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Research Article

Development of Climate-Resilient quality Rice Seeds through Integrated Soil– Plant Health Management under Net-Zero Production Systems in Eastern India

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Abstract: Climate change poses a serious threat to global food security, particularly for rice-based production systems dominated by smallholder farmers. Seed quality is a foundational determinant of crop establishment, yield stability, and climate resilience. This study documents a farmer-participatory field experiment undertaken during 2022–23 in Nadia district, West Bengal, India, aimed at developing climate resilient, 'Net Zero' Paddy Seeds using Integrated plant and soil health management technology (based on *Inhana* Rational Farming (IRF) Technology). The program integrated organic soil health management through waste bio converted compost with intensive plant health management protocols. Results indicated a significantly higher seed yield (4021 kg ha^{-1}) under the Net Zero Clean Seed system compared with conventional seed production (≈2850 kg ha^{-1}). Seed quality evaluation showed superior germination (92%), viability (98.4%), seed vigour indices, and markedly improved performance under water stress, salt stress, and accelerated ageing. A composite Climate Resilience Index (CRI), primarily derived from abiotic stress germination parameters, was 35.5% higher than conventional seeds. The treatment-wise carbon footprint assessment further indicated that the Net Zero Clean Paddy Seed system recorded a negative net carbon balance (−30.13 t CO_2 ha^{-1}) with a carbon footprint of −7.49 kg CO_2 kg^{-1} grain, whereas conventional management showed positive emissions per unit grain produced. The same treatment also showed lower incidence of major insect pests and significantly reduced white ear formation (4.1%) compared to the conventional system (11.8%), indicating better crop performance under field conditions. The study establishes that climate resilient seed development requires an integrated focus on plant metabolic health in addition to soil fertility, offering a scalable pathway for safe, sustainable, and low carbon rice production.

Keywords: Carbon footprint, Climate resilient seeds, Net Zero agriculture, Paddy; Seed Vigour, Integrated plant- soil health management, Organic seed systems, Sustainability.

Introduction

Rice (Oryza sativa L.) is the primary staple food for more than half of the world's population and plays a pivotal role in ensuring food and nutritional security across Asia, particularly in India. Globally, rice is cultivated on approximately 165 million hectares, with India accounting for the largest area under rice cultivation [1]. In eastern India, and especially in West Bengal, rice occupies nearly 50% of the total arable land and forms the backbone of rural livelihoods. However, rice-based production systems are increasingly threatened by climate change–induced stresses, including erratic rainfall, temperature extremes, drought, flooding, and rising soil salinity, all of which directly affect crop establishment, productivity, and yield stability [2,3].

Rice is uniquely vulnerable to climate change because it is a C_3 plant with relatively lower photosynthetic efficiency compared to C_4 cereals and because its cultivation is highly dependent on water and nitrogen-intensive management practices. Flooded paddy ecosystems alone consume nearly 34–43% of the world's irrigation water and contribute up to 10% of global anthropogenic methane emissions, making rice cultivation both a victim of climate change and a significant contributor to greenhouse gas emissions [4,5]. Consequently, enhancing the resilience and resource-use efficiency of rice systems has become a global priority within climate-smart agriculture frameworks [6].

Among the various determinants of crop performance, seed quality represents the most fundamental and non-substitutable input in agriculture. It is estimated that quality seed alone contributes 15–20% to yield enhancement, which can increase up to 40–45% when complemented by efficient crop and soil management practices [7,8]. Despite this, the Indian seed system remains critically constrained: only about 30% of seeds used by farmers are certified, while the availability of organically produced or climate-resilient seeds is negligible. Conventional high-yielding varieties are predominantly bred and multiplied under high-input, fertilizer-responsive environments, resulting in seed lots that often lack physiological robustness, nutrient-use efficiency, and resilience against abiotic and biotic stresses when exposed to low-input or climatically unstable field conditions [9,10].

Seed vigour and resilience are increasingly recognized as critical determinants of successful crop establishment under sub-optimal field environments. Laboratory germination tests conducted under optimal conditions frequently fail to predict field emergence, particularly under stress-prone agro-ecosystems [11,12]. Seeds developed under biologically degraded, chemically intensive systems often exhibit poor membrane integrity, reduced antioxidant capacity, and higher susceptibility to osmotic, salinity, and ageing stresses, leading to uneven emergence and yield instability [13,14].

In contrast, seeds produced under biologically active and organically managed systems have been reported to express superior vigour, enhanced stress tolerance, and improved adaptive performance [15,16].

Climate-resilient seed development requires a paradigm shift from the conventional focus on soil nutrient supply alone toward an integrated framework that simultaneously restores soil biological health and activates plant metabolic efficiency. In this context, climate-resilient seed development requires an integrated framework that simultaneously addresses soil biological functioning and plant physiological regulation. *Inhana* Rational Farming (IRF) Technology was considered in the present study as a management-based approach that emphasizes plant metabolic balance, nutritional efficiency, and internal resource utilization as key factors influencing plant response to biotic and abiotic stresses. Assessment of carbon footprint associated with different paddy management systems is also important to understand the potential of climate-resilient seed production models in achieving low-carbon or net-zero rice cultivation.

The present study was undertaken under the Phase-II IBM–IORF Sustainability Project to develop and scientifically evaluate climate-resilient, 'Net Zero' Clean Paddy Seeds through a farmer-participatory approach in Nadia district, West Bengal, India. Specifically, the study aimed to

- Assess the impact of integrated organic soil health management and IRF-based plant health management on paddy seed yield.
- Evaluate seed quality, vigour, and resilience under multiple abiotic stress conditions.
- Develop a composite Climate Resilience Index (CRI) to quantitatively compare Net Zero Clean Paddy Seeds with conventional seed systems. The findings are expected to contribute to the emerging discourse on climate-smarseed systems as a foundational strategy for sustainable and low-carbon rice agriculture.

Materials and Methods

1. Study Area and Experimental Context

The field study was conducted as part of a farmer-participatory sustainability programme implemented during the 2022-23 cropping season at farmers' fields in Nadia district, West Bengal, India (23.4–23.6° N latitude; 88.3–88.6° E longitude). The region falls within the lower Gangetic alluvial plains and represents a typical eastern Indian rice-growing agro-ecosystem characterized by monsoonal rainfall, high relative humidity, and episodic climatic variability during the kharif season. Such environments are particularly vulnerable to erratic rainfall, transient water stress, and temperature fluctuations, making them suitable for evaluating climate-resilient seed systems [2,3].

