Assessment of Genotype × Management Interaction to Enhance Rice Productivity in Southern Thailand

Tajamul Hussain

A Thesis Submitted in Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Plant Science
Prince of Songkla University
2022

Assessment of Genotype × Management Interaction to Enhance Rice Productivity in Southern Thailand

Tajamul Hussain

A Thesis Submitted in Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Plant Science
Prince of Songkla University
2022

Thesis Title Assessment of Genotype × Management Interaction to Enhance Rice Productivity in Southern Thailand
Author Mr. Tajamul Hussain
Major Program Plant Science

Major Advisor

....
(Asst. Prof. Dr. Saowapa Duangpan)

Co-advisors:

....
(Assoc. Prof. Dr. Charassri Nualsri)

....
(Assoc. Prof. Dr. Mukhtar Ahmed)

Examining Committee:

....Chairperson
(Asst. Prof. Dr. Janejira Duangjit)

.... Committee
(Asst. Prof. Dr. Saowapa Duangpan)

.... Committee
(Assoc. Prof. Dr. Charassri Nualsri)

.... Committee
(Assoc. Prof. Dr. Mukhtar Ahmed)

.... Committee
(Dr. Jakarat Anothai)

The Graduate School, Prince of Songkla University, has approved this thesis as fulfillment of the requirements for the Doctor of Philosophy Degree in Plant Science

....
(Prof. Dr. Damrongsak Faroongsarng)
Dean of Graduate School

This is to certify that the work here submitted is the result of the candidate’s own investigations. Due acknowledgement has been made of any assistance received.

....Signature
(Asst. Prof. Dr. Saowapa Duangpan)
Major Advisor

....Signature
(Mr. Tajamul Hussain)
Candidate

I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

....Signature
(Mr. Tajamul Hussain)
Candidate

Thesis Title	Assessment of Genotype × Management Interaction to Enhance Rice Productivity in Southern Thailand
Author	Mr. Tajamul Hussain
Major Program	Plant Science
Academic Year	2021

ABSTRACT

Rice is a major cereal crop, is a staple food, and is the source of calories, protein, and nutrients and significantly contributes to the dietary needs in Thailand. Seasonal variations in weather patterns caused by climate change and increased intensity of drought intervals have impacted rice production potential in Thailand. In addition, antiquated production technology, improper agronomic management and traditional farming practices adopted by farmers led to decline in rice production. Objectives of the two years experimental study aimed at contributing for stable, sustainable, and profitable rice production in Thailand comprised of, i) identification of drought tolerance in lowland rice, and ii) agronomic management of nitrogen (N) fertilization according to planting date (PD) for upland rice. Genotypes including Look Pla, Pathum Thani−1, Hom Pathum, Dum Ja, Sang Yod, and Lep Nok were identified as local lowland drought stress tolerant genotypes that can be recommended in drought prone lowland areas to stabilize rice productivity and can be used for further research in rice breeding program for exploring desired traits. Strong associations of stress response indices including GMP, STI, M_{PRO} and M_{HAR} with grain yield under well−watered and terminal water stress conditions, indicated that these indices could be used as rapid identifiers to indicate stress tolerance in rice crop breeding program.

Ideal agronomic management for identification of optimal N fertilizer rate (NFR) synchronized with ideal PD is an important strategy to enhance resource use efficiency and productivity of upland rice. Results indicated that N application enhanced upland rice performance and productivity and fertilization of 90 kg N ha^{-1} at PD2 (end of September or start of October) improved the yields and performance of yield attributes, enhanced straw N and grain N content and total plant N uptake as well as improved crop water productivity. Nitrogen fertilization increased profitability and application of 90 kg N ha^{-1} resulted in maximum profit at all PD. Based on the results, it was suggested that 90 kg N ha^{-1} should be applied, and upland rice should be planted at the end of September or the start of October for enhancing resource use efficiency, improving productivity, and maximum profitability. Furthermore, since a linear relationship between NFR, agronomic traits of upland rice, N uptake and crop water productivity was observed, and a significant seasonal effect indicated, long–term field investigations considering a range of NFR and adoption of forecasting measures *i.e.*, rainfall forecasting and yield prediction using crop simulation and modeling techniques to adjust seasonal planting dates are recommended for upland rice cultivation in Thailand.

Keywords: Rice, Drought stress tolerance, Stress indices, Nitrogen use efficiency, Productivity, Profitability

Acknowledgements

All the admires are for ALMIGHTY GOD (The Most Merciful, and The Most Beneficent), Who bestowed me potential for the successful completion of this task. I pay my humble gratitude to Holy Prophet MUHAMMAD (Peace Be upon Him), Who is forever a model of guidance and minaret of knowledge for humanity.

I deem it my utmost pleasure to express my gratitude to my honorable supervisor, Asst. Prof. Dr. Saowapa Duangpan, for generous transfer of knowledge, and enlightened supervision during the whole study period. I am deeply grateful to my co–advisors Assoc. Prof. Dr. Charassri Nualsri and Assoc. Prof. Dr. Mukhtar Ahmed, for their inspiration, and great support to accomplish this work. I would like to express my deepest gratitude to my family, colleagues and friends for great moral support and help to overcome difficulties and complete this research.

I acknowledge Faculty of Natural Resources and Graduate School, Prince of Songkla University for providing scholarship through Thailand Education Hub scholarship program along with partial research support. I am thankful to Agrotechnology Innovation Center, Universitas Gadjah Mada (UGM) for providing scholarship for summer school held at UGM in Indonesia and Food Security Center of the University of Hohenheim, Germany in providing scholarship grant for summer school held at SEARCA Headquarters, Philippines. I would like to acknowledge CLIFF–GRADS program of CGIAR on CCAFS and GRA for providing research award, administrated through Ryan Institute of National University of Ireland Galway (NUI Galway) and Dr. Hero T. Gollany for hosting me at U.S. Department of Agriculture–Agricultural Research Service (USDA–USA).

Tajamal Hussain

Relevance, Importance and Application of Research Work to Thailand

The purpose of this Doctor of Philosophy Thesis in Plant Science is to obtain research evidence and contribute to stable, sustainable, and profitable rice production in Thailand. Seasonal variations in weather patterns caused by climate change and increased intensity of drought intervals have impacted rice production potential in Thailand. In addition, antiquated production technology, improper agronomic management and traditional farming practices adopted by farmers led to decline in rice productivity in Thailand. Local lowland drought stress tolerant genotypes were identified that can be recommended in drought prone lowland areas and can be used for further research in rice breeding program for exploring desired traits. Nitrogen uptake, nitrogen use efficiency, crop water productivity, grain production and profitability were evaluated for upland rice. Hence, the results can be used to enhance resource use efficiency, productivity, and profitability of upland rice.

Obtained research evidence can be used for various recommendations at farmer fields for stable, sustainable, and profitable rice production in Thailand. Results provide valuable research base for future assessments and are useful to be considered for recommendations by various research institutes and government and non−government organizations in Thailand *i.e.*,

- Regional Rice Research Institutes
- Division of Rice Research Development (DRRD)
- Department of Agriculture (DOA)
- Office of Agricultural Economics (OAE)
- Ministry of Agriculture and Cooperatives
- Agricultural Research Development Agency (ARDA)

CONTENTS

Title **Pages**

List of Tables

List of Figures

List of Publications

This thesis is based on the following papers, referred to their Roman numericals in the text. The publications are attached as appendices. Reprints are made with the permission of respective publishers.

Paper I **Hussain, T.**, Hussain, N., Ahmed, M. Nualsri, C. and Duangpan, S. 2021. Responses of Lowland Rice Genotypes under Terminal Water Stress and Identification of Drought Tolerance to Stabilize Rice Productivity in Southern Thailand. *Plants*. **10:** 2565.
doi:10.3390/plants10122565.
(Reprinted with the permission from *Plants* journal)

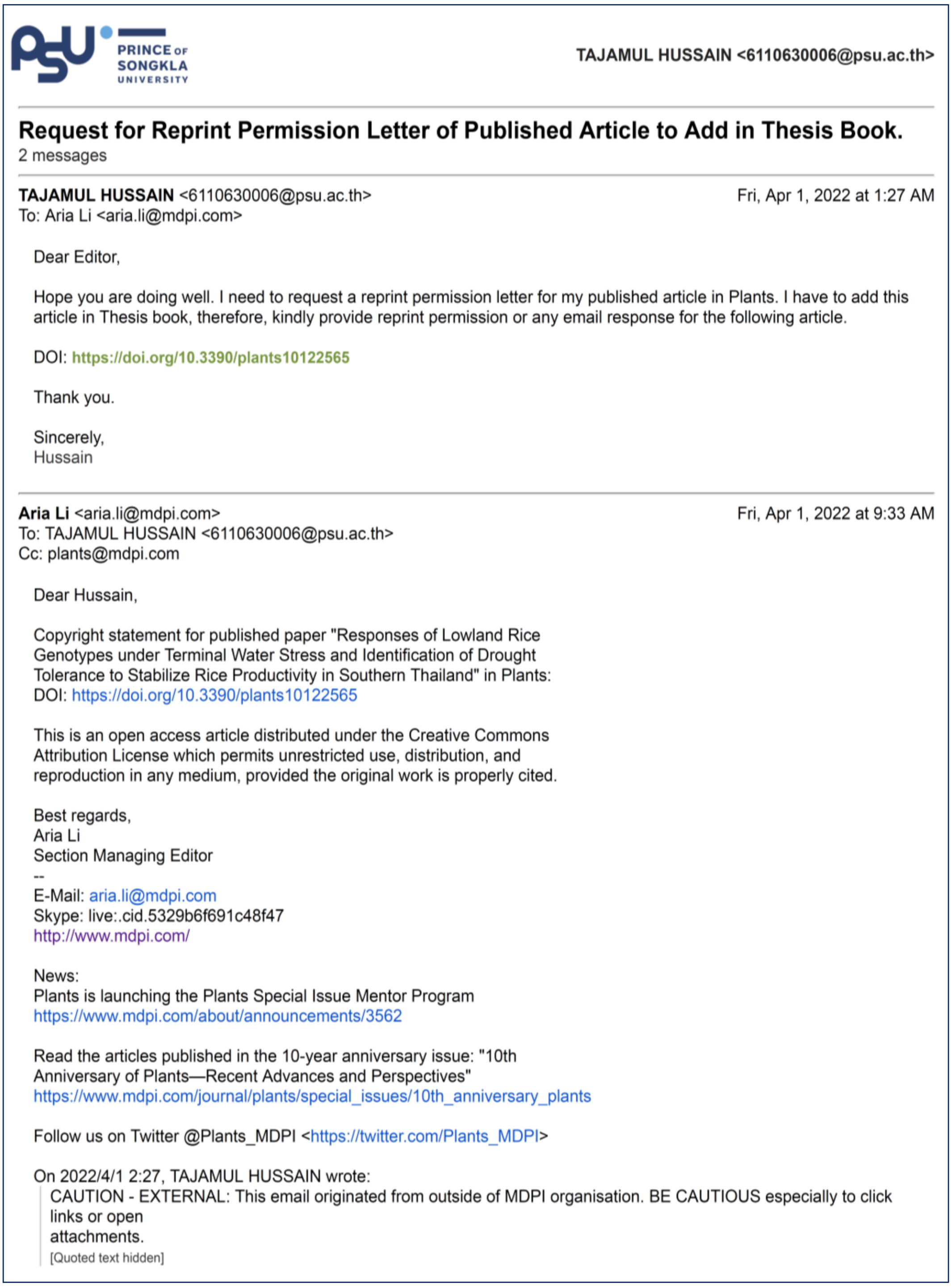
Paper II **Hussain, T.**, Hussain, N., Ahmed, M. Nualsri, C. and Duangpan, S. 2022. Impact of Nitrogen Application Rates on Upland Rice Performance, Planted under Varying Sowing Times. *Sustainability*. **14:** 1997. *doi:10.3390/su14041997*.
(Reprinted with the permission from *Sustainability* journal)

Paper III **Hussain, T.**, Gollany, H.T., Hussain, N., Ahmed, M. Tahir, M. and Duangpan, S. 2022. Synchronizing Nitrogen Fertilization and Planting Date to Improve Resource Use Efficiency, Productivity and Profitability of Upland Rice. *Frontiers in Plant Science*. **13:** 895811. *doi:10.3389/fpls.2022.895811*.
(This manuscript is accepted in *Frontiers in Plant Science* journal)

Reprints were made with permission from the publishers

Paper I

Reprinted with permission of *Plants* Journal



TAJAMUL HUSSAIN <6110630006@psu.ac.th>

Request for Reprint Permission Letter of Published Article to Add in Thesis Book.
2 messages

TAJAMUL HUSSAIN <6110630006@psu.ac.th> Fri, Apr 1, 2022 at 1:27 AM
To: Aria Li <aria.li@mdpi.com>

Dear Editor,

Hope you are doing well. I need to request a reprint permission letter for my published article in Plants. I have to add this article in Thesis book, therefore, kindly provide reprint permission or any email response for the following article.

DOI: **https://doi.org/10.3390/plants10122565**

Thank you.

Sincerely,
Hussain

Aria Li <aria.li@mdpi.com> Fri, Apr 1, 2022 at 9:33 AM
To: TAJAMUL HUSSAIN <6110630006@psu.ac.th>
Cc: plants@mdpi.com

Dear Hussain,

Copyright statement for published paper "Responses of Lowland Rice Genotypes under Terminal Water Stress and Identification of Drought Tolerance to Stabilize Rice Productivity in Southern Thailand" in Plants:
DOI: https://doi.org/10.3390/plants10122565

This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Best regards,
Aria Li
Section Managing Editor
--
E-Mail: aria.li@mdpi.com
Skype: live:.cid.5329b6f691c48f47
http://www.mdpi.com/

News:
Plants is launching the Plants Special Issue Mentor Program
https://www.mdpi.com/about/announcements/3562

Read the articles published in the 10-year anniversary issue: "10th Anniversary of Plants—Recent Advances and Perspectives"
https://www.mdpi.com/journal/plants/special_issues/10th_anniversary_plants

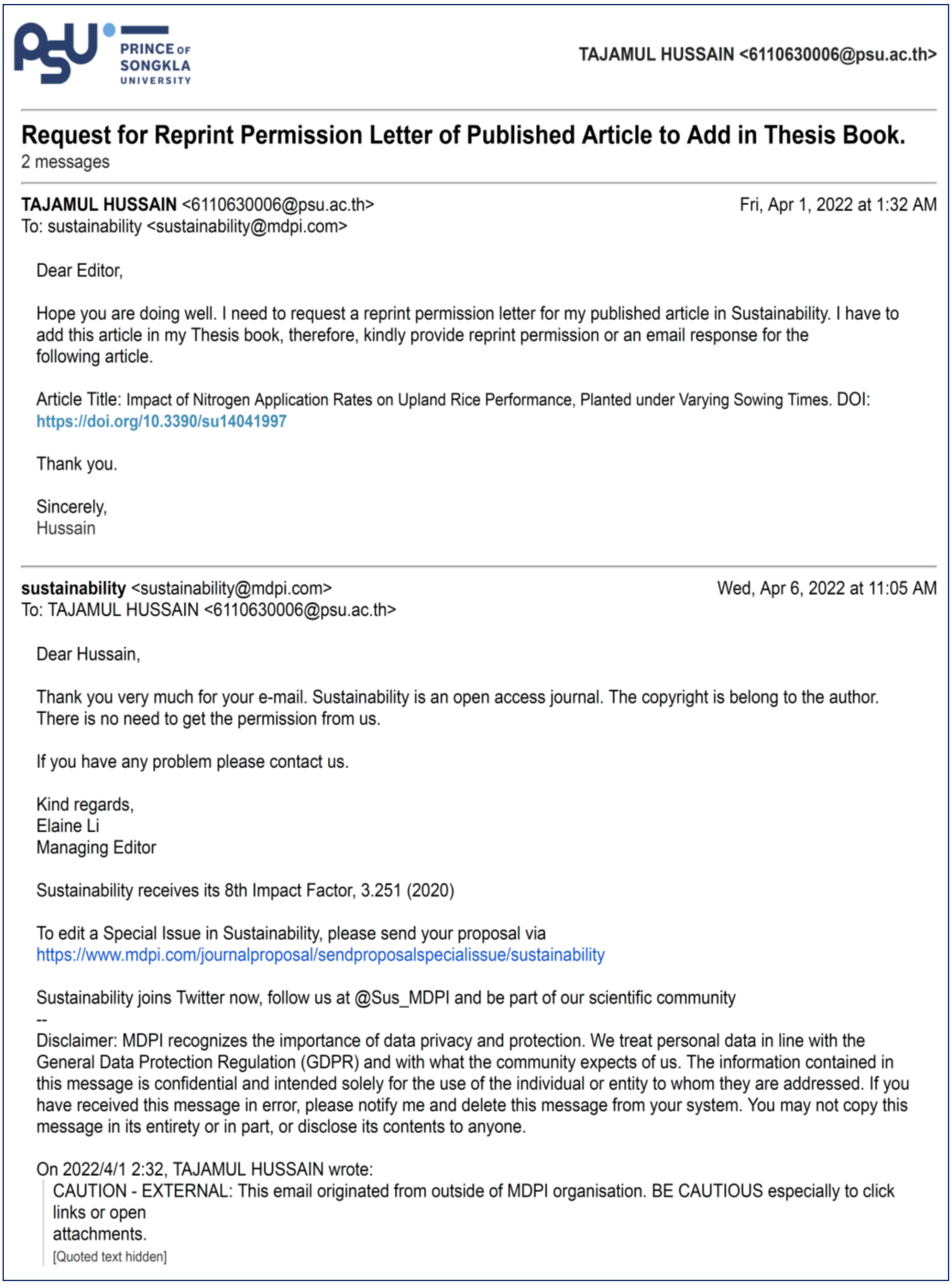
Follow us on Twitter @Plants_MDPI <https://twitter.com/Plants_MDPI>

On 2022/4/1 2:27, TAJAMUL HUSSAIN wrote:

> CAUTION - EXTERNAL: This email originated from outside of MDPI organisation. BE CAUTIOUS especially to click links or open
> attachments.
> [Quoted text hidden]

Paper II

Reprinted with permission of *Sustainability* Journal



TAJAMUL HUSSAIN <6110630006@psu.ac.th>

Request for Reprint Permission Letter of Published Article to Add in Thesis Book.
2 messages

TAJAMUL HUSSAIN <6110630006@psu.ac.th> Fri, Apr 1, 2022 at 1:32 AM
To: sustainability <sustainability@mdpi.com>

Dear Editor,

Hope you are doing well. I need to request a reprint permission letter for my published article in Sustainability. I have to add this article in my Thesis book, therefore, kindly provide reprint permission or an email response for the following article.

Article Title: Impact of Nitrogen Application Rates on Upland Rice Performance, Planted under Varying Sowing Times. DOI: https://doi.org/10.3390/su14041997

Thank you.

Sincerely,
Hussain

sustainability <sustainability@mdpi.com> Wed, Apr 6, 2022 at 11:05 AM
To: TAJAMUL HUSSAIN <6110630006@psu.ac.th>

Dear Hussain,

Thank you very much for your e-mail. Sustainability is an open access journal. The copyright is belong to the author. There is no need to get the permission from us.

If you have any problem please contact us.

Kind regards,
Elaine Li
Managing Editor

Sustainability receives its 8th Impact Factor, 3.251 (2020)

To edit a Special Issue in Sustainability, please send your proposal via
https://www.mdpi.com/journalproposal/sendproposalspecialissue/sustainability

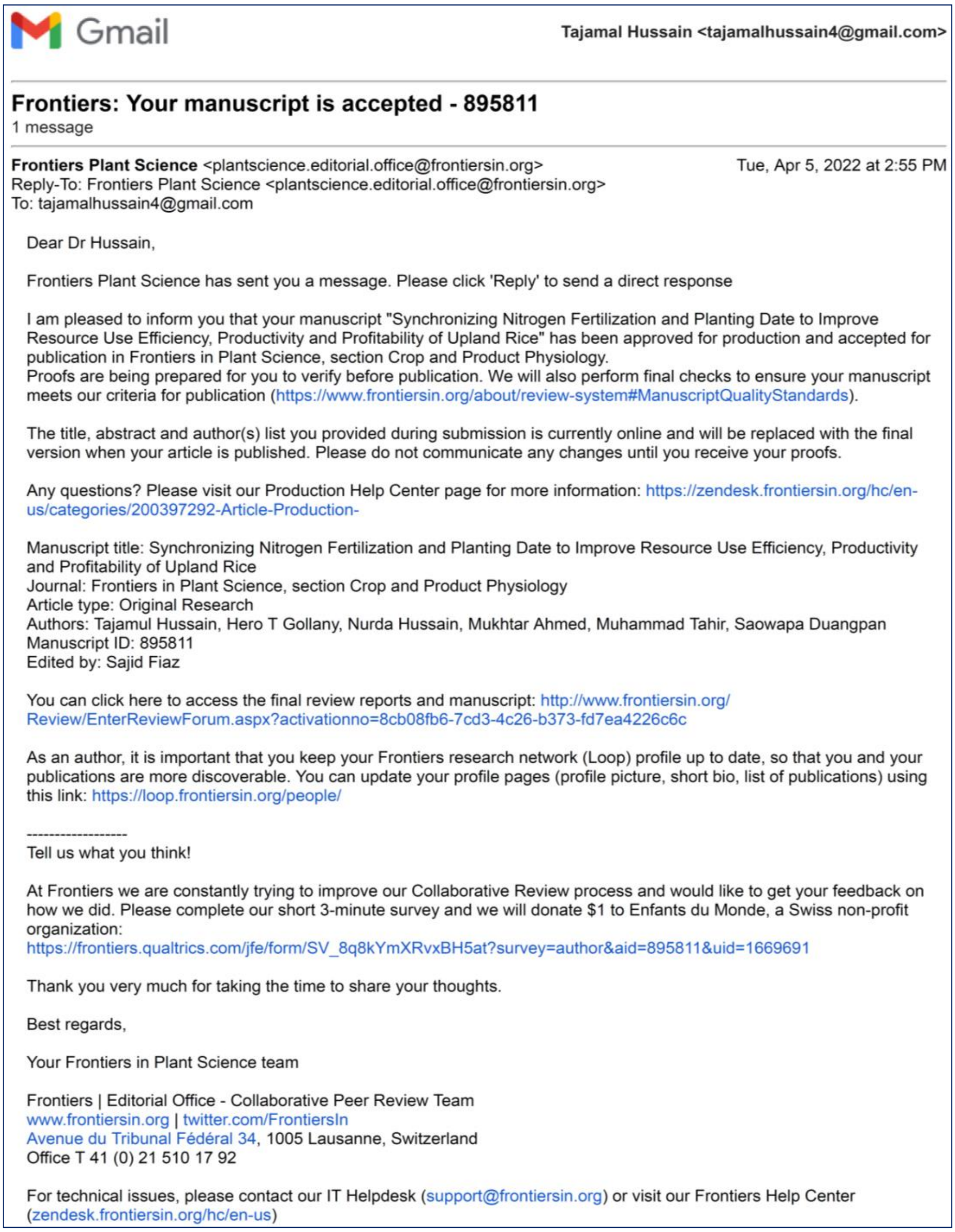
Sustainability joins Twitter now, follow us at @Sus_MDPI and be part of our scientific community
--
Disclaimer: MDPI recognizes the importance of data privacy and protection. We treat personal data in line with the General Data Protection Regulation (GDPR) and with what the community expects of us. The information contained in this message is confidential and intended solely for the use of the individual or entity to whom they are addressed. If you have received this message in error, please notify me and delete this message from your system. You may not copy this message in its entirety or in part, or disclose its contents to anyone.

On 2022/4/1 2:32, TAJAMUL HUSSAIN wrote:

> CAUTION - EXTERNAL: This email originated from outside of MDPI organisation. BE CAUTIOUS especially to click links or open
> attachments.
> [Quoted text hidden]

Paper III

This manuscript is accepted in *Frontiers in Plant Science* journal



Tajamal Hussain <tajamalhussain4@gmail.com>

Frontiers: Your manuscript is accepted - 895811

1 message

Frontiers Plant Science <plantscience.editorial.office@frontiersin.org> Tue, Apr 5, 2022 at 2:55 PM
Reply-To: Frontiers Plant Science <plantscience.editorial.office@frontiersin.org>
To: tajamalhussain4@gmail.com

Dear Dr Hussain,

Frontiers Plant Science has sent you a message. Please click 'Reply' to send a direct response

I am pleased to inform you that your manuscript "Synchronizing Nitrogen Fertilization and Planting Date to Improve Resource Use Efficiency, Productivity and Profitability of Upland Rice" has been approved for production and accepted for publication in Frontiers in Plant Science, section Crop and Product Physiology.
Proofs are being prepared for you to verify before publication. We will also perform final checks to ensure your manuscript meets our criteria for publication (https://www.frontiersin.org/about/review-system#ManuscriptQualityStandards).

The title, abstract and author(s) list you provided during submission is currently online and will be replaced with the final version when your article is published. Please do not communicate any changes until you receive your proofs.

Any questions? Please visit our Production Help Center page for more information: https://zendesk.frontiersin.org/hc/en-us/categories/200397292-Article-Production-

Manuscript title: Synchronizing Nitrogen Fertilization and Planting Date to Improve Resource Use Efficiency, Productivity and Profitability of Upland Rice
Journal: Frontiers in Plant Science, section Crop and Product Physiology
Article type: Original Research
Authors: Tajamul Hussain, Hero T Gollany, Nurda Hussain, Mukhtar Ahmed, Muhammad Tahir, Saowapa Duangpan
Manuscript ID: 895811
Edited by: Sajid Fiaz

You can click here to access the final review reports and manuscript: http://www.frontiersin.org/Review/EnterReviewForum.aspx?activationno=8cb08fb6-7cd3-4c26-b373-fd7ea4226c6c

As an author, it is important that you keep your Frontiers research network (Loop) profile up to date, so that you and your publications are more discoverable. You can update your profile pages (profile picture, short bio, list of publications) using this link: https://loop.frontiersin.org/people/

Tell us what you think!

At Frontiers we are constantly trying to improve our Collaborative Review process and would like to get your feedback on how we did. Please complete our short 3-minute survey and we will donate $1 to Enfants du Monde, a Swiss non-profit organization:
https://frontiers.qualtrics.com/jfe/form/SV_8q8kYmXRvxBH5at?survey=author&aid=895811&uid=1669691

Thank you very much for taking the time to share your thoughts.

Best regards,

Your Frontiers in Plant Science team

Frontiers | Editorial Office - Collaborative Peer Review Team
www.frontiersin.org | twitter.com/FrontiersIn
Avenue du Tribunal Fédéral 34, 1005 Lausanne, Switzerland
Office T 41 (0) 21 510 17 92

For technical issues, please contact our IT Helpdesk (support@frontiersin.org) or visit our Frontiers Help Center (zendesk.frontiersin.org/hc/en-us)

1. Introduction

Rice is an important cereal after wheat that contributes to food security worldwide (FAO, 2020). Rice is grown under various ecosystems including irrigated, lowlands and uplands. However, lowland rainfed and lowland irrigated systems are major rice production systems (Varinruk, 2017) representing 6.2 and 4.1 million hectares of production area, respectively (USDA, 2015). Upland rice acreage contributes 9% in Asia (Nascente et al., 2019). Thailand is the sixth largest producer of rice worldwide and the second largest in Southeast Asia (FAO, 2020). Rice plays a key role in Thailand’s economy and food security (Ullah et al., 2019). According to USDA (2015), major rice production in Thailand is in northern, central, and north–eastern regions, whereas Southern Thailand contributes 6% of the cultivated rice area (GRiSP, 2013, Hussain et al., 2021a). Like other regions, lowland rice contributes to major rice production in Southern Thailand, but the cultivated area is limited due to geographic limitations. Upland rice is grown in rainfed conditions (Kumar and Ladha, 2011) and it is cultivated by small land holders during rainy seasons in Southern Thailand (Hussain et al., 2021a). However, rainfed rice production in upland and lowland systems is extremely vulnerable and variable in nature as water stress can occur at any crop growth stages. Climate change has also caused an increase in temperature fluctuations and variability in rainfall occurrence leading to regular heat and drought stress intervals (Ullah et al., 2019, Mansour et al., 2021) which has impacted rice productivity in Thailand.

