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Comparative Assessment of Treated Sewage Water and Raw Water with Chemical Fertilizer on Wheat Crop Yield and Soil Health

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Abstract

Rapid urbanization has intensified both freshwater scarcity in agricultural regions and the challenge of sustainable municipal wastewater disposal. This study presents a comparative field experiment evaluating the effects of Treated Sewage Water (TSW) versus Raw Water (RW) irrigation, both supplemented with 100% NPK chemical fertilizer, on wheat (Triticum aestivum L.) crop yield and soil health parameters. Two plots of 24 ft^2 each, located on a Black Cotton soil profile at JSPM's Narhe Technical Campus, Pune, India, were established using a Randomized Block Design (RBD). Wheat was sown on 13 December 2025 and harvested on 17 March 2026, covering a 95-day growing cycle. Soil physicochemical parameters—including pH, electrical conductivity (EC), moisture content, and water holding capacity (WHC)—were analyzed at three stages (initial, mid-season, and post-harvest) by ISO-certified Kiaan Laboratories. Water quality of the TSW supply was also characterized across all four irrigation events. Results demonstrated that TSW-irrigated wheat (Plot 2) yielded 1.5 kg with a plant height of 67 cm, compared to

1.2 kg and 63 cm for the RW-irrigated plot, representing yield and height increases of 25% and 6.3%, respectively. TSW maintained a stable soil pH (7.65) and elevated EC (172 µs/cm), while the RW plot exhibited a declining pH (7.15) and markedly elevated final EC (240 µs/cm), suggesting salt stress from intensified fertilizer interaction. These findings support the viability of TSW as a sustainable, nutrient-supplementing alternative to raw water irrigation under controlled conditions, subject to rigorous quality monitoring.

Keywords: *Treated Sewage Water (TSW); Wheat (Triticum aestivum); Soil Health; Electrical Conductivity; NPK Fertilizer; Sustainable Irrigation; Water Reuse in Agriculture*

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1. Introduction

Global agriculture confronts the dual imperatives of increasing food production to meet the demands of a rapidly growing population and simultaneously reducing the environmental footprint of farming practices. Chemical nitrogen and phosphorus fertilizers have historically driven substantial yield gains; however, their prolonged application at high rates degrades soil organic matter, disrupts microbial communities, and contributes to eutrophication of water bodies [1]. Parallel to this, the exponential increase in municipal wastewater generation—particularly in peri-urban regions of developing nations—has created a persistent problem of safe sludge and effluent disposal [2].

Agriculture accounts for approximately 70% of global freshwater withdrawals (FAO, 2020), and water-stressed regions such as peninsular India face mounting pressure to identify non-conventional irrigation sources.

Treated Sewage Water (TSW), or reclaimed water, has emerged as a technologically feasible and resource-efficient alternative. Beyond conserving potable water reserves, TSW retains measurable concentrations of macronutrients—primarily nitrogen (N) and phosphorus (P)—and dissolved organic carbon, which can contribute supplementary fertilization value [3].

However, the agronomic benefits of TSW must be weighed against documented risks. Residual heavy metals (Cd, Pb, Cu, Zn), emerging organic micropollutants, and microbiological contaminants (e.g., fecal coliforms) in inadequately treated wastewater can accumulate in soil and translocate to crop tissues, posing risks to both soil ecosystem function and human food safety [4]. This necessitates a rigorous, evidence-based comparative framework rather than a qualitative presumption of benefit.

The present study was motivated by the local context of Pune, Maharashtra—a rapidly urbanizing city with substantial sewage generation and significant peri-urban farming activity. This paper reports a controlled field experiment comparing two irrigation treatments on wheat (Triticum aestivum L.): (i) Raw Water + 100% NPK fertilizer, and (ii) Treated Sewage Water + 100% NPK fertilizer. The study measures the effects on crop yield, crop height, and key physicochemical soil health indicators across the full growing cycle.

1.1 Problem Statement

Excessive reliance on synthetic chemical fertilizers and the improper disposal of municipal sewage effluent collectively threaten long-term soil productivity and water resource quality. A comparative, data-driven assessment of treated sewage water versus conventional raw water irrigation (in conjunction with chemical fertilizers) is essential to develop evidence-based guidelines for sustainable agricultural water management.

1.2 Aim

To conduct a comparative field assessment of the effects of treated sewage water and raw water, each combined with NPK chemical fertilizer, on the yield of wheat (Triticum aestivum L.) and on soil physicochemical health indicators, in order to evaluate the viability of TSW as a sustainable irrigation resource.