2. Baseline Soil Quality Assessment

Prior to field preparation, composite soil samples (0–15 cm depth) were collected from representative locations across the experimental fields following standard soil sampling protocols [17]. Samples were air-dried, sieved (<2 mm), and analyzed for key physical, chemical, and biological attributes to establish baseline soil health.

Soil texture was determined using the hydrometer method, while soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil–water suspension using a calibrated digital pH–EC meter.

Soil organic carbon was estimated following the Walkley and Black wet oxidation method. Available nitrogen was determined using the alkaline $KMnO_4$ method, available phosphorus by the Olsen method, available potassium by ammonium acetate extraction followed by flame photometry, and available sulphur by calcium chloride extraction [17,18]. Soil biological health was assessed through indicators of microbial activity, which serve as sensitive markers of soil functional status under long-term chemical-intensive management [19].

Table 1: Baseline soil quality status of the experimental fields.

Parameter	Observed status	Interpretation
Texture	Silty clay loam–silt loam	Suitable for rice
pH	6.3 (average)	Slightly acidic–neutral
EC (dS m^{-1})	0.04	Non-saline
Organic carbon (%)	<1.0	Poor–very poor
Available N	Moderate	–
Available P & K	High	–
Available S	Low	Deficient
Microbial activity	Low	Degraded biological health

3. Seed material and seed treatment protocol

The rice variety IET 4786 (Shatabdi), a high-yielding and fertilizer-responsive variety widely cultivated in West Bengal, was selected to evaluate whether physiological resilience could be enhanced without genetic modification. Source seeds met minimum certification standards for purity and germination.

Seeds were subjected to seed treatment protocol designed to enhance metabolic activation and physiological robustness. The process included controlled solar exposure to stimulate enzymatic activity, thorough washing to remove inert and unproductive seeds, hydration through soaking in clean water for 24 h, followed by treatment with *Inhana* Seed Treatment Solution (1.5 L ha^{-1} seed rate). Treated seeds were incubated under warm, humid conditions for 48 h to initiate pre-germinative metabolic processes. Such pre-sowing physiological conditioning has been shown to improve germination, seedling vigour, and stress tolerance [20,14].

4. Crop Establishment, soil-plant Health Management

Organic seedbeds (0.01 ha) were prepared following two manual harrowing, after which waste bio-converted *Novcom* compost was applied at 300 kg per seedbed and allowed to stabilize for seven days before final preparation. For the main field, *Novcom* compost was applied at 38 t ha^{-1} during the second ploughing, followed by puddling.

Seedlings were uprooted at appropriate physiological age and subjected to root-zone treatment with a solution (*Inhana* Seedling Treatment Solution) immediately prior to transplanting to enhance root regeneration, transplant shock tolerance, and early establishment.

Plant health management in the main field was implemented through scheduled foliar application of an ‘Energy Solutions’, developed under the Element Energy Activation (EEA) principle. These applications were synchronized with critical phenological stages to enhance photosynthetic efficiency, internal nutrient utilization, and host defence mechanisms. Plant metabolic activation has been identified as a key determinant of crop resilience and reduced pest susceptibility under changing climatic conditions [10,21].

Under Integrated Soil Health Management (ISHM) in both seedbed and main field, *Novcom* green matter compost was applied @ 40 t ha^{-1} seven days prior to primary land preparation, followed by application of cow dung slurry @ 200 L ha^{-1}, which was thoroughly incorporated into the soil using a tractor. Seeds were treated with Seed Treatment Solution prior to sowing, and Integrated Plant Health Management (PHM) solutions were applied as per the prescribed *Inhana* protocol [40,41]. Two rounds of PHM solutions were applied in the nursery, followed by root dipping of seedlings in the recommended seedling treatment solution before transplanting. Subsequently, at seven days after transplanting, five different PHM solutions were sprayed at 7–10 day intervals up to the flower initiation stage, as per protocol, with formulation details provided in earlier studies[42,43]. Under conventional management, nutrients were applied at 60:30:30 kg $N:P_2O_5:K_2O$ ha^{-1} through urea, single super phosphate (SSP), and muriate of potash (MOP). For yellow stem borer management, neem oil @ 2 ml L^{-1} (Azadirachtin 10000ppm) of water along with soap solution @ 1 ml L^{-1} of water was sprayed twice in treatment T4. In treatments T1, T2, and T3, under moderate stem borer infestation, two rounds of insecticidal application were undertaken, with Cartap hydrochloride 50% SP @ 2.0 kg ha^{-1} applied at the first appearance of infestation, followed by Chlorantraniliprole 18.5% SC@150 ml ha^{-1}) after a 7 days interval.

5. Treatment details

A comparative field evaluation was undertaken using a model farm approach to isolate the individual and combined effects of soil health management and plant health management. The treatments were:

- **T1:** Integrated soil and plant health management applied at the seedbed stage; integrated soil health management with conventional crop management in the main field.
- **T2:** Integrated soil and plant health management applied at the seedbed stage; conventional soil and crop management practices in the main field
- **T3:** Conventional fertilizer- and pesticide-based management (farmers' practice).
- **T4:** Integrated soil–plant health management applied throughout both seedbed and main field stages (Net Zero–aligned clean seed production system).

All agronomic operations other than specified treatments were kept uniform across plots to minimize confoun ding effects.

- **T1:** In this treatment, integrated soil and plant health management was applied only at the seedbed stage. Organic seedbeds were prepared through manual harrowing, followed by application of waste bio-converted (Novcom) compost. Seeds were treated as per IRF-based seed treatment protocol and seedlings received root-zone treatment prior to transplanting. In the main field, integrated soil health management was continued through application of Novcom compost during land preparation. However, crop management practices during the growing period followed conventional fertilizer- and pesticide-based practices, without application of IRF-based plant health management interventions.
- **T2:** Under this treatment, integrated soil and plant health management was applied only during the seedbed stage. Seedbeds were prepared organically with Novcom compost, and IRF-based seed treatment and seedling treatment were carried out before transplanting. In the main field, all operations followed conventional farmers' practices, including chemical fertilizer and pesticide-based management. No organic soil amendments or IRF-based plant health management were applied after transplanting.
- **T3:** This treatment represented the fully conventional system. Both seedbed and main field management followed existing farmers' practices. Crop nutrition was managed using chemical fertilizers and pest management through synthetic pesticides. No organic compost, no IRF-based seed treatment, seedling treatment, or plant health management interventions were applied at any stage of crop growth.
- **T4:** In this treatment, integrated soil and plant health management was applied continuously throughout the entire crop cycle. At the seedbed stage, organic seedbeds were prepared using Novcom compost. Seeds were subjected to IRF-based seed treatment, and seedlings received root-zone treatment prior to transplanting. In the main field, compost (Novcom) was applied during land preparation as part of integrated soil health management. Plant health management was implemented through scheduled foliar application of Energy Solutions developed under the Element Energy Activation (EEA) principle. These applications were synchronized with critical phenological stages to support plant metabolic efficiency, photosynthetic activity, and internal nutrient utilization.

