

RESEARCH ARTICLE

Synergistic Effects of Precision Irrigation and Organic Soil Amendments on the Physiological Performance of Rice (*Oryza Sativa* L.)

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ABSTRACT

The escalating crisis of freshwater scarcity and the environmental pollution caused by rice straw burning necessitate a transition toward climate-resilient cultivation. This study investigated the interactive effects of irrigation and in-situ straw decomposition on the physiological performance of rice in Tamil Nadu, India. Using a strip-plot design, we evaluated three irrigation regimes and six organic mitigation strategies. Results revealed that incorporating rice straw with dual microbial consortia (Pusa Decomposer and TNAU Biomineralizer) acted as a vital physiological buffer against moisture stress. This treatment (S₄) recorded a peak photosynthetic rate of 31.4 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and optimal stomatal conductance (0.727 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), significantly outperforming plots without organic amendments. Notably, alternate Wetting and Drying (AWD) at 10 cm depletion paired with microbial-mediated straw recycling maintained higher chlorophyll retention and gas exchange efficiency than traditional continuous flooding. These results show that 15-30% water savings can be achieved without the usual yield penalty by combining precision irrigation with microbial straw management. In tropical rice ecosystems, this method provides a scalable, beneficial system for water-smart agriculture and sustainable residue recycling.

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INTRODUCTION

More than 3.5 billion people in Asia, Sub-Saharan Africa and Latin America rely on rice (*Oryza sativa* L.) as their main source of calories, making it the crop with the greatest socioeconomic impact in human history (FAO, 2023). Rice is the second most widely grown crop in the world, covering around 167 million hectares, or roughly 11% of all arable land, although

it has a disproportionately large environmental impact (Bandumula, 2018). According to (Sandhu *et al.*, 2021; Mallareddy *et al.*, 2023), rice agroecosystems account for 34-43% of the world's irrigation withdrawals. Conventional flooded cultivation requires 1,000-2,000 litres of water per kilogram of milled grain, far more than wheat (*Triticum aestivum* L.) or maize

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(*Zea mays* L.) under similar conditions. The long-term sustainability of conventional puddled rice agriculture is becoming increasingly unfeasible in the face of accelerating climate change, growing urbanization and intersectoral competition for freshwater (Calvin *et al.*, 2023).

Compared with continuous flooding, Alternate Wetting and Drying (AWD) reduces irrigation inputs by 15-30% and methane (CH₄) emissions by 30-70%. It has become one of the most widely validated water-saving technologies for lowland rice (Lampayan *et al.*, 2015; Carrijo, Lundy and Linqvist, 2017; Kritee *et al.*, 2018). However, the cyclical imposition of soil moisture deficits can cause consequential water stress responses, such as reduced leaf water potential (Ψ), declining net CO₂ assimilation rates (Anet) and partial stomatal closure. These responses collectively limit canopy photosynthesis and carbon partitioning during crucial reproductive and grain-filling stages, which limits the widespread adoption of AWD in water-scarce regions (Yang and Zhang, 2010; Govindan, 2023; Bwire *et al.*, 2024).

AWD in rice fields reduces methane (CH₄) emissions significantly, while causing only a moderate increase in nitrous oxide (N₂O). Global studies report CH₄ reductions of about 47-65% and N₂O increases of 19-52% under AWD (Zhao, Qiu, Zhang, Luo, & Agathokleous, 2024). Despite this trade-off, the overall global warming potential (GWP) decreases by nearly 36-47% compared to continuous flooding. Field experiments across Asia and Latin America also show similar trends, with CH₄ reductions outweighing the rise in N₂O. In most cases, N₂O contributes only a small share of total GWP. Therefore, AWD is considered an effective climate-smart water management practice, especially under “safe AWD” conditions that maintain crop yield while minimizing greenhouse gas emissions (Liao *et al.*, 2020).