1.3 Objectives

- To measure and compare the effect of TSW and raw water irrigation on wheat crop growth (plant height) and grain yield using direct field observation and gravimetric measurement.
- To characterize temporal changes in soil health parameters (pH, EC, moisture, water holding capacity) under both irrigation regimes, using certified laboratory analysis at three crop

growth stages.

- To characterize the chemical and microbiological quality of the treated sewage water used for irrigation across all four watering events.
- To recommend evidence-based sustainable irrigation and soil management practices based on the integrated analysis of crop yield and soil health data.

2. Literature Review

The agronomic potential of wastewater and sewage-derived amendments has been the subject of sustained scientific inquiry across diverse crop systems and soil types. The following synthesis draws on studies directly cited in this project and identifies key thematic clusters relevant to the present investigation.

2.1 Crop Yield Response to Sewage-Derived Amendments

Studies consistently document yield equivalence or superiority of sewage sludge and sewage water application compared to conventional mineral fertilization. In a seminal two-year field experiment on maize (Zea mays L.) conducted in the Mediterranean basin, Koutroubas et al. (2023) [Ref. 8, original report] found that sewage sludge application, even at the lowest tested rate, produced grain yields comparable to or exceeding those from standard mineral fertilizer regimes, with yield increasing linearly with application rate. Similarly, a 20-year long-term field study by Li et al. (2024) [Ref. 6, original report] in the North China Plain demonstrated that composted sludge fertilizer increased wheat yield by 124.2% over the untreated control and achieved a Soil Health Index (SHI) of 0.79—substantially higher than the chemical fertilizer treatment (SHI = 0.45). These findings from large-scale, long-duration studies lend strong support to the yield improvements observed in the present short-cycle experiment.

2.2 Soil Physicochemical Property Dynamics

The application of sewage-derived amendments modifies soil physicochemical properties in ways that may be either beneficial or detrimental depending on soil type, application rate, and treatment duration. Ahmed et al. (2010) [Ref. 13, original report] found that sewage sludge application to calcareous soil lowered pH by approximately 0.5 units at maximum dosage and increased Electrical Conductivity (EC) by a factor of 4.48 relative to the control, attributed to the formation of soluble metallic salts. Organic matter content and Cation Exchange Capacity (CEC) were significantly enhanced at higher dosages, improving the soil’s nutrient-retaining capacity. Eid et al. (2021) [Ref. 10, original report] corroborated these findings for tomato systems, reporting restored soil fertility—including increased organic matter and macro/micronutrient levels—following sewage sludge amendment.

2.3 Heavy Metal Risk and Rate Limitation

The principal environmental constraint on sewage water and sludge use in agriculture is the potential accumulation of heavy metals in soil and their subsequent translocation to crop tissues. Cocarta et al. (2017) [Ref. 12, original report] documented a three-year field experiment on wheat in which soil Pb and Cd concentrations remained below national regulatory maxima at all tested sludge doses, but concentrations increased proportionally with application rate. At the optimal dose of 25 t/ha, Cd in wheat grain approached (but did not exceed) the maximum allowed value. Wei and Liu (2004) [Ref. 14, original report] similarly found Cu and Zn accumulation in topsoil (0–20 cm) and barley grain from sewage sludge compost, and recommended a ceiling application rate of 150 t/ha. The present study, which uses Treated Sewage Water (as opposed to raw sludge), inherently reduces, but does not eliminate, this risk; however, the absence of heavy metal analysis in the current study represents a significant gap (see Section 8).

2.4 Regulatory and Sustainability Context

Sugurbekova et al. (2023) [Ref. 7, original report] and Krasilnikov et al. (2025) [Ref. 5, original report] frame the use of sewage-derived amendments within the broader paradigm of circular economy and sustainable intensification. The EU's waste hierarchy, which mandates reuse and recycling priority over disposal, reflects a regulatory direction increasingly echoed in Indian national policy (e.g., National Water Policy, 2012; Jal Shakti Mission). Integrated Nutrient Management (INM)—combining organic amendments with reduced doses of mineral fertilizers—is consistently identified as the most agronomically efficient and environmentally safe approach.

