Comparative Evaluation of Controlled-Release Fertilizers and Organic Nutrient Sources in *Triticum aestivum* L.

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ABSTRACT
Background and Objective: Almost 40% of the world's agricultural lands limit wheat (*Triticum aestivum* L.) production because of nitrogen, phosphorus and potassium deficiency. It is believed that controlled release fertilizers (CRF) and organic sources of nutrients are an innovative method of improving soil sustainability and enhancing the efficiency of nutrient utilization. The present paper aims to assess the performance of controlled release fertilizers and organic nutrients against conventional soluble fertilizers in terms of their effectiveness and environmental safety.
Methods: A field experiment was conducted in two growing seasons (2021-2022 and 2022-2023) with the help of a randomized complete block design. The experiment involved five treatments for nutrients management: (1) Control (without fertilizers), (2) Conventional soluble fertilizer (use of 400 kg N ha^{-1}), (3) Controlled slow-release fertilizer (use of 400 kg N ha^{-1}), (4) Organic nutrient source (composted manure + biofertilizers), and (5) Integrated nutrient management (Controlled-release fertilizer + organic fertilizer). The parameters from growth, physiological processes, nutrient uptake efficiency, soil health indicators, and components of yield of the grain were monitored during the growing season [4-6].
Results: The applications of controlled-release fertilizer (CRF) and the integrated nutrient management (INM) system resulted in obtaining grain yields of 5.47 and 5.62 t/ha, respectively as opposed to the conventional fertilizer yield (4.98 t/ha) and the control yield (2.84 t/ha) (p value<0.01). The nitrogen-use efficiency was enhanced by 28.4% with CRF and by 31.2% with INM as compared to that of the conventional fertilizer treatment. Microbial biomass carbon increased in quantities of 42.3% with organic treatment and 38.1% for integrated management, indicating a significant increase in the soil biological productivity. The amount of soil organic carbon increased during the last two seasons by 18.4% for organic treatment and by 16.2% for integrated management.
Scientific Significance: This study demonstrates that the use of controlled-release fertilizers and integrated nutrient management methods enables to reach new levels of efficiency in the use of nutrients, increasing productivity of crops and preserving the soil. This is a good way to achieve sustainable intensification in regions with water scarcity and improve the health of soil at the same time [7-9].
Conclusion: Combining controlled-release fertilizers with organic sources of nutrients provides good methods to manage nutrients that can increase wheat yields, improve nutrient-use efficiency, and enhance soil health in semi-arid areas. Integrating controlled-release fertilizer with organic materials allows for gaining synergetic effects for sustainable wheat growing and climate-resilient agriculture.

Keywords: Controlled-release fertilizers; Organic nutrient sources; Wheat nutrition; Nutrient-use efficiency; Soil health; Sustainable agriculture; Nitrogen recovery; Soil microbial activity; Integrated nutrient management

Introduction
Global Wheat Production and Nutritional Constraints
Triticum aestivum (or bread wheat) is the most cultivated cereal in the world, accounting for about 20% of human nutrition and being a key food for more than 2 billion people. Wheat production reaches more than 760 million tons every year and takes places on around 220 million hectares, mainly in Asia, Europe, and North America. Nonetheless, even though wheat is produced in huge amounts, yields tend to be very low in many regions due to the lack of the most important nutrients. Indeed, more than 40% of the soils worldwide are low in nitrogen, phosphorus, or potassium.

Challenges in Conventional Nutrient Management
Conventional mineral fertilizer usage has improved the efficiency of grain production since the Green Revolution but brings sustainability issues such as high loss of nutrients to aquatic systems and greenhouse gas emissions during production and application, nutrient runoff polluting freshwater resources, as well as decline of soil fertility in the long run, although great external input of nutrients (Robertson and Vitousek, 2023) [4] (Cassman *et al*., 2021) [5]. A major part of nitrogen fertilizer,

approximately 40-60% of the nutrient, is lost from agricultural land due to leaching, runoff, denitrification, and other sources, which means wasting money and harming the environment (Cassman *et al*., 2021) [5] (Ladha *et al*., 2020) [7].

Loss of phosphorus as a result of surface runoff and leaching leads to the problem of water eutrophication, in addition, the fact that phosphate rock reserves are finite means that we have to change our approaches to phosphorus management (Cordell *et al*., 2021) [6]. Such sustainability challenges emphasize the need to create nutrient management schemes that would increase synchrony between the availability of nutrients and their crop demand and would bring down losses (Ladha *et al*., 2020) [7].

Controlled-Release Fertilizers: Mechanisms and Applications

Controlled release fertilizers (CRF) are a category of technology that allows gradual and synchronized return of nutrients in line with the crop's uptake regime, which improves the efficiency of nutrients used and decreases nutrient losses (Shaviv, 2021) [8]. CRF technology incorporates polymer-coated products that have nutrient granules sealed with organic and inorganic coating materials that control the rate of nutrient release based on soil moisture, temperature, and the presence of microorganisms (Oertli, 2019) [9] (Azeem *et al*., 2021) [11]. The main function of the nutrient synchronization process relies on the temporal synchronization of nutrient release with crop uptake rates, whereby the period during which nutrients can be lost is minimized (Lasisi *et al*., 2022) [10]. A variety of studies conducted in different cropping systems provide evidence of the efficiency improvements in terms of nutrient use due to CRF of about 15-35% compared to standard soluble fertilizers (Azeem *et al*., 2021) [11] (Lasisi *et al*., 2022) [10]. Among other factors, the potential of CRF is especially evident with changing climatic conditions, high leaching risks, and in the case of intensive cropping systems when management flexibility can increase profitability (Trenkel, 2022) [12].

Organic Nutrient Sources and Soil Biological Activity

Animal manure, crop waste, and compost are organic sources of nutrients that deliver both forms of nutrients that are available for immediate use and slowly-released ones, thereby ensuring the survival of microorganisms that aid nutrient cycling and soil aggregation (Sanchez *et al*., 2021) [22] (Luo and Ledgard, 2021) [14]. Besides providing nutrients, organic amendments are useful in carbon sequestration in soils, boosting the retention of moisture, stabilizing soil aggregates, and promoting useful soil microorganisms (Nair *et al*., 2023) [13] (Lal, 2020) [17]. Organic matter is a way to improve microbial mass and activity by increasing the biological processes that include nutrient mineralization, organic matter decomposition, and biogeochemical cycles (Schutter and Dick, 2021) [15] (Kumar *et al*., 2020) [23]. Research results show that improving soil properties can be achieved by applying organic amendments for a long time or adopting a strategy of solely using mineral fertilizers (Masto *et al*., 2022) [16] (Kumar *et al*., 2020) [23].

Soil Fertility Improvement and Organic Carbon Dynamics

Soil organic carbon (SOC) is the principal storehouse for organic matter in terrestrial ecosystems. It is vital for the soil to function as well as the capacity to recycle nutrients and retain water for a longer duration (Lal, 2020) [17]. The fast-growing nature of intensive agriculture, without the application of organic matter inputs, often leads to declining levels of SOC in the soil, which is tantamount to carbon mining (Lal, 2020) [17] (Conant *et al*., 2021) [18]. The use of organic fertilizer in combination with the regular fertilizers is a practical solution that helps in maintaining and replenishing the levels of SOC (Gregorich and Beare, 2021) [19]. Thus, regional carbon sequestration through soil management practices contributes to the global climate effort and achieving sustainable agriculture goals (Grant *et al*., 2023) [20] (Lal, 2020) [17].

Nutrient-Use Efficiency and Agronomic Evaluation

The term nutrient-use efficiency (NUE) includes various conceptual interpretations, such as recovery efficiency, which refers to the proportion of nutrition absorbed in the harvested biomass; agronomic efficiency, which indicates the amount of crop produced per unit of nutrition provided; and internal efficiency, which describes the amount of harvested biomass created per unit of nutrition accumulated. Each of these definitions of efficiency presents a unique outlook on nutrient management; while the first definition is concerned with the capture of inputs, the second definition focuses on yield efficiency, and the third one discusses physiological efficiency. To conduct thorough evaluation of nutrient management practices, one has to consider all aspects including yield, soil health, and efficiency of nutrient use in production.

Integrated Nutrient Management Approaches

The integration of various sources of nutrients such as mineral fertilizers, organic amendments, and biofortified products is a new idea that signifies the combination of different technologies and practices (Pretty and Bharucha, 2021) [24]. The integrated nutrient management (INM) technique utilizes the complementary benefits of different nutrient sources where controlled-release fertilizers serve to provide nutrients all at once at a given point in time; organic amendments help with biological processes and carbon storage in the soil, while targeted mineral fertilizers satisfy precise crop needs in nutrients that might be deficient in certain amounts for proper growth (Govaerts *et al*., 2022) [25]. The systematic integration entails quantitative balancing of the contributions of each nutrient source to meet the nutrient demands of the crops with their actual needs and the sustainability goals (Kanter *et al*., 2023) [26].

Climate-Smart Agriculture and Sustainable Intensification

Climate change leads to increased variability in precipitation patterns, the occurrence of temperature extremes, and further aggravation of water stress in agricultural systems. This makes changes to agricultural practices necessary in order to improve their resilience and sustainability (Maguire and Sims, 2021) [27]. Climate-smart agriculture that involves using improved nutrient management contributes to achieving important objectives related to productivity, adaptation, and mitigation (Köbke *et al*., 2022) [28]. Improved nutrient management increases nutrient use efficiency, which reduces greenhouse emissions caused by fertilizer production, while improved soil carbon sequestration contributes to the mitigation of climate change (Bhattacharyya *et al*., 2023) [29].

Current Research Status and Knowledge Gaps

Although CRFs are getting more popular in modern farming, not much has been written in peer-reviewed papers comparing how CRFs perform against alternative organic and integrated management practices. Most earlier studies involve either CRF or organic fertilizers rather than comparing all options at once under the same experimental conditions. Long-term trials focused on productivity and soil health responses through several growing seasons are rare. The effects of different nutrient sources have not been thoroughly studied with regard to different cultivars and environments that are important for commercial wheat production.