Global rice agriculture faces an urgent residue management dilemma amid water scarcity. An estimated 731-1,128 million tonnes of rice straw are produced annually, most of which is burned in open fields throughout South and Southeast Asia (Singh *et al.*, 2023). Every year, about 23 million tonnes of rice straw are burned in India alone, destroying soil microbial communities, volatilizing nitrogen and sulphur and depleting soil organic carbon (SOC), which is the fundamental value of soil fertility. This process also produces toxic PM2.5, black carbon and

greenhouse gases (Bhuvaneshwari, Hettiarachchi and Meegoda, 2019; Lal, 2020; Subbiah and Rao, 2023).

These crises convergence offers a strong chance for integrated agronomic intervention. Although incorporating raw straw increases the risk of nitrogen immobilisation, allelopathic phytotoxicity and root impedence, its controlled decomposition by microbial consortia improves macro-aggregate stability, increases cation exchange capacity (CEC) and reduces soil moisture fluctuations during AWD drying cycles (Bhattacharyya *et al.*, 2012; Lal, 2020). The Pusa Decomposer (ICAR-IARI, New Delhi) is a fungal consortium based on capsules that breaks down the lignocellulosic matrix of rice straw enzymatically in 20-25 days, speeding up in-situ decomposition (Sruthy *et al.*, 2023). The TNAU Biomineralizer was developed by Tamil Nadu Agricultural University as an effective microbial consortium for the quick breakdown of lignocellulosic agricultural leftovers like paddy straw. It has helpful bacteria that can break down cellulose, hemicellulose and lignin to speed up the development of compost. Paddy straw's composting time was drastically shortened to approximately 85 days by applying biomineralizer and adjusting the C:N ratio with urea. This improved compost quality resulted in a lower C:N ratio of 18:1 and a better nutritional content. Additionally, the technique lessens environmental pollution and encourages sustainable residue recycling in agriculture by preventing the open-field burning of paddy wastes (Babu *et al.*, 2022)

Organic amendments may act as a crucial physiological buffer by maintaining favourable soil moisture during AWD inter-irrigation intervals. This would reduce stomatal closure, maintain mesophyll conductance and sustain turgor-driven metabolic activity in leaf and panicle tissues. In order to develop climate-resilient agronomic frameworks for sustainable rice food security, the current study examines the synergistic interaction between AWD-based precision irrigation and organic rice straw amendments. It focuses on how this combined strategy modulates gas exchange parameters, chlorophyll fluorescence, root hydraulic conductivity and oxidative stress biomarkers in *Oryza sativa* L (Flexas *et al.*, 2012; Clemente *et al.*, 2019)

MATERIALS AND METHODS

2.1 Site Description

The field experiment was

conducted during the summer 2023 at Wetland Farm, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India (Figure. 1) during the summer season. The experimental site is located in Tamil Nadu's Western Agroclimatic Zone and has coordinates of 11°00'11.5N, 76°55'37.1E and an elevation of 411 meters above mean sea level. The average Maximum and minimum temperatures of 37°C and 30.1°C were recorded during the 16th and 27th Standard weeks, respectively. The total rainfall received during the cropping period is about 287.5 mm in 23 rainy days.

2.2 Experimental Description

The Tamil Nadu Rice Research Institute in Aduthurai, Tamil Nadu, India, released ADT 53 in 2019, which is the variety selected for the experiment. This variety extends about 110 to 115 days.

The experimental site's soil type is clay loam, with EC and pH values of 0.67 ds/m and 8.2, respectively. The initial soil undergone physiochemical study before the formation of the field layout. Three main plots for water management and six subplots for mitigation strategies were used in the strip plot design experiment, which was carried out in three replications.

Continuous flooding (M_1), AWDI at soil moisture depletion by 10 cm (M_2), AWDI at soil moisture

depletion by 15 cm (M_3) in the main plot. Rice straw incorporation + 75% RDF (S_1), Rice straw incorporation with Pusa Decomposer Capsules + 75% RDF (S_2), Rice straw incorporation with TNAU Bio mineralizer + 75% RDF (S_3), Rice straw incorporation with Pusa Decomposer Capsules + TNAU Bio mineralizer + 75% RDF (S_4), 75% RDF (S_5), 100% RDF (S_6) in the subplot, were studied.