This treatment constituted the Net Zero Clean Paddy Seed production system, with integrated soil and plant health management applied throughout both seedbed and main field stages.

6. Seed Quality, Vigour, and Stress Resilience Assessment

Harvested seeds were cleaned, dried to safe moisture levels, and subjected to laboratory evaluation following International Seed Testing Association (ISTA) protocols. Standard germination tests were conducted under optimal conditions to determine germination percentage. Seed moisture content was estimated using the oven-drying method, while seed viability was assessed using the tetrazolium chloride (TZ) test, which reflects dehydrogenase enzyme activity and respiratory potential [22,23].

Seed vigour was quantified using Seed Vigour Index I (SV-I: germination × seedling length) and Seed Vigour Index II (SV-II: germination × seedling dry weight), which provide integrated measures of seedling performance beyond laboratory germination [11].

Stress resilience was evaluated through germination tests under induced water stress and salinity stress (−0.6 MPa osmotic potential) using mannitol and sodium chloride solutions, respectively. Storage and ageing tolerance were assessed through accelerated ageing tests. Membrane integrity was evaluated through electrical conductivity (EC) measurements of seed leachates, with lower EC values indicating superior membrane stability and vigour [13,14].

7. Climate Resilience Index (CRI)

A composite Climate Resilience Index (CRI) was developed to integrate seed performance under multiple abiotic stress conditions. The index is based on the principle that root and shoot growth rates adjust to environmental conditions according to the genetic program of plant development, and that a higher root-to-shoot ratio enhances nutrient and water uptake, contributing to improved biomass production and resistance to stresses such as drought and nutrient limitation.

Seed resilience was evaluated using germination responses under water stress, salt stress, and accelerated ageing. Germination under water stress (GWS) and salt stress (GSS) was assessed at an induced osmotic potential of −0.6 MPa, while germination after accelerated ageing (GAA) represented seed vigour under thermal stress. Root and shoot dry weights were recorded 14 days after germination, and the root-to-shoot ratio (RS) was calculated. Membrane stability was assessed through electrical conductivity (EC) measurements (μS cm^{-1}) using n seeds immersed in 50 ml of distilled water. Germination percentage under control conditions (G) was used for normalization.

The Climate Resilience Index was calculated as:

$$CRI = RS \times \frac{n}{EC} \times \frac{(G_{WS} + G_{SS} + G_{AA})}{(3 \times G)}$$

Where,

CRI = Climate Resilience Index
RS = Root-to-shoot ratio at 14 days (dry weight basis)
EC = Electrical conductivity (μS cm^{-1})
n = Number of seeds used for EC measurement (in 50 ml water)
G = Germination percentage under control conditions
G_{WS} = Germination under water stress (−0.6 MPa osmotic potential)
G_{SS} = Germination under salt stress (−0.6 MPa osmotic potential)
G_{AA} = Germination under accelerated ageing conditions

The resulting CRI is a dimensionless composite index, with higher values indicating superior climate resilience, reflecting improved biomass allocation, membrane stability, and maintenance of germination capacity under multiple abiotic stress environments.

8. Carbon Footprint Assessment Framework

Carbon footprint of paddy cultivation under different management systems was quantified using ACFA version 2.0, jointly developed by the Institute of Organic Research and Farming (IORF), Kolkata and ICAR–ATARI, Kolkata, representing India's first standardized carbon computing framework for sustainable agriculture across diverse agro-ecosystems. The assessment followed a multi-basket greenhouse gas accounting approach, wherein carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions were computed over a 100-year time horizon, consistent with IPCC 2006 and 2018 Guidelines, while methane (CH_4), the dominant emission in flooded rice systems, was evaluated using a 24-year global warming potential ($GWP_{(24)} = 75$) in line with IPCC 2019 refinements to reflect its high short-term climate forcing. The framework integrates emissions from seed, nursery management, land preparation, nutrient and plant protection inputs, and crop operations, alongside methane emissions from anaerobic soil conditions, while simultaneously accounting for carbon sequestration through organic matter inputs. This integrated life-cycle based accounting enabled treatment-wise comparison of net carbon balance and carbon footprint per unit grain yield, thereby capturing both emission intensity and mitigation potential of contrasting paddy management practices under eastern Indian conditions.

9. Experimental Design, Replication, and Statistical Analysis

The field study was carried out during the 2022–23 cropping season using a randomized complete block design (RCBD) comprising four management treatments (T1–T4). Each treatment was replicated three times under field conditions, with farmer-managed plots considered as independent experimental units. The use of blocking accounted for spatial variability within the experimental area and enhanced the precision of treatment comparisons. Except for the specified treatment differences, all agronomic operations were kept uniform across plots.

Seed quality, vigour, and stress-resilience assessments were conducted under laboratory conditions using four independent replications per treatment, with each replication consisting of 100 seeds, following standard International Seed Testing Association (ISTA) guidelines. All replications were prepared, incubated, and evaluated independently to ensure proper estimation of experimental error and degrees of freedom. Germination tests under water stress, salinity stress, and accelerated ageing were performed separately for each replication to maintain statistical independence.

Data obtained from field and laboratory experiments were analyzed independently using analysis of variance (ANOVA) to evaluate treatment effects. Percentage data were examined for assumptions of normality and homogeneity of variance and were arcsine square-root transformed where necessary prior to analysis, however, original mean values are presented in the tables to facilitate interpretation.

All statistical analyses were carried out using R statistical software. Results are expressed as mean ± standard error (SE).

Results and Discussions

The agronomic performance of paddy variety IET 4786 under contrasting management systems revealed clear differentiation in plant resilience and yield production under an unusually adverse climatic year marked by temperature fluctuations, erratic rainfall, and heightened pest pressure in the Haringhata block of Nadia district. While basic stand establishment parameters such as hills m^{-2} and seedling density remained comparable across treatments, substantial divergence emerged at the reproductive and yield-determining stages, indicating that management effects were expressed primarily through stress buffering rather than vegetative exaggeration. Across treatments, plant height and tiller number per hill exhibited limited variation, suggesting that early vegetative growth was not the principal determinant of yield differences.

