Vol. 23, No. 2, pp. 255-263 (2023)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in

Research Article

Yield Gap Analysis and Optimization of Nitrogen Management Practices towards Closing the Yield Gap of Rice: A DSSAT- CERES Modelling Approach

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ABSTRACT

Bridging the yield gap presents a rewarding opportunity to enhance rice production through the adoption of suitable crop management practices. This study aimed to analyze the yield gap and compare various nitrogen (N) fertilizer management practices to reduce yield using the DSSAT–CERES model. Three production levels i.e potential yield, attainable yield, and actual farmer's yieldswere estimated for two rice varieties, Jaya and Jyothi. The DSSAT–CERES model was employed for calculating potential yield and simulating yield responses under different nitrogen management practices. The total yield gap for variety Jaya was 3457 kg ha^{-1}, and for variety Jyothi, it was 3357 kg ha^{-1}. According to the simulation results, the optimum nitrogen dose was 140 kg ha^{-1} for both varieties. Among different nitrogen practices, applying three split doses of nitrogen through irrigation water increased yield and decreased the yield gap. The study highlights the efficiency of the CERES rice model as a tool for formulating management practices to close the yield gap.

Key words: Yield gap, DSSAT- CERES model, Closing the yield gap, Potential yield, Attainable yield, Actual yield

Introduction

The global population, predicted to exceed 9 billion by 2050, will demand an additional 80% in food production. A substantial yield gap exists between attainable and farm-level yields in many rice-growing countries. Quantifying this gap indicates the potential for increased yields. Closing the yield gap requires realistic solutions (FAO, 2015). Aggarwal *et al*. (2008) reported a significant yield gap across all states in India, with the highest gap observed in rice production (1670 kg ha^{-1}) among different crops.

Simulation modeling serves as a modern research tool, complementing field experiments by generating data on crop responses to soil, climate, and management variables. It offers a cost-effective and time-efficient alternative to detailed field experiments. Calibration and validation of the simulation model are essential prerequisites for accurate insights into crop management under diverse soil and climatic conditions (Jalota *et al*., 2006). Accurately calibrated crop simulation models are employed to evaluate crop yield across various environmental and management conditions (Foster *et al*., 2014; Kumar *et al*., 2023). According to FAO (2004), different approaches for calculating the yield

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gap, including modeling, are suggested. More complex models like CERES are commonly used because they capture specific cultivar genetic features and critical interactions between water and nitrogen. Timsina *et al*. (2004) suggest that crop simulation models can estimate potential and actual yield, overcoming other methods of yield gap analysis. Attainable yield is obtained from high-yielding research plots where the best available management practices are followed. According to Van Wart *et al*. (2013), quantifying the yield gap is essential to forming policies and prioritizing research to achieve food security without degrading natural resources.

After assessing the yield gap, appropriate management practices can be developed to close it. Comparing various management practices through field experiments is time and resource-consuming. Crop simulation models serve as effective tools to compare yield responses under different management practices. Debnath *et al*. (2021) identified promising agronomic strategies to close the yield gap through model-based assessment. In this study, different nitrogen management practices were compared using the CERES model to address the yield gap. This type of study was not done previously in the study area. Conducting yield gap analysis in an area where no such study has been undertaken before is crucial. It serves as a key step in unlocking the agricultural potential of the region, fostering sustainable practices, tackling food security challenges, and informed policymaking.

Materials and Methods

Experimental materials and methods

The experiment utilized two rice varieties, Jaya and Jyothi. Jaya, with a 130-day duration, is recommended for nationwide cultivation in both *kharif* and *rabi* seasons. It originated from a cross between Taichung (Native) 1 and the local photosensitive variety T-141 of Orissa. Jyothi, adaptable to all three seasons and diverse field conditions, has a duration of 110-115 days. It resulted from a cross between PTB-10, a short-duration local strain, and IR 8, a renowned high-yielding genotype. The study aimed to assess the performance of these varieties under specific conditions. The study used a split-plot experimental design, with five planting dates (at 15-day intervals from June 5th to August 5th) as the main plot treatments. The sub plot treatments included two varieties, Jyothi and Jaya. The entire design was replicated four times to ensure robustness and reliability in the experimental results. The experiment was conducted at Agricultural research station, Mannuthy, Thrissur (76°13′ E, 10° 3′ N) during the *viruppu* season (*kharif*) of 2019.