2.3 Microbial Consortia preparation

Pusa decomposer capsules were obtained from the Division of Microbiology, ICAR-Indian Agricultural Research Institute (IARI), Pusa, New Delhi, India. To create culture, 150 grams of old jaggery were heated in five litres of water and the filth that rose to the top of the boiling water was sieved out of the mixture. The jaggery solution was cooled to room temperature and then mixed with around 50 g of chickpea flour. A wooden stick was used to thoroughly mix the well-blended chickpea flour and after that four Pusa decomposer capsules were added in the mixture. Then the mixture was placed in a plastic tub, covered with a thin towel and stored for a week in a warm place. For rice straw, TNAU biomineralizer (2 kg/tonne) was utilized and water (20 litres for 2 kg biomineralizer) was applied.

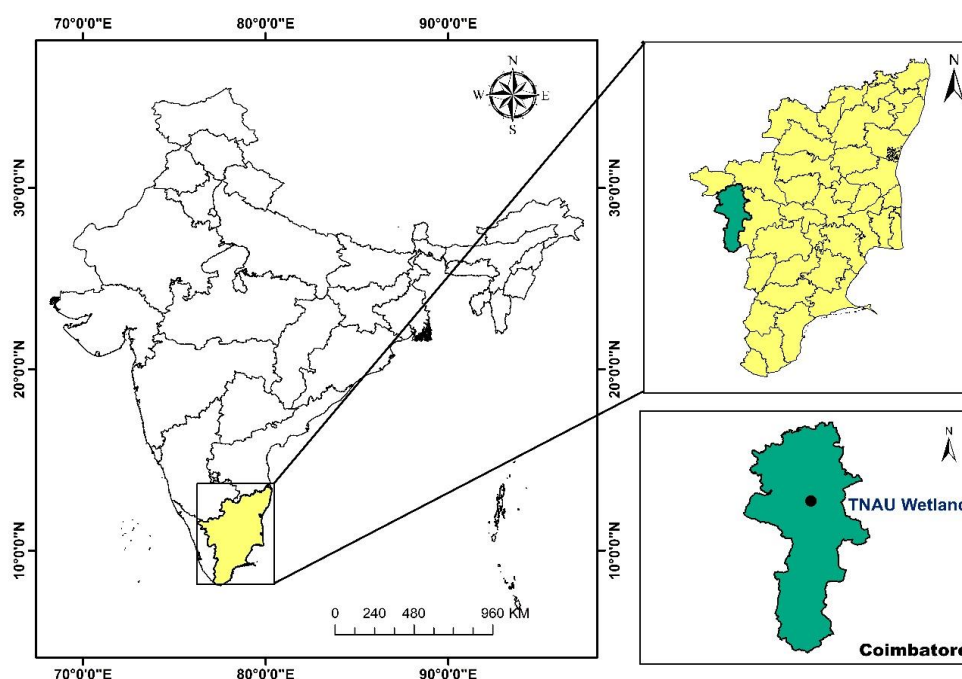


Figure 1. Location of experimental site



Photosynthetic parameters were measured using a Portable Photosynthesis System (PPS) on fully expanded upper canopy leaves during clear sky conditions. Observations were recorded between 09:00 and 11:00 AM to minimize diurnal variation. The instrument measured net photosynthetic rate, stomatal conductance, transpiration rate, and internal CO₂ concentration under field conditions (Long, Farage, & Garcia, 1996; Suwannarut, Violet-Chabrand, & Kaiser, 2023).

2.4 Statistical Analysis

The data was subjected to Analysis of Variance (ANOVA) using statistical tools and R programming. Least Significant Difference (LSD) was used to evaluate the significant differences between mean values at a 5% probability level, as advised by (Gomez and Gomez, 1984). When treatment differences were statistically significant, critical differences were analyzed at the 5% significance level (F test). NS denotes that there was no statistically significant difference between the treatments.