However, the conversion efficiency of tillers into productive panicles, reflected by productive panicles m^{-2} and affectivity index, was markedly superior under T4. The significantly higher productive panicle density (229 m^{-2}) and affectivity index (74.5%) in T4 indicate enhanced tiller survival and panicle initiation under climatic stress, a response commonly associated with improved root-zone functionality, nutrient buffering, and hormonal stability under biologically active soil systems [24,25]. Reproductive character further highlighted the stress-mitigating effects of integrated management. T4 consistently recorded longer panicles, higher grains per panicle, and substantially greater filled grains per panicle compared to conventional practice. Most notably, grain sterility declined sharply to 12.7% under T4, compared to over 20% under partially integrated or fully conventional systems. Grain sterility in rice is highly sensitive to temperature instability and moisture stress during anthesis, primarily through impaired pollen viability and spikelet fertilization [26,27]. The pronounced reduction in sterility under IRF-based plant health management suggests improved physiological buffering during flowering, likely mediated by enhanced assimilate supply, reduced oxidative stress, and moderated pest-induced damage to reproductive organs. Yield outcomes reflected the cumulative effects of these improvements in reproductive stability. Despite only marginal differences in thousand-grain weight across treatments, grain yield under T4 increased by over 41% relative to the conventional baseline, accompanied by the highest harvest index (51.09%). This indicates superior assimilate partitioning toward economic yield rather than indiscriminate biomass accumulation, a hallmark of stress-resilient crop systems [28]. In contrast, conventional management failed to sustain yield under climatic adversity, resulting in productivity levels below the zonal average, consistent with documented vulnerability of input-centric rice systems to climate variability [29]. Collectively, these results demonstrate that the combined application of IRF-based intensive plant health management and *Novcom*-based soil health management functioned as a system-level resilience mechanism rather than a yield-enhancement input. By stabilizing reproductive development, reducing sterility, and improving tiller to panicle conversion under climatic and pest stress, the integrated approach enabled yield sustainability in a season otherwise unfavourable for paddy cultivation. The findings underscore the importance of biologically driven soil–plant health frameworks for climate-risk mitigation in smallholder rice systems.

Table 2: Comparative study of Agronomic parameters of Paddy under different management systems.

Parameter	**Treatment**			
	T1	**T2**	**T3**	**T4**
Plant height (cm)	115.4 ± 1.2^{a}	117.2 ± 1.4^{a}	114.6 ± 1.6^{a}	114.6 ± 1.1^{a}
Seedlings hill^{-1}	3.5 ± 0.2^{a}	3.5 ± 0.2^{a}	4.5 ± 0.3^{a}	3.5 ± 0.2^{a}
Hills m^{-2}	29 ± 0.5^{a}	29 ± 0.5^{a}	29 ± 0.5^{a}	29 ± 0.5^{a}
Tillers hill^{-1}	10.4 ± 0.3^{a}	10.3 ± 0.4^{a}	10.5 ± 0.3^{a}	10.6 ± 0.4^{a}
Panicles hill^{-1}	7.8 ± 0.4^{b}	7.6 ± 0.5^{b}	7.8 ± 0.4^{b}	8.7 ± 0.5^{a}
Productive panicles m^{-2}	198 ± 6^{b}	184 ± 7^{b}	187 ± 8^{b}	229 ± 9^{a}
Panicle length (cm)	34.5 ± 0.3^{a}	34.5 ± 0.4^{a}	34.8 ± 0.4^{a}	35.2 ± 0.3^{a}
Grains panicle^{-1}	108.2 ± 3.5^{a}	106.2 ± 3.8^{a}	109.5 ± 4.1^{a}	110.1 ± 3.6^{a}
Filled grains panicle^{-1}	81 ± 3^{b}	84 ± 4^{b}	86 ± 5^{b}	96 ± 4^{a}
Unfilled grains panicle^{-1}	27 ± 2^{a}	22 ± 2^{b}	23 ± 2^{b}	14 ± 1^{c}
1000-grain weight (g)	19.47 ± 0.06^{a}	19.36 ± 0.05^{a}	19.40 ± 0.06^{a}	19.46 ± 0.05^{a}
Straw yield (kg ha^{-1})	3290 ± 95^{b}	3650 ± 102^{a}	3360 ± 98^{b}	3850 ± 110^{a}
Harvest index	0.46 ± 0.02^{b}	0.44 ± 0.02^{b}	0.46 ± 0.01^{b}	0.51 ± 0.02^{a}
Grain sterility (%)	25.0 ± 1.1^{a}	20.8 ± 0.9^{b}	21.1 ± 1.0^{b}	12.7 ± 0.6^{c}
Affectivity index (%)	65.7 ± 2.1^{b}	61.6 ± 2.3^{b}	61.4 ± 2.2^{b}	74.5 ± 2.5^{a}

Values represent mean ± standard error (SE). Field data are based on three independent replications, while laboratory seed quality and stress-resilience measurements were obtained from four replications of 100 seeds each. Treatment means within a row followed by different lowercase letters are significantly different at $P \leq 0.05$ as determined by Tukey's HSD test.

T1: Integrated soil and plant health management (seedbed); Integrated soil health management + conventional plant health (main field), T2: Integrated soil and plant health management (seedbed); conventional (main field), T3: Fully conventional (Farmers Practice),T4: Net Zero Clean Seed (ISHM + IPHM throughout).

1. Effect of Integrated Soil and Plant Health Management on Paddy Seed Yield

Paddy seed yield differed markedly among the evaluated management systems, demonstrating the causative importance of sustained integration between soil biological functionality and plant physiological regulation (Table 2). The Net Zero (NZ) Clean Paddy Seed system (T4), which applied Novcom-based Integrated Soil Health Management (ISHM) together with IRF-based Integrated Plant Health Management (IPHM) throughout both the seedbed and main field phases, recorded a mean seed yield of 4021 kg ha^{-1}. This corresponded to an approximately 41% increase relative to the fully conventional fertilizer- and pesticide-based system (T3: 2850 kg ha^{-1}). By contrast, treatments T1 and T2, where IPHM interventions were restricted to the seedbed stage and not sustained during the main field growth period, produced seed yields (2810–2880 kg ha^{-1}) statistically comparable to the conventional control. The lack of yield differentiation among T1, T2, and T3 indicates that partial soil or early-stage interventions alone were insufficient to generate yield resilience under field conditions. This observation aligns with earlier findings that soil health improvement enhances yield potential but does not guarantee realized yield gains unless plant physiological processes are actively supported during stress-sensitive growth stages [24,30].