Different weather parameters on daily basis (maximum temperature, minimum temperature, rainfall, and bright sunshine hours) were collected from Agromet observatory of College of Agrticulture, Vellanikkara during the year 2019.

Model performance evaluation

In the present study, the CERES-rice model was run to simulate yield and phenology using the weather, soil, crop management practices and experimental data for the year 2019 for two varieties Jyothi (short duration) and Jaya (Medium duration). Genetic coefficients for the model was calibrated for these varieties during previous years of studies by Vysakh *et al*.(2016) and Haritharaj (2019). Fine tuning of these genetic coefficients were done by comparing simulated outputs with the experimental data on rice yield and phenophase collected from the experimental plot at Agricultural Research Station, Mannuthy, Kerala. The following statistics are used to evaluate model performance.

Root Mean Square Error

RMSE measures the average magnitude of the errors or differences betweensimulated data and observed values and provides a single value that reproduces the overall model accuracy. A lower RMSE indicates that the model's predictions are, closer to the observed values, suggesting better model accuracy. A higher RMSE indicates that the model's predictions are, away from the observed values, indicating lower model accuracy (Zhang *et al*., 2012).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{n}}$$

Where, Pi, Oi and n denotes predicted value, observed value and number of observations respectively.

d-Stat index

The d-statistic (d) serves as a valuable metric for assessing the effectiveness of models and simulations. A value closer to 0 signifies superior model performance, while a value closer to 1 suggests poorer performance. This metric quantitatively gauges the fidelity of a model in reproducing observed data, rendering it a useful tool in diverse scientific and modeling applications. An acceptable threshold for the d-statistic is equal to or greater than 0.70, as suggested by Jing *et al*. (2017).

$$D-stat=1-\left[\frac{\sum (P_i-O_i)^2}{\sum (O_i-\bar{O})^2}\right]$$

Where, P_i corresponds to the simulated values, O_i to the observed values, $\bar{O}$ to mean of observed values, and n to the total number of observations for the variables under investigation.

Estimation of different yield levels

For yield gap analysis, three different yield levels were considered: potential yield (Yp), attainable yield (Ya), and actual farmer's yield (Yf). The potential yield is defined as the maximum yield of a variety under specific climatic conditions (solar radiation, maximum and minimum temperature) without restrictions on water and nutrients, and with optimal cultural management (Patel *et al*., 2008). Potential yield was simulated using the DSSAT-CERES model, considering unlimited water and nutrient conditions in an experimental data file, for all five planting dates. Attainable yield was determined from the maximum yield achieved in experimental plots under best management practices recommended by Kerala Agricultural University, with planting on June 20 chosen for comparison with farmer's field data based on information from the agriculture office in Mannuthy. The yield gap analysis involved calculating the differences between various production levels (Yp, Ya, and Yf). The total yield gap represents the disparity between potential yield and actual farmer's yield and is further divided into Gap I and Gap II (Fig. 1). Gap I is the difference between potential yield and attainable yield, while Gap II is the difference between attainable yield and actual farmer's yield (FAO, 2004). Each yield gap is expressed as a percentage of potential yield.