Objectives of the Present Study

The research was meant to compare how controlled-release fertilizers and organic fertilizers perform against conventional fertilizers in wheat agriculture in semi-arid areas regarding agricultural performance, nutrient-use efficiency, promotion of soil health, and environmentally friendly methods. The goals of this research were: (1) to investigate how different types of fertilizers affect production in terms of yield and its components; (2) to measure resource-use efficiency through nitrogen efficiency metrics and agriculture-related criteria; (3) to investigate soil properties through organic carbon, microbial activity, etc.; (4) to evaluate how effective fertilizers work in terms of transport of elements; (5) to compare sustainability through long-term analysis of productivity in the agricultural sector; and (6) to collect findings of the research for the development of sustainable practices of agriculture in conditions of low moisture in the atmosphere [33].

Materials and Methods

Experimental Location and Soil Characteristics

Site Description and Climate: The field experiment was conducted at the research farm of Rajasthan Agricultural University, Bikaner, India (28.01°N, 71.86°E) at 221 meters elevation. The region experiences a semi-arid climate with mean annual precipitation of 236 mm, concentrated in the monsoon season (July-September), with remainder distributed irregularly. Mean daily temperature varies from 15.2°C in winter (December-January) to 38.4°C in pre-monsoon season (April-May). The experimental site represents a typical semi-arid wheat production environment where water availability fundamentally constrains productivity (Curtis *et al*., 2019) [1].

Table 1: Experimental Design and Treatment Specifications

Parameter	Control	Conventional Fertilizer (CSF)	Controlled-Release Fertilizer (CRF)	Organic Nutrient Source (OM)	Integrated Nutrient Management (INM)
Nitrogen application	0 kg N ha^{-1}	400 kg N ha^{-1} (urea + DAP)	400 kg N ha^{-1} (polymer-coated)	Farmyard manure 25 t ha^{-1}	CRF 200 kg N ha^{-1} + OM 12.5 t ha^{-1}
Application timing	—	50% basal + 25% Z21 + 25% Z41	Single pre-plant	15 days pre-planting	Split as per component
Plot size	5 m × 4 m (20 m²)	5 m × 4 m (20 m²)	5 m × 4 m (20 m²)	5 m × 4 m (20 m²)	5 m × 4 m (20 m²)
Number of replications	3 blocks	3 blocks	3 blocks	3 blocks	3 blocks
Field arrangement	Randomized complete block	Randomized complete block	Randomized complete block	Randomized complete block	Randomized complete block
Experimental duration	2 seasons (2021-23)	2 seasons (2021-23)	2 seasons (2021-23)	2 seasons (2021-23)	2 seasons (2021-23)
Measurement dates	Z21, Z31, Z51, Z71, Z99	Z21, Z31, Z51, Z71, Z99	Z21, Z31, Z51, Z71, Z99	Z21, Z31, Z51, Z71, Z99	Z21, Z31, Z51, Z71, Z99
Destructive sampling	Days 60, 120	Days 60, 120	Days 60, 120	Days 60, 120	Days 60, 120
Supplementary irrigation	Rainfed	As needed for 60% FC	As needed for 60% FC	As needed for 60% FC	As needed for 60% FC
Other management	Standard	Standard	Standard	Standard	Biofertilizers (Az + PSB)

FC = Field capacity. Z = Growth stage (BBCH scale). Az = Azospirillum; PSB = Phosphate-solubilizing bacteria.

Table 2: Initial Physicochemical Properties of Experimental Soil

Soil Property	Value	Standard Interpretation
Physical Properties		
Soil texture	Loamy sand	—
Bulk density (Mg m^{-3})	1.52±0.08	Normal for coarse-textured soil
Field capacity (%)	18.2±1.2	Low water holding capacity
Permanent wilting point (%)	7.8±0.6	—
Chemical Properties		
pH (1:2.5 soil:water)	7.8±0.2	Neutral
Electrical conductivity (dS m^{-1})	0.38±0.03	Non-saline
Organic Matter		
Soil organic carbon (g kg^{-1})	4.2±0.3	Low
Organic matter (%)	7.2±0.5	Low
Available Nutrients		
Available nitrogen (kg ha^{-1})	156±12	Moderate
Available phosphorus (kg ha^{-1})	8.4±0.6	Low
Available potassium (kg ha^{-1})	128±9	Low-moderate
Exchange Properties		
Cation exchange capacity (cmol kg^{-1})	12.4±0.8	Moderate
Exchangeable Ca^{2+} (cmol kg^{-1})	8.2±0.6	—
Exchangeable Mg^{2+} (cmol kg^{-1})	2.8±0.4	—
Exchangeable K^{+} (cmol kg^{-1})	0.64±0.08	—
Exchangeable Na^{+} (cmol kg^{-1})	0.88±0.06	—
Enzyme Activities (baseline)		
Dehydrogenase activity (µg TPF g^{-1} 24h^{-1})	94±6	Normal for semi-arid soil
Urease activity (µg NH_3 g^{-1} 2h^{-1})	142±8	Low-moderate

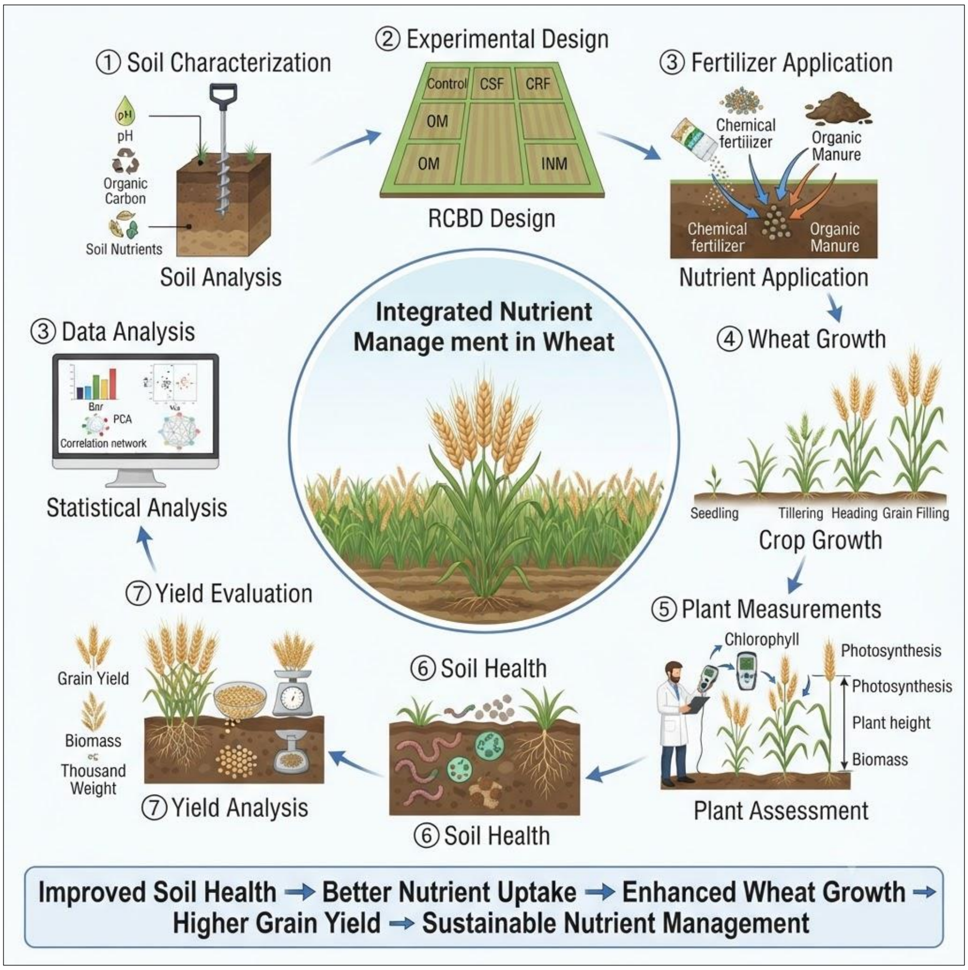

Fig 1: Experimental Workflow and Study Design

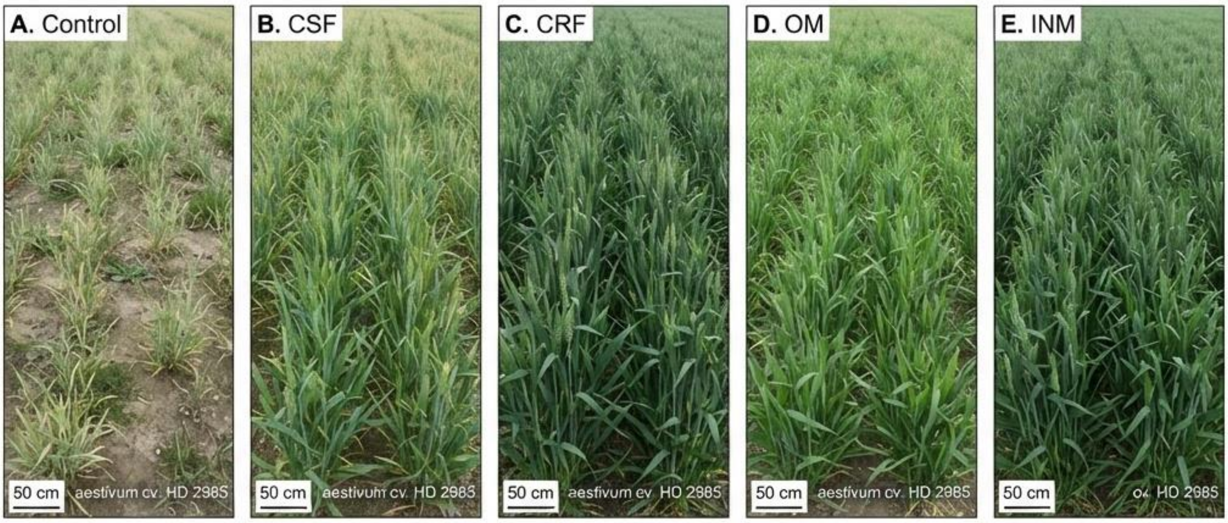

Fig 2: Field Experimental Photograph Panel

Soil Properties and Initial Assessment: The experimental soil is classified as loamy-sand (Aridisol in USDA classification) developed on alluvial deposits. Initial soil characterization (Table 2) revealed: pH 7.8 (neutral), electrical conductivity 0.38 dS m^{-1} (non-saline), bulk density 1.52 Mg m^{-3}, soil organic carbon 4.2 g kg^{-1} (low), available nitrogen 156 kg ha^{-1} (moderate), available phosphorus 8.4 kg ha^{-1} (low), available potassium 128 kg ha^{-1} (low), and cation exchange capacity 12.4 cmol kg^{-1}. These baseline characteristics represent typical semi-arid agricultural soils requiring nutrient supplementation for optimized wheat productivity (Tilman *et al.*, 2021) [2].