The pronounced yield advantage under T4 highlights the critical role of continuous plant health management during the main field phase, particularly in sustaining photosynthetic activity, assimilate translocation, and grain filling under climatic perturbations observed during tillering and seed-setting stages. Maintenance of plant metabolic homeostasis under abiotic stress is a key determinant of yield stability in rice systems, as disruptions in carbon assimilation and sink strength during reproductive stages have been shown to result in irreversible yield penalties [26,31]. The sustained application of IRF technology appears to have supported plant-level stress buffering and metabolic efficiency, enabling effective utilization of soil-derived nutrients. From a systems perspective, the results indicate a functional complementarity between Novcom and IRF technologies. Novcom-based ISHM establishes a biologically active and structurally resilient soil environment, enhancing nutrient cycling, microbial-mediated availability, and root-zone stability, which are widely recognized as prerequisites for sustained productivity in intensive rice systems [25,32]. However, the yield plateau observed in treatments lacking full-season IPHM confirms that soil health restoration alone cannot compensate for physiological limitations at the plant level when crops are exposed to environmental stress.

Collectively, these findings provide empirical evidence that sustained and integrated soil–plant health management is the primary causative factor underpinning improved and stabilized paddy seed productivity under the NZ Clean Seed system. The combined Novcom–IRF framework therefore represents a biologically coherent, climate-responsive production strategy, rather than an additive or substitution-based input model, with implications for yield reliability, resource-use efficiency, and Net Zero–aligned agricultural intensification.

Table 3: Paddy seed yield under different management systems.

Treatment	Management description	Seed yield (kg ha^{-1})	Relative change (%)
T1	Integrated soil and plant health management (seedbed); Integrated soil health management + conventional plant health (main field)	2880 ± 85 b	+1.1
T2	Integrated soil and plant health management (seedbed); conventional (main field)	2810 ± 92 b	−1.4
T3	Fully conventional (Farmers Practice)	2850 ± 88 b	Reference
T4	Net Zero Clean Seed (ISHM + IPHM throughout)	4021 ± 104 a	+41.1

Values represent mean ± standard error (SE). Field data are based on three independent replications, while laboratory seed quality and stress-resilience measurements were obtained from four replications of 100 seeds each. Treatment means within a row followed by different lowercase letters are significantly different at $P \leq 0.05$ as determined by Tukey's HSD test.

T1: Integrated soil and plant health management (seedbed); Integrated soil health management + conventional plant health (main field). T2: Integrated soil and plant health management (seedbed); conventional (main field). T3: Fully conventional (Farmers Practice). T4: Net Zero Clean Seed (ISHM + IPHM throughout).

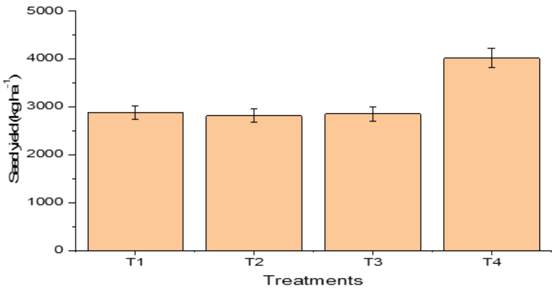

Figure 1: Effect of different treatments on grain yield.

2. Seed Physical Quality and Certification Parameters

Seeds produced under the Net Zero (NZ) Clean Seed system exhibited consistently superior physical and physiological quality attributes when benchmarked against the Indian Seed Certification Standards prescribed for both Foundation and Certified seed classes (Table 4). Physical purity of the evaluated Shatabdi (*Oryza sativa* L., IET 4786) variety seed lot reached 99.85%, exceeding the minimum statutory requirement of 98.0%. High seed purity is a critical determinant of varietal identity, field uniformity, and agronomic predictability, particularly in self-pollinated crops such as rice where genetic admixture can directly affect yield expression and quality traits [33,34].

The exceptionally low inert matter content (0.15%) indicates high-efficiency seed cleaning and post-harvest processing, minimizing non-biological load that can interfere with seed placement, germination, and early seedling vigour. Elevated inert fractions have been shown to adversely affect seeding accuracy and micro-environmental conditions around the germinating seed, especially under mechanized sowing systems [22]. The Net Zero Clean Seed system effectively reduced this risk well below regulatory ceilings. From an agronomic and seed system perspective, the complete absence of husk less grains, other crop seeds, and weed seeds represents a performance level beyond certification norms, which allow defined thresholds of physical admixture. Such zero-admixture status reflects stringent field-level isolation, rogueing, and processing controls, and carries direct implications for weed seed bank suppression, reduced interspecific competition, and long-term field hygiene [35,36]. In rice-based systems, contamination by weed and volunteer seeds has been linked to increased herbicide dependence and yield instability, underscoring the functional importance of this outcome. Physiological quality indicators further confirm the robustness of the Net Zero Clean Seed production protocol. Laboratory germination of 92% substantially exceeded the statutory minimum of 80%, indicating high seed viability, membrane integrity, and metabolic competence. Germination percentage is widely recognized as a proxy for field emergence uniformity and early crop vigour, both of which are critical for achieving optimal plant stand density and competitive advantage against weeds [22,14]. content was maintained at 9.32%, significantly below the maximum permissible level of 13.0%. Lower moisture levels are associated with enhanced storability, reduced respiratory losses, and lower susceptibility to fungal infestation, particularly under tropical storage conditions [37,38]. From a systems perspective, improved storability reduces seed replacement frequency and post-harvest losses, indirectly contributing to resource efficiency and climate-aligned seed supply chains. Collectively, these results demonstrate that the Net Zero Clean Seed system not only meets statutory certification benchmarks but establishes a functionally superior seed quality profile, with downstream benefits for crop establishment reliability, input-use efficiency, and sustainability outcomes. Such enhancements align with contemporary paradigms in seed system intensification, where quality gains are leveraged as a foundational intervention for productivity stabilization and emissions-sensitive agricultural transitions [39].

Table 4: Evaluation of Net Zero Clean Paddy Seeds as per Indian Seed Certification Standards.