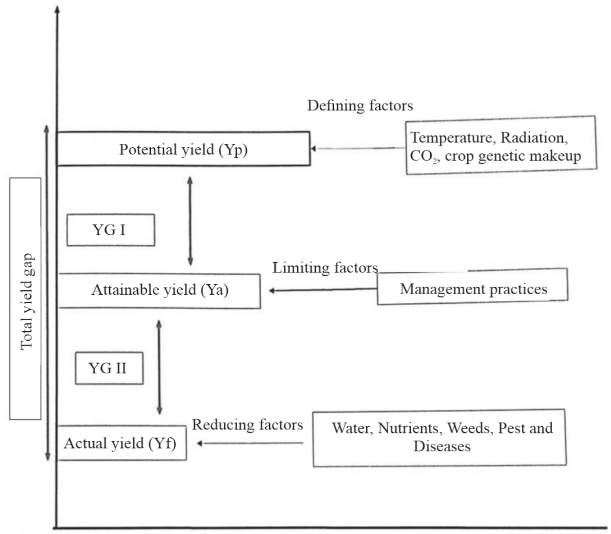

Fig. 1. The different yield levels and yield gaps

Gap I = Potential yield – Attainable yield

Gap II = Attainable yield – Actual farmer's yield

Total yield gap = Potential yield – Actual farmer's yield

Yield gap expressed as the percentage of potential yield was calculated by,

$$\%Yg=\frac{\text{Yield gap}}{\text{Potential yield}}\times 100$$

Comparison of nitrogen management practices to reduce yield gap

Yield was simulated under different nitrogen (N) management practices using the CERES rice model. The general N recommendation for Jaya was 90 kg ha^{-1}. To compare various N application methods, yield was simulated for this amount of N under two split doses (45:45) and three split doses (45:23:23). For Jyothi, the recommended N amount was 70 kg ha-1, and yield simulations were conducted for this quantity using two splits (47:23) and three splits (35:18:18). Broadcasting nitrogen applications are common in the experimental area. The simulated yield obtained under the broadcasting method was compared with yields simulated when N was applied through irrigation water and using urea super granule methods (chosen due to limited model options). Yields for each N application method were simulated, and the corresponding yield gaps were also estimated

Table 1. Genetic coefficients of Jyothi and Jaya used in CERES-Rice model

Genetic coefficient	Jyothi	Jaya
P1	551	575.2
P2R	22.3	75.6
P5	444	443.9
P2O	11.4	12.9
G1	50.4	48.5
G2	0.0256	0.028
G3	1.1	1
G4	1.1	1
PHINT	82	82

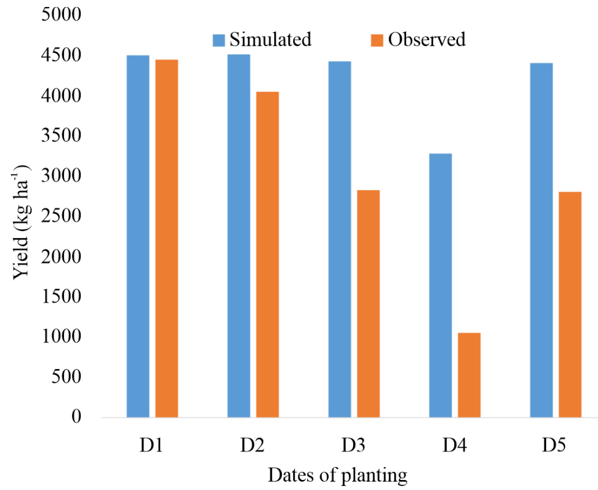

Fig. 2. Variation of simulated and observed yield with different dates of planting for Jaya

Results and Discussion

Model performance evaluation

The observed data of phenology, yield, and yield attributes were used for evaluating model performance. Weather files, crop management files, soil files, and experimental files were prepared to give as input to run the CERES-Rice model for Jaya and Jyothi during the year 2019. The previously calibrated genetic coefficients were fine-tuned using 6000 iterations for both varieties separately. Fine-tuned genetic coefficients used in the study are depicted in Table 1. Model performance evaluation was done by comparing predicted output and observed output using two statistics i.e RMSE and d-stat value for both varieties (Table 2). In the case of Jyothi, the simulated grain yield showed good agreement with the observed yield, with an RMSE value of 1043 and a D-index of 0.61. For Jaya, the model predicted the grain yield with an RMSE value of 1488 and a D-stat value of 0.57, demonstrating good agreement with the observed yield. Similar findings were reported by Jha *et al*. (2020), who predicted grain yield in good agreement with the observed yield, having an RMSE value of 4.4% and a D-stat value of 0.67. A wide variation in observed and simulated yield for both Jaya and Jyothi was noticed with a delay in planting and represented in Fig. 2 and Fig. 3 respectively. This finding was consistent with results observed by Vysakh *et al.* (2014). There was a good agreement between simulated and observed phenology for both Jaya and Jyothi, except for the duration of physiological maturity in Jyothi. Simulated anthesis day was reasonably in agreement with the observed anthesis date. In Jaya, the model predicted the anthesis date with an RMSE value of 1.84 and a D-stat value of 0.49. In Jyothi, it predicted the anthesis date with an RMSE value of 1.673 and a D-stat value of 0.686. Predicted panicle initiation showed good agreement with observed panicle initiation dates, with an RMSE

Table 2. Model performance evaluation for both Jaya and Jyothi

Variety	Parameters	Observed	Simulated	RMSE	d-Stat
Jaya	Yield (kg ha^{-1})	3036	4281	1488.63	0.57
	Anthesis	69	69	1.844	0.49
	Panicle initiation	39	36	3.72	0.584
	Physiological maturity	104	102	3.55	0.584
Jyothi	Yield (kg ha^{-1})	2672	3451	1043	0.61
	Anthesis	67	69	1.673	0.686
	Panicle initiation	34	35	1.949	0.643
	Physiological maturity	98	102	4.98	0.328