RESULTS AND DISCUSSION

3.1 Chlorophyll content (SPAD)

The Chlorophyll content in terms of SPAD varied significantly across both irrigation management regimes and organic amendment treatments at all growth stages. Among subplot treatments, the highest

Chlorophyll content was recorded under rice straw incorporation with Pusa Decomposer Capsules + TNAU Bio-mineralizer + 75% RDF (S₄) at 38.8, 41.3 and 38.2 at 30, 60 and 90 DAT respectively, followed by S₂ (38.5, 40.3 and 37.8) (Figure 2), attributable to enhanced nitrogen availability facilitated by accelerated straw decomposition where nitrogen being the principal determinant of leaf greenness and photosynthetic capacity during grain filling, ultimately improving photosynthate supply to developing seeds (Kaewpradit et al., 2009; Lee et al., 2009). With respect to irrigation management, continuous flooding (M₁) recorded the maximum Chlorophyll content of 38.4, 40.4 and 37.8 at 30, 60 and 90 DAT respectively, while the minimum was observed under AWD at 15 cm soil moisture depletion (M₃), reflecting the suppressive effect of intermittent water deficit on stomatal conductance and nutrient uptake, both of which are critical regulators of chlorophyll biosynthesis and retention in rice (Shao et al., 2022).

3.2 Photosynthetic Rate

The photosynthetic rate (μmol CO₂ m⁻² s⁻¹) varied significantly across irrigation regimes and organic amendment treatments at all growth stages. Among irrigation management methods, AWD at 10 cm soil moisture depletion (M₂) recorded the highest photosynthetic rate of 24.7, 30.9 and 26.22 μmol

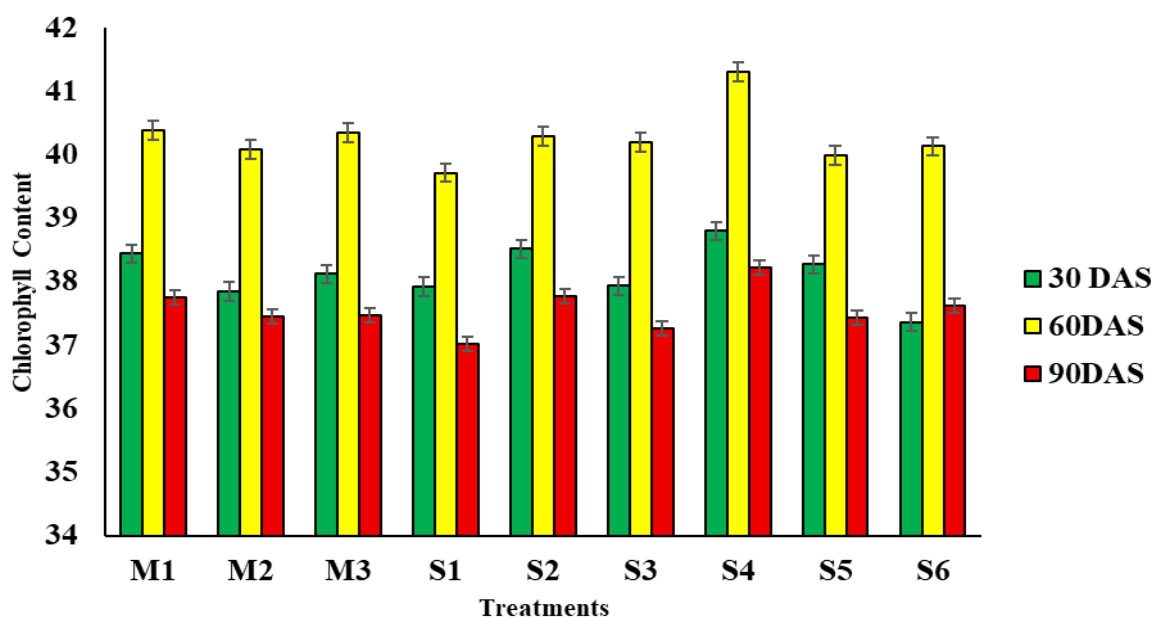


Figure 2. Effect of irrigation and nutrient management on Chlorophyll content at 30, 60 and 90 DAT