Seed Quality Parameter	Indian Seed Certification Standards – Foundation	Indian Seed Certification Standards – Certified	'Net Zero' Clean Paddy Seed developed under IRF Technology
Variety	–	–	**IET-4786**
Pure seed (min.)	98.0%	98.0%	**99.85%**
Inert matter (max.)	2.0%	2.0%	**0.15%**
Husk less seeds (max.)	2.0%	2.0%	**No**
Other crop seeds (max.)	10/kg	20/kg	**No**
Total weed seeds (max.)	10/kg	20/kg	**No**
Germination (min.)	80%	80%	**92%**
Moisture (max.)	13.0%	13.0%	**9.32**

3. Seed Viability, Vigour, and Stress Resilience under Integrated Soil–Plant Health Management

Marked differences in seed viability, vigour, and stress resilience were observed among the evaluated seed sources (Table 5), indicating that seed physiological quality was strongly influenced by the production environment and crop health management strategy. Seeds produced under the Net Zero (NZ) Clean Paddy Seed system consistently outperformed both control and conventionally managed farmer-saved seeds across all measured parameters. The NZ Clean Paddy Seeds recorded the highest germination (93%) and seed viability (98.35%), reflecting superior embryo integrity and metabolic readiness. Germination value index (GVI) and seed vigour indices (SVI-I and SVI-II) were also markedly elevated, indicating faster germination rates and enhanced seedling biomass accumulation. Seed vigour is widely recognized as a key determinant of field emergence uniformity and early stress avoidance, particularly under suboptimal environmental conditions [14,33].

Stress resilience assays further highlight the functional superiority of NZ Clean Seeds. Germination under water stress (G^{WS}), salinity stress (G^{SS}), and accelerated ageing (G^{AA}) conditions was consistently higher than in conventionally produced seeds. Elevated germination following accelerated ageing indicates greater membrane stability and reduced lipid peroxidation, which are hallmarks of high-quality, stress-tolerant seed lots. This interpretation is supported by the lower electrical conductivity (EC) values observed in NZ Clean Seeds, reflecting reduced solute leakage and superior membrane integrity during imbibition. From a mechanistic perspective, these improvements can be attributed to the synergistic action of *Novcom*-based Integrated Soil Health Management (ISHM) and IRF-based Integrated Plant Health Management (IPHM) during seed development. *Novcom* technology enhances soil organic carbon pools, microbial diversity, and nutrient buffering capacity, thereby ensuring a steady and balanced nutrient supply during reproductive growth. Improved soil biological activity and nutrient synchrony are known to enhance assimilate availability during grain filling, which directly influences seed reserve accumulation and physiological maturity [25,32].

Concurrently, IRF technology operates at the plant system level by supporting metabolic efficiency, redox balance, and hormonal regulation under abiotic stress. Maintenance of photosynthetic competence and sink–source coordination during flowering and seed filling is critical for the deposition of carbohydrates, proteins, and protective metabolites in developing seeds [26,31]. Enhanced metabolic regulation during these stages likely contributed to the observed increases in seed vigour and post-stress germination performance. Importantly, the superior stress tolerance of NZ Clean Seeds reflects not merely improved genetic potential but enhanced physiological conditioning during seed development, a phenomenon well documented in seed ecology and stress biology literature [35]. The combined *Novcom*–IRF management framework thus creates a production environment that conditions seed for resilience by stabilizing both the soil resource base and plant metabolic responses throughout the crop cycle. Collectively, the data demonstrate that integrated soil and plant health management is a primary causal factor in enhancing seed vigour and stress tolerance, positioning the NZ Clean Seed system as a biologically coherent and climate-resilient seed production strategy.

Table 5: Comparative study of Seed Viability, Seed Vigour and Seed Resilience against Stress, of Clean Paddy Seed.

Parameter	Control (Average of T1 and T2)	Conventional (T3)	NZ Clean Seed (T4)
Germination (%)	90 ± 1.5 b	85 ± 1.8 c	93 ± 1.2 a
Seed viability (%)	95.0 ± 0.9 b	86.7 ± 1.1 c	98.35 ± 0.6 a
Germination velocity index	11.76 ± 0.32 b	11.96 ± 0.35 b	13.56 ± 0.28 a
SVI-I	687.6 ± 21 b	656.2 ± 24 b	729.1 ± 18 a
SVI-II	0.29 ± 0.01 b	0.28 ± 0.01 b	0.31 ± 0.01 a
GWS (%)	70 ± 2.0 c	75 ± 1.8 b	80 ± 1.6 a
GSS (%)	85 ± 1.7 b	83.5 ± 1.6 b	90 ± 1.5 a
GAA (%)	86.7 ± 1.5 b	95 ± 1.2 a	98.35 ± 0.8 a
EC ($\mu S\ cm^{-1}$)	0.034 ± 0.001 a	0.033 ± 0.001 a	0.030 ± 0.001 b

Note: [1]G %: Germination %, [2]SV %: Seed Viability %, [3]GVI: Germination Velocity Index, [4]SVI-I: Seed Vigour Index-I, [5]SVI- II: Seed Vigour Index-II, [6]GWS %: Germination under water stress (-0.6 MPa induced osmotic potential); [7]GSS %: Germination under Salt Stress (-0.6 MPa induced osmotic potential), [8]GAA%: Germination under Accelerated Ageing; [9]EC: Electrical Conductivity.

4. Germination under Water Stress Conditions

Germination under water stress represents one of the most critical bottlenecks in crop establishment, as seed imbibition, metabolic activation, and radicle emergence are highly sensitive to reduced water potential.

The data presented in Table 6 clearly demonstrate a progressive decline in germination percentage across all seed lots with increasing osmotic stress induced by mannitol. However, the magnitude and rate of decline differed substantially among management systems, indicating pronounced differences in intrinsic seed physiological resilience.

Under non-stress conditions (0 ψ_0), all seed lots exhibited high germination, though 'NZ' Clean Paddy Seeds achieved 100% germination, reflecting superior baseline seed vigour. As osmotic potential decreased to 0.3 ψ_0, germination reduction in conventional farmer-saved seeds was sharp (26.32%), whereas 'NZ' Clean Paddy Seeds showed only a modest decline (12%). This early divergence is critical, as mild water stress during sowing is common under rainfed and climate-variable systems, and seeds that fail at this threshold often determine final plant population.

At moderate osmotic stress (0.6 ψ_0), conventional seeds exhibited stagnation in germination improvement, while 'NZ' Clean Paddy Seeds maintained relatively higher germination with controlled reduction. This suggests better regulation of early metabolic processes, including reserve mobilization and cell elongation, under reduced water availability. Such responses are closely linked to membrane integrity, osmotic adjustment capacity, and antioxidant defense systems developed during seed maturation [20].

The most striking contrast emerged under severe water stress (1.2 ψ_0), where germination in control seeds collapsed to 10%, indicating near-complete failure of seedling establishment. In contrast, both conventional and 'NZ' Clean Paddy Seeds retained 45% germination, but the relative reduction was substantially lower for NZ seeds, demonstrating greater tolerance to extreme osmotic stress. Survival under such conditions reflects enhanced desiccation tolerance, stable enzymatic activity, and improved protection of cellular structures during imbibitional stress, traits strongly influenced by the seed production environment and maternal plant health [35,33].