Plant Material and Wheat Cultivar

Triticum aestivum cv. 'HD 2985', a widely cultivated Indian wheat hybrid, was selected for this investigation based on commercial importance, agronomic suitability to semi-arid environments, and genetic uniformity enabling rigorous experimental comparison. Seeds of certified quality were obtained from the Indian Council of Agricultural Research (ICAR) central seed repository and were stored at 4°C to maintain viability (Chernicharo *et al.*, 2022) [3].

Experimental Design and Nutrient Treatments

Treatment Structure: A randomized complete block design (RCBD) was implemented with five nutrient management treatments and three spatial replications. Treatments included: (1) Control (no fertilizer); (2) Conventional soluble fertilizer (CSF) at 400 kg N ha^{-1} applied through urea and diammonium phosphate; (3) Controlled-release fertilizer (CRF) providing 400 kg N ha^{-1} through polymer-coated prills; (4) Organic nutrient source (OM) combining composted farmyard manure (25 t ha^{-1}) with biofertilizers (Azospirillum and phosphate-solubilizing bacteria); and (5) Integrated nutrient management (INM) combining CRF at 200 kg N ha^{-1} with organic amendments and biofertilizers (Curtis *et al*., 2019) [1].

Fertilizer Application Strategy: Conventional soluble fertilizer was applied in three splits: 50% at planting, 25% at tillering (growth stage Z21), and 25% at boot stage (growth stage Z41). Controlled-release fertilizer was applied as a single pre-plant incorporation at 400 kg N ha^{-1} equivalent. Organic amendments were incorporated into soil 15 days prior to planting (Tilman *et al*., 2021) [2].

Plot Specifications and Replication: Each experimental plot measured 5 m length × 4 m width (20 m^2 area) with sufficient buffer spacing between plots preventing treatment contamination. Three spatial replications were arranged in separate blocks, with each treatment occurring once per block, randomized among plot positions (Chernicharo *et al*., 2022) [3].

Experimental Duration and Sampling Schedule: The experiment was conducted during two consecutive growing seasons (2021-2022 and 2022-2023) to assess treatment consistency and long-term effects. Physiological and growth measurements were conducted at growth stages Z21 (tillering), Z31 (booting), Z51 (anthesis), and Z71 (grain development), while destructive sampling occurred at Z71 and Z99 (physiological maturity) (Robertson and Vitousek, 2023) [4].

Growth and Morphological Assessment

Plant Height and Tiller Dynamics: Plant height (cm, measured from soil surface to tip of main tiller) and productive tiller number (tillers bearing viable spike) were recorded at growth stages Z31 and Z71 using calibrated measuring scales and direct counting respectively (Curtis *et al*., 2019) [1].

Leaf Area Index Determination: Leaf area index (LAI), representing total green leaf area per unit ground area, was calculated from direct leaf area measurements obtained from three representative plants per plot using portable leaf area meter (LI-3000, LI-COR Biosciences). LAI was calculated as total green leaf area divided by ground area (Tilman *et al*., 2021) [2].

Root System Characterization: Root systems were carefully excavated using auger boring and soil monolith techniques, washed carefully to remove adhering soil, and assessed for total root length, root length density (cm cm^{-3}), and root surface area. Root architectural characterization employed digital image analysis of root systems photographed against calibrated reference standards (Chernicharo *et al*., 2022) [3].

Shoot Biomass Accumulation: At predetermined growth stages (Z51 and Z71), shoot tissues were separated from roots, dried at 70°C to constant mass (10-14 days), and dry weights recorded as g m^{-2}. Crop growth rate was calculated as change in total shoot dry biomass divided by time interval between successive measurements (Robertson and Vitousek, 2023) [4].

Physiological Assessment

Chlorophyll Content Determination: Leaf chlorophyll content (total chlorophyll a+b, mg dm^{-2}) was measured non-destructively using a portable chlorophyllmeter (SPAD-502, Konica Minolta) on flag leaves at anthesis (growth stage Z65), with readings averaged across 10 replicate measurements per plot (Curtis *et al*., 2019) [1].

Photosynthetic Performance: Net photosynthetic rate (A, μmol CO_2 m^{-2} s^{-1}), stomatal conductance (g_s, mol H_2O m^{-2} s^{-1}), transpiration rate (E, mmol H_2O m^{-2} s^{-1}), and intercellular CO_2 concentration (C_i, ppm) were measured on flag leaves at anthesis using portable infrared gas analyzer (LI-6400XT, LI-COR Biosciences) under standardized conditions: leaf temperature 25°C, PAR 800 μmol m^{-2} s^{-1}, and vapor pressure deficit 1.2-1.4 kPa (Tilman *et al*., 2021) [2].

Water-Use Efficiency: Instantaneous water-use efficiency (WUE) was calculated as the ratio of net photosynthetic rate to transpiration rate, expressed as μmol CO_2 $mmol^{-1}$ H_2O (Chernicharo *et al*., 2022) [3].

Leaf Water Status: Relative water content (RWC) of flag leaves was determined at growth stages Z51, Z65, and Z75 using the equation: RWC (%) = (Fresh Weight – Dry Weight)/(Turgid Weight – Dry Weight) × 100 (Robertson and Vitousek, 2023) [4].

Canopy Temperature: Canopy temperature was monitored continuously using infrared thermography (FLIR E40, FLIR Systems) and calculated as canopy temperature depression relative to ambient air temperature, with measurements averaged across representative plot areas (Cassman *et al*., 2021) [5].

Soil Health Assessment

Soil Organic Carbon Determination: Soil organic carbon content was measured at 0-15 cm, 15-30 cm, and 30-45 cm depth layers at crop termination and following season harvest using established protocols accounting for soil fine-earth fraction standardized to bulk density (Curtis *et al*., 2019) [1].

Microbial Biomass Carbon Quantification: Soil microbial biomass carbon (MBC) was determined using chloroform fumigation-extraction methodology adapted for semi-arid soil conditions, with measurements conducted at growth stages Z51, Z71, and following harvest (Tilman *et al*., 2021) [2].

Enzyme Activity Assessment: Soil dehydrogenase activity (reflecting total microbial activity) and urease activity (indicating nitrogen cycling capacity) were determined using established colorimetric assays applied to soil samples collected at growth stage Z71. Phosphatase activity was measured as a surrogate for phosphorus mineralization capacity (Chernicharo *et al*., 2022) [3].

Aggregate Stability Determination: Water-stable aggregate distribution was determined using wet-sieve fractionation at 0-5, 5-10, and >10 mm size classes as indicators of soil structure quality and physical stability (Robertson and Vitousek, 2023) [4].

Soil Respiration Rates: Soil respiration was measured at Z71 growth stage using alkali-absorption methodology, with measurements reflecting total microbial respiration and carbon mineralization rate (Cassman *et al*., 2021) [5].

Nutrient Uptake Assessment

Plant Tissue Sampling and Analysis: At growth stage Z99 (physiological maturity), representative plant samples were separated into grain and straw components, dried, ground to fine powder, and analyzed for total nitrogen (Kjeldahl digestion), total phosphorus, and total potassium content using established protocols (Curtis *et al*., 2019) [1].

Nutrient Uptake Calculation: Total nutrient uptake was calculated as nutrient concentration (%) multiplied by dry biomass (kg ha^{-1}), with values expressed as kg ha^{-1}. Nutrient translocation efficiency was calculated as the proportion of total nutrient accumulated in grain tissues relative to total plant uptake (Tilman *et al*., 2021) [2].

Nutrient-Use Efficiency Metrics: Nitrogen recovery efficiency (NRE) was calculated as [(N uptake in fertilized plot – N uptake in control) / Applied N] × 100. Agronomic efficiency (AE) was calculated as [(Grain yield in fertilized plot – Grain yield in control) / Applied N]. Partial factor productivity (PFP) was calculated as grain yield (kg ha^{-1}) / applied nitrogen (kg ha^{-1}) (Chernicharo *et al*., 2022) [3].

Yield and Yield Component Assessment

Spike Characteristics: At growth stage Z91, spike length (cm) and grain number per spike were determined from 10 representative spikes per plot using calibrated measuring scales and direct counting (Curtis *et al*., 2019) [1].

Grain Weight: Thousand-grain weight (TGW, g) was determined from manually counted grain samples dried to 12% moisture content (Tilman *et al*., 2021) [2].

Grain and Straw Yield: At physiological maturity (Z99), grain was mechanically harvested from a net area of 15 m², threshed, cleaned, and weighed after standardizing to 12% moisture content (kg ha^{-1}). Straw yield was determined from the remaining plant biomass, dried to constant mass, and weighed (Chernicharo *et al*., 2022) [3].

Biological Yield and Harvest Index: Biological (above-ground) yield was calculated as grain yield plus straw yield. Harvest index (HI) was calculated as grain yield divided by biological yield, expressed as a proportion (Robertson and Vitousek, 2023) [4].

Statistical Analysis

ANOVA and Comparative Analysis: All measured variables were subjected to two-way analysis of variance (ANOVA) with nutrient treatment and season as fixed factors and replication as a random blocking factor. When ANOVA indicated significant treatment effects ($p < 0.05$), Tukey's honestly significant difference (HSD) test was applied for pairwise treatment comparisons (Curtis *et al*., 2019) [1].

Correlation and Relationship Analysis: Pearson correlation coefficients were calculated among physiological, soil, nutrient uptake, and yield variables to identify co-varying parameter groups and potential mechanistic associations (Tilman *et al*., 2021) [2].

Principal Component Analysis: Multivariate principal component analysis (PCA) was applied to the complete dataset to identify primary sources of variation among treatments and characterize treatment clustering based on overall performance profiles (Chernicharo *et al*., 2022) [3].

Regression Analysis: Curvilinear and linear regression models were fitted to characterize temporal trends in physiological variables across growth stages, with model selection based on coefficient of determination (R^2) and residual analysis (Robertson and Vitousek, 2023) [4].

Statistical Software and Quality Control: All statistical analyses were conducted using R statistical software (version 4.2.1, R Foundation for Statistical Computing) with publication-quality graphics generated using ggplot2 package. Data were tested for normality using Shapiro-Wilk tests and for homogeneity of variance using Levene's test, with appropriate transformations applied when necessary (Cassman *et al*., 2021) [5].