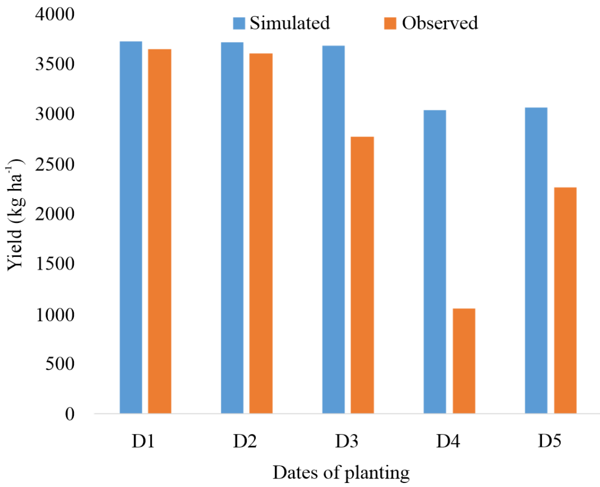

Fig. 3. Variation of simulated and observed yield with different dates of planting for Jyothi

value of 3.72 for Jaya and 1.94 for Jyothi, and a D-stat value of 0.584 for Jaya and 0.643 for Jyothi. Simulated maturity date and observed maturity date showed good agreement in Jaya with an RMSE value of 3.55 and a D-stat value of 0.584. Similar results were reported by Haritharaj in 2019.

In a recent study conducted by Riya and Ajithkumar (2023) also found that CERES rice model performed well in this particular study area for the variety Jyothi.

Estimated yield gap

The actual farmer's yield of Jaya was 2430 kg ha^{-1}, and for Jyothi, it was 2330 kg ha^{-1}. The attainable yield for Jaya was 4057 kg ha^{-1}, and for Jyothi, it was 3609 kg ha^{-1}. The potential yield simulated for June 20th planting was 5797 kg ha^{-1} for Jaya and 5687 kg ha^{-1} for Jyothi. The different levels of yield gap calculated for rice varieties are represented in Fig.4. In the case of Jaya, yield gap I was calculated as 1740 kg ha^{-1}, which was 30% of potential yield, and yield gap II was 1717 kg ha^{-1}, which was 29.6% of potential yield. For Jyothi, 2078 kg ha^{-1} was obtained as yield gap I, which was 36.5% of potential yield, and the calculated value of yield gap II was 1279, which was 22.3% of potential yield. In both varieties, yield gap I was more compared to yield gap II, i.e., the difference between potential yield and attainable yield was more compared to the difference between attainable yield and actual farmer's yield. The total yield gap in the case of Jaya was calculated as 60% of potential yield, i.e., 3457 kg ha^{-1}, whereas in Jyothi, the total yield gap was 59% of potential yield, i.e., 3357 kg ha^{-1}. Various scientists have used a similar approach to analyze yield gap using crop models (Timsina *et al*., 2004; Singh *et al*., 2016; Dias *et al*., 2018; Zhang *et al*., 2019).

Simulation of yield responses under different nitrogen management practices using CERES rice model

Yield gap analysis under different doses of nitrogen

Basic doses of nitrogen, as recommended by KAU, are 90 kg ha^{-1} for Jaya and 70 kg ha^{-1} for Jyothi. The yield response of both varieties under higher nitrogen application rates was simulated using the model. The yield response and corresponding total yield gap for each input of nitrogen for Jaya and Jyothi are represented in Fig. 4 and Fig. 5, respectively. From the figures, it was understood that with an additional increase in nitrogen, yield increased and reached a plateau after 140 kg ha^{-1} nitrogen for both varieties (Jaya and Jyothi). Yield increased with an increase in nitrogen input up to 140 kg ha^{-1}, and the corresponding yield gap decreased.