The overall trend confirms that seeds produced under integrated soil and plant health management exhibit superior water-stress resilience during germination. While soil health management contributes to improved nutrient provisioning during seed development, the sustained performance of 'NZ' Clean Paddy Seeds under osmotic stress indicates a decisive role of plant physiological regulation during seed filling, consistent with the Seed Production and Management Environment (SPME) concept. These findings reinforce that resilience to early-stage water stress is not solely a genetic trait, but a management-induced seed quality attribute, particularly relevant under increasing climate variability where erratic rainfall and transient drought frequently coincide with sowing periods.

Table 6: GWS or Germination under Water Stress (under different induced osmotic potential).

Osmotic potential	Control % (Average of T1 and T2)	Conventional % (T3)	NZ Clean Seed % (T4)
0 ψ_0	90 ± 1.4 b	95 ± 1.3 a	100 ± 0.0 a
0.3 ψ_0	85 ± 1.6 b	70 ± 1.9 c	88 ± 1.5 a
0.6 ψ_0	80 ± 1.8 b	70 ± 2.0 c	75 ± 1.7 a
1.2 ψ_0	10 ± 0.8 c	45 ± 1.5 b	45 ± 1.4 b

5. Climate Resilience Index (CRI)

The Climate Resilience Index (CRI) illustrated in Figure 2 integrates normalized germination responses under water stress, salinity stress, and accelerated ageing, thereby functioning as a composite indicator of seed physiological robustness across multiple abiotic stress pathways. The marked separation among management systems reflects fundamental differences in the Seed Production and Management Environment (SPME) under which the seeds were developed. Seeds produced under the NZ Clean Paddy system (combined soil and plant health management) consistently exhibited the highest CRI values, exceeding conventional fertilizer-based practice (CFP) by 35.5% and organic soil-management-only systems (OSM) by 14.6%. Within the SPME framework, seed quality is understood as an emergent property of the entire crop growth environment, encompassing soil biological status, plant physiological regulation, stress exposure during reproductive development, and pest–pathogen pressure during seed maturation [33;35]. The superior CRI of NZ Clean Paddy Seeds indicates that integrated plant health management fundamentally alters the seed production environment by stabilizing metabolic and hormonal processes during grain filling, thereby enhancing membrane integrity, antioxidant capacity, and reserve mobilization efficiency in the developing seed. These traits are central determinants of seed vigour, longevity, and stress tolerance under adverse germination conditions.

In contrast, the relatively modest improvement in CRI under OSM compared to CFP demonstrates that soil-focused interventions alone can partially improve the SPME by enhancing nutrient availability and microbial activity, but fail to fully protect seed physiological quality in the absence of targeted plant health regulation. This finding is consistent with seed science literature showing that abiotic stress during flowering and seed maturation, particularly temperature and moisture fluctuations, can irreversibly impair pollen viability, assimilate translocation, and seed storage compound stability, regardless of soil fertility status [26,27].

Importantly, the CRI approach operationalizes the SPME concept by translating complex, multi-stage stress responses into a single quantitative metric that captures cumulative resilience rather than isolated tolerance traits. The significantly higher CRI of NZ Clean Paddy Seeds therefore provides empirical validation that plant health management is a necessary complement to soil health management within climate-smart SPME frameworks. These results challenge the prevailing assumption in sustainable agriculture that "feeding the soil" alone is sufficient to ensure resilient seed systems and instead demonstrate that physiological conditioning of the mother plant is a critical control point for climate resilience at the seed stage. Under increasing climate variability, SPME models that integrate both soil and plant health management are likely to be essential for maintaining reliable crop establishment and yield stability.

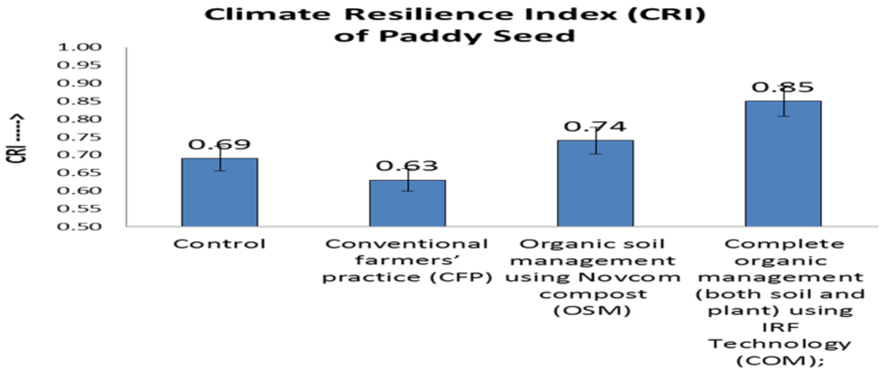

Figure 2: Climate Resilience Index (CRI) comparison of different treatments.

1. Effect of Integrated Soil–Plant Health Management on Insect Pest Incidence in rice

The incidence of major insect pests in rice variety IET 4786 showed clear variation among the different management systems at both 40 and 60 days after transplanting (DAT). Pest incidence increased with crop age in all treatments; however, the magnitude of infestation differed depending on the type and continuity of management practices followed.

At 40 DAT, the conventional farmers' practice (T3) recorded the highest levels of infestation by whorl maggot, leaf folder and dead heart, indicating greater vulnerability of the crop during the early vegetative stage. In comparison, the treatment receiving integrated soil–plant health management throughout the crop period (T4) exhibited markedly lower pest incidence. Whorl maggot, leaf folder and dead heart percentages under T4 were almost half of those recorded under conventional management. Treatments T1 and T2, where interventions were limited mainly to the seedbed stage, showed intermediate levels of pest damage, suggesting partial but insufficient protection during early crop growth.

At 60 DAT, pest incidence increased across all treatments, reflecting higher insect activity during the later growth stages. The highest infestation levels were again observed under conventional management (T3), particularly for leaf folder and dead heart, which subsequently resulted in the maximum white ear formation (11.8%). This indicates substantial reproductive-stage damage and potential yield loss under chemical-based management. In contrast, the integrated soil–plant health management system (T4) maintained significantly lower pest incidence even at this stage. White ear formation under T4 remained limited to 4.1%, demonstrating a pronounced reduction in economic damage compared with the conventional system.

Table 7: Incidence of major insect pests in rice variety IET-4786 under different management systems at 40 and 60 DAT.