Water stress is considered an important abiotic stress deleteriously affecting field crop productivity (Ray et al., 2019, Mansour et al., 2021). Due to seasonal variations in rainfall and occurrence of water stress at different crop developmental stages, rice production is drastically affected. Occurrence of water stress at various crop growth stages negatively influences the performance of specific attributes (Ahmadikhah, 2016), leading to declined yield (Zhou et al., 2007). Timing of stress occurrence during early growth, mid−season and at terminal crop stages impact on severity of yield losses (Fischer et al., 2003). Water availability after the stress interval at the early growth stage helps plants recover, leading to lesser loss in yield. However, terminal water stress (TWS) intervals highly influence plant performance and lessens the chances of recovery to occur, leading to increased yield losses as rice is extremely sensitive to TWS (Agarwal et al., 2016). TWS delays various plant development stages including panicle initiation and flowering (Rahman et al., 2002), leading to spikelet sterility and reduction in number of panicles (Yue et al., 2006). In addition, TWS causes abortion of ovules, deteriorates the grain filling process and alters source to sink distribution of assimilates, leading to reduced grain yield (GY) (Ovenden et al., 2017). Stress−tolerant genotypes are genotypes that have the potential to maintain higher productivity under water stress (Farooq et al., 2010). Due to the extreme sensitivity of rice to TWS, different rice genotypes exhibit differential responses (Chutia and Borah, 2012). The GY of stress−tolerant genotypes is less affected under water stress as compared to stress susceptible genotypes. High yielding genotypes under a diverse range of environments are desired and the cultivation of such genotypes could help to maintain rice productivity (Ichsan et al., 2020). Hence, the identification of stress tolerant genotypes from local germplasm is necessary to stabilize productivity under terminal water stressed environments.

Stable upland rice production is a significant factor to meet increasing demand and ensuring food security. Climate change has affected rice production due to changes in seasonal variability in rainfall and increases in average temperature. In this scenario, maintaining a higher yield per unit area is a primary objective of upland rice production systems. Upland rice productivity is low especially in Thailand due to various factors, including seasonal weather patterns and traditional agronomic management practices. In comparison to climatic factors including air temperature, rainfall, solar radiation, soil moisture, insect, pests and weeds, planting time (Ferrari et al., 2018), and nitrogen (N) fertilization management are the factors that are highly associated with yields and are easy for farmers to adjust and manipulate. Nitrogen is a critical nutrient that affects crop growth (Santiago−Arenas et al., 2021) hence significantly influencing crop productivity. Nitrogen deficiency in rice plants causes yellowing of leaves, reduces leaf size, and leads to low productivity, whereas excessive N fertilization results in agronomic and economic losses. Therefore, it becomes imperative that a sufficient and optimum N dose be applied to obtain stable grain production. In northern areas of Thailand, the application of 10–75 kg N ha^{-1} by farmers in upland rice fields was reported in a survey conducted by Chiang Mai University, Thailand (CARSR, 2003). Different NFR have been observed as N fertilization of 61.25 kg N ha^{-1} (Suwanasa et al., 2018), 61.25 kg N ha^{-1} (Hussain et al., 2018a), 61.25 kg N ha^{-1} (Hussain et al., 2018b), and a basal fertilization of 15 kg N ha^{-1} (Islam et al., 2020) in upland rice farming in southern Thailand. Corresponding to the Division of Rice Research and Development (DRRD) of Thailand (DRRD, 2016; Norsuwan et al., 2020), 48.75–82.5 kg N ha^{-1} based on soil N status, was recommended to use as N fertilization management in rice production. In addition to this, DRRD advised applying 40–45 kg N ha^{-1} in splits including 20–45 kg N ha^{-1} as basal dose and remaining dose before heading stage for foothill rice areas (DRRD, 2017). Fertilization of 34–39 kg N ha^{-1} for photoperiod–sensitive and 59–69 kg N ha^{-1} for photoperiod–insensitive was recommended based on the photoperiod sensitivity of rice cultivars in Songkhla province (experimental area) of Thailand. Variable range of N fertilization prevailed in Thailand and no specific or optimum recommendations have been observed according to different planting times for upland rice production. Therefore, farmers usually practiced fertilization of 10–75 kg N ha^{-1} in upland rice fields.

Ideal planting date is a useful agronomic management factor for upland rice, which can ensure maximum use of climatic contributors (*i.e.,* photosynthetic radiation, favorable temperature, and precipitation). Planting dates affect rice productivity as soil water status and environmental conditions differ over time. Upland rice is grown during the rainy season in Thailand (Hussain et al., 2018b), and rainy season lasts from May till October (Limsakul and Singhruck, 2016; Ullah et al., 2019). High variability prevails in the climate of Thailand, and most rain in the east of southern Thailand occurs from November to February of the subsequent year (Limsakul and Singhruck, 2016). Farmers in Thailand perform early or delayed upland rice planting depending on soil water availability. Upland rice planted too early or late are affected by hot and dry intervals when the rice is at reproductive stages. Too early or delayed planting results in high plant sterility, with the numbers of effective tillers are reduced (Nazir, 1994). Grain productivity is also decreased due to incomplete development of yield contributing traits at different crop growth phases. The yield potential of a cultivar depends upon tillering occurred at vegetative stages and panicle density achieved at panicle formation stages. Unsuitable planting dates and less precipitation at the reproductive stage of upland rice results in higher yield losses (Hussain et al., 2018b). Planting photosensitive upland cultivars in southern Thailand (Watcharin et al., 2020) is another critical aspect affecting upland rice productivity. Recommendation of development and cultivation of photoperiod insensitive upland rice cultivars to stabilize rice productivity (Watcharin et al., 2020) also threatened due to the impact of climate change as climate change has resulted in high rainfall variability and increased drought occurrence (Ullah et al., 2019; Mansour et al., 2021). In this scenario, photoperiod insensitive cultivars will also be affected due to seasonal variations in rainfalls, which cause drought or flood incidents leading to reduced N availability or removal of N from soil surface in high rainfall events, respectively. Farmers are applying supplementary irrigation to upland rice during hot and dry intervals increases the input cost, and crop water productivity is affected.

Traditional agronomic practices for N fertilization, general recommendation rates, and prevalence of wide planting windows have led to increased vulnerability of upland rice production. To the best of our knowledge, field evaluations for identifying suitable NFR alone or synchronized with ideal planting dates have not been conducted for upland rice production in Thailand. Therefore, it was necessary to determine upland rice responses to NFR and planting dates. We hypothesized that adjusting planting date and application of suitable N rate synchronized with planting date assures improved resource use efficiency, enhances productivity, and maximizes profitability of upland rice production.

2. Objectives of Research

The purpose of this study was the assessment of genotype (G), and management (M) interaction to stabilize and enhance rice productivity in Southern Thailand which consisted of following two objectives.

2.1. Objective I

Responses of lowland rice genotypes under terminal water stress (TWS) and identification of drought tolerance and promising stress response indices

2.2. Objective II

Synchronizing nitrogen fertilization and sowing time / planting date to enhance resource use efficiency, productivity, and profitability of upland rice

3. Results and Discussion

3.1. Objective I:

Responses of Lowland Rice Genotypes under Terminal Water Stress (TWS) and Identification of Drought Tolerance and Promising Stress Response Indices

3.1.1. Effect of Terminal Water Stress on Yield Performance and Productivity

Different lowland rice genotypes were assessed based on the performance of yield and yield attributes in response to terminal water stress (TWS) applied at the terminal crop growth stage. In both years, treatment and genotype effect resulted as highly significant different ($p < 0.001$) for most of the yield attributes except a non−significant difference for days to maturity (DM) under treatment effect in 2018–19 (Table 1). Interactions of genotype and treatment effects indicated non−significant differences in both years, except for a significant difference for days to flowering (DF) ($p < 0.05$) and a highly significant difference for DM ($p < 0.001$) in 2018–19 (Table 1). DF, number of tillers (NT), number of panicles (NP), grain yield (GY) and biomass were highly significant different. Mean comparisons indicated that all tested genotypes differed and a significant variability in performance prevailed under well−watered (WW) and TWS conditions.

Terminal water stress resulted in a delay in flowering duration (Figure 1 a, b: Paper I) of all genotypes except genotype 9 in the first year (Figure 1a: Paper I). Flowering occurred 4 days earlier in genotype 9 (Table 2). Delay in flowering duration ranged 2−19 days in the first year while 1−4 days in the second year (Table 2). The maximum delay in flowering was observed for the top three genotypes 7, 12 and 6 by 19, 8 and 6 days in the first year and for 11, 8, 3, 4 and 5 by 7 and 4 days in the second year, respectively. TWS caused delays in the maturity duration (Figure 1 c, d: Paper I) of most of the genotypes except for genotypes 7, 9 and 10 in the first year (Figure 1a: Paper I). Genotypes 7, 9 and 10 matured earlier in the first year by 19, 5 and 11 days (Table 2). In the second year, maturity duration was increased for all genotypes under TWS (Figure 1d: Paper I). The delay in maturity duration ranged 4−14 days in the first year while 3−8 days in the second year (Table 2). Generally, in our study, DF and DM were increased and were significantly positive and strongly correlated. TWS caused delay in panicle emergence; hence, delaying the flowering time of most of genotypes. Delayed flowering in rice was also observed under water stress by Davatgar et al. (2009), Saikumar et al. (2016) and Hussain et al. (2018). Late flowering in rice under TWS is considered as a common impact of TWS (Zhao et al., 2010). Delayed panicle emergence and longer grain filling duration increased the time to maturity, thus increasing the total irrigation water input under TWS (Figure 1). All genotypes consumed more water input under delayed maturity under TWS after resuming irrigation.

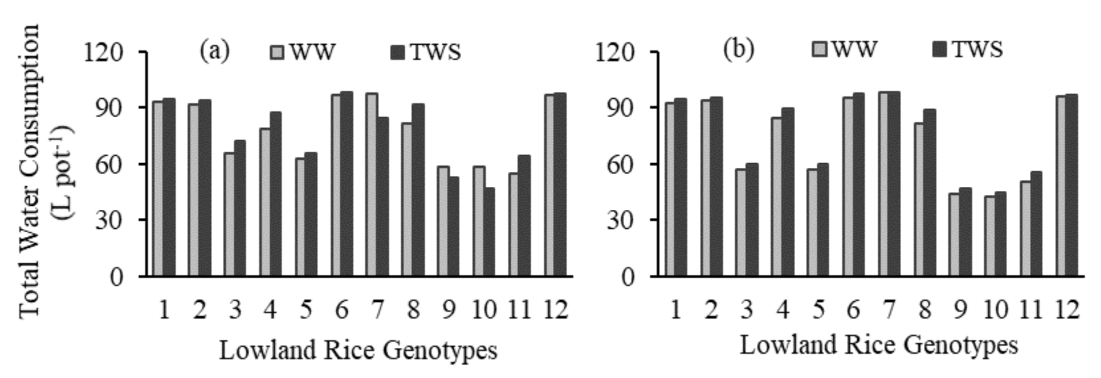


Figure 1. Total amount of irrigation water consumed by lowland rice genotypes under well−watered (WW) and terminal water−stressed (TWS) conditions during 2018−19 (a) and 2019−20 (b).

Plant height was reduced under TWS for all genotypes in both years (Figure 1 e, f: Paper I). PH was reduced 4−13% in the first year and 2−14% in the second year (Table 2). Reduction in PH was higher than 10% for genotypes 1, 2, 4, 7, 8 and 11 (Table 2). PH was decreased for all genotypes possibly due to limited water availability resulting in reduced cell elongation. Reduction in the PH of rice genotypes under water stress has been reported in numerous studies (Davatgar et al., 2009, Saikumar et al., 2016, Anantha et al., 2016, Hussain et al., 2018, Torres et al., 2018). NT (Figure 2 a, b: Paper I) and NP (Figure 2 c, d: Paper I) were reduced under TWS. However, reduction in NT and NP ranged one−two tillers and panicles per plant (Table 2). No change was observed in NT of genotypes 1, 5 and 6 in the first year and genotypes 2, 5, 6, 8, 9 and 10 in the second year (Table 2). Genotypes 1 and 3 maintained their NP under TWS in the first year, whereas the NP of all genotypes were affected in the second year (Table 2). NT and NP were reduced for all genotypes under TWS in both years. Increase in tiller mortality with increased duration of water stress has been reported by Zain et al. (2014). According to Davatgar et al. (2009), water stress at terminal crop stages alters the source to sink association, which results in a reduced number of panicles. NT and NP were highly correlated, which indicated that more tillers produced more panicles.

Terminal water stress caused decline in GY (Figure 3 a, b: Paper I) and biomass (Figure 3 c, d: Paper I) of all genotypes in both years. GY was decreased 17−45% in the first year, whereas 21−52% in the second year (Table 2). The GY of genotypes 1, 7, 9, 11 and 12 in the first year and GY of genotypes 2, 9, 11 and 12 in the second year decreased more than 30%, indicating a major decline in GY under TWS (Table 2). Similarly, biomass was reduced 20−41% in the first year and

15−38% in the second year (Table 2). Biomass reduction of genotypes 4 and 12 in the first year and genotypes 1, 3 and 10 in the second year was more than 30%, indicating a major decline in biomass under TWS (Table 2). Stress induced at the terminal stage significantly reduced GY and biomass of all genotypes. TWS increases spikelet sterility and reduced grain weight resulting in declined final GY. Reduction in final GY under various water stress levels have been reported in several studies (Pantuwan et al., 2004, Kumar et al., 2009, Torres et al., 2013, Saikumar et al., 2016). Biomass of all genotypes was reduced under TWS. However, genotypes with higher biomass produced higher GY. Strong positive association among GY and biomass was observed, and our results were in line with the findings of Torres and Henry (2018), Torres et al. (2013) and Kumar et al. (2009). High variability among genotypes for their performance of yield and yield attributes indicated that the genotypes could be used in the rice crop breeding program to exploit specific plant attributes such as early maturity, shorter plant height, higher tillering capacity and better GY under TWS for improvement in drought tolerance.

Table 1. The analysis of variance for days to flowering (DF), days to maturity (DM), plant height (PH), number of tillers (NT), number of panicles (NP), grain yield (GY) and biomass (BM) of twelve lowland rice genotypes.

Year	**Traits**	**Treatment (T) Effect**	**Genotype (G) Effect**	**Interaction (T × G)**
2018–19	DF	***	***	*
	DM	ns	***	***
	PH	***	***	ns
	NT	***	***	ns
	NP	***	***	ns
	GY	***	***	ns
	BM	***	***	ns
2019–20	DF	***	***	ns
	DM	***	***	ns
	PH	***	***	ns
	NT	**	***	ns
	NP	***	***	ns
	GY	***	***	ns
	BM	***	***	ns

***: highly significant ($p < 0.001$), **: moderately significant ($p < 0.01$), *: significant ($p < 0.05$), ns: non−significant.

Table 2. Changes in performance of yield and yield attributes of twelve lowland rice genotypes under terminal water stressed conditions. Changes in days to flowering (DF) and days to maturity (DM) are presented by difference in days. Changes in number of tillers (NT) and number of panicles (NP) are presented by difference in numbers (no.), whereas changes in plant height (PH), grain yield (GY) and biomass (BM) are presented by % difference.

Year	**Genotypes**	**DF**	**DM**	**PH**	**NT**	**NP**	**GY**	**BM**
		days	**days**	**%**	**no.**	**no.**	**%**	**%**
2018−2019	1	3	5	−9	0	0	−39	−20
	2	4	7	−10	−1	−1	−26	−24
	3	5	8	−4	1	−0	−28	−21
	4	3	10	−13	−1	−1	−18	−41
	5	2	5	−3	0	−1	−21	−21
	6	6	5	−4	0	−1	−23	−28
	7	4	−19	−11	−1	−1	−31	−20
	8	19	14	−8	−1	−1	−17	−25
	9	−4	−5	−4	−1	−2	−30	−28
	10	2	−11	−8	−1	−1	−26	−26
	11	3	11	−11	−1	−1	−45	−29
	12	8	4	−5	−1	−1	−36	−38
2019−2020	1	3	7	−10	−1	−1	−25	−38
	2	3	4	−12	0	−1	−43	−20
	3	4	4	−8	−2	−2	−26	−30
	4	4	6	−8	−1	−1	−26	−24
	5	4	5	−5	0	−1	−24	−19
	6	−2	8	−8	0	−1	−22	−24
	7	1	4	−10	−1	−1	−21	−23
	8	4	7	−14	0	−1	−25	−22
	9	1	4	−2	0	−1	−52	−17
	10	2	3	−6	0	−1	−36	−38
	11	7	6	−3	−1	−1	−34	−19
	12	3	3	−7	−1	−1	−33	−15

3.1.2. Association among Yield and Yield Attributes under TWS

Association among various yield and yield attributes under well−watered and terminal water stress conditions was evaluated based on computed Pearson's correlation coefficients. Associations were characterized into positive and negative, highly significant, moderately significant, significant, and non−significant associations and are indicated in Figure 2 (Figure 4: Paper I).

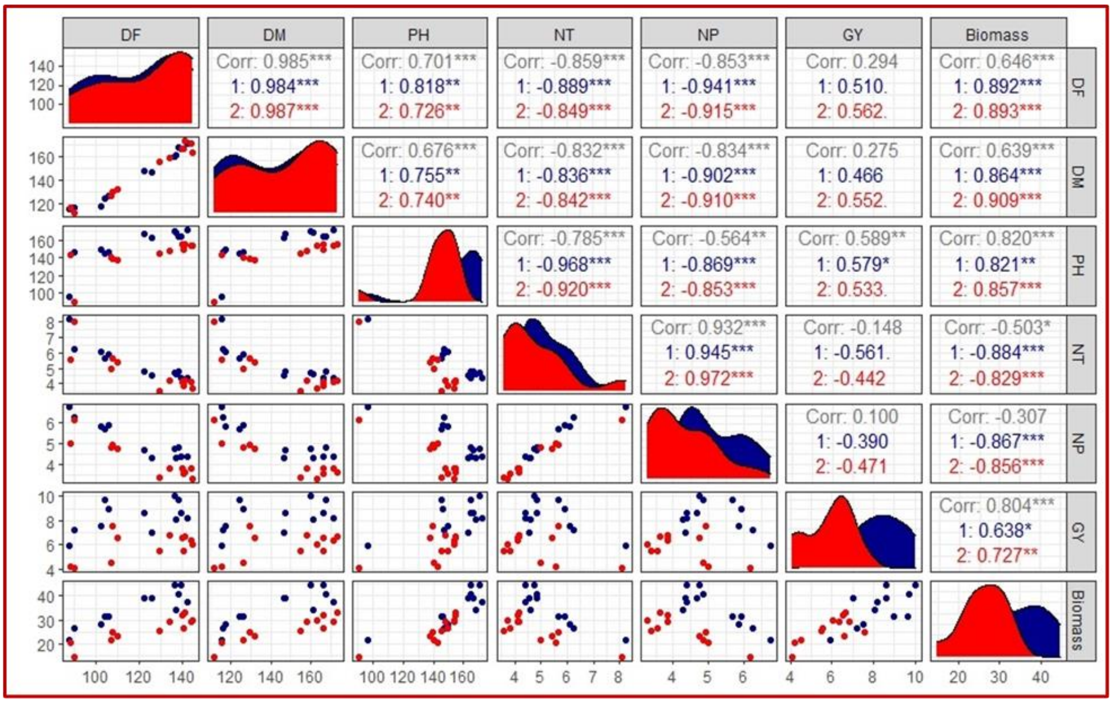


Figure 2. Combined correlation matrix, scatter plot and data distribution for yield and yield attributes of twelve lowland rice genotypes under well−watered (WW) and terminal water stressed (TWS) conditions. Diagonals indicate the distribution of each parameter. Scatter plots are shown in the bottom of diagonals. Values of correlations and significance are indicated with stars and are shown on the top of the diagonal. Values and stars in the blue color (1) indicate correlation among parameters in WW whereas, values and stars in the red color (2) indicate correlation among parameters in TWS conditions. DF: days to flowering, DM: days to maturity, PH: plant height, NT: number of tillers, PN: number of panicles, GY: grain yield, ***: highly significant ($p < 0.001$), **: moderately significant ($p < 0.01$), *: significant ($p < 0.05$).

3.1.3. Genotypic Classification Corresponding to Stress Indices

Seven stress tolerance indices, including stress susceptibility index (SSI) (1) (Fischer and Maurer, 1978), geometric mean productivity (GMP) (2) (Fernandez, 1992), stress tolerance index (STI) (3) (Fernandez, 1992), mean productivity index (M_{PRO}) (4) (Hossain et al., 1990), harmonic mean index (M_{HAR}) (5) (Schneider et al., 1997), tolerance index (TI) (6) (Rosielle and Hamblin, 1981) and yield stability index (YSI) (Bouslama and Schapaugh, 1984) were computed to distinguish stress−tolerant genotypes from stress−sensitive ones based on grain yield (GY) and relative yield (RY) and the promising values of stress indices under TWS conditions (Table 3: Paper I). In addition, stress tolerance indices were also studied for hierarchical clustering using a heatmap shown in Figure 3 (Figure 5: Paper I) and the assessed genotypes were categorized into two main groups: (1) stress tolerant and (2) stress susceptible group and four sub−groups (A−D).

Explored genotypes exhibited highly significant variability in their GY productivity under WW and TWS conditions, which demonstrated that studied genotypes possessed significant genetic variability. Genotypes were differentiated based on GY productivity, RY and performance of computed stress indices which were further categorized into stress tolerant, and stress susceptible groups based on hierarchical clustering. Subgroup A was highly stress tolerant; subgroup B was stress tolerant; subgroup C was moderately stress tolerant, whereas subgroup group D was found stress susceptible. Highly stress−tolerant genotypes indicated the highest GY, RY, and improved indices under TWS, whereas tolerant genotypes indicated higher GY, RY and better indices. However, stress−susceptible genotypes indicated lowered GY, RY, and inadequate performance for stress indices. According to GY and performance of stress indices, hierarchical clustering aided to identify similarly acting genotypes under evaluation. Highly significant and positive correlation observed among GY under WW and GY under TWS exhibited that genotypes that performed better in WW conditions also produced well under TWS. Similar findings were also reported by Raman et al. (2012).

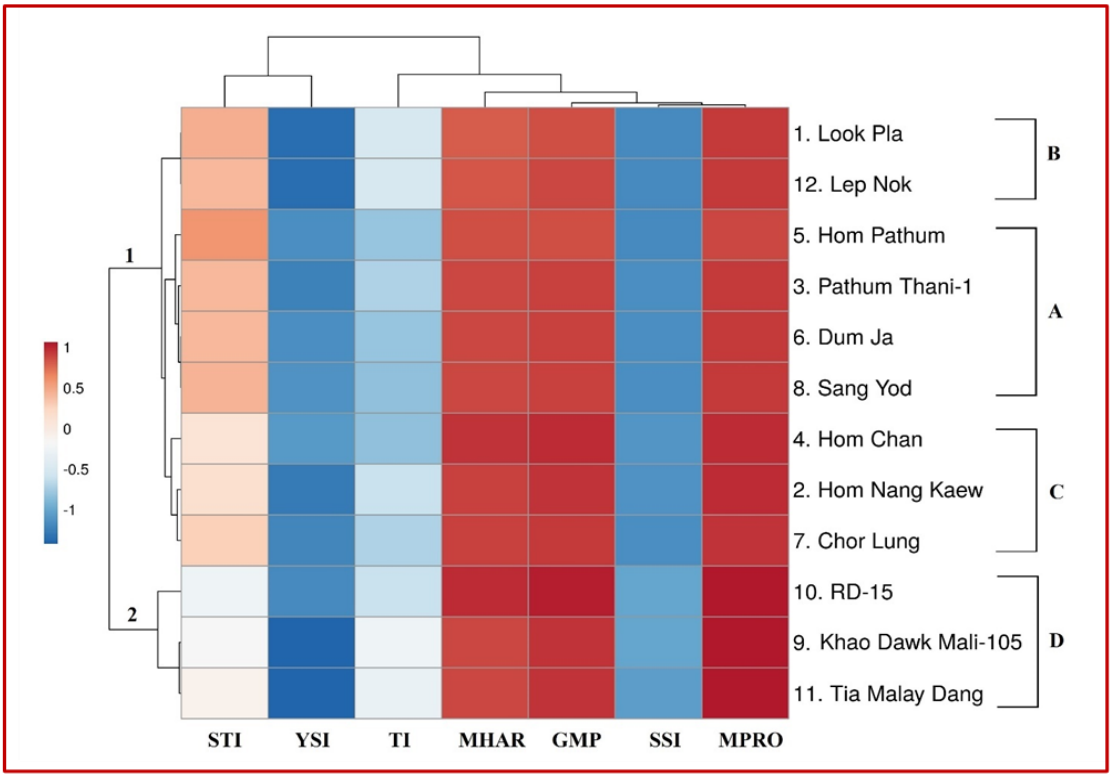


Figure 3. Heatmap of stress indices among twelve lowland rice genotypes under well−watered and terminal water stressed conditions. Group 1 refers to stress−tolerant genotypes, whereas group 2 refers to stress susceptible genotypes. Subgroup A is highly stress tolerant; subgroup B is stress tolerant; subgroup C is moderately stress tolerant, whereas subgroup group D is stress susceptible. Dark red and dark blue colors indicate higher correlation followed by light red and light blue with minimum or no correlation among genotypes and indices.

3.1.4. Association among Stress Tolerance Indices and Grain Yield

Correlation matrix (Pearson's) of grain yield under well−watered, grain yield under terminal water stress, SSI, GMP, STI, M_{PRO}, M_{HAR}, TI and YSI for lowland rice genotypes were computed by taking average values from two growing years 2018−19 and 2019−20 and are shown in Figure 4 (Figure 6: Paper I). Strongly significant and positive associations of stress indices, GMP, STI, M_{PRO}, M_{HAR} with GY under WW and TWS were observed, which indicated that GMP, STI, M_{PRO} and M_{HAR} were better performer and promising indices to evaluate rice genotypes under WW and TWS conditions. Raman et al. (2012) found that GMP and STI were suitable indices in identifying entries under non−stressed and extreme water stressed conditions. GMP has also been reported (Wasae, 2021) as a better predictor for GY under water stress when stress was applied at the flowering stage. SSI, TI and YSI were not correlated with GY under WW. SSI was negatively correlated, YSI was significant and positively correlated, whereas TI was not correlated with GY under TWS. Weak associations of SSI, TI and YSI indicated that these indices were not adequate for evaluating lowland rice genotypes under TWS. Anwar et al. (2011) also found that SSI, TI and YSI were not appropriate predictors of GY under WW and stressed conditions for evaluating wheat genotypes for drought stress tolerance. GMP, STI, M_{PRO} and M_{HAR} have been found to be suitable stress indices to evaluate genotypes under WW and stressed conditions for various crops including rice, wheat, maize and soyabean. Therefore, it was concluded that GMP, STI, M_{PRO} and M_{HAR} were appropriate indices for their use as rapid selection criteria for screening stress tolerant lowland rice genotypes grown under water stressed conditions, especially when stress is applied at reproductive or terminal crop stages.