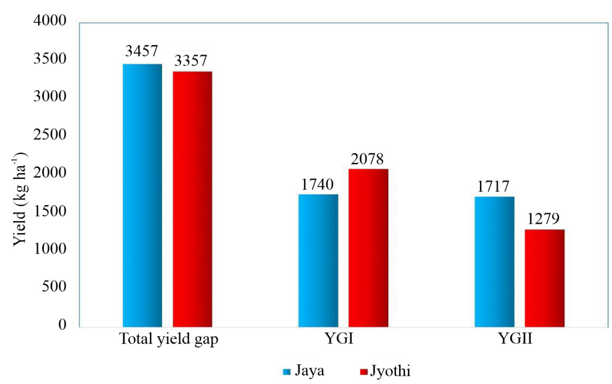

Fig. 4. Different levels of yield gap calculated in both Jaya and Jyothi varieties

Yield gap analysis under different splits doses of nitrogen

A comparison was made between two split doses of nitrogen applications and three split doses of

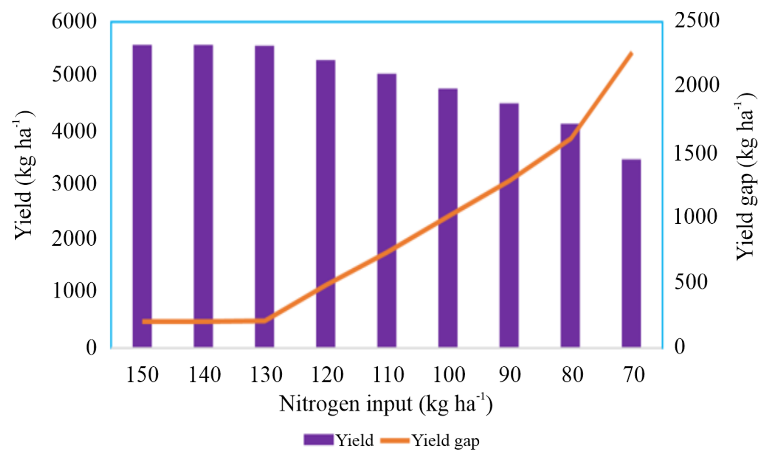

Fig. 5. Yield response and corresponding yield gap with different doses of nitrogen input for Jaya

nitrogen applications. For Jaya, the nitrogen recommendation was 90 kg ha^{-1}, as per KAU. The yield of Jaya was simulated when 90 kg ha^{-1} was applied in two split doses (45 kg ha^{-1} during 15 days after planting and the remaining 45 kg ha^{-1} after panicle initiation) and three split doses (45 kg ha^{-1} during 15 days after planting, 23 kg ha^{-1} during active tillering, and 23 kg ha^{-1} after panicle initiation). For Jyothi, the nitrogen recommendation was 70 kg ha^{-1}, as per KAU. The yield of Jyothi was simulated when 70 kg ha^{-1} was applied in two split doses (47 kg ha^{-1} during 15 days after planting and the remaining 23 kg ha^{-1} after panicle initiation) and three split doses (35 kg ha^{-1} during 15 days after planting, 18 kg ha^{-1} during active tillering, and 18 kg ha^{-1} after panicle initiation). Simulated yield was higher under three split doses of nitrogen application compared to two split doses in Jaya during all five planting dates. In the case of Jyothi, simulated yield was higher under three split doses during the first three planting dates and higher under two split doses during the last two planting dates. The yield increment under three split doses of nitrogen was greater in Jaya compared to Jyothi. A similar approach was taken by Hameed (2019), who simulated yield under different nitrogen rates and split doses. According to him, the yield was maximum when nitrogen was applied at a rate of 300 kg ha^{-1}, and the yield was found to be higher under four split doses of nitrogen application compared to a single split.

Yield gap analysis under different nitrogen application methods

Yield responses under different nitrogen application methods and doses were simulated using

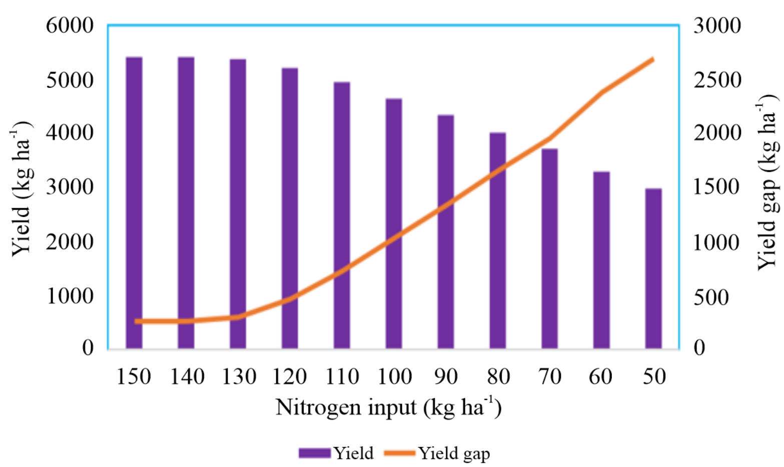

Fig. 6. Yield response and corresponding yield gap with different doses of nitrogen input for Jyothi