CO₂ m² s⁻¹ at 30, 60 and 90 DAT respectively, followed by M₃ (24.2, 30.7 and 26.0) and M₁ (24.0, 30.3 and 25.9 μmol CO₂ m² s⁻¹), suggesting that mild, controlled soil drying under M2 optimizes root oxygen availability and stomatal regulation, thereby enhancing mesophyll CO₂ assimilation capacity more effectively than continuous anaerobic flooding can consistent with the established role of irrigation management in modulating plant carbon assimilation and productivity (Wang *et al.*, 2018) (Figure 3). Among organic amendment treatments, the highest photosynthetic rate was recorded under S₄ (rice straw + Pusa Decomposer Capsules + TNAU Bio-mineralizer + 75% RDF) at 24.8, 31.4 and 26.7 μmol CO₂ m² s⁻¹ at 30, 60 and 90 DAT respectively, followed by S₂ (24.6, 30.8 and 26.2 μmol CO₂ m² s⁻¹), attributable to enhanced nutrient mineralization and improved chlorophyll synthesis facilitating greater light absorption and electron transport efficiency (Maxwell and Johnson, 2000). The progressive increase in photosynthetic rate from 30 to 60 DAT across all treatments corroborates the developmental pattern reported by (Santanoo *et al.*, 2023), wherein photosynthetic activity peaks during active vegetative growth before photosynthates are increasingly partitioned toward reproductive sink organs.

3.3 Transpiration Rate

The transpiration rate (mmol H₂O m² s⁻¹) varied

significantly across irrigation regimes and organic amendment treatments at 30, 60 and 90 DAT. Among irrigation management methods, AWD at 15 cm soil moisture depletion (M₃) recorded the highest transpiration rates of 7.0, 8.7 and 6.8 mmol H₂O m² s⁻¹ at 30, 60 and 90 DAT respectively, followed by M₂ (6.5, 8.6 and 6.5) and M₁ (6.2, 8.4 and 6.4 mmol H₂O m² s⁻¹), indicating that greater soil drying under M₃ induces an elevated leaf-to-atmosphere vapor pressure gradient, thereby amplifying stomatal-mediated water loss as the plant attempts to sustain hydraulic continuity under increasing soil matric potential (Figure 4). Among organic amendment treatments, the highest transpiration rate was recorded under S₄ (rice straw + Pusa Decomposer Capsules + TNAU Bio-mineralizer + 75% RDF) at 7.0, 8.9 and 7.1 mmol H₂O m² s⁻¹ at 30, 60 and 90 DAT respectively, attributable to the enhanced water-holding capacity and improved soil structure conferred by rice straw incorporation, which sustains adequate root-zone moisture and supports active stomatal aperture maintenance creating a favorable rhizosphere microenvironment for root development and water uptake (Meharg and Meharg, 2015). The lowest transpiration rate was consistently recorded under 75% RDF alone (S₅) at 6.1, 8.2 and 6.2 mmol H₂O m² s⁻¹ across all stages, reflecting the limited soil moisture retention capacity in the absence of organic matter inputs.

