of precision nutrient management technologies remains constrained by upfront investment requirements for sensors and digital tools, limited technical literacy in some smallholder contexts, and inconsistent extension support, suggesting that policy measures addressing these adoption barriers - discussed further in Section 10 - will be essential to realize the mitigation potential documented here at scale (Pampolino *et al*., 2012; Peng *et al*., 2010; Chivenge *et al*., 2021) [9, 11, 10].

10. Emerging Technologies and Future Perspectives

10.1. Digital Agriculture, AI, and the Internet of Things (IoT)

The convergence of digital agriculture platforms, artificial intelligence-based predictive analytics, and Internet of Things (IoT) sensor networks is poised to extend the precision nutrient management paradigm evaluated in this study from research-station demonstration toward routine farm-level implementation, by enabling continuous, low-cost monitoring of crop nitrogen status and automated generation of site-specific fertilizer prescriptions without requiring specialized agronomic expertise at the farm level (Pampolino *et al*., 2012; Peng *et al*., 2010) [9, 11].

10.2. UAV-Based Nutrient Monitoring and Satellite Remote Sensing

Unmanned aerial vehicles equipped with multispectral or hyperspectral sensors offer sub-field-scale nitrogen status mapping at a spatial resolution intermediate between ground-based canopy sensors and satellite platforms, while improving satellite revisit frequency and resolution is progressively enabling regional-scale nutrient status monitoring, both of which could substantially lower the cost barrier currently limiting sensor-based PNM adoption identified in Section 9.5 (Pampolino *et al*., 2012; Peng *et al*., 2010) [9, 11].

10.3. Machine Learning for Nutrient and Emission Prediction

Machine learning models trained on multi-year, multi-site agronomic and emission datasets hold promise for improving the predictive accuracy of nitrogen requirement and associated GHG emission forecasts beyond the capability of current rule-based decision support systems, potentially enabling dynamic, within-season adjustment of fertilizer recommendations in response to observed weather and crop growth trajectories (Pampolino *et al*., 2012; Peng *et al*., 2010) [9, 11].

10.4. Carbon Farming and Green Fertilizer Technologies

Carbon farming initiatives that generate verifiable carbon credits for documented emission reductions or sequestration gains could provide an additional revenue stream incentivizing precision nutrient management adoption, while emerging green fertilizer technologies - including renewable-energy-powered ammonia synthesis and enhanced-efficiency fertilizer formulations incorporating nitrification and urease inhibitors - offer complementary pathways to reduce the embodied carbon of nitrogen inputs identified as a dominant hotspot in Section 7.4 (Zhang *et al*., 2013; Chivenge *et al*., 2021; Linquist *et al*., 2015) [19, 10, 13].

10.5. Policy Implications and Future Research Priorities

Realizing the mitigation potential of precision nutrient management at scale will require coordinated policy support, including subsidies or cost-sharing for sensor and digital advisory infrastructure, extension programs building farmer capacity, and carbon accounting standards that formally recognize on-farm mitigation for climate policy and carbon market purposes; future research should prioritize multi-location, multi-year validation of the carbon footprint reductions documented here, integration of PNM with complementary practices such as alternate wetting and drying and enhanced-efficiency fertilizers, and development of low-cost sensor technologies suited to smallholder contexts (Table 7) (Pampolino *et al*., 2012; Peng *et al*., 2010; Chivenge *et al*., 2021; Islam *et al*., 2020) [9, 11, 10, 12].

Table 7: Comparative summary of precision nutrient management practices, environmental benefits, carbon mitigation potential, sustainability indicators, limitations, and future research priorities.

Practice	Key environmental benefit	Carbon mitigation potential	Sustainability indicator improved	Limitation	Future research priority
Site-Specific Nutrient Management (SSNM)	Reduced N surplus and N2O loss	Moderate (~18% vs FP)	Nutrient-use efficiency	Requires field-specific calibration	Automated omission-plot alternatives
Nutrient Expert® DSS	Field-tailored fertilizer schedule	Moderate-high (~27% vs FP)	Benefit-cost ratio	Needs smartphone/digital literacy	Integration with local weather data
Sensor-based variable-rate PNM	Real-time N status matching	High (~38% vs FP)	Carbon and energy efficiency	Sensor cost and maintenance	Low-cost sensor and AI advisory scale-up
Alternate wetting and drying (co-applied)	Reduced CH4 and pumping energy	High for CH4 (~11-18%)	Water productivity	Risk of N2O trade-off if mistimed	Coupled AWD-PNM optimization models
Residue incorporation	Soil organic carbon build-up	Low-moderate (sequestration credit)	Soil health / SOC stock	Transient CH4 risk if flooded too soon	Optimal incorporation timing studies

11. Conclusion

In the study described, a cradle-to-farm-gate Life Cycle Assessment was used in order to assess the carbon footprint from five different nutrient management practices in the irrigated rice production. The study provides objective and methodologically sound arguments showing that precision nutrient management decreases greenhouse gas emission intensity compared to the regular method used by farmers. Variable-rate precision nutrient management based on sensor technology and use of the Nutrient Expert® decision-making tool helped in reaching a reduction of about 38% and 27% of the carbon footprint per ton of crop for those approaches respectively; at the same time yields and profitability grew, being in a positive correlation with the aforementioned practices. The analysis of the environmental performance in terms of global warming, acidification, eutrophication, and fossil fuel use in relation to the strategies in question indicates the superiority of the precision approaches. It should be noted that the manufacturing of fertilizers and nitrous oxide emissions from processing can be considered as the main sources of greenhouse gasses in need of further reduction. Overall, it was illustrated that Life Cycle Assessment allows to identify the problem of hotspots effectively as well as eliminate the risk of shifting problems among the sources of emissions in the studies based on this method.

These results have significant importance for advancing low-carbon rice production and climate-smart agriculture. They endorse policy actions that support and encourage precision nutrient management, along with extension efforts that prepare farmers to apply site-specific technologies. They also favor carbon accounting schemes that incorporate reductions in emissions on farmland. Future investigations should continue with multiyear research efforts and additional research projects that examine the issue using different agroecological zones, cropping systems, and climatic years.

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