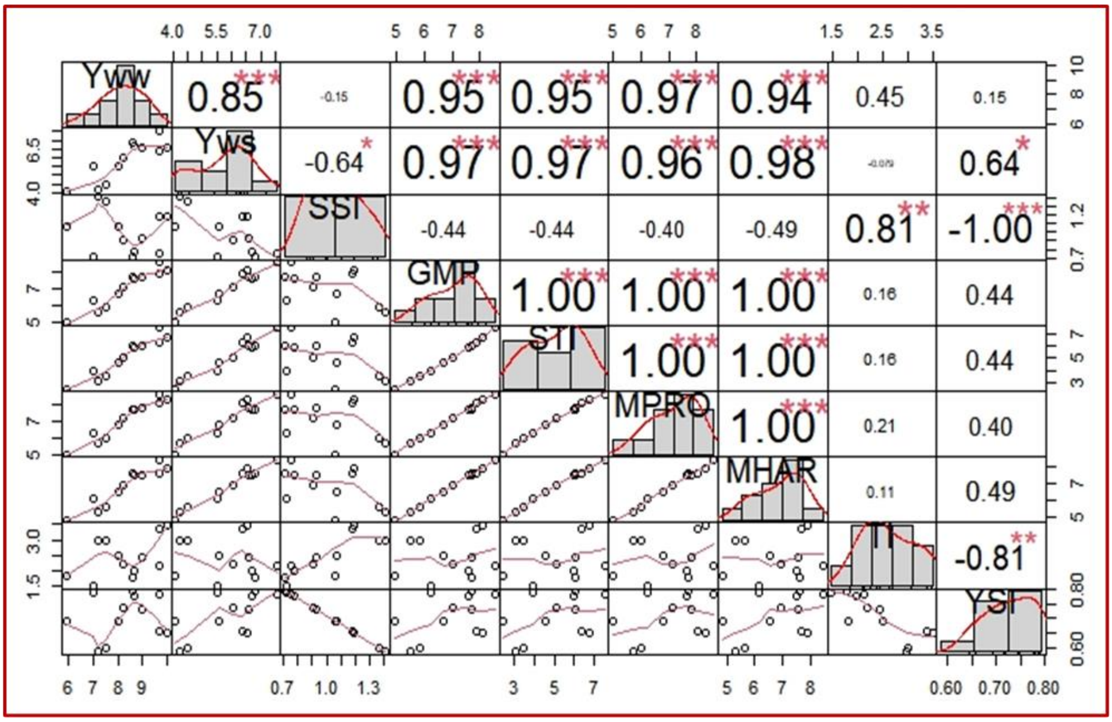


Figure 4. Correlation matrix (Pearson's) of grain yield under well−watered (Y_{WW}), grain yield under terminal water stress (Y_{WS}), stress susceptibility index (SSI), geometric mean productivity (GMP), stress tolerance index (STI), mean productivity index (M_{PRO}), harmonic mean index (M_{HAR}), tolerance index (TI) and yield stability index (YSI) for lowland rice genotypes. Values were taken as average from two growing years 2018−19 and 2019−20. Diagonals indicate the distribution of each parameter. Scatter plots with lines are shown in the bottom of diagonals. Values of correlations and significance levels indicated with stars are shown on the top of diagonals. Correlation coefficients are proportional to intensity of color and size of correlation values. ***: highly significant ($p < 0.001$), **: moderately significant ($p < 0.01$), *: significant ($p < 0.05$).

3.2. Objective II:

Synchronizing Nitrogen Fertilization and Sowing Time / Planting Date to Enhance Resource Use Efficiency, Productivity, and Profitability of Upland Rice

3.2.1. Upland Rice Growth and Productivity under Greenhouse Conditions

Upland rice growth and productivity responses were evaluated under greenhouse conditions in relation to nitrogen application rates (NR), sowing time (ST), and their interactions (NR × ST). Results from the analysis of variance (ANOVA) for observed traits and computed parameters for Dawk Pa–yawm using the LSD–test ($p < 0.05$) indicated highly significant ($p < 0.001$) differences for days to flowering and days to maturity with respect to the ST, whereas there were no significant differences observed with respect to NR and NR × ST for both years (Tables 3). There were highly significant differences ($p < 0.001$) for plant height, number of tillers, number of panicles, grain yield and biomass with respect to NR during both years except moderate significant differences ($p < 0.01$) for the number of tillers and number of panicles during 2019–2020 (Table 3). Highly significant differences ($p < 0.001$) were observed for days to flowering, days to maturity, plant height and grain yield with respect to ST in both years, whereas moderately significant differences ($p < 0.01$) were observed for the number of tillers, number of panicles and biomass in 2018–2019 and for biomass in 2019–2020 with respect to the ST (Table 3). The number of tillers and number of panicles were significantly different ($p < 0.05$) during 2019–2020. ANOVA for the interactions of the NR and ST indicated non−significant differences for days to flowering, days to maturity, plant height, number of tillers, number of panicles, grain yield and biomass in both years except a moderate significant (*p* < 0.01) difference for plant height during 2019–2020 under the interaction of NR and ST.

Flowering days (Figure 1 A, B: Paper II) and maturity duration (Figure 1 C, D: Paper II) were not significantly affected by an increase in NR for both years. Plant height (Figure 2 A, B: Paper II), number of tillers (Figure 3 A, B: Paper II) and the number of panicles (Figure 3 C, D: Paper II), grain yield (Figure 4A, B: Paper II) and biomass (Figure 4C, D: Paper II) were increased with increased N supply whereas ST altered the performance of all these attributes.

The quantity of applied N significantly influences the physiological processes and photosynthesis of plants (Zhang et al., 2020), which ultimately impacts the performance of yield attributes and defines the rice yield potential. Our results indicate that the performance of yield attributes and the yield of upland rice varied significantly under varying NR and N nutrition remarkably improved the overall performance. An increase in plant height occurred possibly due to the contribution of added N which improved the growth, internode length and overall metabolism. Enhanced N application is well documented in encouraging cell expansion, and it subsequently stimulated stem elongation (Millard, 1988, Wu et al., 2020). Jahan et al. (2020) stated that an increase in N supply to rice genotypes caused a significant increase in the height of rice plants. In the present study, higher nitrogen application resulted in higher tillers and panicle numbers and previous studies have also observed that panicle numbers were increased with an increase in NR (Zhang et al. 2020). Wang et al. (2018) demonstrated that N availability controls rice tiller numbers through the regulation of the nitrate transporter. An elevated nitrogen level in rice plants leads to increased tiller numbers and tiller bud outgrowth (Chen et al., 2020).

Jahan et al. (2020) observed that N fertilization increased the number of tillers m^{-2}, which resulted due to the increased N availability for cell division. An increase in yield possibly occurred due to the increased performance of yield attributes. Zhang et al. (2020) observed that an increase in NR significantly increased grain yield; however, this increase in grain yield was in the limited range of NR. Chen et al. (2020) also observed that grain yield and biomass of rice were positively affected by increased NR. Similarly, an increase in plant biomass with N fertilization has also been reported in a rice experimental study by Jahan et al. (2020). In our experimental results, it was noticed that grain yield was in an increasing trend up to NR 4.8 g N pot^{-1}, indicating the need for an increase in further levels of NR in future experimentation to observe the curve for better optimization of the N application rate.

Table 3. Mean squares of ANOVA of yield and yield attributes of Dawk Pa–yawm, straw N uptake, grain N uptake, total N uptake and water use efficiency during 2018–2019 and 2019–2020.

Year	Traits	NR Effect	ST Effect	(NR × ST)	Error	CV%
2018–2019	DF	0.88^{ns}	286.36***	2.81^{ns}	2.47	1.4
	DM	2.44^{ns}	255.86***	0.08^{ns}	1.83	1.02
	PH	738.56***	1002.69***	26.14^{ns}	37.64	5.83
	NT	8.54***	3.69**	0.21^{ns}	0.44	12.06
	NP	7.89***	3.58**	0.14^{ns}	0.39	11.34
	GY	13.07***	11.04***	0.52^{ns}	0.45	13.8
	BM	330.79***	24.38**	2.29^{ns}	3.6	9.76
	SNU	1.37***	0.13***	0.06***	0.009	12.1
	GNU	0.01***	0.05***	0.01***	0.001	12.78
	TNU	2.14***	0.03^{ns}	0.04*	0.009	9.07
	WUE	0.003***	0.001**	0.0001^{ns}	0.0001	12.8
2019–2020	DF	1.07^{ns}	1177.53***	3.38^{ns}	2.47	1.44
	DM	7.66^{ns}	166.08***	3.60^{ns}	2.67	1.28
	PH	452.32***	5466.03***	91.77**	24.42	4.76
	NT	10.11**	8.44*	0.67^{ns}	1.72	23.39
	NP	9.14**	5.86*	0.42^{ns}	1.25	21.52
	GY	13.52***	20.93***	1.81^{ns}	0.84	18.36
	BM	143.18***	71.57**	3.59^{ns}	9.81	18.27
	SNU	0.821***	0.491***	0.090*	0.031	22.04
	GNU	0.057***	0.033***	0.004^{ns}	0.002	18.16
	TNU	1.281***	0.663***	0.097^{ns}	0.042	19.58
	WUE	0.030***	0.090***	0.005*	0.001	15.73

NR = Nitrogen application rate, ST = Sowing time, DF = Days to flowering, DM = Days to maturity, PH = Plant height, NT = Number of tillers, NP = Number of panicles, GY = Grain yield, BM = biomass, SNU = Straw nitrogen uptake, GNU = Grain nitrogen uptake, TNU = Total nitrogen uptake, WUE = Water use efficiency, *** = Highly significant (p < 0.001), ** = Moderately significant (p < 0.01), * Significant (p < 0.05), ns = non−significant.

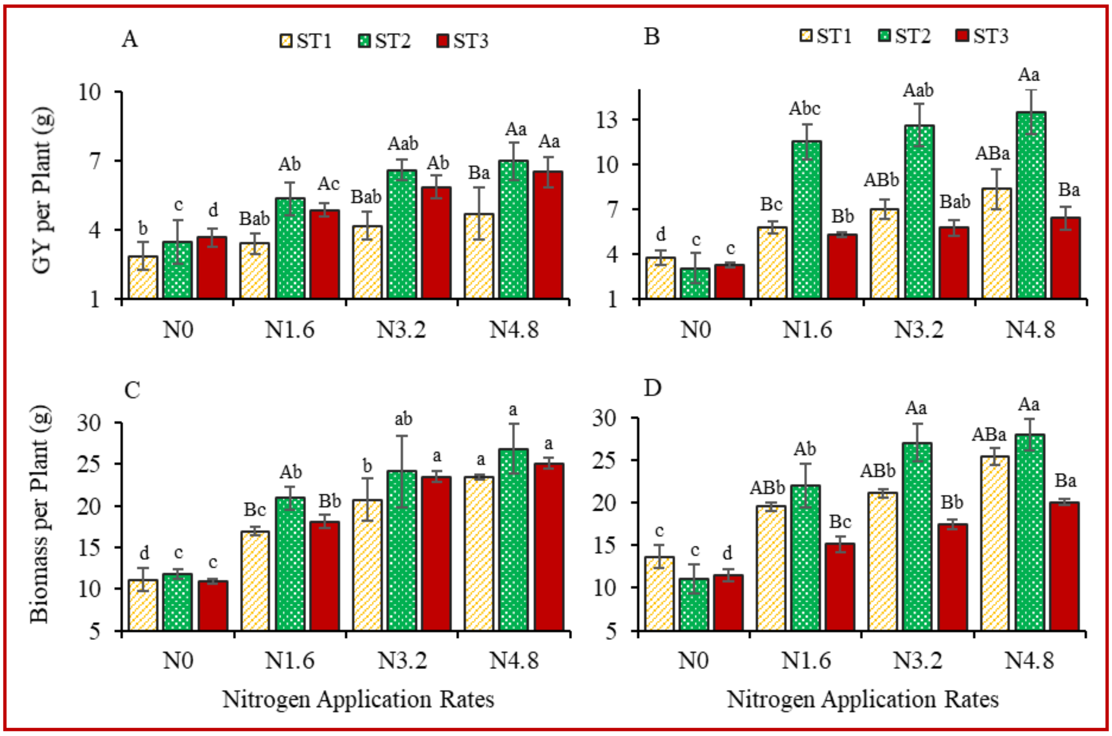


Figure 5. Effect of nitrogen application rates and sowing times on grain yield (**A**, **B**) and biomass (**C**, **D**) during 2018–2019 (**A**, **C**) and 2019–2020 (**B**, **D**). Vertical bars indicate ± standard errors of means (*n* = 3). Mean values are presented, and vertical bars indicate ± standard errors of means (*n* = 3). Uppercase letters indicate significant differences (*p*–value < 0.05) of grain yield and biomass under different sowing times within each nitrogen application rate. Lowercase letters indicate significant differences (*p*–value < 0.05) of grain yield and biomass at different nitrogen application rates within each sowing time. ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late). N0: no applied N, N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

3.2.2. Field Evaluation and Weather Conditions

Mean daily maximum and minimum temperature ranged 24−37 °C and 21−26 °C during the first season and 27−37 °C and 22−26 °C during second season respectively (Figure 6: Figure 1 of Paper III). Mean maximum and minimum temperatures were similar within respective planting dates (PD) during both seasons.

However, mean maximum and minimum temperature were slightly different from planting to flowering and from flowering to maturity during each planting date in both seasons. According to Buddhaboon et al. (2011), the optimal temperature for rice growth is 27 °C. The average temperature that prevailed during the rice growth period in both seasons was higher than that of an optimal temperature range of 25−30 °C (Sparks, 2009). Temperature difference significantly impacts crop growth duration, and planting date regulates the use of environmental resources influencing crop performance (Varinruk, 2017). High and low temperatures occurring under changing climate affect plant growth and development (Aslam et al., 2022). Grain and biomass productivity was highly correlated to the life cycle (Aslam et al., 2017). In general, crop growth duration decreased with an increase in temperature due to a higher crop growth rate (Yoshida, 1973; Ahmed et al., 2014). We observed that days to flowering and days to maturity were decreased significantly in both seasons as the temperature from flowering to physiological maturity increased under PD2 and PD3.

The highest total rainfall received during PD1 was 1152 mm during the first season and 1061 mm during the second season. Whereas PD2 and PD3 received 997 mm and 652 mm during the first season and 823 mm and 444 mm during the second season, respectively (Figure 6: Figure 1 of Paper III). However, rainfall distribution during planting to flowering and from flowering to physiological maturity period of each planting date was highly variable. Rainfall distribution was also different and highly variable among planting dates and seasons. Maximum rainfall and high rainfall intervals occurred during PD1 in both seasons. All planting dates received maximum rainfall from planting to flowering. The PD2 received a suitable distribution of rainfall during the growth period as compared to PD1 and PD3 therefore, supplementary irrigation was reduced at PD2. Due to less rainfall from planting to flowering and from flowering to physiological maturity, at PD3, supplementary irrigation was increased. As PD1 received the highest rainfall from planting to flowering and particularly from flowering to maturity, crop duration was increased due to extended plant growth and developmental phases in the first season. Previous research has confirmed that rice crop growth duration can be delayed on rainy days or during the occurrence of low temperatures at terminal stages, whereas sunny or hot days may shorten the crop growth duration (GRiSP, 2013). In the second season, PD1 received maximum rainfall during the planting to flowering period and received only 1.0 mm from flowering to physiological maturity accompanied by higher average temperatures, hence the crop growth duration was significantly decreased.

The difference in temperature and rainfall distribution influenced the crop duration and supplementary irrigation. We observed that PD1 received the highest rainfall, thus maximum runoff and flash events occurred during PD1, whereas PD2 received a moderate distribution of rain, which was favorable as compared to PD1 and PD3. Therefore, to enhance the utilization of rainwater, slight delays in planting would be advantageous, which not only prevent heavy runoff events but also a better rainwater distribution for plants. Luo et al. (2022) reported similar results in crop water requirement and irrigation demand for rice. The early rice required less irrigation frequency and may not require additional irrigation, while middle and late rice planting required increased water demand. In addition, an assessment of climate change impact, predicted that 30 days delayed planting of Thai rice KDML–105 cultivar would enhance yield by 23% in the 2050s (Babel et al., 2011). Results from our study and findings of Luo et al. (2022) and Babel et al. (2011) strongly support that adjustment in planting date would help to enhance natural resource use efficiency, particularly the optimal use of rainfall with the benefit of reduced or even no supplementary irrigation.

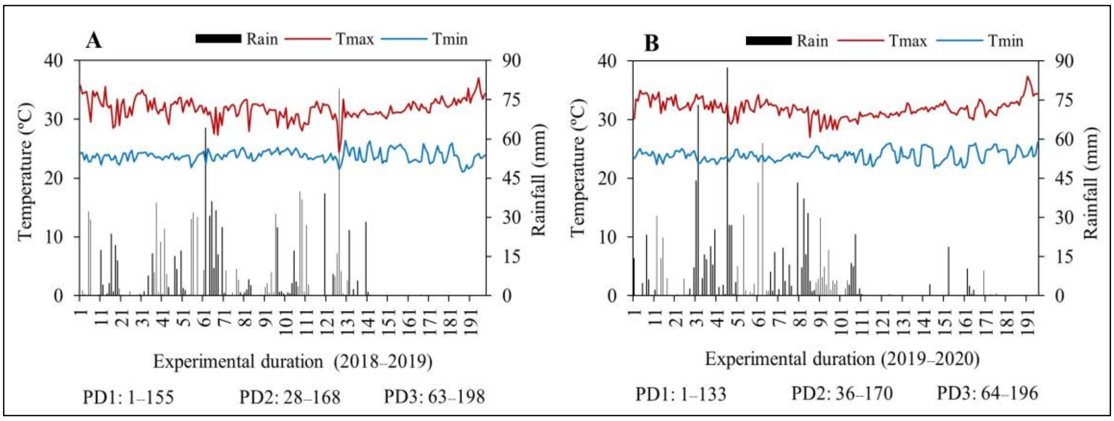


Figure 6. Mean daily maximum (Tmax) and minimum temperature (Tmin) and daily rainfall during the experimental growing period (days) of the first season: 2018−2019 (A) and second season: 2019−2020 (B). PD: Planting date. (Data source: Kho Hong; Hat Yai Agrometeorology−Agricultural Information Center: Thai Meteorological Department, Thailand).

3.2.3. Upland Rice Growth and Productivity under Field Conditions

Statistical analysis indicated that various nitrogen fertilization rate (NFR), under the effect of seasons (S) and in the interaction of NFR × planting date (PD), NFR × S, and NFR × PD × S did not significantly affect days to flowering. However, PD alone and in the interaction with the seasons (PD × S), significantly influenced day to flowering. Whereas the interactions of NFR and PD were not significantly different. Similarly, N fertilization under various NFR alone and in the interaction of NFR, PD, and S did not significantly affect days to maturity. Though days to maturity were significantly influenced under the effect of PD, S, NFR × PD, NFR × S, and PD

× S. Stem height, stem density and panicle density acted similarly and were significantly affected under NFR, PD, S, and in the interaction of NFR × S; whereas, they were not significantly influenced under NFR × PD, PD × S and NFR × PD × S. Grain yield and aboveground biomass acted similarly and were affected significantly under NFR, PD, S, NFR × PD, NFR × S, and; PD × S whereas, they were not influenced under the combined interaction of NFR, PD, and S (Table 2: Paper III).

Phenology was not significantly influenced by N fertilization; however, flowering in PD1 during the first season crop under N_{90} occurred four days earlier than N_0; whereas maturity was delayed under N fertilization compared to N_0. Planting date significantly affected phenology, and day to flowering and maturity were decreased under PD2 and PD3 at various NFR except days to maturity during the second season (Figure 2A–D: Paper III). Crop duration was relatively shorter in the second season compared to the first season and possibly due to the prevailing climatic conditions.

Stem height (Figure 2 E, F: Paper III), stem density (Figure 3 A, B: Paper III) and panicle density (Figure 3 C, D: Paper III), grain yield (Figure 3 E, F: Paper III) and aboveground biomass (Figure 3 G, H: Paper III) were increased with increased N supply whereas PD altered the performance of all these attributes. Regression analysis (Figure 7: Figure 4 of Paper III) for stem density, panicle density, grain yield and aboveground biomass, and NFR under all planting dates indicated a highly significant linear relationship in both seasons and stem density, panicle density, grain yield, as well as aboveground biomass, continued to increase with increasing NFR in this assessment. The synergy between NFR and stem height was well reported (Millard, 1988; Wu et al., 2020) due to the effective role of N fertilization in cell growth and enhanced stem enlargement. A positive correlation prevails among NFR, stem density and panicle density of rice. According to Chen et al. (2020), high N input resulted in increased stem buds' growth, which increased the stem density. Stem density and increased tillering contribute and determine panicle density. Nitrogen fertilization increased panicle density, and results were supported by the findings of Jahan et al. (2020), who confirmed in their study that higher N availability triggered cell division and caused an increase in panicle density. In contrast, stem density and panicle density were decreased at PD3 under the influence of planting date. A decline in stem density, as well as panicle density, possibly occurred due to overall less rainfall (planting to maturity) and high temperature (particularly from flowering to maturity) prevailed during PD3. If higher temperature prevails during the active stem formation stages it results in a decline in panicle density (Dubey et al., 2018). In addition, limited rainfall occurrence during PD3 possibly resulted in low soil water status, which might have induced mild water stress. The decline in stem density (Zain et al., 2014) and particularly panicle density (Davatgar et al., 2009) of rice under water stress is also well explored (Hussain et al., 2021b). An increase in stem height and stem density contributes to aboveground biomass (Hussain et al., 2021a). While an increase in panicle density contributes to grain yield (Dubey et al., 2018). Nitrogen addition increased the performance of yield attributes and consequently increased grain yield and aboveground biomass. An increase in grain yield with increased NFR was also reported by Zhang et al. (2020), while Chen et al. (2020), as well as Jahan et al. (2020), also reported similar results for an increase in grain yield as well as aboveground biomass under increased N supply.

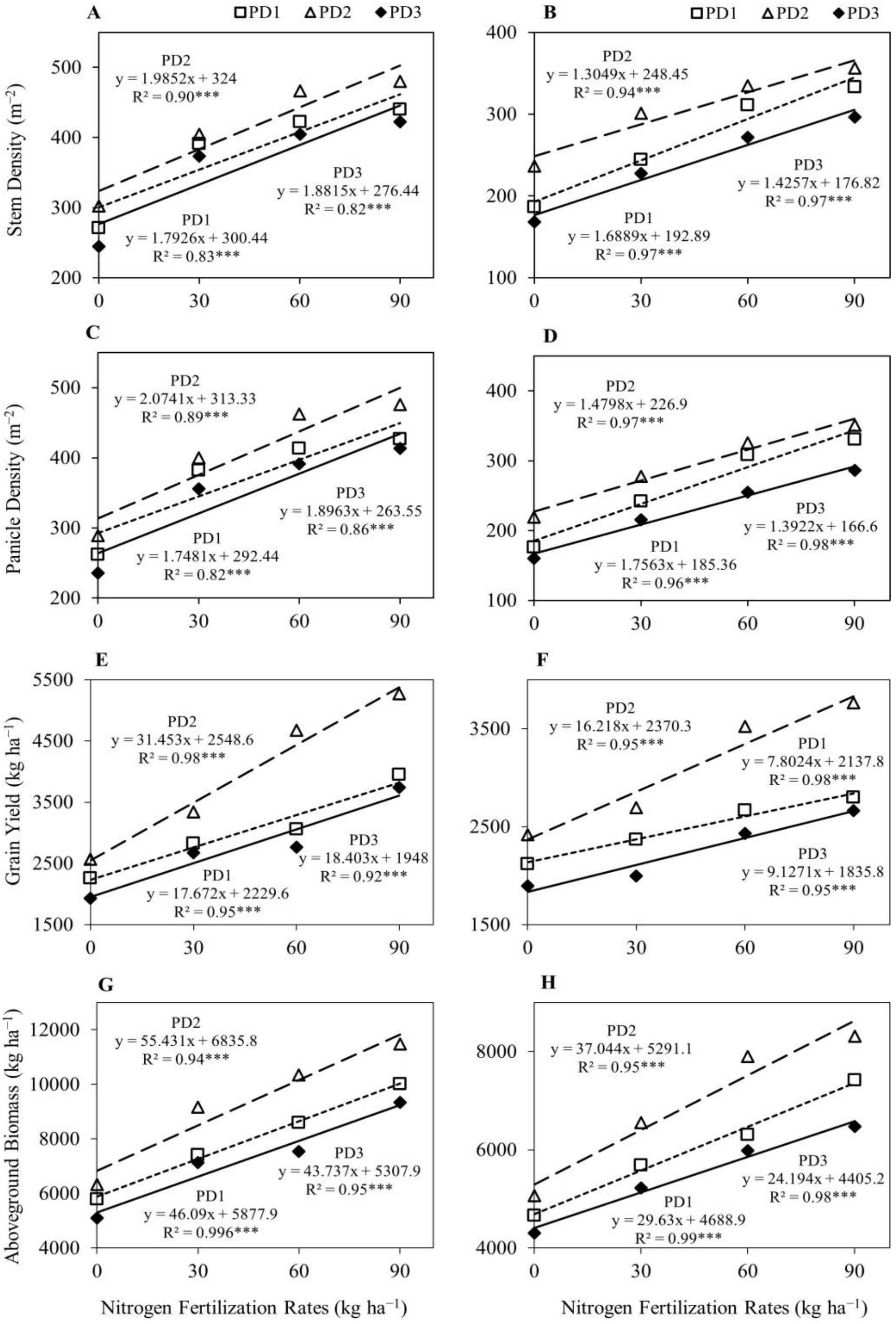


Figure 7. Linear regression relationships between nitrogen (N) fertilization rates and stem density (A–B), between N fertilization rates and panicle density (C–D), between N fertilization rates and grain yield (E–F) and between N fertilization rates and aboveground biomass (G–H) for upland rice obtained from the first season: 2018–2019 (A, C, E, G) and second season: 2019–2020 (B, D, F, H) data.

3.2.4. Nitrogen Uptake under Greenhouse Conditions

Highly significant differences ($p < 0.001$) were observed for straw N uptake, grain N uptake and total N uptake with respect to NR and ST during both years, except a non–significant difference for total N uptake under ST during 2018–2019 (Tables 3). Interactions of the NR and ST indicate highly significant ($p < 0.001$) differences for straw N uptake and grain N uptake and a significant difference ($p < 0.05$) for total N uptake during 2018–2019. Straw N uptake was significantly different ($p < 0.05$), whereas non–significant differences for grain N uptake and total N uptake were observed with respect to NR × ST in 2019–2020. Straw (stem + leaves) N uptake (Figure 5A, B: Paper II), grain N uptake (Figure 5C, D: Paper II), and total N uptake (Figure 5E, F: Paper II) were increased with increasing NR whereas, ST altered the performance of these attributes and the maximum Straw (stem + leaves) N uptake, grain N uptake, and total N uptake were observed at ST2. The results exhibit that medium ST (ST2) was the most favorable ST for maximum N extraction from soil and increase in total plant N uptake as well as for maximum mobility of N from plant parts to grains.

Nitrogen application and N uptake by plants significantly influence the physiological processes of rice. Synchronization of crop N requirement and N supply is an important step to enhance N use in rice plants. The ratio between N uptake and N loss regulates plant growth and development, and higher plant biomass is produced if more N is absorbed (Ullah et al., 2019). Variations in the increase in straw and grain N concentrations and N uptake were observed at varying NR under different ST which indicates the impact of ST. Jahan et al. (2020) also reported that rice's response to applied NR was associated with growing seasons. An increase in rice straw N, grain N concentration and N uptake was also observed by Chen et al. (2020). Higher N uptake is an indication of the achievement of crop N requirement under ideal NR availability and optimal conditions. It was indicated that an increase in NR under delayed sowing could not increase grain N uptake. Total N uptake was also observed at its maximum under ST2 at 4.8g N pot^{-1}, indicating that increasing NR under ST2 increased total N uptake. N uptake was also decreased in late sowing as reported by Pal et al. (2017).