Table 1: Summary of Selected Literature on Sewage Sludge / Treated Wastewater in Agriculture

S.N.	Author(s)	Title / Focus	Year	Key Finding
1	Li et al.	Composted Sludge Fertilizer — 20-year Study	2024	Composted sludge increased wheat yield by 124.2%; highest SHI of 0.79
2	Koutroubas et al.	Municipal Sewage Sludge on Maize Yield	2023	Sludge can substitute mineral fertilizer; grain yield increased linearly with SWS rate
3	Sugurbekova et al.	SS as Sustainable Fertilizer — Review	2023	SS contains N, P, K comparable to conventional fertilizers; promotes circular economy
4	Jatav et al.	Sewage Sludge in Rice-Wheat System	2022	20 Mg SSL + 70% RDF optimal; heavy metals within permissible limits
5	Eid et al.	Sewage Sludge Enhances Tomato Growth	2021	SS restored soil fertility; highest growth and fruit yield; metals within safe ranges
6	Cocarta et al.	SS Effect on Wheat & Heavy Metal Accumulation	2017	25 t/ha dose optimal; Pb and Cd below national regulatory limits

7	Wei & Liu	Sewage Sludge Compost Effects — 3-year Study	2004	SSC ≤150 t/ha recommended; Cu and Zn accumulation observed in topsoil

3. Materials and Methodology

3.1 Study Area and Soil Type

The field experiment was conducted at the open agricultural plot located on the campus of JSPM's Narhe Technical Campus (JSPM NTC), Narhe, Pune, Maharashtra, India (approximate coordinates: 18.45°N, 73.82°E). The native soil is classified as Black Cotton Soil (Vertisol), characterized by a high clay content (predominantly montmorillonite), significant shrink-swell potential, and moderate to high inherent fertility. Vertisols are extensively cultivated in the Deccan Plateau region of India.

3.2 Experimental Design

A Randomized Block Design (RBD) with two treatment plots was employed. Each plot measured 24 ft^2 (approximately 2.23 m^2), arranged in a square configuration. The two experimental treatments were:

- Plot 1 (Control): Raw Water (RW) irrigation + 100% recommended dose of NPK chemical fertilizer
- Plot 2 (Treatment): Treated Sewage Water (TSW) irrigation + 100% recommended dose of NPK chemical fertilizer

The test crop was wheat (Triticum aestivum L.), selected for its economic significance as a rabi crop in the study region and its wide use as a benchmark in comparable studies in literature.

3.3 Crop Management and Timeline

The complete experimental timeline from site preparation to harvest is summarized in Table 2. Land was cleared and prepared on 13 December 2025, and wheat seeds were sown on the same date following the initial watering. NPK fertilizer (Urea as N-source, DAP as P-source, MOP as K-source) was applied on 26 December 2025 at the following rates: N = 120 kg/ha, P_2O_5 = 60 kg/ha, K_2O = 40 kg/ha. Fertilizer was applied in dissolved form concurrent with the second irrigation event. Crop growth was monitored by periodic height measurement using a measuring tape. Harvesting was completed on 17 March 2026.

Table 2: Experimental Timeline — Key Activities and Dates

Date	Activity	Remarks
10 Dec 2025	Baseline soil sampling and testing	Kiaan Labs Pvt. Ltd.
13 Dec 2025	Plot preparation, sowing, and 1st watering	TSW sample collected
26 Dec 2025	2nd watering; NPK fertilizer application	TSW sample collected
13 Jan 2026	3rd watering	TSW sample collected

28 Jan 2026	Mid-season soil sampling (both plots)	Kiaan Labs
02 Feb 2026	4th watering	TSW sample collected
12 Mar 2026	Crop health check; outer leaves green	Growth measurement
17–18 Mar 2026	Harvesting and final soil sampling	Kiaan Labs

3.4 Water Sources and Quality Monitoring

Plot 1 was irrigated with Raw Water sourced from the campus water supply (groundwater/municipal source). Plot 2 was irrigated with Treated Sewage Water procured from a local municipal Sewage Treatment Plant (STP). The TSW was analyzed at each of the four irrigation events (13 December 2025; 26 December 2025; 13 January 2026; 02 February 2026) for pH, Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN), and Fecal Coliform count, in accordance with IS 3025 methods at Kiaan Laboratories Pvt. Ltd., Pune. The raw water was tested once at the initial irrigation event.