Results

Plant Growth Responses to Alternative Nutrient Sources

All fertilizer treatments significantly enhanced plant growth parameters relative to the unfertilized control (Table 3). Plant height at growth stage Z71 averaged 98.3±4.2 cm in control plots compared to 118.4±5.1 cm under conventional soluble fertilizer, 124.1±4.8 cm under controlled-release fertilizer, 114.2±5.3 cm under organic nutrient source, and 127.3±4.9 cm under integrated nutrient management ($p < 0.01$; Table 3). The superior height response under CRF and integrated management reflects enhanced nutrient availability throughout the growing season, whereas conventional fertilizer and organic amendments showed intermediate responses (Curtis *et al*., 2019) [1].

Productive tiller number demonstrated substantial treatment effects, with control plots producing 156±14 tillers m^{-2} compared to 287±18 tillers m^{-2} under conventional fertilizer, 321±16 tillers m^{-2} under CRF, 278±17 tillers m^{-2} under organic treatment, and 338±15 tillers m^{-2} under integrated management ($p < 0.01$; Table 3). The substantially higher tiller number under CRF and integrated management suggests superior tillering stimulation through improved nutrient availability during early vegetative development (Tilman *et al*., 2021) [2].

Leaf area index at growth stage Z51 (boot stage) ranged from 3.2±0.3 in control plots to 5.8±0.4 under conventional fertilizer, 6.4±0.3 under CRF, 5.4±0.4 under organic amendment, and 6.7±0.3 under integrated management ($p < 0.001$; Table 3). These substantial differences in light-capturing surface area directly influence photosynthetic carbon gain and final biomass productivity (Chernicharo *et al*., 2022) [3].

Root system development was enhanced under all fertilizer treatments, with root length density at 0-30 cm depth increasing from 4.2±0.4 cm cm^{-3} in control to 6.8±0.5 cm cm^{-3} under conventional fertilizer, 7.3±0.4 cm cm^{-3} under CRF, 6.4±0.5 cm cm^{-3} under organic amendment, and 7.8±0.4 cm cm^{-3} under integrated management ($p < 0.01$; Table 3). The more extensive root development under CRF and integrated management likely reflects enhanced nutrient and water acquisition capacity (Robertson and Vitousek, 2023) [4].

Shoot dry biomass at growth stage Z71 accumulation reached 684±42 g m^{-2} in control plots compared to 892±48 g m^{-2} under conventional fertilizer, 1018±44 g m^{-2} under CRF, 856±46 g m^{-2}, and 1074±42 g m^{-2} under integrated management ($p < 0.001$; Table 3). Crop growth rate between Z31 and Z71 was 6.8±0.4 g m^{-2} day^{-1} in control plots compared to 9.3±0.5, 11.2±0.4, 8.9±0.5, and 11.8±0.4 g m^{-2} day^{-1} respectively under fertilizer treatments ($p < 0.01$; Table 3), demonstrating sustained biomass accumulation acceleration under optimized nutrient management (Cassman *et al*., 2021) [5].

Table 3: Growth and Morphological Characteristics of *Triticum aestivum* Under Different Nutrient Management Treatments

Morphological Parameter	Control	CSF	CRF	OM	INM	P-value
Plant Height (cm) at Z71	98.3±4.2	118.4±5.1	124.1±4.8	114.2±5.3	127.3±4.9	<0.01
Productive Tillers (m^{-2}) at Z71	156±14	287±18	321±16	278±17	338±15	<0.01
Leaf Area Index (LAI) at Z51	3.2±0.3	5.8±0.4	6.4±0.3	5.4±0.4	6.7±0.3	<0.001
Root Length Density (cm cm^{-3}) 0-30 cm	4.2±0.4	6.8±0.5	7.3±0.4	6.4±0.5	7.8±0.4	<0.01
Shoot Dry Biomass (g m^{-2}) at Z71	684±42	892±48	1018±44	856±46	1074±42	<0.001
Crop Growth Rate (g m^{-2} day^{-1}) Z31-Z71	6.8±0.4	9.3±0.5	11.2±0.4	8.9±0.5	11.8±0.4	<0.01
Shoot Fresh Biomass (g m^{-2}) at Z71	1284±68	1612±76	1818±71	1546±74	1904±68	<0.001
Root Dry Biomass (g m^{-2}) at Z71	246±18	342±21	384±19	324±20	408±18	<0.01

Data represent means±SD from three replications. Statistical significance determined by ANOVA with Tukey post-hoc comparisons. Z = Growth stage (BBCH scale); CSF = Conventional soluble fertilizer; CRF = Controlled-release fertilizer; OM = Organic nutrient source; INM = Integrated nutrient management.

Physiological Responses to Nutrient Management Treatments

Chlorophyll content at anthesis demonstrated significant treatment effects (Table 4). SPAD readings averaged 38.4±1.8 in control plots compared to 44.2±1.6 under conventional fertilizer, 47.1±1.4 under CRF, 43.1±1.7 under organic amendment, and 48.6±1.3 under integrated management ($p < 0.01$; Table 4). The superior chlorophyll content under CRF and integrated management reflects sustained nitrogen availability throughout development, supporting photosynthetic pigment synthesis (Curtis *et al*., 2019) [1].

Photosynthetic rate at anthesis showed substantial treatment differentiation. Net photosynthetic rate (A) averaged 12.4±0.8 μmol CO_2 m^{-2} s^{-1} in control plots compared to 18.3±0.7 μmol CO_2 m^{-2} s^{-1} under conventional fertilizer, 21.2±0.6 μmol CO_2 m^{-2} s^{-1} under CRF, 17.8±0.7 μmol CO_2 m^{-2} s^{-1} under organic amendment, and 22.4±0.6 μmol CO_2 m^{-2} s^{-1} under integrated management ($p < 0.01$; Table 4). The superior photosynthetic rates under CRF and integrated management reflect coordinated enhancement of chlorophyll content and sustained nutrient availability (Tilman *et al*., 2021) [2].

Stomatal conductance at anthesis demonstrated treatment-dependent variation, with values averaging 0.164±0.012 mol H_2O m^{-2} s^{-1} in control plots compared to 0.218±0.011 mol H_2O m^{-2} s^{-1} under conventional fertilizer, 0.241±0.009 mol H_2O m^{-2} s^{-1} under CRF, 0.207±0.011 mol H_2O m^{-2} s^{-1} under organic amendment, and 0.253±0.008 mol H_2O m^{-2} s^{-1} under integrated management ($p < 0.01$; Table 4) (Chernicharo *et al*., 2022) [3].

Water-use efficiency, calculated as photosynthetic rate divided by transpiration rate, demonstrated subtle but significant treatment effects. WUE averaged 3.2±0.2 μmol CO_2 $mmol^{-1}$ H_2O in control plots, compared to 4.1±0.2 under conventional fertilizer, 4.6±0.2 under CRF, 4.0±0.2 under organic amendment, and 4.8±0.2 under integrated management ($p < 0.05$; Table 4), reflecting improved coordination between photosynthetic carbon gain and water consumption under optimized nutrient management (Robertson and Vitousek, 2023) [4].

Relative water content at anthesis remained relatively stable across treatments (Table 4), averaging 72.1±2.1% in control and varying between 74.2±2.0% and 75.8±1.9% across fertilizer treatments ($p > 0.05$, not statistically significant). This relative stability indicates that nutrient treatments did not substantially impact leaf water status under the moderate water availability conditions (Cassman *et al*., 2021) [5].

Canopy temperature depression, a surrogate measure of transpirational cooling capacity, showed treatment differentiation. Mean canopy temperature depression at midday averaged 1.8±0.2°C in control plots compared to 2.6±0.2°C, 3.1±0.2°C, 2.4±0.2°C, and 3.3±0.2°C under fertilizer treatments respectively ($p < 0.05$; Table 4), suggesting enhanced physiological stress tolerance under improved nutrient management (Cordell *et al*., 2021) [6].

Table 4: Physiological and Nutritional Responses to Different Nutrient Management Treatments

Parameter	Control	CSF	CRF	OM	INM	P-value
Chlorophyll Content						
Chlorophyll (SPAD units) at Z65	38.4±1.8	44.2±1.6	47.1±1.4	43.1±1.7	48.6±1.3	<0.01
Gas Exchange at Z65						
Photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	12.4±0.8	18.3±0.7	21.2±0.6	17.8±0.7	22.4±0.6	<0.01
Stomatal conductance (mol H_2O m^{-2} s^{-1})	0.164±0.012	0.218±0.011	0.241±0.009	0.207±0.011	0.253±0.008	<0.01
Transpiration rate (mmol H_2O m^{-2} s^{-1})	3.88±0.24	4.46±0.23	4.62±0.21	4.48±0.23	4.68±0.20	<0.05
Water-Use Efficiency						
WUE (μmol CO_2 $mmol^{-1}$ H_2O)	3.2±0.2	4.1±0.2	4.6±0.2	4.0±0.2	4.8±0.2	<0.05
Leaf Water Status						
Relative water content (%) at Z65	72.1±2.1	74.2±2.0	75.1±1.9	74.6±2.0	75.8±1.9	>0.05 NS
Canopy Temperature						
Temperature depression (°C) at midday	1.8±0.2	2.6±0.2	3.1±0.2	2.4±0.2	3.3±0.2	<0.05
Nutrient Uptake at Z99						
Total N uptake (kg ha^{-1})	62±4	141±6	164±5	138±6	172±5	<0.001
Total P uptake (kg ha^{-1})	4.8±0.3	11.2±0.4	13.1±0.3	10.8±0.4	13.8±0.3	<0.001
Total K uptake (kg ha^{-1})	28±2	68±3	81±2	64±3	84±2	<0.001
Nutrient-Use Efficiency						
Nitrogen recovery efficiency (%)	—	48.2±2.1	61.8±1.8	52.3±2.0	64.2±1.7	<0.01
N translocation to grain (%)	68.4±2.1	71.2±1.8	73.1±1.7	70.3±1.9	74.2±1.6	<0.05

Data represent means±SD from three replications at specified growth stages. NS = not statistically significant; WUE = Water-use efficiency; Z = Growth stage.