3.2.5. Nitrogen Uptake under Field Conditions

Rice straw N content, grain N content, and total plant N uptake were significantly ($p < 0.001$) differed under the effect of treatments and their interactions including NFR, PD, S, NFR × PD, NFR × S, PD × S, and NFR × PD × S (Table 2: Paper III). A significant increase in straw, grain, and total N uptake was observed with an increase in NFR under all planting dates during both seasons. In response to N fertilization, maximum straw N content, grain N content and total plant N uptake were observed at N_{90} and under the influence of planting dates, maximum straw N content, grain N content and total plant N uptake were observed at PD2 and all NFR during both seasons (Figure 5: Paper III). Regression analysis (Figure 8: Figure 6 of Paper III) indicated a highly significant linear relationship in both seasons and straw N content, grain N content as well as total plant N uptake, continued to increase with increasing NFR in this assessment. Jahan et al. (2020) noted that NFR resulted in increased rice straw and grain N contents and total plant N uptake, and the seasonal impact was significant. Planting date influenced straw and grain N contents and total plant N uptake due to high rainfall events at PD1 and low rainfall at PD3.

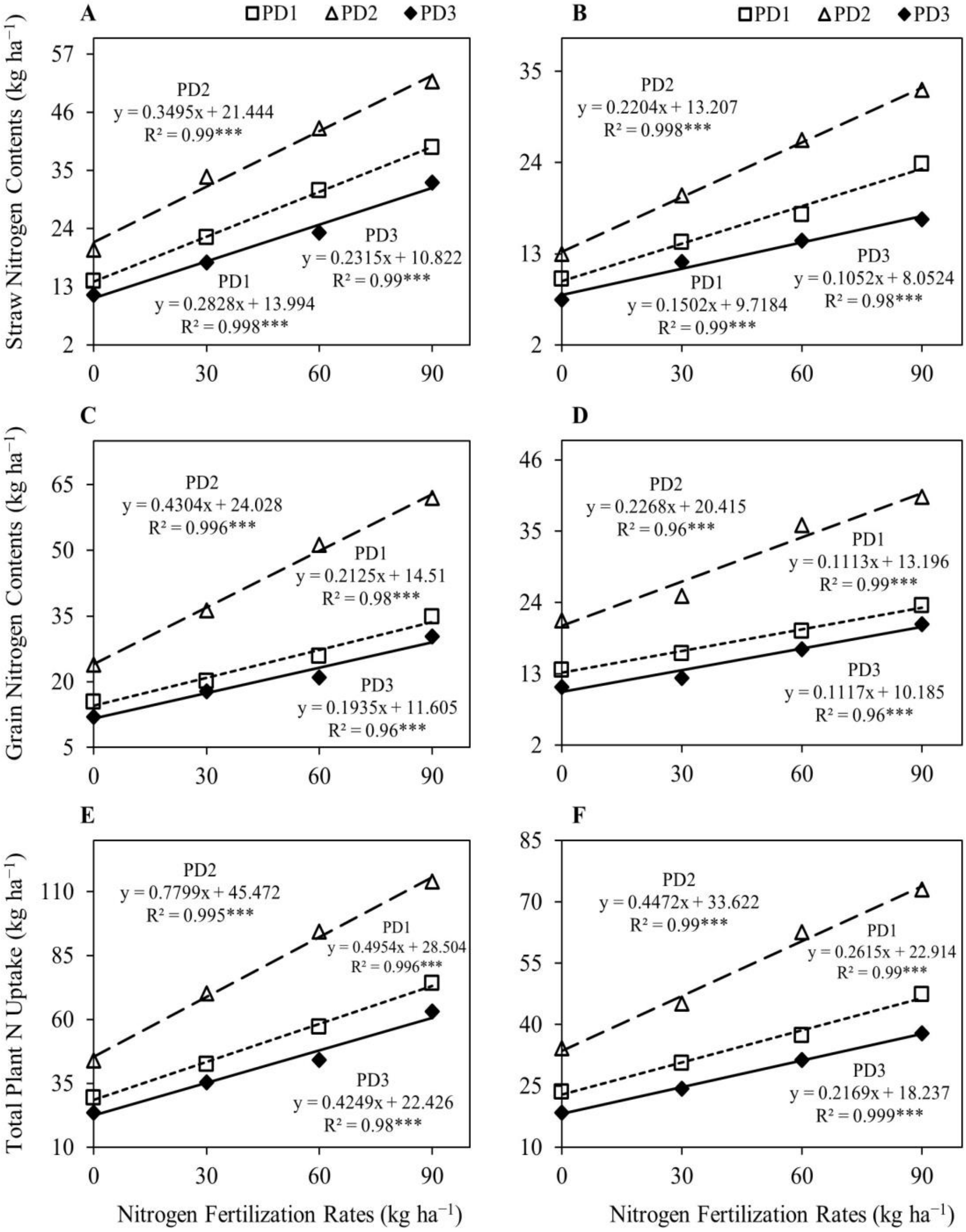


Figure 8. Linear regression relationships between nitrogen (N) fertilization rates and straw N contents (A–B), between N fertilization rates and grain N contents (C–D) and between N fertilization rates and total plant N uptake (E–F) for upland rice obtained from the first season: 2018–2019 (A, C, E) and second season: 2019–2020 (B, D, F) data.

3.2.6. Nitrogen Use Efficiencies under Greenhouse Conditions

Enhancing N use efficiencies in upland rice systems is one of the main objectives of N fertilization. We observed that increased NR influenced N use efficiencies. Nitrogen supply significantly affected N efficiencies including agronomic efficiency (NAE) (Figure 6A, B: Paper II) and nitrogen use efficiency (NUE) (Figure 6C, D: Paper II) in both years. NAE and NUE were increased with applied N: increasing NR up to 4.8 g N pot^{-1} under all ST in both years. However, under the influence of ST maximum NAE and NUE were observed at ST2.

3.2.7. Nitrogen Use Efficiencies under Field Conditions

Nitrogen supply significantly affected N efficiencies including agronomic efficiency (NAE), recovery efficiency (NRE), partial factor productivity (PFP) and nitrogen harvest index (NHI) in both years. N efficiencies varied under N fertilization however, under the influence of PD maximum NAE, NUE, NRE and NHI were observed at PD2 (Figure 7: Paper III). Nitrogen use efficiencies including $AE_{N,}$ $RE_{N,}$ and NHI varied among NFR while, PFP decreased under increased NFR. The NUE is decreased under a higher N supply (Barbieri et al., 2008) in rice production systems due to high concentrations of N in the soil (Santiago–Arenas et al., 2021). Our results for PFP were in line with the findings of Santiago–Arenas et al. (2021), that PFP and $AE_{N,}$ of direct−seeded rice decreased with increasing NFR. Variation and decline for $AE_{N,}$ $RE_{N,}$ and NHI under increased N supply possibly occurred because of increased N fertilization and low grain yield compared to control and vice versa. Thus, we observed improved N use efficiencies under N fertilization.

3.2.8. Water Use Efficiency / Crop Water Productivity under Greenhouse Conditions

Water use efficiency (WUE) was estimated for each treatment for both years (Figure 7: Paper II). There was a highly significant ($p < 0.001$) difference for WUE with respect to NR and a moderate significant difference ($p < 0.01$) with respect to ST and a non−significant difference for the interactions of NR and ST in 2018–2019 (Table 3). During 2019–2020, highly significant ($p < 0.001$) differences for WUE with respect to NR and ST and a significant difference ($p < 0.05$) with respect to the interactions of NR and ST were observed (Table 3). An increase in NR up to 4.8 g N pot^{-1} significantly increased WUE in both years (Figure 7A, B: Paper II). Maximum WUE was observed at N 4.8 g N pot^{-1} under all ST whereas, under the influence of ST maximum WUE was observed at ST2. WUE was also associated with NR, and higher NR 4.8g N pot^{-1} resulted in higher WUE. The association of NUE and WUE has also been well reported (Ullah et al., 2019, Lupini et al., 2021).

3.2.9. Water Use Efficiency / Crop Water Productivity under Field Conditions

Crop water productivity was significantly ($p < 0.001$) different under the effect of NFR, PD, S, NFR × PD and NFR × S; whereas no significant interaction was observed for the PD × S and NFR × PD × S (Table 2: Paper III). Crop water productivity was highly influenced by seasons. An increase in crop water productivity was observed with an increase in NFR and maximum crop water productivity was at N_{90} under all planting dates during both seasons whereas, delayed planting (PD3) resulted in a decline of crop water productivity (Figure 8: Paper III). Crop water productivity also indicated a linear relationship with NFR (Figure 9: Paper III). Crop water productivity was positively associated with plant N uptake and grain yield. An increasing trend of crop water productivity is usually accompanied by a high grain yield with a high N supply (Santiago–Arenas et al., 2021).

3.2.10. Profitability of Upland Rice under Field Conditions

Economic analysis for Dawk Pa–yawm grain productivity per hectare computed for field experiments indicated that the increase in NFR up to 90 kg N ha^{-1} provided the highest economic benefit for all planting dates during both seasons (Table 4: Table 3 of Paper III). Considering the impact of planting date, profitability from applied N as compared to control was influenced by the highest gross return, and gross profit margins were observed at PD2 with N_{90} during both seasons. If the Marginal benefit–cost ratio (MBCR) is considered, maximum MBCR was also observed at PD2. An increase in grain yield productivity and profitability with an increase in nitrogen rate up to N_{60} at PD2 indicated the highest MBCR with values of 60.37 and 31.72 for the first and second season, respectively.

Table 4: Grain yield production, nitrogen fertilization cost, and economic return of upland rice (*genotype: Dawk Pa–yawm*) calculated for various nitrogen fertilization rates as affected by planting dates.

Growing season	Nitrogen fertilization rate kg ha^{-1}	Planting dates	Grain yield t ha^{-1}	Gross return US$ ha^{-1}	Nitrogen fertilization cost US$ ha^{-1}	Additional profit over control US$ ha^{-1}	Gross margin over control US$ ha^{-1}	[a]MBCR
2018–2019	0	PD1	2.26	4024.64	–	–	–	–
		PD2	2.57	4574.72	–	–	–	–
		PD3	1.93	3436.05	–	–	–	–
	30	PD1	2.83	5031.19	30.99	1006.55	975.56	32.48
		PD2	3.34	5948.35	30.99	1373.63	1342.64	44.32
		PD3	2.67	4755.62	30.99	1319.57	1288.58	42.58
	60	PD1	3.06	5450.21	61.98	1425.58	1363.60	23.00
		PD2	4.67	8316.67	61.98	3741.95	3679.96	60.37
		PD3	2.76	4915.69	61.98	1479.64	1417.66	23.87
	90	PD1	3.95	7030.59	92.97	3005.95	2912.98	32.33
		PD2	5.27	9383.87	92.97	4809.15	4716.18	51.73
		PD3	3.74	6658.50	92.97	3222.42	3129.48	34.66
2019–2020	0	PD1	2.12	3770.95	–	–	–	–
		PD2	2.42	4306.48	–	–	–	–
		PD3	1.89	3372.24	–	–	–	–
	30	PD1	2.37	4219.25	30.99	448.30	417.30	14.47
		PD2	2.69	4793.26	30.99	486.78	455.79	15.71
		PD3	2.00	3554.68	30.99	182.44	151.45	5.89
	60	PD1	2.67	4746.65	61.98	975.70	913.72	15.74
		PD2	3.52	6272.76	61.98	1966.28	1904.30	31.72
		PD3	2.43	4329.57	61.98	957.33	895.34	15.45
	90	PD1	2.80	4983.99	92.97	1213.03	1120.06	13.05
		PD2	3.76	6700.11	92.97	2393.62	2300.65	25.75
		PD3	2.66	4738.57	92.97	1366.33	1273.36	14.70

[a]MBCR; Marginal benefit−cost−ratio

4. Concluding Remarks

4.1. Responses of Lowland Rice Genotypes under Terminal Water Stress (TWS) and Identification of Drought Tolerance and Promising Stress Response Indices

Terminal water stress (TWS) significantly reduced the performance of yield and yield attributes. Studied genotypes were found unique in their yield potential as they reflected different responses under well−watered (WW) and TWS conditions. Genotypes Look Pla, Pathum Thani−1, Hom Pathum, Dum Ja, Sang Yod, and Lep Nok were found water stress tolerant as they produced relatively higher grain yield (GY), promising values for stress indices and improved performance under TWS. The performance of stress tolerant genotypes was less affected under TWS as compared to stress susceptible genotypes. Hence, these genotypes are potentially recommended for sustaining yield productivity in such environments where TWS occurrence is predicted, especially in southern Thailand. Stress−tolerant genotypes could be used in obtaining better GY under TWS and for acquiring desired traits for improvement in drought tolerance. Strong associations of GMP, STI, M_{PRO} and M_{HAR} with GY under WW and, especially under TWS conditions, indicated that these indices could be used to indicate stress tolerance in rice crop breeding programs as rapid identifiers.

4.2. Synchronizing Nitrogen Fertilization and Sowing Time / Planting Date to Enhance Resource Use Efficiency, Productivity, and Profitability of Upland Rice

Ideal agronomic management for identification of optimal N fertilizer rate (NFR) synchronized with ideal planting date (PD) is an important strategy to enhance resource input efficiency and productivity of upland rice. Results obtained from greenhouse experiments indicated that NFR and PD influenced growth, productivity, nitrogen use efficiencies and water use efficiency (WUE) of upland rice. In addition to grain yield, N uptake was enhanced. Maximum performance for yield, yield attributes and WUE was achieved at 4.8 g N pot^{-1} (90 kg N ha^{-1}). Whereas the highest plant, grain and total N uptake and N use efficiencies were achieved at 3.2 g N pot^{-1}. Considering the impact of ST, the maximum performance for yield, grain N uptake, N use efficiencies and WUE was achieved under PD2.

In the field evaluation, similar results were obtained, and N fertilization positively influenced the resource use efficiency, upland rice productivity, and profitability; however, variation in PD significantly altered the results. We found that fertilization of 90 kg N ha^{-1} at PD2 (end of September or start of October) improved the yields and performance of yield attributes as well as enhanced straw N, and grain N content and total plant N uptake. N fertilization increased profitability and application of 90 kg N ha^{-1} resulted in maximum profit at all PD. However, the highest marginal benefit–cost ratio (MBCR) was observed in N_{60} at PD2 during both seasons. Based on the results, it was suggested that 90 kg N ha^{-1} should be applied, and upland rice should be planted at the end of September or the start of October for enhancing resource use efficiency, improving productivity, and maximum profitability. Furthermore, since a linear relationship between NFR, agronomic traits of upland rice, N uptake and crop water productivity was observed, and a significant seasonal effect indicated, long–term field investigations considering a range of NFR and adoption of forecasting measures *i.e.*, rainfall forecasting and yield prediction using crop simulation and modeling techniques to adjust seasonal planting date are recommended for upland rice cultivation in Thailand.

REFRENCES

Ahmed, S., Humphreys, E., Salim, M. and Chauhan, B.S. 2014. Optimizing sowing management for short duration dry seeded aman rice on the high ganges river floodplain of Bangladesh. *Field Crops Res.* 169: 77–88. doi:10.1016/j.fcr.2014.09.009.

Agarwal, P., Parida, S.K., Raghuvanshi, S., Kapoor, S., Khurana, P., Khurana, J.P. and Tyagi, A.K. 2016. Rice improvement through genome-based functional analysis and molecular breeding in India. *Rice.* 9: 1–17. doi:10.1186/s12284-015-0073-2.

Ahmadikhah, A. and Marufinia, A. 2016. Effect of reduced plant height on drought tolerance in rice. *Biotech.* 6: 1–9. doi:10.1007/s13205-016-0542-3.

Anantha, M.S., Patel, D., Quintana, M., Swain, P., Dwivedi, J.L., Torres, R.O., Verulkar, S.B., Variar, M., Mandal, N.P. and Kumar, A. 2016. Trait combinations that improve rice yield under drought: Sahbhagi Dhan and new drought-tolerant varieties in South Asia. *Crop Sci.* 56: 408–421. doi:10.2135/cropsci2015.06.0344.

Anwar, J., Subhani, G.M., Hussain, M., Ahmad, J., Hussain, M. and Munir, M. 2011. Drought tolerance indices and their correlation with yield in exotic wheat genotypes. *Pak. J. Bot.* 43: 1527–1530.

Aslam, M.A., Ahmed, M., Stöckle, C.O., Higgins, S.S., Ul Hassan, F. and Hayat, R. 2017. Can growing degree days and photoperiod predict spring wheat phenology? *Front. Environ. Sci.* 5: 1–10. doi:10.3389/fenvs.2017.00057.

Aslam, M.A., Ahmed, M., Hassan, F.U., Afzal, O., Mehmood, M.Z., Qadir, G., Asif, M.; Komal, S. and Hussain, T. 2022. Impact of temperature fluctuations on plant morphological and physiological traits: *In*: Jatoi, W.N., Mubeen, M., Ahmad, A., Cheema, M.A., Lin, Z. and Hashmi, M.Z. Eds. Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective. Springer International Publishing: Cham. pp 25–52. ISBN 978-3-030-79408-8.

Babel, M.S., Agarwal, A., Swain, D.K. and Herath, S. 2011. Evaluation of climate change impacts and adaptation measures for rice cultivation in Northeast Thailand. *Clim. Res.* 46: 137–146. doi:10.3354/cr00978.

Barbieri, P.A., Echeverría, H.E., Saínz Rozas, H.R. and Andrade, F.H. 2008. Nitrogen use efficiency in maize as affected by nitrogen availability and row spacing. *Agron. J.* 100: 1094–1100. doi:10.2134/agronj2006.0057.

Buddhaboon, C., Jintrawet, A. and Hoogenboom, G. 2011. Effects of planting date and variety on flooded rice production in the deepwater area of Thailand. *Field Crops Res.* 124: 270–277. doi:10.1016/j.fcr.2011.06.019.

Bouslama, M. and Schapaugh, W.T. 1984. Stress tolerance in soybeans. I. Evaluation of three screening techniques for heat and drought tolerance. *Crop Sci.* 24: 933–937.

CARSR. 2003. Rice Production Status-Highland Farming System. Report of Center for Agricultural Resource System Research, Faculty of Agriculture, Chiang Mai University, Thailand. Available online: http://www.mcc.cmu.ac.th/agsust/highland_SA/riceproduction_highland.htm?fbclid=IwAR1Mjn6SlS7z2N7cUR_U7F9Bnl4MijMGyFti106tFpo_RYdjoDRmyPxtkHg (accessed on 15 October 2021).

Chen, Z., Wang, Q., Ma, J., Zou, P. and Jiang, L. 2020. Impact of controlled–release urea on rice yield, nitrogen use efficiency and soil fertility in a single rice cropping system. *Sci. Rep.* 1–10. doi:10.1038/s41598–020–67110–6.

Chutia, J. and Borah, S.P. 2012. Water stress effects on leaf growth and chlorophyll content but not the grain yield in traditional rice (*Oryza sativa* Linn.) genotypes of Assam, India II. Protein and proline status in seedlings under PEG induced water stress. *Am. J. Plant Sci.* 3: 971–980. doi:10.4236/ajps.2012.37115.

Davatgar, N., Neishabouri, M.R., Sepaskhah, A.R. and Soltani, A. 2009. Physiological and morphological responses of rice (*Oryza sativa* L.) to varying water stress management strategies. *Int. J. Plant Prod.* 3: 19–32. doi:10.22069/ijpp.2012.660.

DRRD. 2016. Rice Knowledge Bank: Division of Rice Research Development. Available online: https://brrd.ricethailand.go.th/ (accessed on 13 September 2017).

DRRD. 2017. Soil and Fertilizer Management in Rice Fields, Fertilizer Recommendations for Southern Region. Rice Knowledge Bank: Division of Rice Research Development. Available online: https://webold.ricethailand.go.th/rkb3/title-index.php-file=content.php&id=043.htm#p9 (accessed on 22 December 2021).

Dubey, A.N., Verma, S., Goswami, S. and Devedee, A.K. 2018. Effect of temperature on different growth stages and physiological process of rice crop-a review. *Bull. Env. Pharmacol. Life Sci.* 7: 129–136.

FAO. 2020. FAOSTAT. Available online: http://www.fao.org/faostat/en/#home (accessed on 18 August 2021).

Farooq, M., Kobayashi, N., Ito, O., Wahid, A. and Serraj, R. 2010. Broader leaves result in better performance of indica rice under drought stress. *J. Plant Physiol.* 167: 1066–1075. doi:10.1016/j.jplph.2010.03.003.

Fernandez, G.C. 1992. Effective selection criteria for assessing plant stress tolerance. *In:* Proceedings of the International Symposium on Adaptation of Vegetables and other Food Crops in Temperature and Water Stress, Shanhua, Taiwan. 13–16 August 1992. pp. 257–270.

Ferrari, S., Pagliari, P. and Trettel, J. 2018. Optimum sowing date and genotype testing for upland rice production in Brazil. *Sci. Rep.* 8: 1–8. doi:10.1038/s41598-018-26628-6.

Fischer, R.A. and Maurer, R. 1978. Drought resistance in spring wheat cultivars. I. Grain yield responses. *Aust. J. Agric. Res.* 29: 897–912. doi:10.1071/AR9780897.

Fischer, K., Lafitte, R., Fukai, S., Atlin, G. and Hardy, B. 2003. Breeding rice for drought-Prone environments. International Rice Research Institute. Los Baños, Philippines. ISBN 9712201899.

GRiSP. 2013. Rice Almanac, 4th ed.; International Rice Research Institute. Los Baños, Philippines.

Hossain, A.B.S., Sears, R.G., Cox, T.S. and Paulsen, G.M. 1990. Desiccation tolerance and its relationship to assimilate partitioning in winter wheat. *Crop Sci.* 30: 622–627.

Hussain, T., Anothai, J., Nualsri, C. and Soonsuwon, W. 2018a. Application of CSM-CERES-Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield. *Indian J. Agric. Res.* 52: 140–145. doi:10.18805/IJARe.A-321.

Hussain, T., Anothai, J., Nualsri, C. and Soonsuwon, W. 2018b. Evaluating performance of sixteen upland rice genotypes under field conditions for further breeding process. *J. Agric. Sci.* 10: 144. doi:10.5539/jas.v10n3p144.

Hussain, T., Hussain, N., Ahmed, M., Nualsri, C. and Duangpan, S. 2021a. Responses of lowland rice genotypes under terminal water stress and identification of drought tolerance to stabilize rice productivity in Southern Thailand. *Plants*. 10: 2565. https://doi.org/10.3390/plants10122565.

Hussain, N., Ahmed, M., Duangpan, S., Hussain, T. and Taweekun, J. 2021b. Potential impacts of water stress on rice biomass composition and feedstock availability for bioenergy production. *Sustainability*. 13: 10449. doi:10.3390/su131810449.

Ichsan, C.N., Basyah, B., Zakaria, S. and Efendi, E. 2020. Differences of water status and relationship with roots growth and yield of rice under water stress. *Syst. Rev. Pharm.* 11: 611–618.

Jahan, A., Islam, A., Sarkar, M.I.U., Iqbal, M., Ahmed, M.N. and Islam, M.R. 2020. Nitrogen response of two high yielding rice varieties as influenced by nitrogen levels and growing seasons. *Geol. Ecol. Landsc.* 1–8. https://doi.org/10.1080/24749508.2020.1742509.

Kumar, A., Verulkar, S., Dixit, S., Chauhan, B., Bernier, J., Venuprasad, R., Zhao, D. and Shrivastava, M.N. 2009. Yield and yield-attributing traits of rice (*Oryza sativa* L.) under lowland drought and suitability of early vigor as a selection criterion. *Field Crop Res.* 114: 99–107. doi:10.1016/j.fcr.2009.07.010.

Kumar, V. and Ladha, J.K. 2011. Direct Seeding of Rice. Recent Developments and Future Research Needs, 1st ed. Elsevier Inc. Amsterdam, The Netherlands. 111. ISBN 9780123876898.

Lupini, A., Preiti, G., Badagliacca, G., Abenavoli, M.R., Sunseri, F., Monti, M. and Bacchi, M. 2021. Nitrogen use efficiency in durum wheat under different nitrogen and water regimes in the Mediterranean Basin. *Front. Plant Sci.* 11: 1–19. https://doi.org/10.3389/fpls.2020.607226.

Limsakul, A. and Singhruck, P. 2016. Long-term trends and variability of total and extreme precipitation in Thailand. *Atmos. Res.* 169: 301–317. doi:10.1016/j.atmosres.2015.10.015.

Luo, W., Chen, M., Kang, Y., Li, W., Li, D., Cui, Y., Khan, S. and Luo, Y. 2022. Analysis of crop water requirements and irrigation demands for rice: Implications for increasing effective rainfall. *Agric. Water Manag.* 260: 107285. doi:10.1016/j.agwat.2021.107285.

Mansour, E., Desoky, E.S.M., Ali, M.M.A., Abdul−Hamid, M.I., Ullah, H., Attia, A. and Datta, A. 2021. Identifying drought−tolerant genotypes of faba bean and their agro−physiological responses to different water regimes in an arid Mediterranean environment. *Agric. Water Manag.* 247: 106754. doi:10.1016/j.agwat.2021.106754.

Millard, P. 1988. The accumulation and storage of nitrogen by herbaceous plants. *Plant Cell Environ*. 11: 1–8. doi:10.1111/j.1365-3040.1988.tb01769.x.

Nazir, M. 1994. Crop Production. Bashir, E., Bantel, R., Eds. National Book Foundation: Islamabad, Pakistan. Volume 252.

Nascente, A.S., Lanna, A.C., de Sousa, T.P., Chaibub, A.A., de Souza, A.C.A. and de Filippi, M.C.C. 2019. N Fertilizer dose–dependent efficiency of *Serratia spp.* for improving growth and yield of upland rice (*Oryza sativa* L.). *Int. J. Plant Prod.* 13: 217–226. doi:10.1007/s42106–019–00049–5.

Norsuwan, T., Utasuk, K., Panyasai, T. and Sangchyoswat, C. 2020. Optimization of nitrogen fertilizer application in lowland rice production system of agricultural resource system research station using tailored farm-plot database. Chiang *Mai Univ. J. Nat. Sci.* 19: 333–349. doi:10.12982/CMUJNS.2020.0022.

Ovenden, B., Milgate, A., Lisle, C., Wade, L.J., Rebetzke, G.J. and Holland, J.B. 2017. Selection for water—Soluble carbohydrate accumulation and investigation of genetic × environment interactions in an elite wheat breeding population. *Theor. Appl. Genet.* 130: 2445–2461. doi:10.1007/s00122-017-2969-2.

Pal, R., Mahajan, G., Sardana, V. and Chauhan, B.S. 2017. Impact of sowing date on yield, dry matter and nitrogen accumulation, and nitrogen translocation in dry–seeded rice in North–West India. *Field Crop Res.* 206: 138–148. doi:10.1016/j.fcr.2017.01.025.

Rahman, M.T., Islam, M.T. and Islam, M.O. 2002. Effect of water stress at different growth stages on yield and yield contributing characters of transplanted Aman rice. *Pak. J. Biol. Sci.* 5: 169–172. doi:10.3923/pjbs.2002.169.172.

Raman, A., Verulkar, S.B., Mandal, N.P., Variar, M., Shukla, V.D., Dwivedi, J.L., Singh, B.N., Singh, O.N., Swain, P. and Mall, A.K. 2012. Drought yield index to select high yielding rice lines under different drought stress severities. *Rice.* 5: 1–12. doi:10.1186/1939-8433-5-31.

Ray, D.K., West, P.C., Clark, M., Gerber, J.S., Prishchepov, A.V. and Chatterjee, S. 2019. Climate change has likely already affected global food production. *PLoS ONE*. 14: e0217148. doi:10.1371/journal.pone.0217148.