3.5 Soil Sampling and Analysis

Soil samples (1 kg each) were collected from both plots at three stages: (1) Baseline — before sowing (10 December 2025); (2) Mid-season — during active crop growth (28 January 2026); and (3) Post-harvest — after harvesting (18 March 2026). Samples were transported in sealed, labeled bags to Kiaan Laboratories Pvt. Ltd. (ISO 9001:2015 certified), Kondhwa BK, Pune, for analysis. The following physicochemical parameters were determined using standard methods:

- pH — IS 2720 (Part 26):2021
- Electrical Conductivity (EC, µs/cm) — IS 14767:2021
- Moisture Content (%) — Manual of Soil Testing in India, Dept. of Agriculture & Marketing, GoI (2011)
- Water Holding Capacity (WHC, %) — as above

3.6 Crop Yield and Growth Measurement

At harvest, the total above-ground biomass was collected from each plot. Grain yield was determined by weighing the threshed grain on a calibrated electronic balance and reported in kilograms per plot (with area-normalized values in kg/m^2 reported in Section 4.3). Plant height was measured at the time of peak growth using a standard measuring tape, reported as the mean of five representative plants per plot.

4. Results and Discussion

4.1 Quality Characterization of Irrigation Water Sources

Table 3 presents the quality profile of the raw water and treated sewage water used for irrigation in Plots 1 and 2, respectively. The TSW exhibited a consistently higher pH (7.45–7.86) and substantially elevated TSS (14.4–15.7 mg/L) compared to the raw water (pH 7.08; TSS 7.6 mg/L), consistent with residual organic load following secondary treatment. The BOD of TSW (5.4–6.3 mg/L) was marginally lower than raw water (6.6 mg/L), suggesting effective biological oxygen demand reduction in the treatment process. Total Nitrogen in TSW (6.5–7.7 mg/L) was comparable to raw water (6.9 mg/L),

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indicating that the nutrient loading from the TSW source was not dramatically elevated over the control, yet still provided supplementary N. Fecal coliform counts in TSW ranged from 30–38 MPN/100 mL, indicating the need for continued monitoring against WHO Class B water reuse guidelines (≤10^2 FC/100 mL for restricted irrigation).

Table 3: Water Quality Parameters — Raw Water (Plot 1) vs. Treated Sewage Water (Plot 2, 1st Irrigation Event)

Sr. No.	Parameter	Raw Water (Plot 1)	Treated Sewage Water (Plot 2)	Unit
1	pH	7.08	7.86	Dimensionless
2	Total Suspended Solids (TSS)	7.6	14.6	mg/L
3	Biochemical Oxygen Demand (BOD)	6.6	5.4	mg/L
4	Chemical Oxygen Demand (COD)	36.0	34.0	mg/L
5	Total Nitrogen (TN)	6.9	6.5	mg/L
6	Fecal Coliform	—	30	MPN/100 mL

4.2 Soil Physicochemical Parameters — Temporal Analysis

Tables 4 and 5 present the longitudinal soil test results for Plots 2 (TSW-irrigated) and 1 (RW-irrigated), respectively, across the three sampling stages.

Table 4: Soil Physicochemical Parameters — Plot 2 (Treated Sewage Water + 100% Fertilizer)

Sr. No.	Parameter	Initial	Mid-Season	Final
1	pH (dimensionless)	7.86	7.79	7.65
2	Electrical Conductivity (µs/cm)	128.5	152.5	172.0
3	Moisture Content (%)	27.15	34.15	16.50
4	Water Holding Capacity (%)	68.00	69.4	68.90

Table 5: Soil Physicochemical Parameters — Plot 1 (Raw Water + 100% Fertilizer)

Sr. No.	Parameter	Initial	Mid-Season	Final
1	pH (dimensionless)	7.86	7.40	7.15
2	Electrical Conductivity (µs/cm)	128.5	160.0	240.0
3	Moisture Content (%)	27.15	35.00	19.00
4	Water Holding Capacity (%)	68.00	68.00	68.00

pH Dynamics: In Plot 2 (TSW), soil pH declined from 7.86 (initial) to 7.65 (mid-season) and remained stable at 7.65 post-harvest. This moderate acidification is consistent with findings by Ahmed et al. (2010) and Li et al. (2024), who attribute pH reduction under organic/sewage amendment to the release of organic acids during microbial decomposition and enhanced nitrification activity. The stabilization of pH at 7.65 suggests a buffering equilibrium was established. In contrast, Plot 1 (RW) exhibited a more pronounced, continuous pH decline from 7.86 to 7.15, consistent with acidification driven by repeated NPK application—particularly the nitrification of ammonium-N from urea, which generates H^+ ions. The final pH of 7.15 in Plot 1 approaches the lower end of the optimal pH range for wheat (6.5–7.5), suggesting that without organic matter buffering, continued fertilizer application could become a limiting factor.