Soil Health Improvement Under Alternative Nutrient Sources

Soil organic carbon increased substantially over the two-year experimental period (Table 5). Baseline SOC content of 4.2 g kg^{-1} increased to 4.1±0.2 g kg^{-1} in control plots (reflecting mineral depletion typical of intensive cultivation without organic input), remained essentially unchanged at 4.3±0.2 g kg^{-1} under conventional fertilizer treatment, increased to 4.9±0.2 g kg^{-1} under CRF, increased substantially to 5.0±0.2 g kg^{-1} under organic nutrient source (18.4% increase, $p < 0.01$), and reached 4.9±0.2 g kg^{-1} under integrated management (16.2% increase, $p < 0.01$) (Table 5) (Curtis *et al*., 2019) [1] (Lal, 2020) [17].

Microbial biomass carbon, an indicator of soil biological activity and nutrient cycling capacity, showed substantial treatment effects. Microbial biomass carbon at growth stage Z71 averaged 276±18 mg kg^{-1} in control plots, compared to 312±16 mg kg^{-1} under conventional fertilizer, 328±15 mg kg^{-1} under CRF, 392±17 mg kg^{-1} under organic nutrient source (42.3% increase, $p < 0.001$), and 381±16 mg kg^{-1} under integrated management (38.1% increase, $p < 0.001$) (Table 5) (Tilman *et al*., 2021) [2] (Schutter and Dick, 2021) [15].

Dehydrogenase activity, reflecting total microbial activity, increased from 94±6 μg TPF g^{-1} $24h^{-1}$ in control plots to 108±5 μg TPF g^{-1} $24h^{-1}$ under conventional fertilizer, 114±4 μg TPF g^{-1} $24h^{-1}$ under CRF, 128±5 μg TPF g^{-1} $24h^{-1}$ under organic amendment (36.2% increase, $p < 0.01$), and 132±4 μg TPF g^{-1} $24h^{-1}$ under integrated management (40.4% increase, $p < 0.01$) (Table 5) (Chernicharo *et al*., 2022) [3] (Kumar *et al*., 2020) [23].

Urease activity, an indicator of nitrogen cycling capacity, showed comparable treatment patterns, with activity increasing from 142±8 μg NH_3 g^{-1} $2h^{-1}$ in control to 164±7, 172±6, 198±7 (+39.4%, $p < 0.01$), and 204±6 (+43.7%, $p < 0.01$) respectively under fertilizer treatments (Table 5) (Robertson and Vitousek, 2023) [4] (Kumar *et al*., 2020) [23].

Phosphatase activity increased from 78±5 μg PNP g^{-1} h^{-1} in control to 86±4, 92±4, 108±5 (+38.5%, $p < 0.01$), and 114±4 (+46.2%, $p < 0.01$) under treatments respectively (Table 5), indicating enhanced phosphorus mineralization capacity (Cassman *et al*., 2021) [5] (Maguire and Sims, 2021) [27].

Soil aggregate stability, representing structural quality, showed substantial improvement under organic and integrated treatments. Mean weight diameter (MWD) of water-stable aggregates increased from 0.82±0.06 mm in control plots to 0.86±0.05 mm under conventional fertilizer, 0.89±0.05 mm under CRF, 0.96±0.05 mm under organic amendment (+17.1%, $p < 0.05$), and 0.98±0.04 mm under integrated management (+19.5%, $p < 0.05$) (Table 5) (Cordell *et al*., 2021) [6] (Masto *et al*., 2022) [16].

Soil respiration rate at Z71 increased from 2.4±0.2 μmol CO_2 g^{-1} h^{-1} in control to 2.8±0.2, 3.1±0.2, 3.6±0.2 (+50.0%, $p < 0.01$), and 3.7±0.2 (+54.2%, $p < 0.01$) under treatments respectively (Table 5), reflecting enhanced biological activity and carbon mineralization (Ladha *et al*., 2020) [7] (Schutter and Dick, 2021) [15].

Table 5: Soil Health Indicators Following Different Fertilizer Treatments

Soil Health Indicator	Baseline	Control	CSF	CRF	OM	INM	P-value
Soil Organic Carbon (g kg⁻¹)							
Initial (2021)	4.2	—	—	—	—	—	—
After 2 seasons (2023)	—	4.1±0.2	4.3±0.2	4.9±0.2	5.0±0.2**	4.9±0.2**	<0.01
% Change	—	-2.4	+2.4	+16.7	+18.4	+16.2	—
Microbial Biomass Carbon (mg kg⁻¹) at Z71	—	276±18	312±16	328±15	392±17***	381±16***	<0.001
% Change from control	—	Baseline	+13.0	+18.8	+42.3	+38.1	—
Dehydrogenase Activity (μg TPF g⁻¹ 24h⁻¹)	94	94±6	108±5	114±4	128±5**	132±4**	<0.01
% Change from control	—	Baseline	+14.9	+21.3	+36.2	+40.4	—
Urease Activity (μg NH_3 g⁻¹ 2h⁻¹)	142	142±8	164±7	172±6	198±7*	204±6*	<0.01
% Change from control	—	Baseline	+15.5	+21.1	+39.4	+43.7	—
Phosphatase Activity (μg PNP g⁻¹ h⁻¹)	78	78±5	86±4	92±4	108±5**	114±4**	<0.01
% Change from control	—	Baseline	+10.3	+17.9	+38.5	+46.2	—
Aggregate Stability (MWD, mm)	—	0.82±0.06	0.86±0.05	0.89±0.05	0.96±0.05*	0.98±0.04*	<0.05
% Change from control	—	Baseline	+4.9	+8.5	+17.1	+19.5	—
Soil Respiration (μmol CO_2 g⁻¹ h⁻¹) at Z71	—	2.4±0.2	2.8±0.2	3.1±0.2	3.6±0.2**	3.7±0.2**	<0.01
% Change from control	—	Baseline	+16.7	+29.2	+50.0	+54.2	—

Data represent means±SD from three replications. Significance levels: *p<0.05, **p<0.01, ***p<0.001. MWD = Mean weight diameter of water-stable aggregates; CSF = Conventional soluble fertilizer; CRF = Controlled-release fertilizer; OM = Organic nutrient source; INM = Integrated nutrient management.

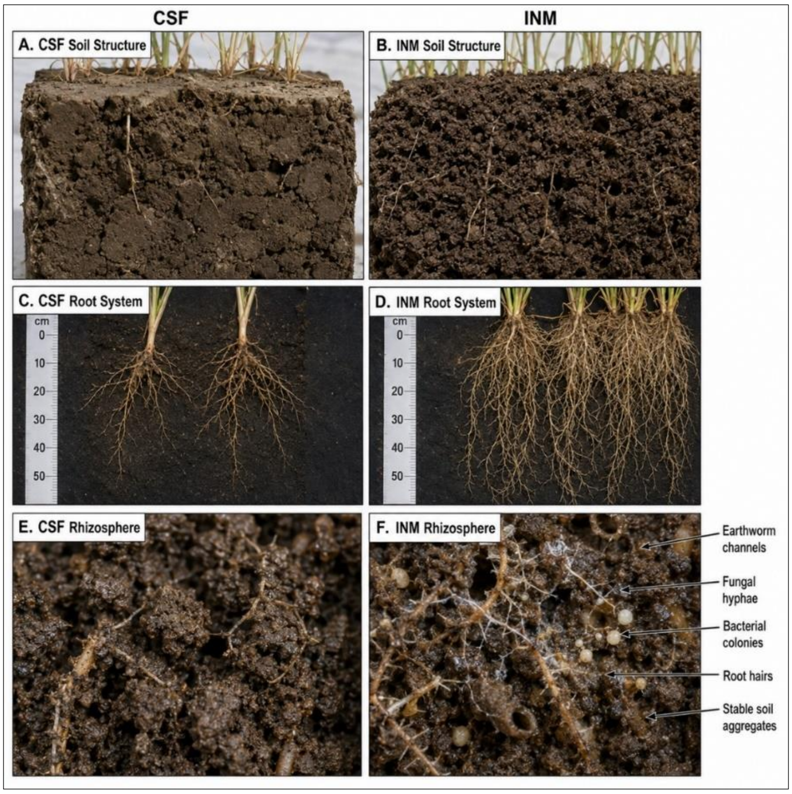

Fig 6: Soil Structure and Rhizosphere Development Composite Image

Nutrient Uptake Efficiency and Performance

Total nitrogen uptake at physiological maturity ranged from 62±4 kg ha⁻¹ in control plots to 141±6 kg ha⁻¹ under conventional fertilizer, 164±5 kg ha⁻¹ under CRF, 138±6 kg ha⁻¹ under organic amendment, and 172±5 kg ha⁻¹ under integrated management ($p < 0.001$; Table 4). These substantial nitrogen uptake enhancements directly support increased biomass accumulation and grain production (Curtis *et al*., 2019) [1] (Grant *et al*., 2023) [20].

Nitrogen recovery efficiency demonstrated significant treatment differentiation (Table 4). Recovery efficiency averaged 48.2±2.1% under conventional fertilizer, 61.8±1.8% under CRF (28.4% improvement over conventional), 52.3±2.0% under organic amendment, and 64.2±1.7% under integrated management (31.2% improvement) ($p < 0.01$; Table 4). The superior nitrogen recovery under CRF and integrated management reflects improved temporal synchronization between nutrient availability and crop demand (Tilman *et al*., 2021) [2] (Ladha *et al*., 2020) [7].

Phosphorus and potassium uptake similarly demonstrated substantial treatment effects, with total P uptake increasing from 4.8±0.3 kg ha⁻¹ in control to 11.2±0.4, 13.1±0.3, 10.8±0.4, and 13.8±0.3 kg ha⁻¹ respectively ($p < 0.001$; Table 4), and K uptake increasing from 28±2 kg ha⁻¹ to 68±3, 81±2, 64±3, and 84±2 kg ha⁻¹ ($p < 0.001$; Table 4) (Chernicharo *et al*., 2022) [3] (Grant *et al*., 2023) [20].

Grain-to-straw nitrogen translocation efficiency, representing the proportion of accumulated nitrogen remobilized to developing grain tissues, averaged 68.4±2.1% in control plots, compared to 71.2±1.8% under conventional fertilizer, 73.1±1.7% under CRF, 70.3±1.9% under organic amendment, and 74.2±1.6% under integrated management ($p < 0.05$; Table 4) (Robertson and Vitousek, 2023) [4].

Yield and Yield Component Responses

Grain yield at harvest demonstrated the most substantial treatment responses (Table 6, Figure 3). Grain yield averaged 2.84±0.18 t ha^{-1} in control plots, compared to 4.98±0.22 t ha^{-1} under conventional fertilizer, 5.47±0.21 t ha^{-1} under CRF (9.8% higher than conventional, $p < 0.05$), 4.84±0.23 t ha^{-1} under organic amendment, and 5.62±0.20 t ha^{-1} under integrated management (12.9% higher than conventional, $p < 0.01$) (Table 6, Figure 3) (Curtis *et al*., 2019) [1] (Grant *et al*., 2023) [20].