Rosielle, A.A. and Hamblin, J. 1981. Theoretical aspects of selection for yield in stress and non-stress environments. *Crop Sci.* 21: 943–946.

Saikumar, S., Varma, C.M.K., Saiharini, A., Kalmeshwer, G.P., Nagendra, K., Lavanya, K. and Ayyappa, D. 2016. Grain yield responses to varied level of moisture stress at reproductive stage in an interspecific population derived from *Swarna/O. glaberrima* introgression line. *NJAS Wagening. J. Life Sci.* 78: 111–122. doi:10.1016/j.njas.2016.05.005.

Santiago-Arenas, R., Dhakal, S., Ullah, H., Agarwal, A. and Datta, A. 2021. Seeding, nitrogen and irrigation management optimize rice water and nitrogen use efficiency. *Nutr. Cycling Agroecosyst.* 120: 325–341. doi:10.1007/s10705-021-10153-6.

Sparks, D. L. 2009. Advances in Agronomy. Elsevier Academic Press. San Deigo.

Suwanasa, C., Nualsri, C., Junsawang, N. and Soonsuwon, W. 2018. Yield trial of upland rice (*Oryza sativa* L.) in Songkhla Province, Thailand. *Songklanakarin J. Pl. Sci.* 5: 1–6.

Schneider, K.A., Rosales-serna, R., Ibarra-perez, F., Cazares-enriquez, B., Acosta-gallegos, J.A., Ramirez-vallejo, P., Wassimi, N. and Kelly, J.D. 1997. Improving common bean performance under drought stress. *Crop Sci.* 37: 43–50.

Torres, R.O., McNally, K.L., Cruz, C.V., Serraj, R. and Henry, A. 2013. Screening of rice gene bank germplasm for yield and selection of new drought tolerance donors. *Field Crop Res.* 147: 12–22. doi:10.1016/j.fcr.2013.03.016.

Torres, R.O. and Henry, A. 2018. Yield stability of selected rice breeding lines and donors across conditions of mild to moderately severe drought stress. *Field Crop Res.* 220: 37–45. doi:10.1016/j.fcr.2016.09.011.

Ullah, H., Santiago–Arenas, R., Ferdous, Z., Attia, A. and Datta, A. 2019. Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: a review, 1st ed.; Elsevier Inc.: Amsterdam, The Netherlands. 156. ISBN 9780128175989.

USDA. 2015. Thailand: Irrigation Shortage Reduces 2015/16 Rice Production. Available online: https://ipad.fas.usda.gov/ highlights/2015/10/th/index.htm (accessed on 25 June 2020).

Varinruk, B. 2017. Thailand rice production and rice research and development on climate change. *In:* Proceedings of Workshop Strengthening APEC Cooperation on Food Security and Climate Change. 19–21 April. Ha Noi, Vietnam.

Wang, J., Lu, K., Nie, H., Zeng, Q., Wu, B., Qian, J. and Fang, Z. 2018. Rice nitrate transporter *OsNPF7.2* positively regulates tiller number and grain yield. *Rice.* 11: 1–13.

Wasae, A. 2021. Evaluation of drought stress tolerance based on selection indices in Haricot Bean varieties exposed to stress at different growth stages. *Int. J. Agron.* 1-9. doi:10.1155/2021/6617874.

Watcharin, S., Kanrob, P., Charassri, N. and Nattapon, J. 2020. Improving photoperiod insensitivity of a Thai upland rice variety by marker–assisted foreground selection. *Int. J. Agric. Technol.* 16: 199–206.

Wu, K., Wang, S., Song, W., Zhang, J., Wang, Y., Liu, Q., Yu, J., Ye, Y., Li, S. and Chen, J. 2020. Enhanced sustainable green revolution yield via nitrogen-responsive chromatin modulation in rice. *Sci.* 367: eaaz2046.

Yoshida, S. 1973. Effects of temperature on growth of the rice plant (*Oryza sativa* L.) in a controlled environment. *Soil Sci. Plant Nutr.* 19: 299–310. doi:10.1080/00380768.1973.10432599.

Zain, N.A.M., Ismail, M.R., Puteh, A., Mahmood, M. and Islam, M.R. 2014. Impact of cyclic water stress on growth, physiological responses and yield of rice (*Oryza sativa* L.) grown in tropical environment. *Ciência Rural*. 44: 2136–2141. doi:10.1590/0103-8478cr20131154.

Zhang, J., Tong, T., Potcho, P.M., Huang, S., Ma, L. and Tang, X. 2020. Nitrogen effects on yield, quality and physiological characteristics of giant rice. *Agron.* 10: 1816. doi:10.3390/agronomy10111816.

Zhao, D.L., Atlin, G.N., Amante, M., Cruz, M.T.S. and Kumar, A. 2010. Developing aerobic rice cultivars for water-short irrigated and drought-prone rainfed areas in the tropics. *Crop Sci.* 50: 2268–2276. doi:10.2135/cropsci2010.10.0028.

Zhou, J., Wang, X., Jiao, Y., Qin, Y., Liu, X., Zhang, Q., Fan, L. and Wang, X. 2007. Global genome expression analysis of rice in response to drought and high-salinity stresses in shoot, flag leaf, and panicle. *Plant Mol. Biol.* 63: 591–608. doi:10.1007/s11103-006-9111-1.

APPENDICES

Paper I

Hussain, T., Hussain, N., Ahmed, M. Nualsri, C. and Duangpan, S. 2021. Responses of Lowland Rice Genotypes under Terminal Water Stress and Identification of Drought Tolerance to Stabilize Rice Productivity in Southern Thailand. *Plants*. **10:** 2565. *doi:10.3390/plants10122565*.

(Reprinted with the permission from *Plants* journal)

plants

Article

Responses of Lowland Rice Genotypes under Terminal Water Stress and Identification of Drought Tolerance to Stabilize Rice Productivity in Southern Thailand

Tajamul Hussain [1], Nurda Hussain [1,2], Mukhtar Ahmed [3], Charassri Nualsri [4] and Saowapa Duangpan [1,*]

[1] Laboratory of Plant Breeding and Climate Resilient Agriculture, Agricultural Innovation and Management Division, Faculty of Natural Resources, Prince of Songkla University, Songkhla 90110, Thailand; 6110630006@psu.ac.th (T.H.); 6310120017@psu.ac.th (N.H.)
[2] Energy Technology Program, Faculty of Engineering, Prince of Songkla University, Songkhla 90110, Thailand
[3] Department of Agronomy, Faculty of Crop and Food Sciences, PMAS Arid Agriculture University, Rawalpindi 46300, Punjab, Pakistan; ahmadmukhtar@uaar.edu.pk
[4] Agricultural Innovation and Management Division, Faculty of Natural Resources, Prince of Songkla University, Songkhla 90110, Thailand; ncharass@yahoo.com
* Correspondence: saowapa.d@psu.ac.th; Tel.: +66-74-286-138

Abstract: Lowland rice is an important cereal crop that plays a key role in the food security and the economy of Thailand. Terminal water stress (TWS) in rainfed lowland areas poses threats to rice productivity due to stress occurrence at terminal crop stages and extreme sensitivity of rice to TWS. A two-year study was conducted to characterize the performance of yield and yield attributes of twelve Thai lowland rice genotypes under TWS, to identify stress-tolerant genotypes using stress response indices and to identify promising stress indices which are correlated with grain yield (GY) under well-watered (WW) and TWS conditions for their use as rapid identifiers in a rice crop breeding program for enhancing drought stress tolerance. Measurements were recorded under WW and TWS conditions. Highly significant variations were observed amongst assessed genotypes for their yield productivity responses. According to stress response indices, genotypes were categorized into stress-tolerant and stress susceptible genotypes. Genotypes Hom Pathum, Sang Yod, Dum Ja and Pathum Thani-1 were found highly stress tolerant and relatively high yielding; genotypes Look Pla and Lep Nok were stress tolerant, whereas genotypes Chor Lung, Hom Nang Kaew and Hom Chan were moderately tolerant genotypes. Hence, stress-tolerant genotypes could be potentially used for cultivation under rainfed and water-limited conditions, where TWS is predicted particularly in southern Thailand to stabilize rice productivity. Stress tolerance indices, including stress tolerance index (STI), geometric mean productivity (GMP), mean productivity index (M_{PRO}) and harmonic mean index (M_{HAR}), indicated strong and positive associations with GY under WW and TWS; thus, these indices could be used to indicate stress tolerance in rice crop breeding program aimed at a rapid screening of lowland rice genotypes for stress tolerance.

Keywords: lowland rice; terminal water stress; grain yield; stress indices; stress tolerance

Citation: Hussain, T.; Hussain, N.; Ahmed, M.; Nualsri, C.; Duangpan, S. Responses of Lowland Rice Genotypes under Terminal Water Stress and Identification of Drought Tolerance to Stabilize Rice Productivity in Southern Thailand. *Plants* **2021**, *10*, 2565. https://doi.org/10.3390/plants10122565

Academic Editor: Shigeto Morita

Received: 21 September 2021
Accepted: 20 November 2021
Published: 24 November 2021

1. Introduction

Rice is an important cereal after wheat that contributes to food security worldwide [1]. However, water stress has limited the production of both cereal crops [2]. Lowland rice systems contribute a major portion of rice production [3], and rainfed lowland rice is cultivated on approximately 6.2 million hectares worldwide [4]. In Thailand, rice is a major crop contributing to the food security and economy of the country. Even though rice production in southern Thailand contributes only 6% of the total rice production [5], it is of great importance to the regional food security. Rainfed lowland rice is a major production system in southern Thailand. However, rainfed lowland rice production systems are extremely vulnerable and variable in nature as water stress can occur at any crop growth stages. Climate change has also caused an increase in temperature and fluctuations in rainfall occurrence leading to regular heat and drought stress intervals [6,7]. Water stress is considered an important abiotic stress deleteriously affecting field crop productivity [6,8]. Rainfed lowland rice is cultivated in the rainy season in Thailand [7,9]. Due to seasonal variations in rainfall and occurrence of WS at different crop developmental stages, lowland rice production is drastically affected.

Water stress occurrence is critical under rainfed conditions as it affects plant growth and development [10]. Occurrence of water stress at various crop growth stages negatively influences the performance of specific attributes [11], leading to declined yield [12]. Timing of stress occurrence during early growth, mid-season and at terminal stages impact on severity of yield losses [13]. A stress event at early rice growth stages has an influence on leaf numbers and size, tillering capacity and stem height and affects panicle development, ultimately resulting in a reduced yield [14,15]. Water availability after the stress interval at the early growth stage helps plants recover, leading to lesser loss in yield. However, terminal water stress (TWS) intervals highly influence plant performance and lessens the chances of recovery to occur, leading to increased yield losses as rice is extremely sensitive to TWS [16]. TWS delays various plant development stages including panicle initiation and flowering [17], leading to spikelet sterility and reduction in number of panicles [18]. In addition, TWS causes abortion of ovules, deteriorates the grain filling process and alters source to sink distribution of assimilates, leading to reduced grain yield (GY) [19,20].

Stress-tolerant genotypes are genotypes that have the potential to maintain higher productivity under water stress [21]. Due to the extreme sensitivity of rice to TWS, different rice genotypes exhibit differential responses [10,18,22]. In the perspective of farmers, a stress-tolerant genotype is that which is highly capable of maintaining yield under limited water availability [23]. Therefore, high yielding genotypes under a diverse range of environments are desired and the cultivation of such genotypes could help to maintain rice productivity [2]. The GY of stress-tolerant genotypes is less affected under water stress as compared to stress susceptible genotypes. Cha-um et al. [24] reported that panicle size and filled grains of two stress tolerant rice genotypes were not significantly reduced as compared to two stress susceptible genotypes. According to Ichsan et al. [2], there are various local genotypes used by farmers around the world that have tolerance against water stress, in addition to stress-tolerant genotypes developed by research institutions and organizations. To enhance the resistance of rice against water stress, these genotypes are potential sources of germplasm, which are available in each growing season. In addition, it was observed that wild genotypes exhibited less decline and maintained GY under water stress as compared to cultivated genotypes [25]. Therefore, the identification and cultivation of stress tolerant genotypes from local germplasm could help to stabilize productivity under terminal water stressed environments.

Several techniques and procedures are used to study water stress tolerance in rice genotypes at different crop growth stages [14,18,26,27]. A drought stress scoring method was used as the main criteria for the assessment and selection of rice cultivars for stress tolerance at reproductive crop growth stages in field trials [28] and genotypes producing high yields under water stress were selected as stress-tolerant genotypes. Numerous stress tolerance indices have been used [6,29–38] based on mathematical association among yield production under well-watered (WW) and water stressed conditions. According to Clarke et al. [38] and Fernandez [32], stress indices are generally based on the stress sensitivity or stress tolerance of tested genotypes. In the selection of stress tolerant genotypes, these indices provide the effect of water stress based on yield losses occurring under stress as compared to optimal or WW conditions [39]. The relative yield performance of a specific genotype in comparison to other tested genotypes under the same water stress indicates stress tolerance [40], and measure of reduction in yield under stress refers to the stress susceptibility of a genotype [41]. The stress susceptibility index (SSI) for a genotype was suggested by Fischer and Maurer [37], whereas geometric mean productivity (GMP) and stress tolerance index (STI) were proposed by Fernandez [32]. The mean productivity

(M_{PRO}) index is an average yield under WW and water stressed conditions [33]. Harmonic mean index (M_{HAR}) was suggested by Schneider et al. [34]. The tolerance index (TI) is the difference in productivity between WW and water stressed conditions [35]. The yield stability index (YSI) was defined by Bouslama and Schapaugh [36]. All these indices have been used widely and are proposed in drought stress tolerance studies. However, the positive or negative associations of these indices with GY may vary. The significant differences among various indices were reported by Golabadi et al. [42] and Saba et al. [43] except SSI. Significant positive associations for GY under WW and stress indices (GMP, MP, STI, YSI, TOL and YI) and GY under water stressed conditions and stress indices (STI, GMP, MP, YSI and YI) have been observed by Golabadi et al. [42] and Arif et al. [44]. Hence, evaluating the associations of stress indices with GY under different environments is necessary. Therefore, the objectives of the current study were to (i) evaluate the performance of yield and yield attributes of Thai lowland rice genotypes under TWS and identify stress tolerant genotypes using stress indices; (ii) to identify promising stress indices which are correlated with GY under WW and TWS conditions for their use as rapid identifiers in rice crop breeding program for enhancing drought stress tolerance.

2. Results

2.1. Effect of Water Stress on Yield Performance and Productivity

In this study, different lowland rice genotypes were assessed based on the performance of yield and yield attributes in response to terminal water stress (TWS) applied at the terminal crop growth stage. In both years, treatment and genotype effect resulted as highly significant different ($p < 0.001$) for most of the yield attributes except a non-significant difference for days to maturity (DM) under treatment effect in 2018–2019 (Table 1). Interactions of genotype and treatment effects indicated non-significant differences in both years, except for a significant difference for days to flowering (DF) ($p < 0.05$) and a highly significant difference for DM ($p < 0.001$) in 2018–2019 (Table 1). DF, number of tillers (NT), number of panicles (NP), grain yield (GY) and biomass were highly significant different; DM was moderately significantly different, whereas no significant difference was observed for plant height (PH) under the effect of years. Mean comparisons indicated that all tested genotypes differed and a significant variability in performance prevailed under well-watered (WW) and TWS conditions. TWS resulted in a delay in flowering duration (Figure 1a,b) of all genotypes except genotype 9 in the first year (Figure 1a). Flowering occurred 4 days earlier in genotype 9 (Table 2). Delay in flowering duration ranged 2–19 days in the first year while 1–4 days in the second year (Table 2). The maximum delay in flowering was observed for the top three genotypes 7, 12 and 6 by 19, 8 and 6 days in the first year and for 11, 8, 3, 4 and 5 by 7 and 4 days in the second year, respectively. TWS caused delays in the maturity duration (Figure 1c,d) of most of the genotypes except for genotypes 7, 9 and 10 in the first year (Figure 1a). Genotypes 7, 9 and 10 matured earlier in the first year by 19, 5 and 11 days (Table 2). In the second year, maturity duration was increased for all genotypes under TWS (Figure 1d). The delay in maturity duration ranged 4–14 days in the first year while 3–8 days in the second year (Table 2). PH was reduced under TWS for all genotypes in both years (Figure 1e,f). PH was reduced 4–13% in the first year and 2–14% in the second year (Table 2). Reduction in PH was higher than 10% for genotypes 1, 2, 4, 7, 8 and 11 (Table 2). NT (Figure 2a,b) and NP (Figure 2c,d) were reduced under TWS (Figure 2). However, reduction in NT and NP ranged one–two tillers and panicles per plant (Table 2). No change was observed in NT of genotypes 1, 5 and 6 in the first year and genotypes 2, 5, 6, 8, 9 and 10 in the second year (Table 2). Genotypes 1 and 3 maintained their NP under TWS in the first year, whereas the NP of all genotypes were affected in the second year (Table 2). TWS caused decline in GY (Figure 3a,b) and biomass (Figure 3c,d) of all genotypes in both years (Figure 3). GY was decreased 17–45% in the first year, whereas 21–52% in the second year (Table 2). The GY of genotypes 1, 7, 9, 11 and 12 in the first year and GY of genotypes 2, 9, 11 and 12 in the second year decreased more than 30%, indicating a major decline in GY under TWS (Table 2). Similarly, biomass was reduced

20–41% in the first year and 15–38% in the second year (Table 2). Biomass reduction of genotypes 4 and 12 in the first year and genotypes 1, 3 and 10 in the second year was more than 30%, indicating a major decline in biomass under TWS (Table 2).

Table 1. The analysis of variance for days to flowering (DF), days to maturity (DM), plant height (PH), number of tillers (NT), number of panicles (NP), grain yield (GY) and biomass (BM) of twelve lowland rice genotypes.

Year	Traits	Treatment (T) Effect	Genotype (G) Effect	Interaction (T × G)	Year Effect
2018–2019	DF	***	***	*	***
	DM	ns	***	***	**
	PH	***	***	ns	ns
	NT	***	***	ns	***
	NP	***	***	ns	***
	GY	***	***	ns	***
	BM	***	***	ns	***
2019–2020	DF	***	***	ns	
	DM	***	***	ns	
	PH	***	***	ns	
	NT	**	***	ns	
	NP	***	***	ns	
	GY	***	***	ns	
	BM	***	***	ns	

***: highly significant ($p < 0.001$), **: moderately significant ($p < 0.01$), *: significant ($p < 0.05$), ns: non-significant.

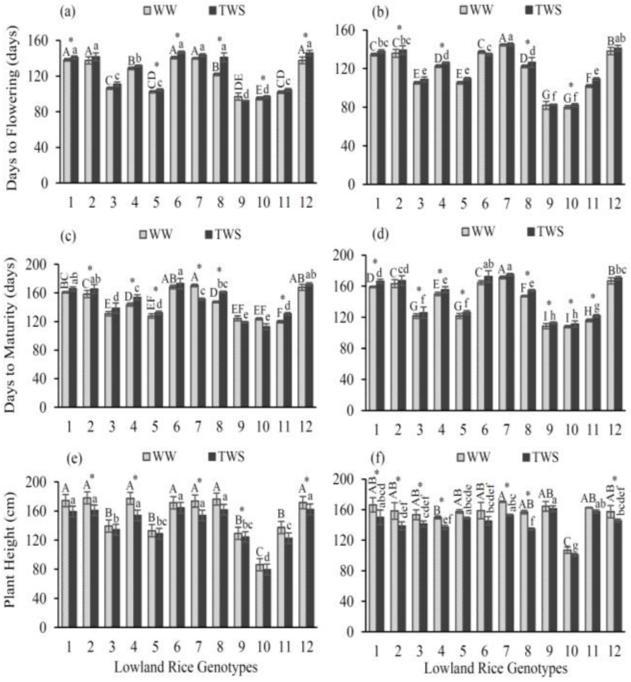


Figure 1. Days to flowering (**a**,**b**), days to maturity (**c**,**d**) and plant height (**e**,**f**) of twelve lowland rice genotypes under well-watered (WW) and terminal water stressed (TWS) conditions during 2018–2019 (**a**,**c**,**e**) and 2019–2020 (**b**,**d**,**f**). Vertical bars show ± standard errors for means of three repetitions. Capital letters represent the significant ($p < 0.05$) differences among genotypes in WW condition. Small letters represent the significant ($p < 0.05$) differences among genotypes in TWS condition. Centered stars above each pair of the bars represent the significance of parameters for each genotype under WW and TWS conditions.

Table 2. Changes in performance of yield and yield attributes of twelve lowland rice genotypes under terminal water stressed conditions. Changes in days to flowering (DF) and days to maturity (DM) are presented by difference in days. Changes in number of tillers (NT) and number of panicles (NP) are presented by difference in numbers (no.), whereas changes in plant height (PH), grain yield (GY) and biomass (BM) are presented by % difference.

Genotypes	2018–2019							2019–2020						
	DF Days	DM Days	PH %	NT no.	NP no.	GY %	BM %	DF Days	DM Days	PH %	NT no.	NP no.	GY %	BM %
1	3	5	−9	0	0	−39	−20	3	7	−10	−1	−1	−25	−38
2	4	7	−10	−1	−1	−26	−24	3	4	−12	0	−1	−43	−20
3	5	8	−4	1	−0	−28	−21	4	4	−8	−2	−2	−26	−30
4	3	10	−13	−1	−1	−18	−41	4	6	−8	−1	−1	−26	−24
5	2	5	−3	0	−1	−21	−21	4	5	−5	0	−1	−24	−19
6	6	5	−4	0	−1	−23	−28	−2	8	−8	0	−1	−22	−24
7	4	−19	−11	−1	−1	−31	−20	1	4	−10	−1	−1	−21	−23
8	19	14	−8	−1	−1	−17	−25	4	7	−14	0	−1	−25	−22
9	−4	−5	−4	−1	−2	−30	−28	1	4	−2	0	−1	−52	−17
10	2	−11	−8	−1	−1	−26	−26	2	3	−6	0	−1	−36	−38
11	3	11	−11	−1	−1	−45	−29	7	6	−3	−1	−1	−34	−19
12	8	4	−5	−1	−1	−36	−38	3	3	−7	−1	−1	−33	−15

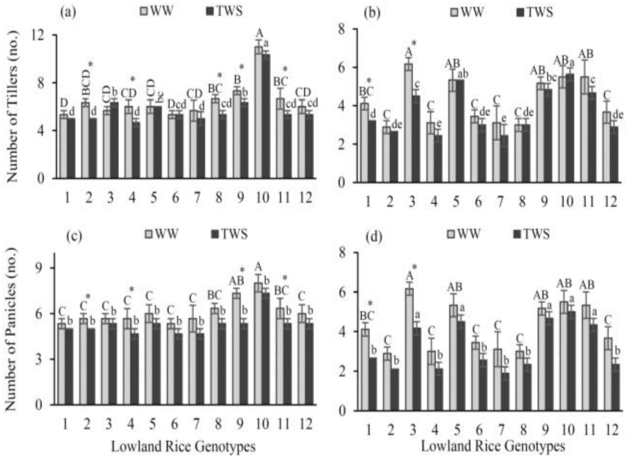


Figure 2. Number of tillers (**a**,**b**), and number of panicles (**c**,**d**) of twelve lowland rice genotypes under well-watered (WW) and terminal water stressed (TWS) conditions during 2018–2019 (**a**,**c**) and 2019–2020 (**b**,**d**). Vertical bars show ± standard errors for means of three repetitions. Capital letters represent the significant ($p < 0.05$) differences among genotypes in WW condition. Small letters represent the significant ($p < 0.05$) differences among genotypes in TWS condition. Centered stars above each pair of the bars represent the significance of parameters for each genotype under WW and TWS conditions.

2.2. Association among Yield and Yield Attributes under Terminal Water Stress

Figure 4 indicates combined correlations among yield and yield attributes, including the DF, DM, PH, NT, NP, GY and biomass of twelve lowland rice genotypes. Under WW condition, highly positive associations among DF and biomass (0.89), DF and DM (0.98), DM and biomass (0.86), NT and NP (0.95), moderately positive associations among DF and PH (0.82), DM and PH (0.76), PH and biomass (0.82) and positive associations among PH and GY (0.56) and GY and biomass (0.64) were observed. Whereas highly negative associations among DF and NP (−0.94), DM and NP (−0.90), DM and NT (−0.84), PH and NP (−0.87), PH and NT (−0.97), NT and biomass (−0.88) and NP and biomass (−0.87) were detected. Under the TWS condition, highly positive associations among DF and biomass (0.89), DF and DM (0.99), DM and biomass (0.91), PH and biomass (0.86), NT and

NP (0.97) and moderately positive associations among DF and PH (0.73), DM and PH (0.74) and GY and biomass (0.73) were observed. Whereas highly negative associations among DF and NP (−0.92), DF and NT (−0.85), DM and NP (−0.91), DM and NT (−0.84), PH and NP (−0.85), PH and NT (−0.92), NT and biomass (−0.83) and NP and biomass (−0.86) were detected (Figure 4).

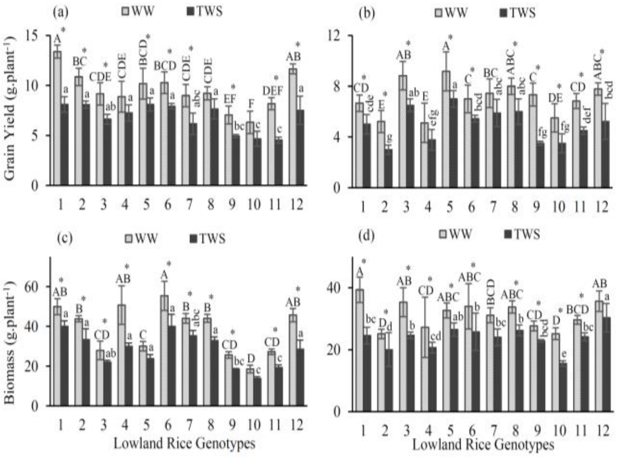


Figure 3. Grain yield (**a**,**b**) and biomass (**c**,**d**) of twelve lowland rice genotypes under well-watered (WW) and terminal water stressed (TWS) conditions during 2018–2019 (**a**,**c**) and 2019–2020 (**b**,**d**). Vertical bars show ± standard errors for means of three repetitions. Capital letters represent the significant ($p < 0.05$) differences among genotypes in WW condition. Small letters represent the significant ($p < 0.05$) differences among genotypes in TWS condition. Centered stars above each pair of the bars represent the significance of parameters for each genotype under WW and TWS conditions.

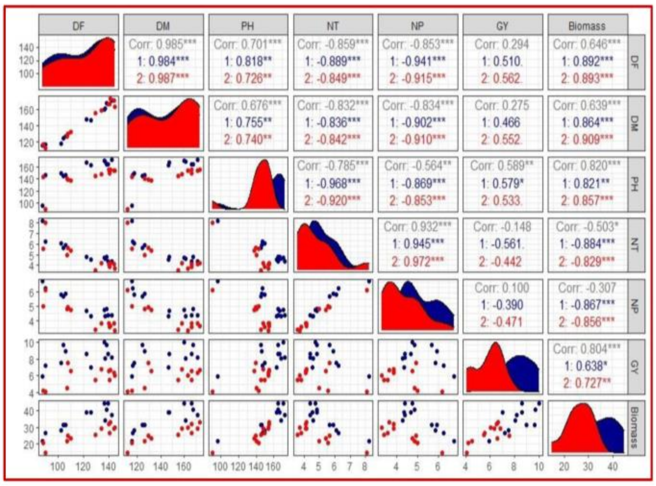


Figure 4. Combined correlation matrix, scatter plot and data distribution for yield and yield attributes of twelve lowland rice genotypes under well-watered (WW) and terminal water stressed (TWS) conditions. Diagonals indicate the distribution of each parameter. Scatter plots are shown in the bottom of diagonals. Values of correlations and significance are indicated with stars and are shown on the top of the diagonal. Values and stars in the blue color (1) indicate correlation among parameters in WW whereas, values and stars in the red color (2) indicate correlation among parameters in TWS conditions. DF: days to flowering, DM: days to maturity, PH: plant height, NT: number of tillers, PN: number of panicles, GY: grain yield, ***: highly significant ($p < 0.001$), **: moderately significant ($p < 0.01$), *: significant ($p < 0.05$).