Treatments	40 DAT			60 DAT			
	Whorl maggot (%)	Leaf Folder	Dead heart (%)	Whorl maggot (%)	Leaf Folder (%)	Dead heart (%)	White ear (%)
T1	6.2	7.5	4.8	5.4	8.6	6.9	8.2
T2	6.8	8.1	5.2	6.1	9.4	7.5	9.1
T3	7.6	9.8	6.4	7.2	11.6	9.2	11.8
T4	3.4	4.2	2.1	2.6	4.9	3.3	4.1

T1: Integrated soil and plant health management (seedbed); Integrated soil health management + conventional plant health (main field), T2: Integrated soil and plant health management (seedbed); conventional (main field),T3: Fully conventional (Farmers Practice),T4: Net Zero Clean Seed (ISHM + IPHM throughout).

Treatments T1 and T2 showed moderate levels of white ear formation at 60 DAT, higher than T4 but lower than T3. This suggests that although early-stage seedbed interventions improved initial crop vigour, the absence of continued plant health management during the main field phase reduced the crop's ability to withstand pest pressure during panicle initiation and flowering. Overall, the results indicate that continuous integration of soil and plant health management plays an important role in reducing insect pest expression, particularly during the reproductive stage. The lower incidence of white ear formation under the integrated system reflects improved plant tolerance and recovery capacity rather than direct pest suppression. These findings highlight the importance of maintaining plant physiological strength throughout the crop cycle to minimize pest-related damage and protect yield under field conditions.

2. Treatment-wise Carbon Footprint of Paddy Cultivation

Treatment-wise carbon footprint analysis revealed clear contrasts among management systems, driven primarily by differences in nutrient inputs, organic carbon addition, and methane emissions. Across all treatments, emissions from seed use, nursery management, land preparation, transplanting, and harvesting remained comparable, indicating that baseline agronomic operations contributed marginally to overall carbon balance. In the partially and fully conventional systems (T2 and T3), nutrient management emerged as a major emission source (423.8 kg CO_2 ha^{-1}), reflecting the embodied carbon of synthetic fertilizers, while the absence of compensatory carbon sequestration resulted in positive net emissions of 791 and 1589 kg CO_2 ha^{-1}, respectively. In contrast, treatments receiving compost at 40 t ha^{-1} (T1 and T4) exhibited exceptionally high negative carbon values due to substantial soil carbon sequestration, which more than offset emissions from land preparation, plant protection, and methane generation. Although methane emissions were higher in compost-amended plots (1652.5 kg CO_2-eq ha^{-1}) compared to conventional treatments (1008.8 kg CO_2-eq ha^{-1}), their climate impact was outweighed by the sequestration benefit, resulting in strongly negative net carbon balances of −30.1 and −30.13 t CO_2 ha^{-1} in T1 and T4, respectively. Consequently, carbon footprint per unit grain yield was negative in compost-based systems (−10.46 kg CO_2 kg^{-1} grain in T1 and −7.49 kg CO_2 kg^{-1} grain in T4), while remaining positive under conventional management (0.28–0.56 kg CO_2 kg^{-1} grain). Notably, the Net-Zero Clean Paddy Seed system (T4) combined the lowest emission intensity with the highest grain yield, demonstrating that integrated soil and plant health management can simultaneously enhance productivity and achieve net-zero or carbon-negative paddy production despite methane dominance in flooded rice ecosystems.

Table 8: Paddy carbon footprint in rice variety Shatabdi (IET 4786) under different management systems.

Management Practice	T1	T2	T3	T4
Seed	0.054	0.054	0.04	0.054
Seed Bed Preparation & Nursery Management	6.002	6.002	6.472	6.002
Main Land Preparation	110.54	110.54	110.54	110.54
Transplanting in the main field	13.565	13.565	13.565	13.565
Nutrient Management	0	423.8	423.8	0
Compost Application 40 ton	-31920	-798	0	-31920
Plant & Pest Management	25.6159	25.6159	25.6159	4.5328
Weed Management	0	0	0	0
Methane Generation	**1652.5**	**1008.8**	**1008.8**	**1652.5**
Harvesting	0.446	0.446	0.446	0.446
Total (kg CO_2 / ha)	-30111	791	1589	-30132
Crop yield (kg/ha)	2880	2810	2850	4021
Carbon Footprint (Kg CO_2/kg)	**-10.46**	**0.28**	**0.56**	**-7.49**

Conclusions

The present study provides scientific evidence that the development of climate-resilient, high-quality rice seeds is fundamentally governed by plant physiological health and metabolic efficiency, rather than by soil nutrient management alone. Through a farmer-participatory, field-scale implementation of Inhana Rational Farming (IRF) Technology, the study successfully demonstrated that 'Net Zero' Clean Paddy Seeds can be produced with substantially higher yield, superior seed vigour, and markedly enhanced tolerance to multiple abiotic stresses under real-world agro-climatic conditions. The Net Zero Clean Paddy Seed system consistently outperformed conventional fertilizer- and pesticide-based seed production, achieving approximately 41% higher seed yield despite complete elimination of synthetic inputs.

More importantly, the seeds expressed significantly higher germination, viability, membrane stability, and resilience under water stress, salinity stress, and accelerated ageing. These attributes collectively translated into a 35.5% higher Climate Resilience Index (CRI), establishing a strong physiological basis for improved crop establishment and yield stability under climate uncertainty.

A critical scientific insight emerging from this study is that soil organic amendments, while necessary for restoring baseline fertility, are insufficient to confer climate resilience unless complemented by systematic plant health management. The superior performance of Net Zero Clean Paddy Seeds underscores the central role of metabolic activation, enhanced photosynthetic efficiency, and improved internal nutrient utilization in strengthening inherent plant defense and stress-adaptive mechanisms. This finding challenges the prevailing “soil-centric” paradigm in sustainable agriculture and reinforces the need for an integrated soil–plant physiological framework. From a broader sustainability perspective, the Net Zero Clean Seed model represents a transformative pathway for climate-smart agriculture. By delivering seeds with zero pesticide footprint, reduced nutrient demand, absence of seed-borne diseases, and enhanced resilience, the approach directly addresses the dual imperatives of climate change mitigation and adaptation. The ability to achieve higher productivity with lower external inputs also positions the model as an economically viable and environmentally sound solution for marginal and smallholder farmers, who are disproportionately vulnerable to climate risks. In conclusion, this study establishes climate-resilient seed systems as a foundational pillar of safe, sustainable, and low-carbon rice production. The results of the present study indicate that an integrated soil–plant health-oriented seed production approach may contribute to improved seed resilience and productivity under variable rice-growing environments. Future research should focus on multi-location validation, long-term seed storability assessment, and integration of the Climate Resilience Index into national seed certification and climate-smart agriculture programs to accelerate large-scale adoption.

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