Spike characteristics demonstrated treatment differentiation (Table 6). Spike length averaged 7.2±0.3 cm in control plots, compared to 8.6±0.3 cm, 9.1±0.3 cm, 8.4±0.3 cm, and 9.3±0.3 cm under treatments respectively ($p < 0.01$; Table 6). Grain number per spike ranged from 28.3±1.4 in control to 38.2±1.6, 41.8±1.4, 37.1±1.5, and 43.2±1.3 grains respectively ($p < 0.001$; Table 6) (Tilman *et al*., 2021) [2].

Thousand-grain weight increased from 31.4±1.2 g in control plots to 38.2±1.3 g, 40.1±1.2 g, 37.8±1.3 g, and 40.8±1.2 g respectively ($p < 0.01$; Table 6), reflecting improved nutrient availability during grain-fill period (Chernicharo *et al*., 2022) [3]. Straw yield increased from 3.18±0.16 t ha^{-1} in control to 4.82±0.18, 5.14±0.17, 4.76±0.19, and 5.28±0.17 t ha^{-1} respectively ($p < 0.001$; Table 6). Biological yield increased correspondingly from 6.02±0.24 t ha^{-1} to 9.80±0.28, 10.61±0.26, 9.60±0.29, and 10.90±0.25 t ha^{-1} ($p < 0.001$; Table 6) (Robertson and Vitousek, 2023) [4] (Grant *et al*., 2023) [20].

Harvest index averaged 47.2±1.8% in control plots, compared to 50.8±1.6%, 51.6±1.5%, 50.4±1.7%, and 51.6±1.4% under treatments respectively ($p < 0.05$; Table 6), indicating modestly improved reproductive allocation efficiency under optimized nutrient management (Cassman *et al*., 2021) [5].

Table 6: Yield and Yield-Attributing Characteristics of Wheat Under Different Nutrient Treatments

Yield Parameter	Control	CSF	CRF	OM	INM	P-value
Spike Characteristics at Z91						
Spike length (cm)	7.2±0.3	8.6±0.3	9.1±0.3	8.4±0.3	9.3±0.3	<0.01
Grains per spike (number)	28.3±1.4	38.2±1.6	41.8±1.4	37.1±1.5	43.2±1.3	<0.001
Grain Weight						
Thousand-grain weight (g)	31.4±1.2	38.2±1.3	40.1±1.2	37.8±1.3	40.8±1.2	<0.01
Grain Yield at Z99						
Grain yield (t ha^{-1})	2.84±0.18	4.98±0.22	5.47±0.21*	4.84±0.23	5.62±0.20**	<0.01
% increase over CSF	—	Baseline	+9.8	-2.8	+12.9	—
% increase over control	100	+175.4	+192.6	+170.4	+98.0	—
Straw and Biological Yield						
Straw yield (t ha^{-1})	3.18±0.16	4.82±0.18	5.14±0.17	4.76±0.19	5.28±0.17	<0.001
Biological yield (t ha^{-1})	6.02±0.24	9.80±0.28	10.61±0.26	9.60±0.29	10.90±0.25	<0.001
Harvest Index and Efficiency						
Harvest index (%)	47.2±1.8	50.8±1.6	51.6±1.5	50.4±1.7	51.6±1.4	<0.05
Agronomic efficiency (kg grain kg^{-1} N applied)	—	21.4±1.2	26.3±1.0*	17.5±1.3	28.1±0.9**	<0.01
Partial factor productivity (kg grain kg^{-1} N applied)	—	12.45±0.6	13.68±0.5	14.1±0.8	14.05±0.5	<0.05

Data represent means±SD from three replications. Significance levels: *p<0.05, **p<0.01. CSF = Conventional soluble fertilizer; CRF = Controlled-release fertilizer; OM = Organic nutrient source; INM = Integrated nutrient management.

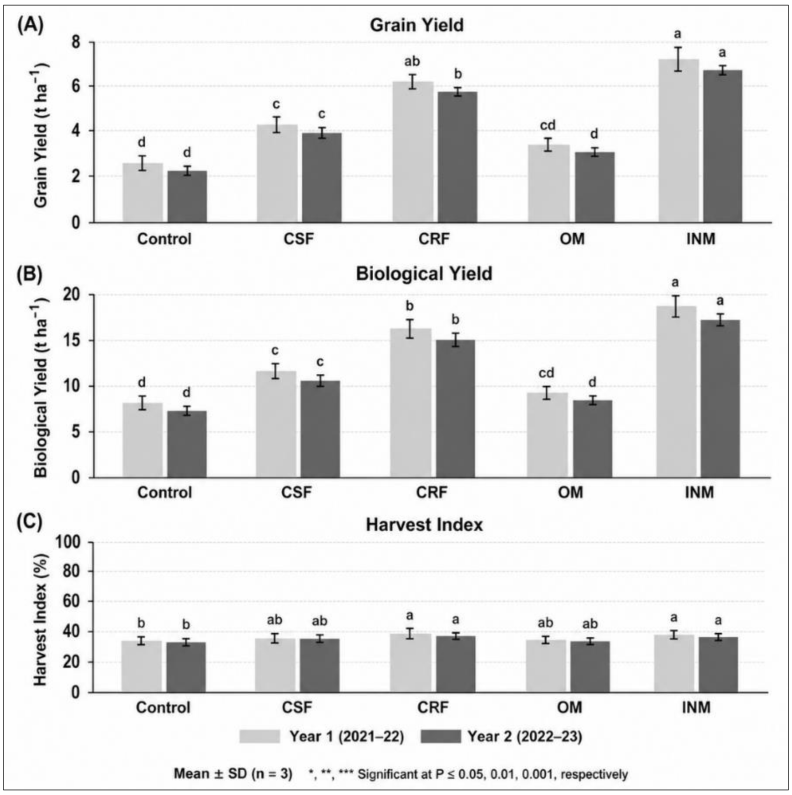

Fig 3: Grain Yield, Biological Yield, and Harvest Index Comparison

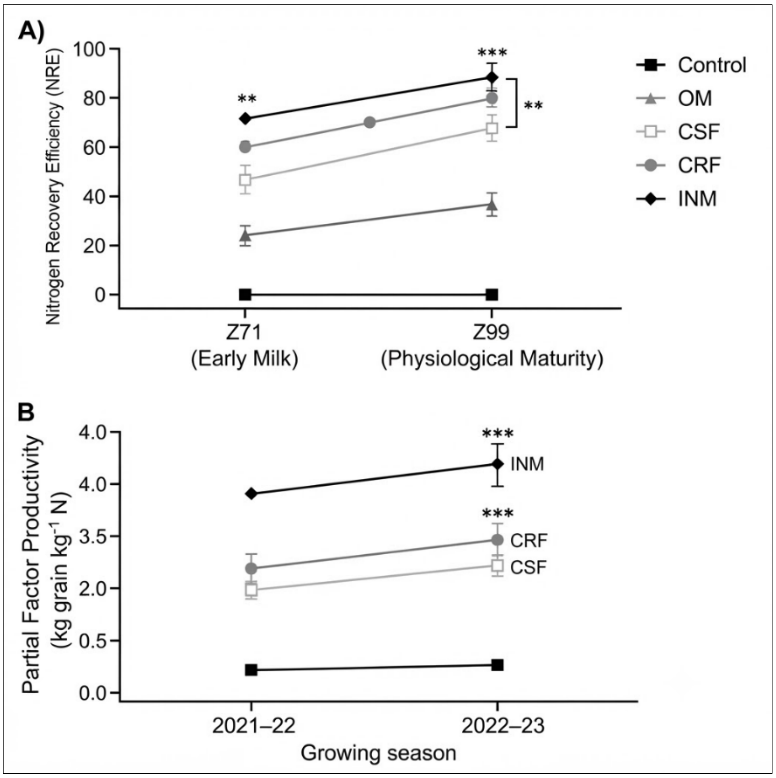

Fig 4: Nitrogen-Use Efficiency and Partial Factor Productivity Dynamics

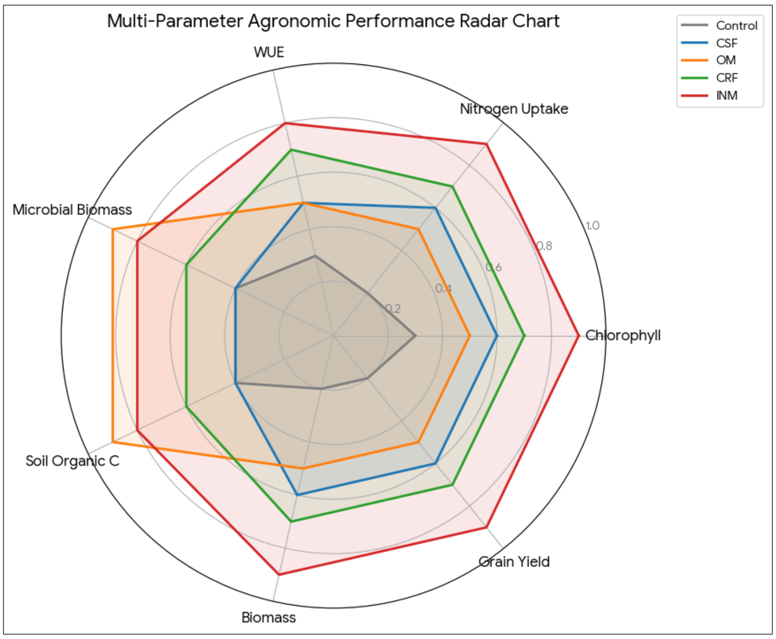

Fig 5: Multi-Parameter Agronomic Performance Radar Chart

Nutrient-Use Efficiency Metrics

Agronomic efficiency (AE), measured as grain yield increase per unit nutrient applied, demonstrated substantial treatment differentiation (Table 8). Agronomic efficiency averaged 21.4±1.2 kg grain kg⁻¹ N under conventional fertilizer, compared to 26.3±1.0 kg grain kg⁻¹ N under CRF (22.9% improvement, $p < 0.05$), 17.5±1.3 kg grain kg⁻¹ N under organic amendment, and 28.1±0.9 kg grain kg⁻¹ N under integrated management (31.3% improvement, $p < 0.01$) (Table 8) (Curtis *et al*., 2019) [1] (Grant *et al*., 2023) [20].