2.3. Genotypic Classification Corresponding to Stress Indices

Seven stress tolerance indices, including SSI, GMP, STI, M_{PRO}, M_{HAR}, TI and YSI, were computed to distinguish stress-tolerant genotypes from stress-sensitive ones based on GY and RY and the promising values of stress indices under TWS conditions (Table 3). In addition, stress tolerance indices were also studied for hierarchical clustering using a heatmap (Figure 5) and the assessed genotypes were categorized into two main groups: (1) stress tolerant and (2) stress susceptible group and four subgroups (A–D). Subgroup A consisted of four genotypes with the highest GY, RY and stress indices values under TWS; hence, these genotypes could be considered as highly tolerant genotypes. Subgroup B consisted of two genotypes with higher GY, RY and higher stress indices values under TWS; hence, they could be considered as stress-tolerant genotypes. Subgroup C was moderate stress tolerant (three genotypes), as they exhibited intermediate values for GY, RY and stress indices. Subgroup D also consisted of three genotypes that exhibited lower values for GY, RY and stress indices; hence, these genotypes were considered stress susceptible genotypes correspondingly.

Table 3. Values of seven stress tolerance indices for lowland rice genotypes based on grain yield observed under well-watered and terminal water stressed conditions. (Values taken as average from two growing years 2018–2019 and 2019–2020).

Lowland Rice Genotypes		Y_{WW}	Y_{TWS}	RY_{TWS}	SSI	GMP	STI	M_{PRO}	M_{HAR}	TI	YSI
1	Look Pla	10.02	6.55	0.87	1.19	8.10	6.75	8.29	7.92	3.47	0.65
2	Hom Nang Kaew	8.04	5.54	0.73	1.07	6.67	4.58	6.79	6.56	2.50	0.69
3	Pathum Thani-1	9.00	6.56	0.87	0.93	7.68	6.07	7.78	7.59	2.43	0.73
4	Hom Chan	7.00	5.52	0.73	0.72	6.21	3.97	6.26	6.17	1.48	0.79
5	Hom Pathum	9.68	7.55	1.00	0.75	8.54	7.51	8.61	8.48	2.13	0.78
6	Dum Ja	8.64	6.68	0.89	0.78	7.60	5.94	7.66	7.54	1.96	0.77
7	Chor Lung	8.22	6.03	0.80	0.91	7.04	5.10	7.12	6.96	2.18	0.73
8	Sang Yod	8.61	6.83	0.90	0.71	7.66	6.04	7.72	7.61	1.78	0.79
9	Khao Dawk Mali-105	7.19	4.22	0.56	1.41	5.51	3.12	5.71	5.32	2.97	0.59
10	RD-15	5.91	4.08	0.54	1.06	4.91	2.48	5.00	4.83	1.82	0.69
11	Tia Malay Dang	7.51	4.52	0.60	1.36	5.82	3.49	6.01	5.64	2.99	0.60
12	Lep Nok	9.72	6.37	0.84	1.18	7.87	6.37	8.04	7.69	3.35	0.66

Y_{WW} is mean yield under well-watered conditions, Y_{TWS} is mean yield under terminal water stressed conditions, $RY_{\mathbf{TWS}}$ is relative yield under water stressed conditions, SSI is stress susceptibility index, GMP is geometric mean productivity, STI is stress tolerance index, M_{PRO} is mean productivity index, M_{HAR} is harmonic mean index, TI is tolerance index and YSI is yield stability index.

2.4. Association among Stress Tolerance Indices and Grain Yield

Highly positive associations were observed among Y_{WW} and Y_{TWS} (0.85), Y_{WW} and GMP (0.95), Y_{WW} and STI (0.95), Y_{WW} and M_{PRO} (0.97), Y_{WW} and M_{HAR} (0.94), Y_{TWS} and GMP (0.97), Y_{TWS} and STI (0.97), Y_{TWS} and M_{PRO} (0.96) and Y_{TWS} and M_{HAR} (0.98). Whereas Y_{TWS} and YSI (0.64) were positively and Y_{TWS} and SSI (−0.64) were negatively correlated (Figure 6). Correlation assessment among stress indices revealed that there were highly positive associations among GMP, STI, M_{PRO} and M_{HAR} (1.00), whereas there was a moderate positive association among SSI and TI (0.81). In contrast, a highly negative association among SSI and YSI (−1.00) and moderate negative association among TI and YSI (−0.81) were observed (Figure 6).

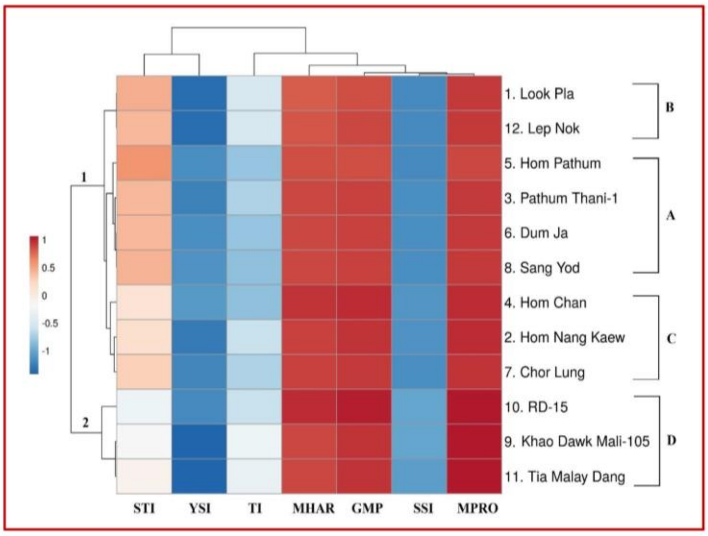


Figure 5. Heatmap of stress indices among twelve lowland rice genotypes under well-watered and terminal water stressed conditions. Group 1 refers to stress-tolerant genotypes, whereas group 2 refers to stress susceptible genotypes. Subgroup A is highly stress tolerant; subgroup B is stress tolerant; subgroup C is moderately stress tolerant, whereas subgroup group D is stress susceptible. Dark red and dark blue colors indicate higher correlation followed by light red and light blue with minimum or no correlation among genotypes and indices.

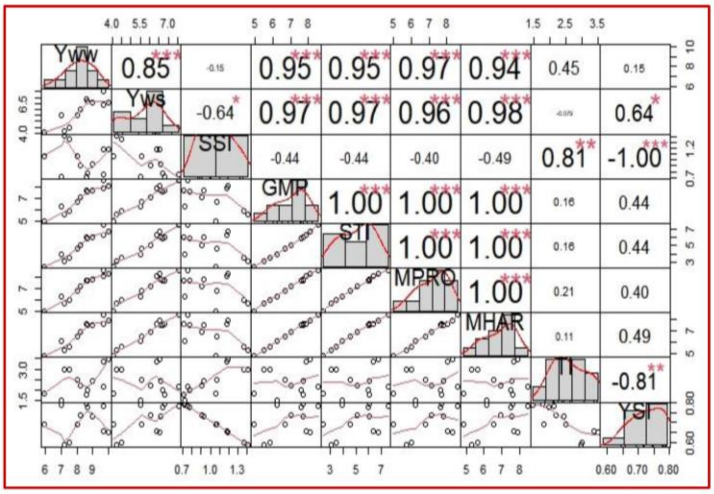


Figure 6. Correlation matrix (Pearson's) of grain yield under well-watered (Y_{WW}), grain yield under terminal water stress (Y_{WS}), stress susceptibility index (SSI), geometric mean productivity (GMP), stress tolerance index (STI), mean productivity index (M_{PRO}), harmonic mean index (M_{HAR}), tolerance index (TI) and yield stability index (YSI) for lowland rice genotypes. Values were taken as average from two growing years 2018–2019 and 2019–2020. Diagonals indicate the distribution of each parameter. Scatter plots with lines are shown in the bottom of diagonals. Values of correlations and significance levels indicated with stars are shown on the top of diagonals. Correlation coefficients are proportional to intensity of color and size of correlation values. ***: highly significant ($p < 0.001$), **: moderately significant ($p < 0.01$), *: significant ($p < 0.05$).

3. Discussion

Water stress is critical to rice crop productivity, especially in rainfed lowland environments. Rainfed lowland rice is vulnerable as it is dependent upon natural precipitation. Variability in seasonal rainfalls and the occurrence of hot, dry spells have increased in rainfed areas. According to Campozano et al. [45] and Spinoni et al. [46], water stress occurrence is expected to be more common, severe and extended as a result of variations in rainfalls due to climate change. Water stress due to climate change would impact on rainfed rice crop productivity. Rice is extremely sensitive to water stress [2,14,15] and rice productivity is significantly affected under terminal water stress (TWS). Different rice genotypes exhibit differential response to TWS, producing a range of grain yield (GY). Hence, it becomes critical to evaluate the performance of yield attributes and yield productivity of rice genotypes under TWS and to identify stress-tolerant genotypes. This strategy will help to stabilize the rice productivity under TWS occurrence and provide sufficient information for genotypic stress tolerance. Furthermore, identification of promising stress tolerance indices under well-watered (WW) and TWS could be useful for their use in rapid selection process for water stress tolerance in the rice crop breeding program.

Twelve lowland rice genotypes were evaluated under WW and TWS conditions in the current experimental study to examine their responses and identify stress-tolerant genotypes. It was observed that all genotypes indicated significant variations in their performance for yield and yield attributes under WW and TWS conditions. Generally, in our study, day to flowering (DF) and day to maturity (DM) were increased and DF and DM were significantly positive and strongly correlated. TWS caused delay in panicle emergence; hence, delaying the flowering time of most of genotypes. Delayed flowering in rice was also observed under water stress by Davatgar et al. [47], Saikumar et al. [48] and Hussain et al. [49]. Late flowering in rice under TWS is considered as a common impact of TWS [50,51]. Delayed panicle emergence and longer grain filling duration increased the time to maturity, thus increasing the total irrigation water input under TWS. All genotypes consumed more water input in delayed maturity under TWS after resuming irrigation. Plant height (PH) was decreased for all genotypes possibly due to limited water availability resulting in reduced cell elongation. Reduction in the PH of rice genotypes under water stress has been reported in numerous studies [47–49,52,53]. Significant positive correlation was observed among PH and GY and biomass while significant negative associations were indicated among PH and number of panicles (NP) and number of tillers (NT). NT and NP were reduced for all genotypes under TWS in both years. Increase in tiller mortality with increased duration of water stress has been reported by Zain et al. [54]. According to Davatgar et al. [47], water stress at terminal crop stages alters the source to sink association, which results in a reduced number of panicles. NT and NP were highly correlated, which indicated that more tillers produced more panicles. Stress induced at the terminal stage significantly reduced GY and biomass of all genotypes. TWS increases spikelet sterility and reduced grain weight resulting in declined final GY. Reduction in final GY under various water stress levels have been reported in several studies [19,48,55,56]. Biomass of all genotypes was reduced under TWS. However, genotypes with higher biomass produced higher GY. Strong positive association among GY and biomass was observed, and our results were in line with the findings of Torres and Henry [53], Torres et al. [56] and Kumar et al. [55]. High variability among genotypes for their performance of yield and yield attributes indicated that the genotypes could be used in the rice crop breeding program to exploit specific plant attributes such as early maturity, shorter plant height, higher tillering capacity and better GY under TWS for improvement in drought tolerance.

Explored genotypes exhibited highly significant variability in their GY productivity under WW and TWS conditions, which demonstrated that studied genotypes possessed significant genetic variability. Genotypes were differentiated based on GY productivity, relative yield (RY) and performance of computed stress indices which were further categorized into stress tolerant, and stress susceptible groups based on hierarchical clustering. Subgroup A was highly stress tolerant; subgroup B was stress tolerant; subgroup C was moderately stress tolerant, whereas subgroup group D was found stress susceptible. Highly stress-tolerant genotypes indicated the highest GY, RY and improved indices under TWS, whereas tolerant genotypes indicated higher GY, RY and better indices. However, stress-susceptible genotypes indicated lowered GY, RY and inadequate performance for stress indices. According to GY and performance of stress indices, hierarchical clustering helped to identify similarly acting genotypes under evaluation. Highly significant and positive correlation observed among GY under WW and GY under TWS exhibited that genotypes that performed better in WW conditions also produced well under TWS. Similar findings were also reported by Raman et al. [57]. Strongly significant and positive associations of stress indices, GMP, STI, M_{PRO}, M_{HAR} with GY under WW and TWS were observed, which indicated that GMP, STI, M_{PRO} and M_{HAR} were better performer and promising indices to evaluate rice genotypes under WW and TWS conditions. Raman et al. [57] found that GMP and STI were suitable indices in identifying entries under non−stressed and extreme water stressed conditions. GMP has also been reported [31] as a better predictor for GY under water stress when stress was applied at the flowering stage. SSI, TI and YSI were not correlated with GY under WW. SSI was negatively correlated, YSI was significant and positively correlated, whereas TI was not correlated with GY under TWS. Weak associations of SSI, TI and YSI indicated that these indices were not adequate for evaluating lowland rice genotypes under TWS. Anwar et al. [29] also found that SSI, TI and YSI were not appropriate predictors of GY under WW and stressed conditions for evaluating wheat genotypes for drought stress tolerance. GMP, STI, M_{PRO} and M_{HAR} have been found to be suitable stress indices to evaluate genotypes under WW and stressed conditions for various crops including rice, wheat, maize and soyabean. Therefore, it was concluded that GMP, STI, M_{PRO} and M_{HAR} were appropriate indices for their use as rapid selection criteria for screening stress tolerant lowland rice genotypes grown under water stressed conditions, especially when stress is applied at reproductive or terminal crop stages.

4. Materials and Methods

4.1. Plant Material

Twelve commonly cultivated Thai lowland rice genotypes including Look Pla (1), Hom Nang Kaew (2), Pathum Thani-1 (3), Hom Chan (4), Hom Pathum (5), Dum Ja (6), Chor Lung (7), Sang Yod (8), Khao Dawk Mali-105 (9), RD-15 (10), Tia Malay Dang (11) and Lep Nok (12) were used for assessment in this study. Germplasm for genotypes 2, 4, 6, 7, 8 and 11 were collected from Phatthalung Rice Research Center, Phatthalung, Thailand (7°33′59.0″ N, 100°07′32.7″ E) (https://ptl-rrc.ricethailand.go.th/address.php (accessed on 21 September 2021)). Germplasm for genotypes 3, 9 and 10 was collected from commercial seed market. Whereas seeds for genotypes 1, 5 and 12 were collected from farmers in Songkhla province, Thailand.

4.2. Site Description and Crop Management

This research study was conducted in the sheds located at field research area (7°00′14.5″ N, 100°30′14.7″ E) of Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla Province, in Southern Thailand (Figure 7) for two consecutive years during 2018–2019 and 2019–2020. Topsoil was prepared and a uniform soil sample was collected prior to soil filling in planting containers for soil properties analysis. Soil physicochemical properties observed for both years are indicated in Table S1. Planting was performed on 12 September 2018 and 2 September 2019 for 2018–2019 and 2019–2020, respectively. Completely randomized design (CRD) with three repeats was used to design the experiments for both years. Seeds were sown at 5 cm soil depth by direct seeding in containers having the capacity of 12 kg soil. Three plants were maintained in each container after thinning at seedling stage. Experiments were subjected to two treatments, including control under well-watered (WW) and drought under terminal water stressed (TWS) conditions. Each genotype in treatments was placed in separate group of containers. Automatic drip irrigation system, having the dripper head water flow capacity of 8 litters of water per hour, was installed to apply irrigation for specified time for each day. Plants in both treatments were irrigated equally till 75 days after planting (DAP). To induce TWS, irrigation was stopped at 75th DAP in TWS treatment only for 13 days until temporary wilting was observed, following which irrigation was resumed till maturity. Irrigation water amount as total water consumption for each genotype in each treatment for both growing years was calculated by dripper water flow capacity, irrigation time duration for each day and size of container used in experiments. Total water consumption for genotypes in WW and TWS conditions for each year is shown in Figure S1. Thinning, weeding, fertilization and insect pest management was completed through standard crop management practices.

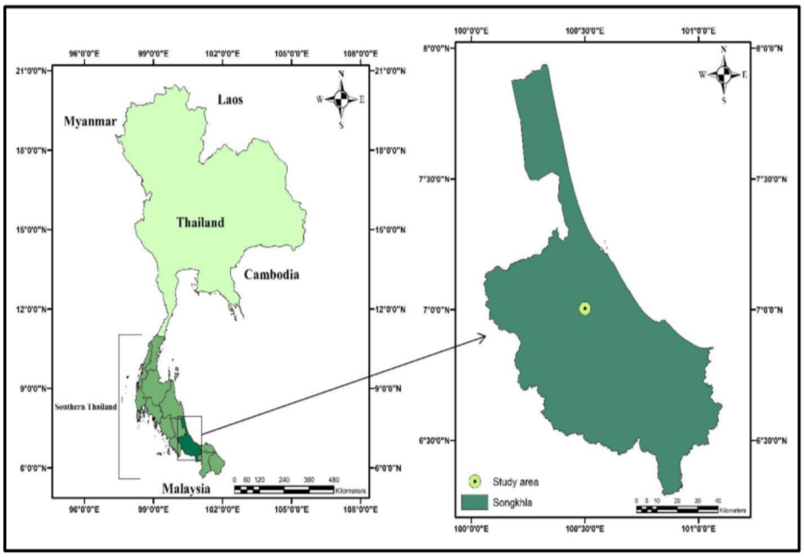


Figure 7. Experimental location at Faculty of Natural Resources, Prince of Songkla University, Songkhla, Thailand (Source: adapted from ArcGIS: $v-10.5$).

4.3. Crop Data Collection

Days to flowering (DF) and days to maturity (DM) were recorded at 50% of panicle emergence and 50% plants at physiological maturity, respectively, from planting date. Plant height (PH) was measured from base of the stems to the flag leaf tip. GY and biomass were recorded by randomly selected three plants for each genotype from each replication as well as each treatment. Plants were hand−harvested, and number of tillers (NT) and number of panicles (NP) were counted per plant as an average from three plants. Grain and plant biomass samples were dried to obtain dry weight in an oven at 70 °C for different time durations till constant weight was observed.

4.4. Computation of Stress Tolerance Indices

Stress tolerance indices were computed to differentiate and identify stress tolerant genotypes from stress susceptible genotypes. GY under WW and TWS conditions was taken as average over 2 years of data to compute stress indices according to methodology adopted by Mansour et al. [6]. Seven different stress tolerance indices comprising stress susceptibility index (SSI) (1) [37], geometric mean productivity (GMP) (2) [32], stress tolerance index (STI) (3) [32], mean productivity index (M_{PRO}) (4) [33], harmonic mean index (M_{HAR}) (5) [34], tolerance index (TI) (6) [35] and yield stability index (YSI) (7) [36] were computed. Mean relative yield (RY) indicates the performance of specific genotype in relation to other examined genotypes under similar level of water stress. Hence, RY under TWS was calculated as GY of each genotype under TWS divided by highest GY achieved in all genotypes. Genotypes with higher GY under WW and TWS, higher RY and exhibiting promising values for stress tolerance indices were classified as stress tolerant genotypes.

$$\text{Stress Suceptibility Index (SSI)} = \left(1 - \frac{Y_{TWS}}{Y_{WW}}\right) / \text{D} \tag{1}$$

$$\text{Geometric Mean Productivity (GMP)} = \sqrt{Y_{WW} \times Y_{TWS}} \tag{2}$$

$$\text{Stress Tolerance Index (STI)} = (Y_{TWS} \times Y_{WW}) / \text{aww} \tag{3}$$

$$\text{Mean Productivity Index } (M_{PRO}) = (Y_{TWS} + Y_{WW}) / 2 \tag{4}$$

$$\text{Harmonic Mean Index } (M_{HAR}) = 2(Y_{WW} \times Y_{TWS}) / (Y_{WW} + Y_{TWS}) \tag{5}$$

$$\text{Tolerance Index (TI)} = (Y_{WW} - Y_{TWS}) \tag{6}$$

$$\text{Yield Stability Index (YSI)} = Y_{TWS} / Y_{WW} \tag{7}$$

where, Y_{TWS} = mean yield under terminal water stressed (TWS) condition, Y_{WW} = mean yield under well-watered (WW) condition, D = environmental stress intensity, which is 1 (mean yield of all genotypes under TWS/mean yield of all genotypes under WW condition) and aww is an average value for all examined genotypes for grain yield under WW conditions.

4.5. Analysis of Data

Data collected from 2 years of experiments was used to test the significance of results and mean comparisons in R software. Two-way analysis of variance (ANOVA) was performed for yield and yield attributes of all genotypes from three replicates with effect to applied treatments. The effect of years among 2018–2019 and 2019–2020 was also examined. Mean comparisons were made by using the least significant difference (LSD) and p-value < 0.05 was considered as significantly different [58], which was represented using capital and small letters and stars. Pearson's correlation analysis was used to correlate yield and yield attributes as well as computed stress tolerance indices. "Corr" and "GGally" packages of R program were used to compute correlation matrices and visuals. ClustVis [59] software was used to create heatmap and hierarchical clustering [58] for various stress indices taken as an average over two years.

5. Conclusions

Terminal water stress (TWS) significantly reduced the performance of yield and yield attributes. Studied genotypes were found unique in their yield potential as they reflected different responses under well-watered (WW) and TWS conditions. Genotypes Look Pla (1), Pathum Thani-1 (3) Hom Pathum (5), Dum Ja (6) Sang Yod (8), and Lep Nok (12) were found water stress tolerant as they produced relatively higher grain yield (GY), promising values for stress indices and improved performance under TWS. The performance of stress tolerant genotypes was less affected under TWS as compared to stress susceptible genotypes. Hence, these genotypes are potentially recommended for sustaining yield productivity in such environments where TWS occurrence is predicted, especially in southern Thailand. Stress-tolerant genotypes could be used in obtaining better GY under TWS and for improvement in drought tolerance. Strong associations of GMP, STI, M_{PRO} and M_{HAR} with GY under WW and, especially under TWS conditions, indicated that these indices could be used to indicate stress tolerance in rice crop breeding programs for a rapid selection process.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/plants10122565/s1, Table S1: Details of soil properties analyzed for experimental soil for 2018–2019 and 2019–2020. Figure S1: Total amount of irrigation water consumed by lowland rice genotypes under well-watered (WW) and terminal water stressed (TWS) conditions during 2018–2019 (a) and 2019–2020 (b).

Author Contributions: T.H. and S.D. conceived and conceptualized the idea. T.H. and N.H. performed the literature review. S.D. and M.A. provided technical expertise to strengthen the basic idea. T.H. conducted experiments and N.H. helped in the collection of data and its analysis. S.D., acquired funds, proofread, and provided intellectual guidance. C.N. proofread the manuscript. All authors read the first draft, helped in revision and approved the article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by Graduate School, Prince of Songkla University and Faculty of Natural Resources, Prince of Songkla University. Research was part of Ph.D. study, supported by Higher Education Research Promotion and the Thailand's Education Hub for Southern Region of ASEAN Countries, Project Office of the Higher Education Commission.

Data Availability Statement: The data presented in this study are available in this article and supplementary materials.

Acknowledgments: Authors are thankful to anonymous reviewers for providing valuable comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FAOSTAT. FAO (Online). 2020. Available online: http://www.fao.org/faostat/en/#home (accessed on 18 August 2021).
2. Ichsan, C.N.; Basyah, B.; Zakaria, S.; Efendi, E. Differences of water status and relationship with roots growth and yield of rice under water stress. *Syst. Rev. Pharm.* **2020**, *11*, 611–618.
3. Varinruk, B. Thailand rice production and rice research and development on climate change. In Proceedings of the Workshop on Strengthening APEC Cooperation on Food Security and Climate Change, Ha Noi, Vietnam, 19–21 April 2017.
4. USDA Thailand: Irrigation Shortage Reduces 2015/16 Rice Production. 2015. Available online: https://ipad.fas.usda.gov/highlights/2015/10/th/index.htm (accessed on 25 June 2020).
5. GRiSP. *Rice Almanac*, 4th ed.; International Rice Research Institute: Los Baños, Philippines, 2013.
6. Mansour, E.; Desoky, E.S.M.; Ali, M.M.A.; Abdul-Hamid, M.I.; Ullah, H.; Attia, A.; Datta, A. Identifying drought-tolerant genotypes of faba bean and their agro-physiological responses to different water regimes in an arid Mediterranean environment. *Agric. Water Manag.* **2021**, *247*, 106754. [CrossRef]
7. Ullah, H.; Santiago−Arenas, R.; Ferdous, Z.; Attia, A.; Datta, A. *Improving Water Use Efficiency, Nitrogen Use Efficiency, and Radiation Use Efficiency in Field Crops under Drought Stress: A Review*, 1st ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2019; Volume 156, ISBN 9780128175989.
8. Ray, D.K.; West, P.C.; Clark, M.; Gerber, J.S.; Prishchepov, A.V.; Chatterjee, S. Climate change has likely already affected global food production. *PLoS ONE* **2019**, *14*, e0217148. [CrossRef] [PubMed]
9. Watcharin, S.; Kanrob, P.; Charassri, N.; Nattapon, J. Improving photoperiod insensitivity of a Thai upland rice variety by marker−assisted foreground selection. *Int. J. Agric. Technol.* **2020**, *16*, 199–206.
10. Chutia, J.; Borah, S.P. Water stress effects on leaf growth and chlorophyll content but not the grain yield in traditional rice (*Oryza sativa* Linn.) genotypes of Assam, India II. Protein and proline status in seedlings under PEG induced water stress. *Am. J. Plant Sci.* **2012**, *3*, 971–980. [CrossRef]
11. Ahmadikhah, A.; Marufinia, A. Effect of reduced plant height on drought tolerance in rice. *Biotech* **2016**, *6*, 221. [CrossRef]
12. Zhou, J.; Wang, X.; Jiao, Y.; Qin, Y.; Liu, X.; Zhang, Q.; Fan, L.; Wang, X. Global genome expression analysis of rice in response to drought and high-salinity stresses in shoot, flag leaf, and panicle. *Plant Mol. Biol.* **2007**, *63*, 591–608. [CrossRef]
13. Fischer, K.; Lafitte, R.; Fukai, S.; Atlin, G.; Hardy, B. *Breeding Rice for Drought-Prone Environments*; International Rice Research Institute: Los Baños, Philippines, 2003; ISBN 9712201899.
14. Singh, B.; Reddy, K.R.; Redoña, E.D.; Walker, T. Screening of rice cultivars for morpho-physiological responses to early-season soil moisture stress. *Rice Sci.* **2017**, *24*, 322–335. [CrossRef]
15. Swain, P.; Raman, A.; Singh, S.P.; Kumar, A. Breeding drought tolerant rice for shallow rainfed ecosystem of eastern India. *Field Crops Res.* **2017**, *209*, 168–178. [CrossRef]
16. Agarwal, P.; Parida, S.K.; Raghuvanshi, S.; Kapoor, S.; Khurana, P.; Khurana, J.P.; Tyagi, A.K. Rice improvement through genome-based functional analysis and molecular breeding in India. *Rice* **2016**, *9*, 5. [CrossRef]
17. Rahman, M.T.; Islam, M.T.; Islam, M.O. Effect of water stress at different growth stages on yield and yield contributing characters of transplanted Aman rice. *Pak. J. Biol. Sci.* **2002**, *5*, 169–172. [CrossRef]
18. Yue, B.; Xue, W.; Xiong, L.; Yu, X.; Luo, L.; Cui, K.; Jin, D.; Xing, Y.; Zhang, Q. Genetic basis of drought resistance at reproductive stage in rice: Separation of drought tolerance from drought avoidance. *Genetics* **2006**, *172*, 1213–1228. [CrossRef] [PubMed]
19. Pantuwan, G.; Fukai, S.; Cooper, M.; Rajatasereekul, S. Yield response of rice (*Oryza sativa* L.) genotypes to drought under rainfed lowlands 4. Vegetative stage screening in the dry season. *Field Crops Res.* **2004**, *89*, 281–297. [CrossRef]
20. Ovenden, B.; Milgate, A.; Lisle, C.; Wade, L.J.; Rebetzke, G.J.; Holland, J.B. Selection for water—Soluble carbohydrate accumulation and investigation of genetic × environment interactions in an elite wheat breeding population. *Theor. Appl. Genet.* **2017**, *130*, 2445–2461. [CrossRef] [PubMed]