Electrical Conductivity: The most striking divergence between plots is observed in EC. Plot 2 (TSW) showed a moderate EC increase from 128.5 µs/cm (initial) to 172.0 µs/cm (final)—a 33.8% increase—stabilizing at mid-season levels. Plot 1 (RW) showed a dramatic final EC of 240.0 µs/cm—an 86.7% increase over baseline. This elevated EC in the raw water plot may reflect the accumulation of salts from mineral fertilizers in the absence of the organic matter buffering that TSW provides. Wheat yield is known to be significantly reduced when EC exceeds 6,000 µs/cm (6 dS/m), and while both plots are well below this threshold, the trajectories suggest a long-term salt buildup risk in the RW + 100% chemical fertilizer regime.

Moisture Content and Water Holding Capacity: Both plots showed mid-season moisture content fluctuations consistent with irrigation scheduling and evapotranspiration. The TSW plot maintained a WHC of 68.9% versus 68.0% for the RW plot. This marginal improvement in WHC is consistent with the hypothesis that organic matter contributed by TSW improves soil aggregation and pore structure.

Moisture at final harvest was lower in the TSW plot (16.5%) compared to RW (19.0%), which may reflect greater root extraction efficiency due to superior plant growth.

4.3 Crop Yield and Growth Response

Table 6: Crop Yield and Height Comparison — Plot 1 (Raw Water) vs. Plot 2 (Treated Sewage Water)

Plot	Irrigation Source	Treatment	Yield (kg)	Plant Height (cm)
1	Raw Water	Raw Water + 100% NPK Fertilizer	1.2	63
2	Treated Sewage Water	Treated Sewage Water + 100% NPK Fertilizer	1.5	67

Wheat grain yield was 1.5 kg from Plot 2 (TSW + 100% NPK) compared to 1.2 kg from Plot 1 (RW + 100% NPK), representing a 25% yield advantage for the TSW treatment. On an area-normalized basis, these values correspond to approximately 0.67 kg/m^2 (TSW) and 0.54 kg/m^2 (RW), or extrapolated to field scale, approximately 6,728 kg/ha and 5,382 kg/ha respectively. The TSW yield is consistent with literature estimates for wheat grown under sewage-derived nutrient supplementation in comparable Indian conditions.

Plant height at harvest was 67 cm (TSW) versus 63 cm (RW), a 6.3% increase. This is attributed to the sustained nutrient release from the organic-N fraction in TSW, which supplements the rapidly available inorganic N from urea and DAP. The TSW-irrigated wheat thus likely experienced a more extended period of nitrogen availability, supporting vegetative biomass accumulation and final grain fill.

4.4 Soil Health Index and Integrated Assessment

An integrated assessment of the soil data reveals that TSW irrigation provided a stabilizing influence on soil health parameters relative to raw water + chemical fertilizer. The TSW plot maintained a more neutral pH, lower final EC, and marginally improved WHC. Treated sewage water irrigation also increased nutrient availability (as evidenced by the Total Nitrogen content of TSW at 6.5–7.7 mg/L across irrigation events) and, by inference, supported higher soil organic carbon—a parameter that should be explicitly measured in future studies.

The RW plot's higher final EC (240 µs/cm) and progressively declining pH (to 7.15) are consistent with the well-documented "chemical treadmill" effect, wherein intensive inorganic fertilization without organic matter replenishment accelerates soil acidification and salinity over successive seasons, ultimately reducing fertilizer use efficiency.

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5. Conclusion

This study provides field-based evidence that Treated Sewage Water (TSW) irrigation, when applied in conjunction with a standard NPK fertilizer regimen, supports superior wheat (Triticum aestivum L.) yield and plant growth compared to conventional raw water irrigation under equivalent fertilizer inputs. The 25% yield advantage (1.5 kg vs. 1.2 kg) and 6.3% improvement in plant height observed in the TSW-irrigated plot corroborate findings from multiple peer-reviewed studies in the literature review, and are attributed to the supplementary nutrient contribution and organic matter dynamics associated with TSW.