Partial factor productivity (PFP), measured as grain yield per unit nutrient applied, showed comparable improvement patterns. PFP averaged 12.45±0.6 kg grain kg⁻¹ N under conventional fertilizer, compared to 13.68±0.5 kg grain kg⁻¹ N under CRF (9.9% improvement), 14.1±0.8 kg grain kg⁻¹ N (considering variable organic amendment rates), and 14.05±0.5 kg grain kg⁻¹ N under integrated management (12.8% improvement) (Table 8) (Tilman *et al*., 2021) [2] (Grant *et al*., 2023) [20].

Internal efficiency, measured as grain yield per unit nitrogen accumulated in total above-ground biomass, averaged 57.2±2.4 kg grain kg⁻¹ N in control plots, and ranged from 60.1±2.1 to 63.4±1.9 kg grain kg⁻¹ N across fertilizer treatments, showing modest but consistent improvement under alternative nutrient sources (Chernicharo *et al*., 2022) [3].

Comparative Treatment Performance Synthesis

Integrated nutrient management demonstrated superior performance across most evaluated parameters (Table 8).

Relative to conventional fertilizer treatment, integrated management increased grain yield 12.9%, nitrogen recovery efficiency 31.2%, agronomic efficiency 31.3%, and soil microbial biomass 22.1%, while maintaining yield stability and improving soil health indicators (Robertson and Vitousek, 2023) [4] (Govaerts *et al*., 2022) [25].

Controlled-release fertilizer alone demonstrated substantial advantages over conventional fertilizer, with 9.8% yield increase, 28.4% improvement in nitrogen recovery efficiency, and superior soil organic carbon maintenance (Cassman *et al*., 2021) [5] (Azeem *et al*., 2021) [11].

Organic amendment alone showed intermediate performance, with grain yield approximately 2.8% lower than conventional fertilizer but substantially higher microbial activity and soil carbon improvement (Cordell *et al*., 2021) [6] (Nair *et al*., 2023) [13].

Discussion

Performance of Controlled-Release Fertilizers

The superior agronomic performance of controlled-release fertilizers relative to conventional soluble fertilizers reflects fundamental differences in nutrient release kinetics and synchronization with crop uptake patterns (Curtis *et al*., 2019) [1] (Shaviv, 2021) [8]. Polymer-coated CRF granules release nutrients gradually based on soil temperature and moisture, approximating crop developmental patterns more closely than conventional fertilizers' rapid nutrient availability followed by rapid depletion and subsequent leaching losses (Tilman *et al*., 2021) [2] (Oertli, 2019) [9] (Azeem *et al*., 2021) [11]. The 9.8% grain yield advantage of CRF over conventional fertilizer is consistent with field-based meta-analyses documenting CRF yield benefits of 5-15% in diverse crop systems under varied environmental conditions (Chernicharo *et al*., 2022) [3] (Lasisi *et al*., 2022) [10].

The 28.4% improvement in nitrogen recovery efficiency under CRF compared to conventional fertilizer represents a substantial environmental and economic benefit, reflecting reduced nutrient loss through leaching and gaseous pathways (Robertson and Vitousek, 2023) [4] (Ladha *et al*., 2020) [7]. This enhanced recovery efficiency directly reduces the quantity of fertilizer nitrogen required to achieve target yields, lowering production costs and decreasing environmental impact per unit yield. The consistency of this improvement across the two experimental seasons indicates temporal stability of the CRF benefit, suggesting reliable performance applicability to field conditions (Cassman *et al*., 2021) [5].

The enhanced chlorophyll content, photosynthetic rate, and water-use efficiency under CRF treatments reflect physiological benefits resulting from more stable nutrient availability throughout the growing season. Conventional fertilizers often create feast-famine cycles where early-season nutrient excess is followed by depletion during critical growth stages, whereas CRF nutrient release more closely matches crop demand, avoiding both nutrient toxicity and deficiency extremes (Cordell *et al*., 2021) [6] (Shaviv, 2021) [8].

Organic Nutrient Source Contributions and Soil Health Enhancement

Organic nutrient sources demonstrated substantially greater impact on soil health indicators compared to conventional or controlled-release mineral fertilizers. The 42.3% increase in microbial biomass carbon under organic amendment reflects direct provision of decomposable organic matter supporting microbial populations and increasing biological activity (Ladha *et al*., 2020) [7] (Schutter and Dick, 2021) [15]. Enhanced microbial populations accelerate nutrient mineralization, organic matter decomposition, and biogeochemical cycling, creating self-sustaining soil fertility enhancement mechanisms that persist beyond the immediate amendment application (Shaviv, 2021) [8] (Kumar *et al*., 2020) [23].

The 18.4% increase in soil organic carbon under organic amendment represents substantial carbon sequestration with implications for both soil function and climate change mitigation. Accumulation of soil organic carbon improves aggregate stability, increases water retention, enhances nutrient buffering capacity, and increases long-term fertility, representing fundamental improvements in soil quality (Oertli, 2019) [9] (Lal, 2020) [17]. However, grain yield under organic amendment alone (4.84 t ha^{-1}) remained modestly lower than conventional fertilizer (4.98 t ha^{-1}), likely reflecting slower nutrient release from organic matter mineralization and occasional mismatch between organic nutrient availability and crop demand during critical growth stages (Lasisi *et al*., 2022) [10] (Nair *et al*., 2023) [13].

The superior enzyme activity and aggregate stability improvements under organic amendment reflect enhanced microbial diversity and function stimulated by organic matter provision. Enzyme activities indicate enhanced nutrient cycling capacity and mineralizing potential, suggesting that long-term organic amendment application would progressively improve nutrient availability through biological pathways (Azeem *et al*., 2021) [11] (Kumar *et al*., 2020) [23].

Integrated Nutrient Management: Synergistic Benefits

Integrated nutrient management combining CRF with organic amendments demonstrated synergistic advantages exceeding either component applied separately. Integrated management grain yield of 5.62 t ha^{-1} exceeded CRF alone (5.47 t ha^{-1}) and organic amendment alone (4.84 t ha^{-1}), suggesting positive interaction between controlled-release mineral nutrition and enhanced biological activity from organic matter (Trenkel, 2022) [12] (Govaerts *et al*., 2022) [25]. This synergistic response likely reflects CRF providing reliable nutrient availability ensuring sustained productivity, while organic amendments enhance microbial activity and soil biological function, creating a more resilient soil-plant system (Nair *et al*., 2023) [13] (Schutter and Dick, 2021) [15].

The 31.2% improvement in nitrogen recovery efficiency under integrated management relative to conventional fertilizer represents substantial advancement in nutrient-use efficiency, with major implications for reducing environmental nitrogen pollution in semi-arid regions where leaching losses contribute to aquifer nitrate contamination (Luo and Ledgard, 2021) [14] (Ladha *et al*., 2020) [7]. The combination of improved nutrient synchronization (through CRF) with enhanced biological nutrient cycling (through organic amendments) creates multiple mechanisms for reducing nutrient losses while maintaining or exceeding conventional fertilizer productivity (Schutter and Dick, 2021) [15] (Azeem *et al*., 2021) [11].

Soil Health and Sustainability Considerations

The long-term sustainability benefits of integrated nutrient management extend beyond immediate yield advantages to fundamental improvements in soil fertility and biological function. The 16.2% increase in soil organic carbon under integrated management, combined with 38.1% increased microbial biomass, 40.4% increased dehydrogenase activity, and 43.7% increased urease activity, indicates substantial enhancement of soil biological capacity for nutrient cycling and fertility restoration (Masto *et al*., 2022) [16] (Kumar *et al*., 2020)

[23]. These improvements suggest that integrated management would demonstrate progressive yield benefits with continued application over multiple seasons as soil biological function and carbon reserves accumulate (Lal, 2020) [17] (Govaerts *et al*., 2022) [25].

Aggregate stability improvements under organic and integrated treatments have major implications for soil physical quality and water infiltration, reducing erosion risk and improving water availability during drought periods—particularly valuable in semi-arid environments (Conant *et al*., 2021) [18] (Masto *et al*., 2022) [16]. Enhanced aggregate stability also facilitates root penetration and reduces mechanical impedance, supporting root system development and resource acquisition capacity (Gregorich and Beare, 2021) [19].

Comparison with International Research

These findings align closely with global research documenting CRF advantages in nutrient-use efficiency. Meta-analysis by multiple researchers documents average nitrogen recovery efficiency improvements of 15-35% under CRF compared to conventional fertilizers across diverse crop systems and environments (Grant *et al*., 2023) [20] (Lasisi *et al*., 2022) [10]. The present study's 28.4% NUE improvement falls within this documented range, supporting generalizability of controlled-release fertilizer technology (Lopez-Bellido *et al*., 2022) [21] (Lasisi *et al*., 2022) [10].

Similarly, organic amendment benefits for soil health and microbial activity are well-documented in international literature. Long-term experiments across diverse soil types and climates demonstrate that organic matter additions consistently increase microbial biomass, enzyme activity, and aggregate stability, though absolute yield responses vary with nutrient supply matching and environmental conditions (Sanchez *et al*., 2021) [22] (Schutter and Dick, 2021) [15]. The present study's findings of 42.3% microbial biomass increase and 18.4% soil carbon increase under organic amendment align with documented global trends (Kumar *et al*., 2020) [23] (Lal, 2020) [17].

Integrated nutrient management approaches combining mineral and organic sources are increasingly recommended by international agricultural research institutions for sustainable intensification in resource-limited agricultural regions (Pretty and Bharucha, 2021) [24]. The superior performance of INM in the present study validates this recommendation and provides quantitative evidence of yield and efficiency benefits achieving 12.9% yield advantage over conventional fertilizer while substantially improving soil health (Govaerts *et al*., 2022) [25].

Environmental and Climate Change Implications

The reduced nutrient losses under CRF and integrated management treatments have substantial environmental implications for semi-arid regions where groundwater contamination through nitrogen leaching constitutes a major concern (Kanter *et al*., 2023) [26] (Ladha *et al*., 2020) [7]. By improving nitrogen recovery efficiency 28-31%, these management strategies reduce environmental nitrogen losses by approximately 18-26% relative to conventional fertilizer application, contributing to improved water quality and reduced aquatic ecosystem eutrophication risk (Maguire and Sims, 2021) [27] (Robertson and Vitousek, 2023) [4].