21. Farooq, M.; Kobayashi, N.; Ito, O.; Wahid, A.; Serraj, R. Broader leaves result in better performance of indica rice under drought stress. *J. Plant Physiol.* **2010**, *167*, 1066–1075. [CrossRef]
22. Wadhwa, R.; Kumari, N.; Sharma, V. Varying light regimes in naturally growing Jatropha curcus: Pigment, proline and photosynthetic performance. *J. Stress Physiol. Biochem.* **2010**, *6*, 67–80.
23. Blum, A. Drought adaptation in cereal crops. In *Drought Adaptation in Cereals*; Haworth Food Products Press: New York, NY, USA, 2006; pp. 301–333.
24. Cha-um, S.; Yooyongwech, S.; Supaibulwatana, K. Water deficit stress in the reproductive stage of four indica rice (*Oryza sativa* L.) genotypes. *Pak. J. Bot.* **2010**, *42*, 3387–3398.
25. Majidi, M.M.; Tavakoli, V.; Mirlohi, A.; Sabzalian, M.R. Wild safflower species (*Carthamus oxyacanthus* Bieb.): A possible source of drought tolerance for arid environments. *Aust. J. Crop Sci.* **2011**, *5*, 1055–1063.
26. Todaka, D.; Shinozaki, K.; Yamaguchi-shinozaki, K. Recent advances in the dissection of drought-stress regulatory networks and strategies for development of drought-tolerant transgenic rice plants. *Front. Plant Sci.* **2015**, *6*, 84. [CrossRef]
27. Hussain, N.; Ahmed, M.; Duangpan, S.; Hussain, T.; Taweekun, J. Potential impacts of water stress on rice biomass composition and feedstock availability for bioenergy production. *Sustainability* **2021**, *13*, 10449. [CrossRef]
28. IRRI. *Standard Evaluation System for Rice*, 5th ed.; The Philippines International Rice Research Institute: Los Banos, CA, USA, 2014.
29. Anwar, J.; Subhani, G.M.; Hussain, M.; Ahmad, J.; Hussain, M.; Munir, M. Drought tolerance indices and their correlation with yield in exotic wheat genotypes. *Pak. J. Bot.* **2011**, *43*, 1527–1530.
30. Rashid, A.; Saleem, Q.; Nazir, A.; Kazım, H.S. Yield potential and stability of nine wheat varieties under water stress conditions. *Int. J. Agric. Biol.* **2003**, *5*, 7–9.
31. Wasae, A. Evaluation of drought stress tolerance based on selection indices in Haricot Bean varieties exposed to stress at different growth stages. *Int. J. Agron.* **2021**, *2021*, 6617874. [CrossRef]
32. Fernandez, G.C. Effective selection criteria for assessing plant stress tolerance. In Proceedings of the International Symposium on Adaptation of Vegetables and other Food Crops in Temperature and Water Stress, Shanhua, Taiwan, 13–16 August 1992; pp. 257–270.
33. Hossain, A.B.S.; Sears, R.G.; Cox, T.S.; Paulsen, G.M. Desiccation tolerance and its relationship to assimilate partitioning in winter wheat. *Crop Sci.* **1990**, *30*, 622–627. [CrossRef]
34. Schneider, K.A.; Rosales-serna, R.; Ibarra-perez, F.; Cazares-enriquez, B.; Acosta-gallegos, J.A.; Ramirez-vallejo, P.; Wassimi, N.; Kelly, J.D. Improving common bean performance under drought stress. *Crop Sci.* **1997**, *37*, 43–50. [CrossRef]
35. Rosielle, A.A.; Hamblin, J. Theoretical aspects of selection for yield in stress and non-stress environments. *Crop Sci.* **1981**, *21*, 943–946. [CrossRef]
36. Bouslama, M.; Schapaugh, W.T. Stress tolerance in soybeans. I. Evaluation of three screening techniques for heat and drought tolerance. *Crop Sci.* **1984**, *24*, 933–937. [CrossRef]
37. Fischer, R.A.; Maurer, R. Drought resistance in spring wheat cultivars. I. Grain yield responses. *Aust. J. Agric. Res.* **1978**, *29*, 897–912. [CrossRef]
38. Clarke, J.M.; Townley-Smith, F.; McCaig, T.N.; Green, D.G. Growth analysis of spring wheat cultivars of varying drought resistance. *Crop Sci.* **1984**, *24*, 537–541. [CrossRef]
39. Mitra, J. Genetics and genetic improvement of drought resistance in crop plants. *Curr. Sci.* **2001**, *80*, 758–762.
40. Hall, A.E. Is dehydration tolerance relevant to genotypic differences in leaf senescence and crop adaptation to dry environments. In *Plant Responses to Cellular Dehydration during Environmental Stress*; Close, T.J., Bray, E.A., Eds.; Current Topics in Plant Physiology: Washington, DC, USA, 1993; pp. 1–10.
41. Blum, A. *Plant Breeding for Stress Environments*; CRC Press: Boca Raton, FL, USA, 2018; p. 212.
42. Golabadi, M.; Arzani, A.; Maibody, M. Assessment of drought tolerance in segregating populations in Durum Wheat. *African J. Agric. Res.* **2006**, *1*, 162–171.
43. Saba, J.; Moghadam, M.; Ghasemi, K.; Nishabouri, M. Genetic properties of drought resistance indices. *J. Agric. Sci. Technol.* **2001**, *3*, 43–49.
44. Arif, A.; Parveen, N.; Waheed, M.Q.; Atif, R.M.; Waqar, I.; Shah, T.M. A comparative study for assessing the drought-tolerance of Chickpea under varying natural growth environments. *Front. Plant Sci.* **2021**, *11*, 2228. [CrossRef]
45. Campozano, L.; Ballari, D.; Montenegro, M.; Avilés, A. Future meteorological droughts in ecuador: Decreasing trends and associated spatio-temporal features derived from CMIP5 models. *Front. Earth Sci.* **2020**, *8*, 17. [CrossRef]
46. Spinoni, J.; Vogt, J.V.; Naumann, G.; Barbosa, P.; Dosio, A. Will drought events become more frequent and severe in Europe? *Int. J. Climatol.* **2018**, *1736*, 1718–1736. [CrossRef]
47. Davatgar, N.; Neishabouri, M.R.; Sepaskhah, A.R.; Soltani, A. Physiological and morphological responses of rice (*Oryza sativa* L.) to varying water stress management strategies. *Int. J. Plant Prod.* **2009**, *3*, 19–32. [CrossRef]
48. Saikumar, S.; Varma, C.M.K.; Saiharini, A.; Kalmeshwer, G.P.; Nagendra, K.; Lavanya, K.; Ayyappa, D. Grain yield responses to varied level of moisture stress at reproductive stage in an interspecific population derived from Swarna/*O. glaberrima* introgression line. *NJAS Wagening. J. Life Sci.* **2016**, *78*, 111–122. [CrossRef]
49. Hussain, T.; Anothai, J.; Nualsri, C.; Soonsuwon, W. Application of CSM-CERES-Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield. *Indian J. Agric. Res.* **2018**, *52*, 140–145. [CrossRef]

50. Pantuwan, G.; Fukai, S.; Cooper, M.; Rajatasereekul, S.; O'Toole, J.C. Yield response of rice (*Oryza sativa* L.) genotypes to drought under rainfed lowland 3. Plant factors contributing to drought resistance. *Field Crops Res.* **2002**, *73*, 181–200. [CrossRef]
51. Zhao, D.L.; Atlin, G.N.; Amante, M.; Cruz, M.T.S.; Kumar, A. Developing aerobic rice cultivars for water-short irrigated and drought-prone rainfed areas in the tropics. *Crop Sci.* **2010**, *50*, 2268–2276. [CrossRef]
52. Anantha, M.S.; Patel, D.; Quintana, M.; Swain, P.; Dwivedi, J.L.; Torres, R.O.; Verulkar, S.B.; Variar, M.; Mandal, N.P.; Kumar, A.; et al. Trait combinations that improve rice yield under drought: Sahbhagi Dhan and new drought-tolerant varieties in South Asia. *Crop Sci.* **2016**, *56*, 408–421. [CrossRef]
53. Torres, R.O.; Henry, A. Yield stability of selected rice breeding lines and donors across conditions of mild to moderately severe drought stress. *Field Crops Res.* **2018**, *220*, 37–45. [CrossRef] [PubMed]
54. Zain, N.A.M.; Ismail, M.R.; Puteh, A.; Mahmood, M.; Islam, M.R. Impact of cyclic water stress on growth, physiological responses and yield of rice (*Oryza sativa* L.) grown in tropical environment. *Ciência Rural* **2014**, *44*, 2136–2141. [CrossRef]
55. Kumar, A.; Verulkar, S.; Dixit, S.; Chauhan, B.; Bernier, J.; Venuprasad, R.; Zhao, D.; Shrivastava, M.N. Yield and yield-attributing traits of rice (*Oryza sativa* L.) under lowland drought and suitability of early vigor as a selection criterion. *Field Crops Res.* **2009**, *114*, 99–107. [CrossRef]
56. Torres, R.O.; McNally, K.L.; Cruz, C.V.; Serraj, R.; Henry, A. Screening of rice genebank germplasm for yield and selection of new drought tolerance donors. *Field Crops Res.* **2013**, *147*, 12–22. [CrossRef]
57. Raman, A.; Verulkar, S.B.; Mandal, N.P.; Variar, M.; Shukla, V.D.; Dwivedi, J.L.; Singh, B.N.; Singh, O.N.; Swain, P.; Mall, A.K.; et al. Drought yield index to select high yielding rice lines under different drought stress severities. *Rice* **2012**, *5*, 2. [CrossRef] [PubMed]
58. Duangpan, S.; Buapet, P.; Sujitto, S.; Eksomtramage, T. Early assessment of drought tolerance in oil palm D × P progenies using growth and physiological characters in seedling stage. *Plant Genet. Resour.* **2018**, *16*, 544–554. [CrossRef]
59. Metsalu, T.; Vilo, J. ClustVis: A web tool for visualizing clustering of multivariate data using principal component analysis and heatmap. *Nucleic Acid Res.* **2015**, *43*, W566–W570. [CrossRef]

Paper II

Hussain, T., Hussain, N., Ahmed, M. Nualsri, C. and Duangpan, S. 2022. Impact of Nitrogen Application Rates on Upland Rice Performance, Planted under Varying Sowing Times. *Sustainability*. **14:** 1997. *doi:10.3390/su14041997*.

(Reprinted with the permission from *Sustainability* journal)

sustainability

MDPI

Article

Impact of Nitrogen Application Rates on Upland Rice Performance, Planted under Varying Sowing Times

Tajamul Hussain [1], Nurda Hussain [1], Mukhtar Ahmed [2], Charassri Nualsri [3] and Saowapa Duangpan [1,]*

[1] Laboratory of Plant Breeding and Climate Resilient Agriculture, Agricultural Innovation and Management Division, Faculty of Natural Resources, Prince of Songkla University, Songkhla 90110, Thailand; 6110630006@psu.ac.th (T.H.); 6310120017@psu.ac.th (N.H.)
[2] Department of Agronomy, Faculty of Crop and Food Sciences, PMAS Arid Agriculture University, Rawalpindi 46300, Punjab, Pakistan; ahmadmukhtar@uaar.edu.pk
[3] Agricultural Innovation and Management Division, Faculty of Natural Resources, Prince of Songkla University, Songkhla 90110, Thailand; charatsri.n@psu.ac.th or ncharass@yahoo.com
* Correspondence: saowapa.d@psu.ac.th; Tel.: +66-74-286-138

Abstract: Application of suitable nitrogen (N) fertilizer application rate (NR) with respect to sowing time (ST) could help to maximize the performance and productivity of upland rice in Southern Thailand. The 2-year experiments were conducted in the sheds to evaluate the agronomic responses of the upland rice genotype, Dawk Pa–yawm, under various combinations of NR and ST between 2018–2019 and 2019–2020 aimed at obtaining sufficient research evidence for the improved design of long-term field trials in Southern Thailand. As with the initial research, four NR were applied as N0 with no applied N, 1.6 g N pot^{-1}, 3.2 g N pot^{-1} and 4.8 g N pot^{-1}, and experiments were grown under three ST including early (ST1), medium (ST2) and late sowing (ST3). Results from the experiments indicate that the application of 4.8 g N pot^{-1} resulted in maximum grain yield under all ST in both years. However, a maximum increase in grain yield was observed under ST2 by 54–101% in 2018–2019 and by 276–339% in 2019–2020. Maximum grain N uptake of 0.57 and 0.82 g pot^{-1} was also observed at NR 4.8 g N pot^{-1} under ST2 in both years, respectively. Application of NR 4.8 g N pot^{-1} resulted in the highest N agronomic efficiency (NAE), nitrogen use efficiency (NUE) and water use efficiency (WUE). However, the performance of yield and yield attributes, N uptake, N use efficiencies and WUE were declined in late sowing (ST3). Significant positive association among yield, yield attributes, N uptake and WUE indicated that an increase in NR up to 4.8 g N pot^{-1} improved the performance of Dawk Pa–yawm. The results suggest that the application of 4.8 g N pot^{-1} (90 kg N ha^{-1}) for upland rice being grown during September (ST2) would enhance N use efficiencies, WUE and ultimately improve the yield of upland rice. However, field investigations for current study should be considered prior to general recommendations. Moreover, based on the findings of this study, the importance of variable climatic conditions in the field, and the variability in genotypic response to utilize available N and soil moisture, authors suggest considering more levels of NR and intervals for ST with a greater number of upland rice genotypes to observe variations in field experiments for the precise optimization of NR according to ST.

Keywords: upland rice; nitrogen application rate; sowing time; yield; nitrogen use efficiencies

check for updates

Citation: Hussain, T.; Hussain, N.; Ahmed, M.; Nualsri, C.; Duangpan, S. Impact of Nitrogen Application Rates on Upland Rice Performance, Planted under Varying Sowing Times. *Sustainability* **2022**, *14*, 1997. https://doi.org/10.3390/su14041997

Academic Editors: José Manuel Mirás-Avalos and Sean Clark

Received: 17 December 2021
Accepted: 7 February 2022
Published: 10 February 2022

1. Introduction

Rice (*Oryza sativa* L.) contributes half of the world's staple food [1,2]. Rice production is also increasing continuously [2,3]. According to FAO [3], a 25% increase was observed only during 2000–2016. Rice is grown under various ecosystems including irrigated, lowlands and uplands. However, lowland rainfed and lowland irrigated systems are major rice production systems [4] representing 6.2 and 4.1 million hectares of production area, respectively [5]. Upland rice acreage contributes 9% in Asia [6]. Thailand is the sixth-largest producer of rice worldwide and the second-largest in Southeast Asia [3]. Rice plays a key role in Thailand's economy and food security [7]. According to USDA [5], major rice production in Thailand is in northern, central, and north-eastern regions, whereas Southern Thailand contributes 6% of the cultivated rice area [8,9]. Like other regions, lowland rice contributes to major rice production in Southern Thailand, but the cultivated area is limited due to geographic limitations. Upland rice is grown in rainfed conditions [10] and it is cultivated by small land holders during rainy seasons in Southern Thailand [11]. Rice supply in Southern Thailand is insufficient for local consumption, and it is imported from other parts of the country. To meet the rice demand and enhance local rice production, upland rice is a good alternative because it does not require additional irrigation, slopy and non-flat area can be utilized, and it can be intercropped with other crops such as young rubber and oil palm. However, efficient upland rice productivity in the southern region has not yet been achieved due to the lack of significant research evidence on agronomic management of upland rice and prevailing traditional management practices. To establish sustainable productivity and enhance upland rice yield, locally adjusted agronomic practices such as optimum nitrogen application rate (NR) with respect to adopted sowing times (ST) should be investigated and recommended.

Nitrogen (N) is a crucial nutrient that has a significant impact on upland rice growth and productivity. According to Kichey et al. [12], N, among all other nutrients, is the most critical element for plant growth, development and quality. N is used extensively to increase rice crop yield by farmers. This is because N improves crop performance, promotes leaf area, plant biomass and ultimately the crop yield [13]. Application of N fertilizer causes N deficiency in rice plants which increases yellowing in color and reduction in leaf size. Reduced N supply at tillering and panicle initiation stages ultimately lead to a reduction in grain yield. Therefore, it is recommended that a suitable N doze should be applied at critical crop stages so that crops can achieve maximum growth and produce better yield potential. Considering N fertilization in rainfed upland rice production in Thailand, various nitrogen application rates (NR) are practiced. Application of 9.8 kg N rai^{-1} or 61.25 kg N ha^{-1} in a yield trial of 43 upland rice genotypes in Songkhla province of Thailand [14], application of 25 kg N ha^{-1} in a simulation of drought stress study on upland rice genotype, Dawk Pa–yawm [15], application of 75 kg N ha^{-1} in a performance evaluation study of 16 upland rice genotypes [16] and application of 15 kg N ha^{-1} as basal doze with an unknown amount of additional urea application during the crop growth period in a correlation and a path analysis study of 10 upland rice genotypes [17] have been reported. A study interviewing the farmers north of Thailand conducted by the Center for Agricultural Resource System Research, Faculty of Agriculture, Chiang Mai University, Thailand, indicated that farmers in the Chiang Mai province usually applied 1.6–12 kg N rai^{-1} or 10–75 kg N ha^{-1} mainly by using N–P–K (16–20–0) as fertilizer source [18]. A general application rate range of 48.75–82.5 kg N ha^{-1} based on soil analysis, soil nutrient status for rainfed and irrigated rice production was recommended by the Division of Rice Research and Development, Thailand [19,20]. According to the Division of Rice Research and Development, Thailand [21], 40–45 kg N ha^{-1} chemical N fertilizer should be applied in two splits at 20–25 kg N ha^{-1} as basal dose and 20 kg N ha^{-1} should be applied 30 days prior to flowering for the upland rice grown in foothill plains. Considering the location, specific to the experimental site (Songkhla Province) and photosensitivity of genotypes, application of 34–39 kg N ha^{-1} and 59–69 kg N ha^{-1} was recommended to be applied for photosensitive and photoperiod insensitive genotypes, respectively [21]. However, according to the authors, no specific study or recommendation regarding a suitable or optimum NR solely or N application according to ST for upland rice production in Thailand has been reported, indicating a research gap. Therefore, a wide range of NR (10–75 kg N ha^{-1}) by farmers has been observed for upland rice production under sole or intercropping systems in Thailand. Urea is commonly used as N fertilizer source to meet N requirements which is highly volatile and result in higher N losses. Due to improper N management, variations in genotypic response, fertilizer types and prevailing climatic conditions i.e., temperature and moisture availability, efficient fertilizer utilization and plant N uptake per unit area are also affected. According to Choudhury and Khanif [22], the utilization efficiency of urea–N is lower in rice systems, which is approximately 30–40%, and N recovery seldom surpasses 50% of the total N applied. This happens due to the N loss by denitrification and leaching. Qiao et al. [23] reported a positive correlation between N loss and NR applied. N uptake and upland rice growth may increase with an increase in NR, though it may result in increased N leaching losses due to a high level of N available in the plant root zone [24]. N leaching loss is also positively correlated with N input and a decrease in NR may decrease N leaching [25]. A decline in N leaching with decreased NR was observed when the NR was decreased from 300 kg N ha^{-1} to 200 kg N ha^{-1} without a decline in yield [26]. To avoid under or excessive application of N which results in a decline in grain yield or agronomic and economic losses, respectively, proper nutrient management is necessary [27]. In this regard, estimating plant N concentrations and uptake could help to identify optimum NR for maximized nitrogen use efficiency (NUE). The agronomic efficiency of applied N (NAE) can be used to determine the impact of N fertilizer applied to the grain yield produced. An increase in NAE can increase in N uptake by the plant resulting in reduced N losses and higher NUE in soil and plant systems. Enhanced NUE is a useful indicator for N utilization by crop plants. Higher NAE and NUE at certain levels of N application could give the indication for optimal NR for upland rice. Hence, for optimized upland rice production, increase in grain yield and higher N use efficiencies, researching the identification of suitable NR is essential.

Optimum sowing time (ST) is an important agronomic management factor that becomes more critical in the case of upland rice, as the moisture availability and prevailing climatic conditions significantly influence the nutrient use efficiency of upland rice. Optimal ST ensures that vegetative growth receives a high level of photosynthetic radiation, and grain filling occurs during favorable temperatures [28]. According to Nazir [29], too early and too delayed sowing time resulted in increased plant sterility and reduced the number of productive tillers, respectively. Significant responses of yield and yield components including the number of effective tillers per area, number of grains per panicle and grain weight under different ST have been reported. Therefore, determination of the suitable sowing period relative to rice growth and development stages is necessary. Photoperiod-sensitive genotypes are affected greatly as compared to photoperiod-insensitive genotypes. According to Watcharin et al. [30], farmers in Southern Thailand usually grow photoperiod-sensitive genotypes during the rainy season which is a critical issue in the current scenario of climate change where high variability in rainfall occurs. Variations in rainfall and moisture availability influence the nutrient availability to upland rice. It was suggested that the cultivation of photoperiod insensitive cultivars could be one of the possible solutions to stabilize the upland rice yields [31] in Southern Thailand. However, photoperiod insensitive genotypes may also suffer at different crop developmental stages due to lower or higher rainfall events which can cause drought stress or flooding leading to reduced nutrient availability for rice plants. The rainy season in Thailand prevails during May–October [7,31,32], in which most rice plantation is performed. However, in Southern Thailand, especially in the eastern part of Southern Thailand, most of the rain is received from November to the February of the next year [32]. Hot and dry intervals at the start of the rainy season and variability in rainfall thus pose potential threats to upland rice production. Water use efficiency (WUE), which is the ratio between yield produced and water consumed or evapotranspiration, is significantly affected. A significant interaction prevails between WUE and NUE. According to Gajri et al. [33], NR influenced the WUE, whereas NUE was also dependent upon water input. Adjustment in crop growth period [7] with modifications in ST results in shifting of critical crop stages to favorable parts of the season. Variations in moisture availability affect the plant nutrient uptake. Thus, the adjustment in ST could benefit with higher WUE as well as enhanced NUE. Therefore, in the current scenario, synchronization of ST with optimum NR could fulfil the rice crop requirements. Adaptation strategies to adjust ST could also help to significantly reduce the extent of climatic impact on upland rice production. Studies conducted in north-eastern Thailand also suggest that adjustment in ST according to local conditions and proper nutrient management could help mitigate the impact of climate change on rice production [34–36].

Based on the significance of NR, ST, limited research evidence availability and the wide range of NR and ST management practices in Southern Thailand, we understood that adjustments in NR with modification in ST and synchronizing their interactions could result in improved NUE, WUE and yield. Therefore, the initial objective of this research was to obtain sufficient information about the impact of NR under varying ST on upland rice performance. The results of the current research will help to adjust the appropriate gradients for NR and intervals for ST for better designing of further long-term, multilocational field trials and propose best and optimized N and ST management practices for enhanced upland rice production, especially in Southern Thailand.

2. Materials and Methods

2.1. Experimental Setup and Crop Management

Experiments were conducted in the sheds located (7°00′16.57″ N, 100°30′01.93″ E) at the Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Thailand (Figure S1) during 2018–2019 and 2019–2020. Topsoil was sieved, straw and plant roots were removed, and a composite soil sample was obtained before filling the soil in the planting pots for soil nutrient status during both years. The soil was sandy clay loam in the texture with pH, 4.77 and 5.29, organic matter of 4.73 and 4.60 g kg^{-1}, total N of 0.34 and 0.30 g kg^{-1}, available P of 13.03 and 35.58 mg kg^{-1} and available K^+, of 41.19 and 58.67 mg kg^{-1} for 2018–2019 and 2019–2020, respectively. Dawk Pa–yawm, an upland rice genotype, famous due to its aroma and commonly grown in Southern Thailand, was used in this study. Experiments were laid out using a completely randomized design with three replications during both years. Planting pots used in the experiments were conical shaped with 30 cm top diameter, 19 cm bottom diameter and 24 cm in height. Each pot was filled with 12 kg of homogenous soil. Seeds were sown at 5 cm soil depth in the pots by a direct seeding method maintaining 3 plants in each pot at the seedling stage. There were 3 pots used for each treatment in each replication, and a total of 27 plants were maintained for each treatment in each experiment. Experiments were subjected to two treatments including NR and ST. Each treatment was designated in a separate block of pots arranged at different coordinates in the shed. As a wide range of NR is practiced at the farmer's scale for rainfed upland rice production under sole or intercropping systems, and keeping in view the current practices, and various recommendations of research institutes in Thailand, initially NR were chosen as a control, N0 with no applied N, 30 kg N ha^{-1}, 60 kg N ha^{-1} and 90 kg N ha^{-1}. NR for pots were calculated on field basis using Equation (1) [37] and were applied as N0 with no applied N, 1.6 g N pot^{-1}, 3.2 g N pot^{-1} and 4.8 g N pot^{-1} as an initial study. Urea was used as the fertilizer source containing 46% N and NR were applied in two equal splits at the start of tillering and panicle initiation stages. Upland rice is grown in the rainy season and most rain in Southern Thailand prevails in May–October. A wide range sowing window prevails in Southern Thailand and farmers perform early or late planting depending upon cultivars sensitivity and moisture availability. However, major rice planting has been in practice by farmers during September–November, while minor rice planting has been in practice during April–June in Southern Thailand [8]. As of initial research, ST were selected as early sowing-ST1 on 05 September 2018, medium-ST2 on 26 September 2018 and late sowing-ST3 on 31 October 2018 for 2018–2019 and early sowing-ST1 on 01 September 2019, medium-ST2 on 06 October 2019 and late sowing-ST3 on 03 November 2019 for 2019–2020. Plants were irrigated with an automatic drip irrigation system and irrigation was applied for a specific time duration for each treatment block frequently to avoid water stress. The amount of irrigation water was then calculated by the irrigation time, dripper head water discharge capacity of 8 tiller per hour and area of pots. Each planting pot in ST1, ST2 and ST3 received 57 liters (L), 68 L and 74 L as an average total amount of irrigation water during both years. Manual weeding and insect, pest and disease management practices were performed as standard practices to reduce yield losses in both years.

$$\text{Fertilizer amount for pot} = \frac{\text{Recommended doze of fertilizer}}{\text{1 hectare}} \times \text{Weight of pot soil} \quad (1)$$

2.2. Sampling, Measurements and Computations

At harvest, plant height and biomass were recorded from 3 out of 9 randomly selected plants and data collection was repeated for each treatment in three replications. Plant height was measured from the base of the stem to the topmost leaf or panicle. The number of days to 50% flowering and 50% maturity were recorded by counting the number of days from respective sowing time. The number of tillers was counted at the maximum tillering stage and tillers with at least one visible leaf were included. Rice plants were manually harvested at maturity, and the number of panicles were counted. Plant and grain samples were dried in an oven at 70 °C for different time durations until a constant weight was achieved to get grain yield and biomass on a dry weight basis. Soil sampling for N analysis was performed for each treatment and each replication at harvest to observe N concentrations. Soil samples collected from the pots from three replicates were first mixed and passed through a 1mm sieve to remove impurities for obtaining a respective composite soil sample for each N treatment for N analysis. Oven-dried plant biomass and grain samples were finely ground and passed through a 1mm sieve as well. Straw, grain and soil samples were then sent to the Central Analytical Laboratory of Faculty of Natural Resources, Prince of Songkla University, Thailand for N analysis to obtain N concentrations and calculate N uptake by plant and grains. Straw and grain N uptake in relation to applied NR [38] were calculated by multiplying straw biomass and grain yield with respective N concentrations. N efficiencies including agronomic efficiency (NAE) (2), which is the number of extra grains harvested per kg of N applied to a grain crop that drives both the agronomic and economic efficiency of fertilizer use, and N use efficiency (NUE) (3), which is the fraction of applied N that is absorbed and used by the plant, were calculated using equations mentioned by Abbasi et al. [39]. WUE was calculated as the ratio between grain yield harvested and total amount of irrigation water per pot using Equation (4) [40].

$$\text{NAE} = \frac{\text{Grain yield}_{\text{N added}} - \text{Grain yield}_{\text{control}}}{\text{Total N fertilizer applied}} \quad (2)$$

$$\text{NUE} = \frac{\text{N uptake}_{\text{N added}} - \text{N uptake}_{\text{control}}}{\text{Total N fertilizer applied}} \times 100 \quad (3)$$

$$\text{WUE} = \frac{\text{Grain yield per pot (g)}}{\text{Amount of irrigation water per pot (L)}} \quad (4)$$

2.3. Statistical Analysis

Data obtained from both year experiments was used in statistical software Statistix (8.1 package, analytical software, Tallahassee, FL, USA) [41] to test the significance of results and mean comparisons for the effects of applied NR and ST. A two-way analysis of variance (ANOVA) was performed for yield and yield attributes of Dawk Pa–yawm, straw and grain N uptake and WUE from three replications with effect to NR, ST and the interactions of NR and ST. Mean comparisons were made using the least significant difference (LSD), and p-value < 0.05 was considered significantly different [42]. Combined Pearson's correlation coefficients were computed for yield and yield attributes of Dawk Pa–yawm, computed straw, grain and total N uptake and WUE to observe associations among various parameters. The "Corrplot" [43] package of R software was used in computing correlation coefficients and graphics.