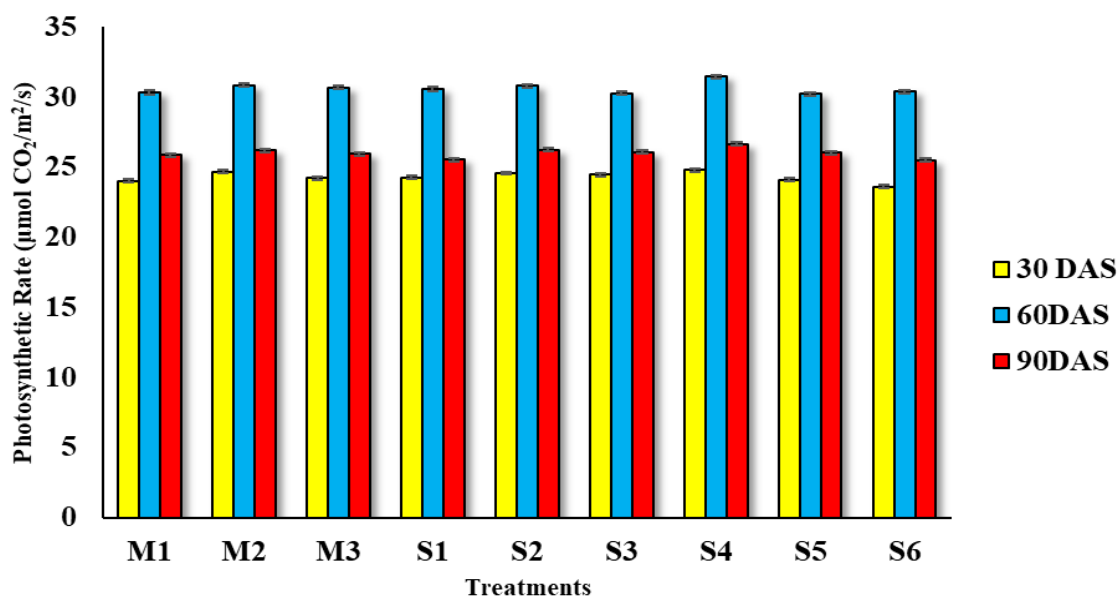


Figure 3. Effect of irrigation and nutrient management on photosynthetic rate (μmol CO₂ m² s⁻¹) at 30, 60 and 90 DAT

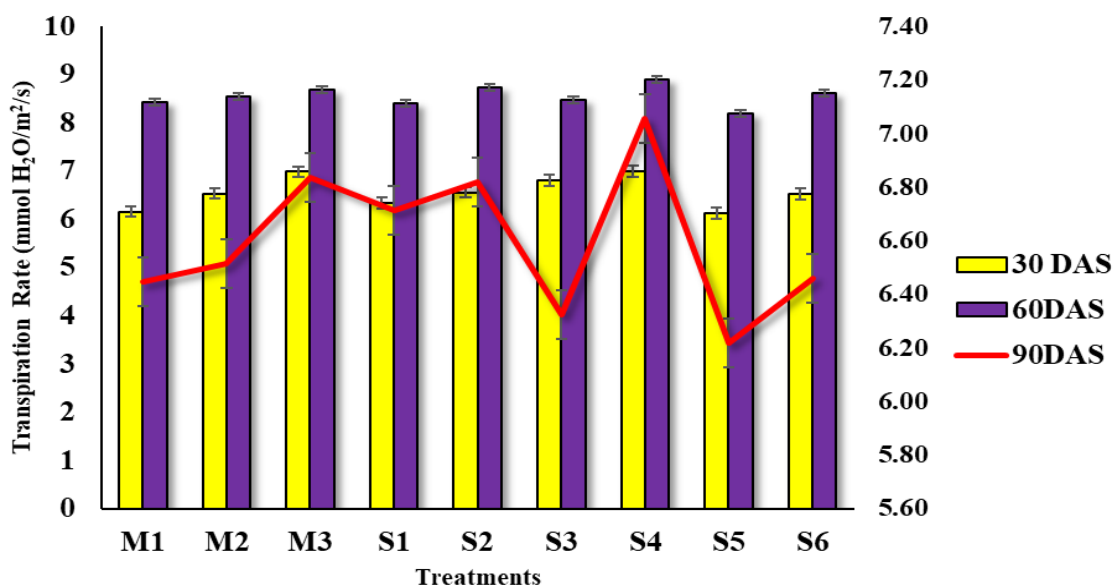


Figure 4. Effect of irrigation and nutrient management on transpiration rate (mmol H₂O m² s⁻¹) at 30, 60 and 90 DAT

3.4 Stomatal Conductance

Stomatal conductance (mmol H₂O m² s⁻¹) differed significantly across both irrigation and amendment treatments at all growth stages. Among irrigation regimes, AWD at 10 cm depletion (M₂) recorded the highest stomatal conductance of 0.521, 0.730 and 0.528 mmol H₂O m² s⁻¹ at 30, 60 and 90 DAT, respectively (Figure 5), followed by M₃ and M₁, indicating that mild aerobic conditions under M₂ optimally regulate guard cell turgor and stomatal aperture for efficient gas exchange without imposing severe hydraulic stress.