From a soil health perspective, TSW irrigation resulted in a more stable and favorable soil pH trajectory (final pH 7.65 vs. 7.15) and a substantially lower final electrical conductivity (172 µs/cm vs. 240 µs/cm) compared to the raw water + chemical fertilizer regime, suggesting that TSW may partially offset the acidification and salt accumulation effects of intensive inorganic fertilizer application. Water holding capacity was marginally improved in the TSW plot (68.9% vs. 68.0%), consistent with organic matter enrichment.

Treated sewage water, when sourced from a properly operating municipal STP and maintained within applicable quality standards (IS 11624:1986; WHO 2006 irrigation guidelines), offers a viable, resource-efficient alternative to raw water for peri-urban agricultural irrigation. Its dual benefit as a water source and partial nutrient source aligns with the principles of Integrated Nutrient Management (INM) and supports SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production).

Nevertheless, the study's conclusions must be contextualized within its limitations: a small plot size, single-season duration, absence of heavy metal analysis, and lack of statistical replication. These gaps preclude definitive policy-level recommendations and should be addressed in expanded future investigations.

5.1 Future Scope

- Multi-season longitudinal study (minimum 3 years) to assess cumulative effects on soil organic carbon, microbial diversity, and heavy metal accumulation in soil and grain.
- Expansion to replicated plot design (minimum 3 replicates per treatment) and inclusion of a no-fertilizer control plot to enable statistical analysis (ANOVA, Tukey's HSD).
- Comprehensive heavy metal analysis (Cd, Pb, Cr, Cu, Zn, Ni) in soil, irrigation water, and harvested grain, benchmarked against FSSAI, CPCB, and WHO standards.
- Comparative assessment across multiple crops (rice, soybean, vegetables) and soil types (laterite, alluvial) to broaden the generalizability of findings.
- Integration of microbial biomass carbon, enzyme activity (urease, phosphatase), and Soil Health Index (SHI) computation to enable holistic soil quality assessment.
- Economic analysis of water and nutrient cost savings from TSW adoption at the farm level, to evaluate feasibility for smallholder farming communities in peri-urban Maharashtra.
- Exploration of optimal blending ratios of TSW and raw water to balance nutrient supply with pathogen and heavy metal risk minimization.

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Appendix A: Gap Analysis Summary

This section consolidates the critical gaps identified throughout the manuscript that must be addressed before submission to a peer-reviewed journal. These represent areas where the existing data and experimental design fall short of standard publication requirements.

A.1 Statistical Analysis [CRITICAL]

All yield and soil data are from single-plot measurements (n=1 per treatment). No inferential statistics (t-test, ANOVA, Tukey's HSD, confidence intervals) are possible without minimum 3 replicates. This is the most fundamental gap. Resolution: replicate the experiment with $n \geq 3$ plots per treatment in the next growing season; report all data as mean ± SD.

A.2 Heavy Metal Analysis [HIGH PRIORITY]

No heavy metal data (Cd, Pb, Cu, Zn, Ni, Cr) are reported for irrigation water, soil, or grain. This is a mandatory parameter for any publication concerning sewage water use in food crop agriculture. Resolution: include AAS or ICP-OES analysis of soil and grain for DTPA-extractable heavy metals in future studies; compare against FSSAI (PFA) grain limits and IS 11624 water quality standards.

A.3 Soil Organic Carbon and Nutrient Profile [MODERATE PRIORITY]

Organic carbon, total N, available P, and available K in soil were not measured. These parameters are central to claims about "soil fertility improvement." Resolution: Include Walkley-Black OC, Kjeldahl-N, Olsen-P, and Flame Photometry K in the soil analysis protocol.

A.4 Plot Size and Scale-Up Validity [MODERATE PRIORITY]

Each plot measures only 24 ft^2 (2.23 m^2). Edge effects, shading, and micro-variation are significant at this scale. Resolution: Use minimum 10 m^2 plots in future studies to reduce border effects; report yields in kg/ha with explicit area calculation.

A.5 Grain Quality Parameters [MODERATE PRIORITY]

No grain quality data (protein %, 1000-grain weight, harvest index) were collected. Resolution: In the next cycle, perform grain protein analysis (Kjeldahl N × 5.7) and record 1000-grain weight for comparative agronomic value.

A.6 Microbial Soil Health Indicators [LOWER PRIORITY — ENHANCES MANUSCRIPT]

Soil microbial biomass carbon, urease, and phosphatase activity were not measured. These are needed to compute a Soil Health Index (SHI) comparable to Li et al. (2024). Resolution: Add microbial analysis in future studies using the fumigation-extraction method for MBC and colorimetric assays for enzyme activity.