Table 3. Yield response simulated under different nitrogen doses and application methods in Jaya

Nitrogen (kg ha^{-1})	Nitrogen application methods					
	Broad casting		Nitrogen applied through irrigation water		Urea super granules	
	Yield	Yield gap	Yield	Yield gap	Yield	Yield gap
150	5587	210	5587	210	5588	210
140	5587	210	5587	210	5588	210
130	5572	215	5572	215	5574	215
120	5308	489	5308	489	5308	489
110	5055	742	5156	591	5198	549
100	4780	1017	4837	920	4775	972
90	4507	1290	4520	1227	4500	1297
80	4135	1612	4145	1602	4140	1607
70	3475	2272	3508	2239	3465	2332

Table 4. Yield response simulated under different nitrogen dose and application method in Jyothi

Nitrogen (kg ha^{-1})	Nitrogen application methods					
	Broad casting		Nitrogen applied through irrigation water		Urea super granules	
	Yield	Yield gap	Yield	Yield gap	Yield	Yield gap
150	5425	262	5425	262	5425	262
140	5425	262	5425	262	5425	262
130	5387	300	5391	296	5409	278
120	5220	467	5264	423	5179	508
110	4960	727	4932	755	4966	721
100	4654	1033	4684	1003	4657	1030
90	4349	1338	4356	1331	4427	1260
80	4025	1662	4049	1638	4008	1679
70	3726	1961	3729	1958	3705	1982
60	3298	2389	3321	2366	3007	2680
50	2985	2702	2988	2699	2945	2742

the CERES model, with results presented in Tables 3 and 4. Simulated yield varied across application methods, even with the same fertilizer amount. Corresponding yield gaps for each method and dose were calculated by the difference between potential yield and model-simulated yield. A comparison of the three application methods indicated higher yields when nitrogen was applied through irrigation at the general nitrogen dose than the other two methods. Yield simulated under nitrogen application through urea super granules was lower than the other two methods. At the optimum nitrogen dose of 130 kg ha^{-1}, yield simulated under all three methods was the same. Simulated yield was higher, and the yield gap was lower when nitrogen was applied through water in both Jaya and Jyothi.

Similarly use of CERES model to compare different nitrogen practices were done by different scientists across the world (Jeong *et al.*, 2014; Kadiala *et al.*, 2015; Prasad *et al.*, 2018; Zhang *et al.*, 2019). Even though crop simulation models, can be used as an effective tool in yield gap analysis, they have some potential limitations. Crop simulation models may not fully capture the complexities of farmer decision-making and management practices. Variability in farmer behavior, such as the adoption of new technologies or changes in cropping practices, can influence yield gaps (Van Ittersum *et al*., 2013). Models may not account for the spatial heterogeneity of soils, landscapes, and farming systems. The scale of analysis may impact the accuracy of yield gap estimates, especially when extrapolating results from plot or field-level simulations to larger regions (Grassini *et al*., 2015). Crop models often focus on abiotic factors and may not fully incorporate the dynamics of pests and diseases, which can significantly impact actual yields (Rosenzweig *et al*., 2014). Yield gap analyses may not consider social and economic factors influencing agricultural productivity, such as access to markets, credit, and education. These factors can contribute to yield gaps but are often challenging to integrate into models (Wiebe *et al*., 2015). These limitations can be considered as the potential sources of uncertainty in yield gap analysis. Hence a continuous work towards the improvement of model accuracy by incorporating more realistic representation of farming systems and socio economic factors to be done in future for better assessment of yield gap.

Conclusion

A sizeable yield gap was existing in the rice production of Kerala. This can be minimized by adopting proper management practices. This study aimed to compare different N management practices to reduce yield gap using CERES model. By comparing different nitrogen doses and application methods, a nitrogen dose of 140 kg ha^{-1} can be considered for maximum yield. Yield was found to be increased under three split doses of N compared to two split doses. Comparison of different application methods suggested that yield can be increased when fertilizer was applied through irrigation water. Adoption of these management practices tend to increase the yield and there by close the yield gap. The study suggests that CERES model can be used as an efficient tool to evaluate different management strategies. This approach consumes less time and conserves resources compared to field experiments.

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Received: 27 June 2023; Accepted: 30 September 2023