Among organic amendments, S₄ (rice straw + Pusa Decomposer Capsules + TNAU Bio-mineralizer + 75% RDF) recorded the highest values of 0.521, 0.727 and 0.538 mmol H₂O m² s⁻¹, attributable to enhanced soil water-holding capacity and nutrient-rich rhizosphere conditions that support optimal stomatal regulation and gas exchange (Chivenge *et al.*, 2019; Liu *et al.*, 2023), while the lowest stomatal conductance was consistently recorded under 75% RDF alone (S₅), reflecting compromised guard cell function in the absence of organic matter input.

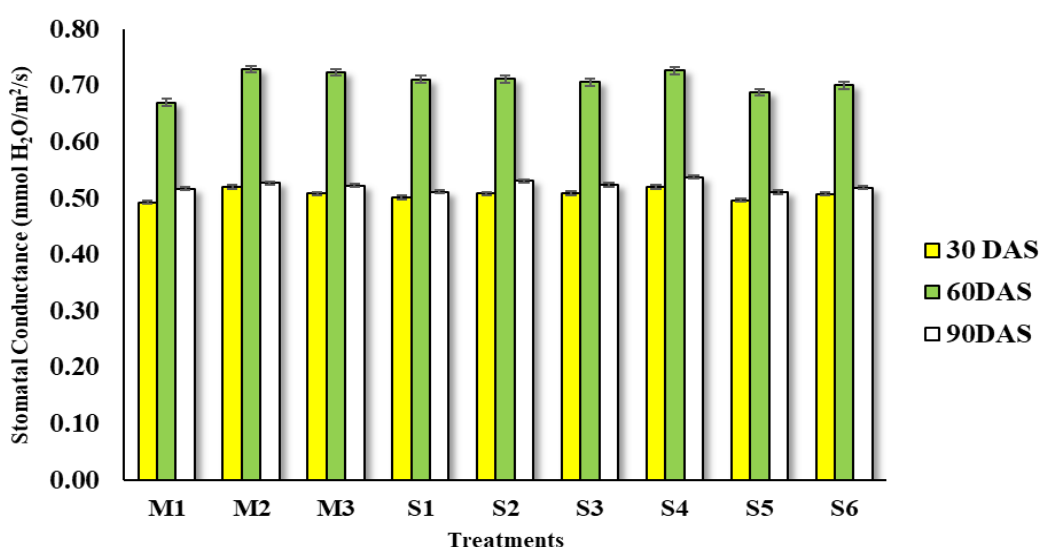


Figure 5. Effect of irrigation and nutrient management on stomatal conductance (mmol H₂O/m²/s) at 30, 60 and 90 DAT