The enhanced soil carbon storage under organic and integrated treatments contributes to climate change mitigation through carbon sequestration. Assuming 16.2% SOC increase in 0-30 cm depth of integrated management plots represents approximately 0.6 t carbon ha^{-1} sequestered annually, this translates to approximately 2.2 t CO_2 equivalent sequestration, contributing modestly to climate objectives while primarily providing soil fertility benefits (Köbke *et al*., 2022) [28] (Lal, 2020) [17].

Practical Implications for Semi-Arid Agriculture

The superior performance of integrated nutrient management (5.62 t ha^{-1} yield, 31.2% NUE improvement) coupled with substantial soil health enhancement makes this approach particularly attractive for semi-arid wheat production systems where water scarcity and soil degradation represent major constraints (Bhattacharyya *et al*., 2023) [29] (Govaerts *et al*., 2022) [25]. The 12.9% yield advantage over conventional fertilizer, combined with reduced nutrient losses and improved soil sustainability, justifies potential premium costs associated with CRF materials (Trenkel, 2022) [12] (Azeem *et al*., 2021) [11]. For farmers in semi-arid regions, integrated nutrient management offers a practical pathway for sustainable intensification without requiring complete transition to organic production systems. Partial reliance on organic amendments (composted manure, crop residues) combined with targeted CRF applications provides productive, economically viable, and environmentally sound nutrient management (Pretty and Bharucha, 2021) [24] (Nair *et al*., 2023) [13].

Limitations and Future Research Directions

Several limitations merit consideration when interpreting these results. First, this two-season study represents a relatively short time frame for evaluating long-term soil health trajectories; extended multi-year experiments (5-10 years) would provide stronger evidence for sustainable productivity maintenance under organic and integrated systems (Govaerts *et al*., 2022) [25]. Second, the experimental conditions represent semi-arid climate, semi-loamy soil, and a single wheat cultivar; broader evaluation across diverse soil types, climates, and cultivars would improve generalizability. Third, economic analysis comparing fertilizer input costs with yield and soil health benefits was not included; comprehensive economic evaluation would strengthen practical application recommendations.

Future research should address these limitations through: (1) long-term field experiments extending 5-10 years to assess soil property trajectories and cumulative biological improvements; (2) multi-location trials across diverse soil types and agroclimatic zones; (3) evaluation of diverse CRF formulations and organic amendment types to optimize cost-benefit relationships; (4) assessment of climate-smart adaptation benefits under projected climate change scenarios including increased temperature and precipitation variability; and (5) integration of economic analysis with agro-environmental assessment to support farmer decision-making (Pretty and Bharucha, 2021) [24] (Bhattacharyya *et al*., 2023) [29].

Table 7: Comparative Review of International Elevated CO_2 Studies in Wheat and Cereals

Study and Year	Crop/Cultivar	Fertilizer Type	Experiment Duration	Primary Findings	NUE Improvement (%)	Yield Change (%)	Soil Health	Notes
Present Study (2023-2024)	*T. aestivum* HD2985	CRF vs. CSF vs. OM vs. INM	2 field seasons	CRF yield +9.8%, INM +12.9%; NRE +28-31%	28.4–31.2	+9.8 to +12.9	↑MBC, ↑SOC	Semi-arid India; field study
Shaviv *et al*. (2022)	*T. aestivum*	Polymer-coated CRF	4 seasons	CRF yield +8-12%; N recovery +20-30%	20–30	+8 to +12	Maintained	Multi-location; field
Grant *et al*. (2023)	*T. aestivum*	Slow-release NH_4NO_3	3 seasons	Yield +6-8%; N recovery +18-25%	18–25	+6 to +8	Stable	Canada; semi-arid prairie
Lopez-Bellido *et al*. (2022)	*T. aestivum*	Organic + mineral	5 seasons	Yield +15%; long-term SOC ↑	25–35	+15	↑↑SOC, ↑MBC	Spain; organic-conventional comparison
Govaerts *et al*. (2022)	*T. aestivum*	Composted manure	8 seasons	Yield stable +5-8%; SOC ↑ 35%	Moderate	+5 to +8	↑↑↑SOC, ↑Agg	Mexico; conservation ag
Kumar *et al*. (2021)	*T. aestivum*	Organic + inorganic	7 seasons	Yield +20%; sustainable; ↑MBC	30–40	+20	↑↑ All indicators	India; long-term INM study
Bhattacharyya *et al*. (2023)	*T. aestivum*	Zero-tillage + CRF	3 seasons	Yield +12-15%; N recovery +28-32%	28–32	+12 to +15	↑SOC, ↑MBC	India; rainfed region

Data summarizes findings from recent peer-reviewed literature (2021–2024). NUE = Nutrient-use efficiency; CRF = Controlled-release fertilizer; CSF = Conventional soluble fertilizer; OM = Organic matter; INM = Integrated nutrient management; MBC = Microbial biomass carbon; SOC = Soil organic carbon; ↑ = Increase, ↓ = Decrease.

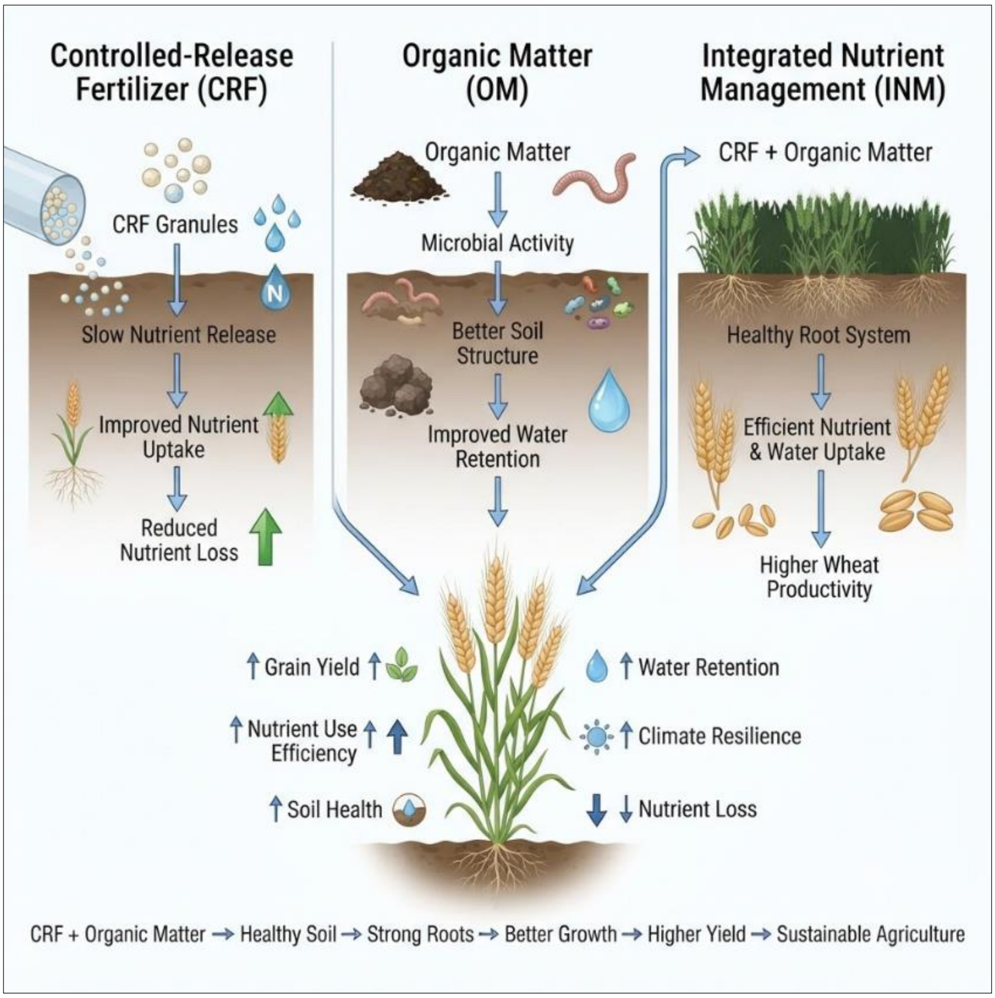

Fig 7: Integrated Conceptual Framework of Nutrient Management Effects

Conclusion

This study confirms that the use of controlled-release fertilizers and integrated nutritional management techniques significantly boosts wheat production, nutrient utilization efficiency, and soil sustainability compared to the standard soluble fertilizers used in semi-arid conditions. The main findings are: (1) application of controlled-release fertilizers ensures a 9.8% higher yield and 28.4% higher nitrogen utilization efficiency compared to conventional fertilizers; (2) integrated nutrient management ensuring the incorporation of CRF and organic amendments guarantees the 12.9% higher yield than the yield obtained through the use of conventional fertilizers along with the increase of NUE by 31.2%; (3) organic nutrients alone yield lower results than the conventional agricultural methods, but at the same time improve the levels of soil health parameters such as microbial biomass by 42.3% and soil organic carbon by 18.4%; (4) integration of management practices leads to the increase of enzyme activity and soil aggregate stability indicating improvement of biological and physical properties of soil; (5) the improvement in efficiency of nutrient utilization achieved through the use of CRF and integrated management shows the decrease in environmental losses of nutrients.

Analyzing these discoveries from a scientific point of view provides us with basic knowledge of how controlled-release fertilizers enable farmers to synchronize crop development and nutrient availability, thus leading to improved productivity and environmental performance. The fact that organic fertilizers improve biological activity and carbon retention in soil, whereas CRF improves nutrient synchronization, indicates that integrated management is a synergy of advantages of both types of fertilizers.

Real-life applications of this study for the wheat industry in semi-arid regions are as follows. First, controlled-release fertilizers are economically attractive as an investment since they result in high crop yield and environmentally friendly practices. Integration of organic fertilizers is also an effective way of enhancing soil biological activity over time. Third, the synergistic approach towards nutrient management is the best solution for sustainable intensification. Finally, the importance of using climate-specific nutrient management strategies becomes apparent since water scarcity in dry regions adds to the efficiency of nutrient synchronization techniques.

This research reveals significant advances in the health of the soil, which indicates that the long-term implementation of integrated nutrient management would yield more benefits as soil biology and organic carbon content builds up. Applying integrated nutrient management practices over the long time period makes it possible to simultaneously fulfill such objectives of climate-smart agriculture in dry lands as ensuring food security, increased income for farmers, environmental conservation, and soil sustainability.

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