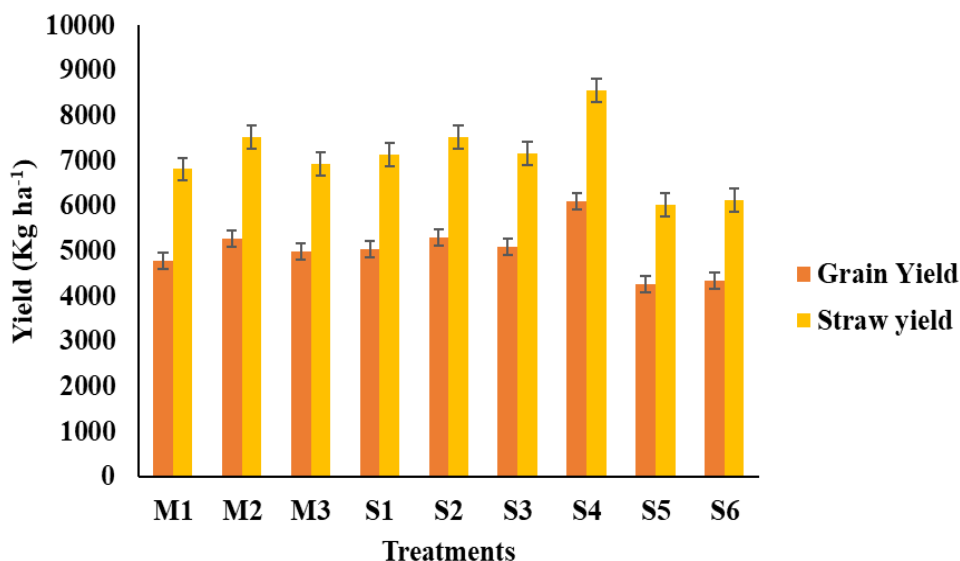


Figure 6. Effect of irrigation and nutrient management on the yield parameters of rice.

3.5 Grain and Straw Yield

In irrigation management, the maximum grain and straw yields are recorded in AWDI at soil moisture depletion by 10 cm (M₂), whereas the minimum grain and straw yields are observed under continuous flooding (M₁) (Figure 6). Rice output is determined by the quantity of photosynthate present in leaves and stems during the seed filling phase, which is largely dependent on the photosynthesis process that occurs after blooming. The use of rice straw compost increases the amount of photosynthates in the leaves. The current results were akin to the findings of (Karam *et al.*, 2022; Islam *et al.*, 2025).

CONCLUSION

This study highlights a crucial transformation in sustainable rice farming, transitioning from the traditional, resource-heavy flooding method to a precision management approach optimised for physiological efficiency. The research clearly shows that the main challenge to the broad implementation of Alternate Wetting and Drying (AWD) is the risk of physiological decline due to water stress, which can be effectively mitigated by strategically using organically amended rice straw. By employing rice straw decomposed using two types of microbial consortia, the soil’s ability to retain moisture was greatly improved, helping sustain optimal stomatal conductance and photosynthesis rates even during the necessary drying phases of the AWD system.

The implementation of precision irrigation at a 10 cm depletion level, coupled with the integration

of straw through microbial processes, has proven to be more effective than the traditional method of continuous flooding, both in terms of physiological efficiency and ultimate grain yield. This study presents a compelling “win-win” strategy for the Cauvery Delta Zone and similar agro-climatic regions by addressing water security, environmental sustainability and crop resilience concurrently. By converting hazardous agricultural waste into a beneficial soil buffer, farmers can achieve significant water conservation while maintaining consistent food production. Future research should focus on the long-term impacts of these microbial consortia on soil carbon storage and the reduction of greenhouse gases to further establish this synergistic approach as a global standard for environmentally responsible and productive rice cultivation.

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Ethics Statement:

This study was conducted using publicly available dataset sources. It did not involve human participants, animals, or any form of personal data. Therefore, ethical approval was not required.



Originality and Plagiarism:

The authors confirm that this manuscript is an original work and has not been published previously, nor is it under consideration for publication elsewhere. All sources of data, concepts, and previously published material have been properly cited and acknowledged. The manuscript has been prepared in accordance with ethical academic standards and plagiarism in any form has been strictly avoided.

Consent for Publication:

All authors have read and approved the final version of the manuscript and consent to its submission and publication in the journal.

Competing Interests:

The authors declare that they have no known financial or non-financial competing interests that could have influenced the work reported in this manuscript

Data Availability:

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions:

Guruanand C: Conceptualisation, Data curation, analysis, visualisation, methodology development, drafting the initial manuscript.

Raju M: Overall coordination of the research work, data interpretation and review.

Boomiraj K: Overall supervision, review and editing of the manuscript, and project guidance.

Gayathri J: Data processing, statistical analysis and support in result interpretation.

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