3. Results

3.1. Upland Rice Growth and Productivity

Results from the analysis of variance (ANOVA) for observed traits and computed parameters for Dawk Pa–yawm using the LSD-test ($p < 0.05$) indicated highly significant ($p < 0.001$) differences for days to flowering and days to maturity with respect to the ST, whereas there were no significant differences observed with respect to NR and NR × ST for both years (Tables S1 and S2). Flowering days and maturity duration were not significantly affected by an increase in NR for both years and the difference ranged 1–3 days for flowering (Figure 1A,B) and similarly 1–3 days for maturity (Figure 1C,D). ST influenced days to flowering, thus, days to flowering and days to maturity were increased under ST3 by 7 days for both years (Figure 1A,B). Days to flowering were decreased only under ST2 for 2019–2020 (Figure 1B). Maturity duration was increased under ST2 and ST3 for year 2018–2019 by 6–9 days (Figure 1C) while increased for 6–8 days under ST3 for 2019–2020 (Figure 1D). There were highly significant differences ($p < 0.001$) for plant height, number of tillers, number of panicles, grain yield and biomass with respect to NR during both years except moderate significant differences ($p < 0.01$) for the number of tillers and number of panicles during 2019–2020 (Tables S1 and S2). Highly significant differences ($p < 0.001$) were observed for days to flowering, days to maturity, plant height and grain yield with respect to ST in both years, whereas moderately significant differences ($p < 0.01$) were observed for the number of tillers, number of panicles and biomass in 2018–2019 and for biomass in 2019–2020 with respect to the ST (Tables S1 and S2). The number of tillers and number of panicles were significantly different ($p < 0.05$) during 2019–2020. ANOVA for the interactions of the NR and ST indicated non-significant differences for days to flowering, days to maturity, plant height, number of tillers, number of panicles, grain yield and biomass in both years except a moderate significant ($p < 0.01$) difference for plant height during 2019–2020 under the interaction of NR and ST. Plant height was gradually increased for both years with an increase in NR (Figure 2A,B) under all ST. Increase in plant height ranged 13–27% for ST1, 2–19% for ST2 and 3–19% for ST3 for 2018–2019 (Figure 2A) and 4–10% for ST1, 18–38% for ST2 and 1–8% for ST3 for 2019–2020 (Figure 2B). The number of tillers (Figure 3A,B) and the number of panicles (Figure 3C,D) were influenced by NR and ST. In total, 1–4 tillers, as well as panicles, per plant were increased under increasing NR up to 4.8 g N pot^{-1}. However, the number of tillers and number of panicles were decreased by 1–3 tillers as well as panicles per plant under ST3 for both years (Figure 3A–D). Grain yield (Figure 4A,B) and biomass (Figure 4C,D) were increased with increasing NR under all ST for both years. Grain yield increased by 19–64% under ST1, 54–101% for ST2 and 32–78% for ST3 in 2018–2019 (Figure 4A) while it increased by 53–121% for ST1, 276–339% for ST2 and 64–94% for ST3 in 2019–2020 (Figure 4B). Biomass increased by 52–111% under ST1, 77–127% for ST2 and 65–127% for ST3 in 2018–2019 (Figure 4C) while it increased by 43–86% for ST1, 98–153% for ST2 and 32–75% for ST3 in 2019–2020 (Figure 4D).

3.2. Nitrogen Uptake

Highly significant differences ($p < 0.001$) were observed for straw N uptake, grain N uptake and total N uptake with respect to NR and ST during both years, except a non-significant difference for total N uptake under ST during 2018–2019 (Tables S1 and S2). Interactions of the NR and ST indicate highly significant ($p < 0.001$) differences for straw N uptake and grain N uptake and a significant difference ($p < 0.05$) for total N uptake during 2018–2019. Straw N uptake was significantly different ($p < 0.05$), whereas non-significant differences for grain N uptake and total N uptake were observed with respect to NR × ST in 2019–2020. Straw (stem + leaves) N uptake (g pot^{-1}) was increased with increasing NR up to N 4.8 g N pot^{-1} for both years (Figure 5A,B) when compared to pots with no applied N. However, ST affected straw N uptake resulting in variations in N uptake under all ST (Figure 5A,B). Grain N uptake was also increased with increasing NR up to 4.8 g N pot^{-1} under all ST in both years (Figure 5C,D). However, maximum grain N uptake was observed under ST2 and it was then decreased under ST3 (Figure 5C,D), indicating the negative impact of delayed sowing on grain N uptake. Maximum grain N uptake valued 0.57 g pot^{-1} at NR 4.8 g N pot^{-1} under ST2 in 2018–2019 (Figure 5C) and 0.82 g pot^{-1} at NR 4.8 g N pot^{-1} under ST2 in 2019–2020 (Figure 5D). These results indicate that ST2 was the favorable ST for increased grain N uptake, and early (ST1) or delayed (ST3) sowing resulted in less translocation of N from the rice straw to grain. Total N uptake including straw and grain-N was also increased with increasing NR up to 4.8 g N pot^{-1} (Figure 5E,F). However, total N uptake was decreased at NR 4.8 g N pot^{-1} under ST3 in 2018–2019 (Figure 5E) and decreased at 3.2 g N pot^{-1} under ST1 in 2019–2020 (Figure 5F), indicating the significant negative impact of ST on total plant N uptake. Total plant N uptake was in an increasing trend under ST2 and maximum total N uptake was observed under ST2 with a value of 2.09 g pot^{-1} in 2019–2020 (Figure 5F). The results exhibit that medium ST (ST2) was the most favorable ST for maximum N extraction from soil and increase in total plant N uptake as well as for maximum mobility of N from plant parts to grains.

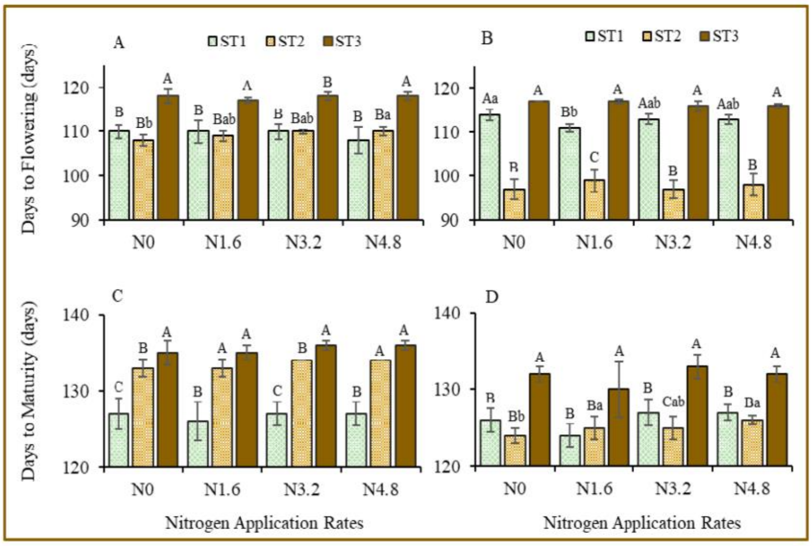


Figure 1. Effect of nitrogen application rates and sowing times on days to flowering (**A**,**B**) and days to maturity (**C**,**D**) during 2018–2019 (**A**,**C**) and 2019–2020 (**B**,**D**). Mean values are presented and vertical bars indicate ± standard errors of means ($n = 3$). Uppercase letters indicate significant differences (p-value < 0.05) of days to flowering and days to maturity under different sowing times within each nitrogen application rate. Lowercase letters indicate significant differences (p-value < 0.05) of days to flowering and days to maturity at different nitrogen application rates within each sowing time. Due to the non-significant differences for sowing times within the same nitrogen application rate, no lowercase letters are presented in Figure 1C. ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late). N0: no applied N, N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

3.3. Nitrogen Use Efficiencies

NR significantly affected N efficiencies including agronomic efficiency (NAE) (Figure 6A,B) and nitrogen use efficiency (NUE) (Figure 6C,D) in both years. NAE was increased with applied N and increasing NR up to 4.8 g N pot^{-1} under all ST in both years (Figure 6A,B). Maximum NAE was observed at N 4.8 g N pot^{-1} under all ST with values 5.35, 10.18 and 8.26 kg kg^{-1} for ST1, ST2 and ST3, respectively, in years 2018–2019 (Figure 6A) and 14.95, 34.16 and 10.14 kg kg^{-1} for ST1, ST2 and ST3, respectively, in years 2019–2020 (Figure 6B). However, ST influenced the NAE and resulted in a decline and variations in both years (Figure 6A,B). The highest NAE was observed under ST2 in both years (Figure 6A,B) and NAE was decreased under delayed sowing ST3, indicating that ST2 was the most favorable ST for improved NAE. NUE was also increased with an increase in NR up to 4.8 g N pot^{-1} under all ST in both years (Figure 6C,D). Maximum NUE was observed at NR 4.8 g N pot^{-1} under all ST up to 119%, 137% and 133% for ST1, ST2 and ST3, respectively, in years 2018–2019 (Figure 6C) and 155%, 171% and 102% for ST1, ST2 and ST3, respectively, in years 2019–2020 (Figure 6D). ST influenced the NUE and resulted in differences in both years (Figure 6C,D). However, the highest NUE was observed under ST2 in both years (Figure 6C,D) and NUE was decreased under delayed sowing, ST3. NUE under ST3 was more affected in 2019–2020 (Figure 6D) as compared to 2018–2019 (Figure 6C).

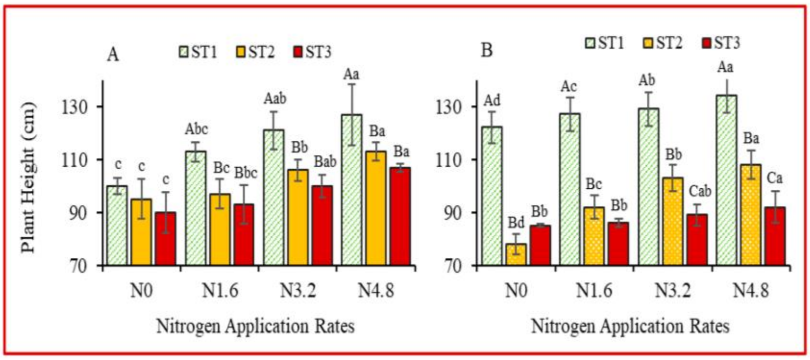


Figure 2. Effect of nitrogen application rates and sowing times on plant height during 2018–2019 (**A**) and 2019–2020 (**B**). Mean values are presented and vertical bars indicate ± standard errors of means ($n = 3$). Uppercase letters indicate significant differences (p-value < 0.05) of plant height under different sowing times within each nitrogen application rate. Lowercase letters indicate significant differences (p-value < 0.05) of plant height at different nitrogen application rates within each sowing time. ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late), N0: no applied N, N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

3.4. Water Use Efficiency

Water use efficiency (WUE) was estimated for each treatment for both years (Figure 7). There was a highly significant ($p < 0.001$) difference for WUE with respect to NR and a moderate significant difference ($p < 0.01$) with respect to ST and a non-significant difference for the interactions of NR and ST in 2018–2019 (Table S1). During 2019–2020, highly significant ($p < 0.001$) differences for WUE with respect to NR and ST and a significant difference ($p < 0.05$) with respect to the interactions of NR and ST were observed (Table S2). An increase in NR up to 4.8 g N pot^{-1} significantly increased WUE in both years (Figure 7A,B). Maximum WUE was observed at N 4.8 g N pot^{-1} under all ST with values 0.25, 0.31 and 0.26 g L^{-1} for ST1, ST2 and ST3, respectively, in years 2018–2019 (Figure 7A) and 0.44, 0.59 and 0.26 g L^{-1} for ST1, ST2 and ST3, respectively, in years 2019–2020 (Figure 7B). WUE increased up to 40% under ST1, 59% under ST2 and 42% under ST3 at NR up to N 4.8 g N pot^{-1} during 2018–2019 and increased up to 50% under ST1, 92% under ST2 and 67% under ST3 at NR up to N 4.8 g N pot^{-1} during 2019–2020 (Figure 7A,B). However, ST influenced the WUE and resulted in a decline in both years under delayed sowing (Figure 7A,B). The highest WUE was observed under ST2 in both years by 59% and 92%, respectively (Figure 7A,B), and it was decreased under delayed sowing, ST3 by 24% in 2018–2019 and by 84% in 2019–2020. The results indicate that ST2 was the optimal ST for better performance for WUE.

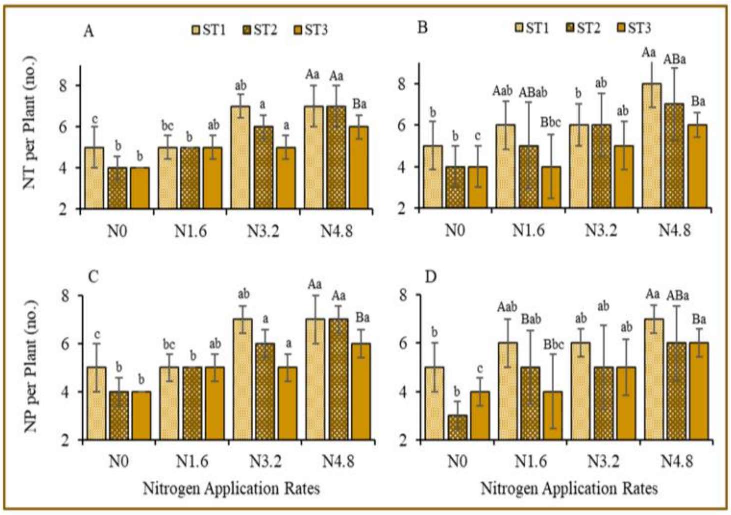


Figure 3. Effect of nitrogen application rates and sowing times on the number of tillers (NT) (**A**,**B**) and the number of panicles (NP) (**C**,**D**) during 2018–2019 (**A**,**C**) and 2019–2020 (**B**,**D**). Mean values are presented and vertical bars indicate ± standard errors of means (n = 3). Uppercase letters indicate significant differences (p-value < 0.05) in the number of tillers and the number of panicles under different sowing times within each nitrogen application rate. Lowercase letters indicate significant differences (p-value < 0.05) in the number of tillers and the number of panicles at different nitrogen application rates within each sowing time. ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late). N0: no applied N, N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

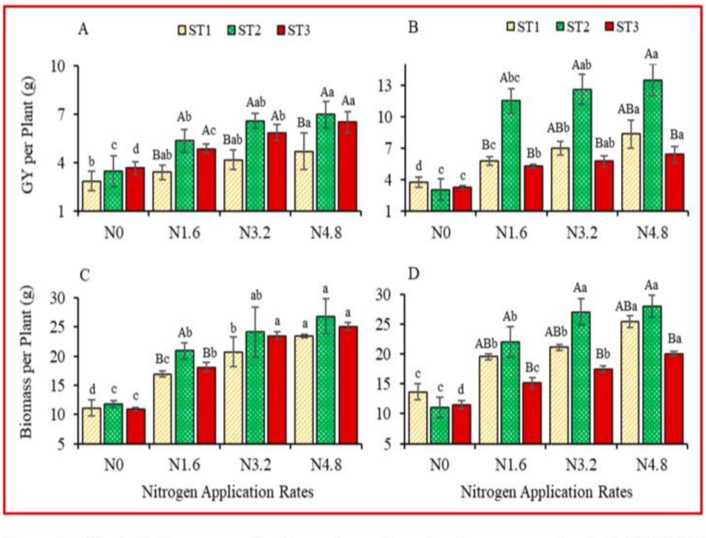


Figure 4. Effect of nitrogen application rates and sowing times on grain yield (GY) (**A**,**B**) and biomass (**C**,**D**) during 2018–2019 (**A**,**C**) and 2019–2020 (**B**,**D**). Vertical bars indicate ± standard errors of means (n = 3). Mean values are presented and vertical bars indicate ± standard errors of means (n = 3). Uppercase letters indicate significant differences (p-value < 0.05) of grain yield and biomass under different sowing times within each nitrogen application rate. Lowercase letters indicate significant differences (p-value < 0.05) of grain yield and biomass at different nitrogen application rates within each sowing time. ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late). N0: no applied N, N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

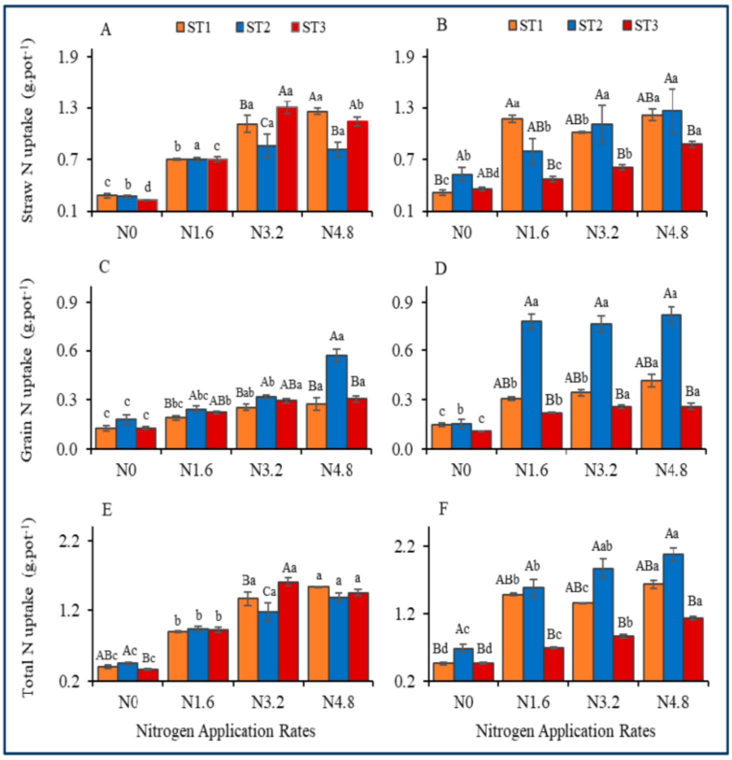


Figure 5. Effect of nitrogen application rates and sowing times on straw N uptake (**A**,**B**), grain N uptake (**C**,**D**) and total N uptake (**E**,**F**) during 2018–2019 (**A**,**C**,**E**) and 2019–2020 (**B**,**D**,**F**). Vertical bars indicate ± standard errors of means (n = 3). Uppercase letters indicate significant differences (p-value < 0.05) of straw N uptake, grain N uptake and total N uptake under different sowing times within each nitrogen application rate. Lowercase letters indicate significant differences (p-value < 0.05) of straw N uptake, grain N uptake and total N uptake at different nitrogen application rates within each sowing time. ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late). N0: no applied N, N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

3.5. Correlation Analysis

Pearson's correlation analysis (Figure 8) indicates that there was a highly significant positive correlation between days to flowering and days to maturity. There was a significant positive correlation between days to flowering and grain yield. Plant height was highly significant and positively correlated with the number of tillers and the number of panicles, whereas a moderately significant and positive association was observed between plant height and biomass. Plant height was also significant and positively correlated with grain yield. The number of tillers were highly significant and positively associated with the number of panicles and biomass, whereas significant and positively correlated with grain yield and straw N uptake. There was a highly significant positive correlation among the number of panicles and biomass whereas a significant correlation was observed among the number of panicles and grain yield. Grain yield was highly associated with biomass, whereas it was significantly associated with straw N uptake. Straw N uptake was highly significant, whereas total N uptake was significantly associated with the biomass. Straw N uptake was also highly associated with the total N uptake. Grain N uptake was moderately associated with the straw N uptake, whereas it was highly associated with total N uptake. Straw N uptake, grain N uptake and total N uptake were highly significant and positively correlated with the WUE. Computed coefficient values are presented in Figure 8.

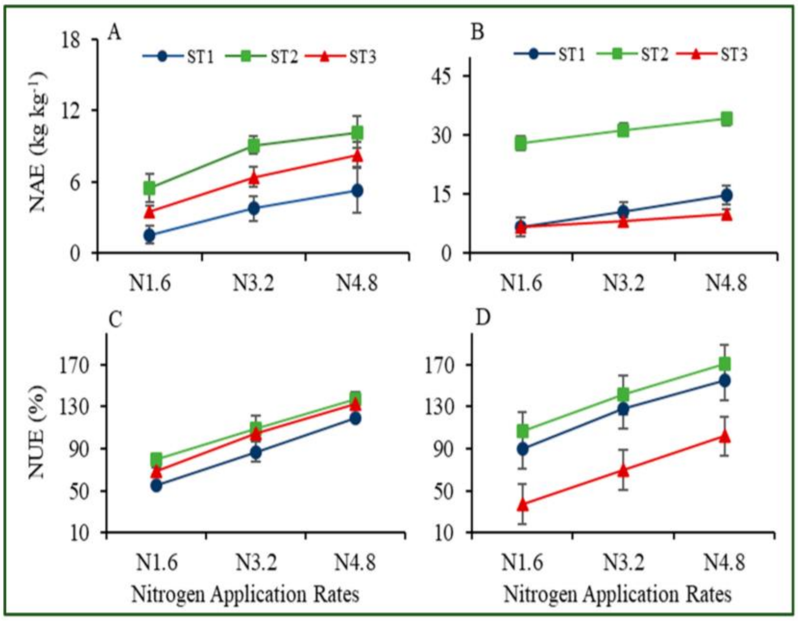


Figure 6. Effect of nitrogen application rates and sowing times on N agronomic efficiency (NAE) (**A**,**B**) and N use efficiency (NUE) (**C**,**D**) during 2018–2019 (**A**,**C**) and 2019–2020 (**B**,**D**). Vertical bars indicate ± standard errors of means (n = 3). ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late). N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

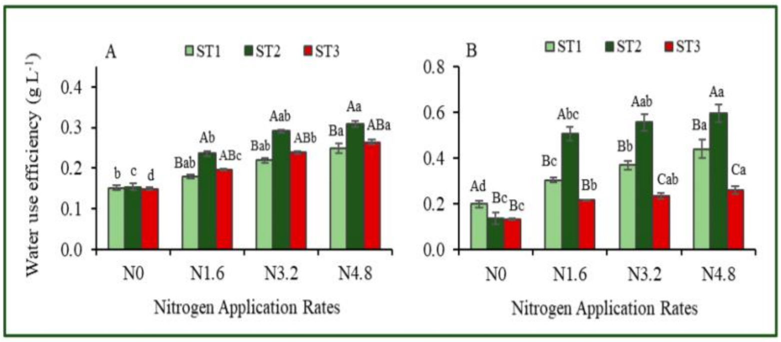


Figure 7. Effect of nitrogen application rates and sowing times on water use efficiency during 2018–2019 (**A**) and 2019–2020 (**B**). Mean values are presented and vertical bars indicate ± standard errors of means (n = 3). Uppercase letters indicate significant differences (p-value < 0.05) of water use efficiency under different sowing times within each nitrogen application rate. Lowercase letters indicate significant differences (p-value < 0.05) of water use efficiency at different nitrogen application rates within each sowing time. ST1: sowing time 1 (early), ST2: sowing time 2 (medium), ST3: sowing time 3 (late). N0: no applied N, N1.6: 1.6 g N pot^{-1}, N3.2: 3.2 g N pot^{-1}, N4.8: 4.8 g N pot^{-1}.

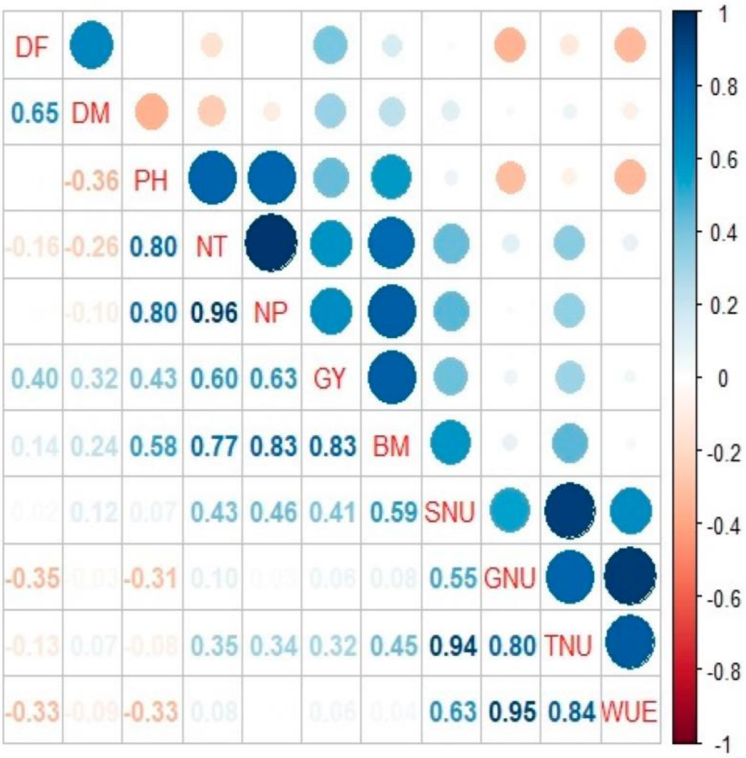


Figure 8. Corrplot of combined Pearson's correlation coefficients among agronomic attributes of Dawk Pa–yawm, nitrogen uptake and water use efficiency. Positive and negative associations are presented in blue and red colored circles, respectively, at the top-right diagonal and squares with an absence of colored circles represent no significant association at *p*-value < 0.005 among respective parameters. Correlation coefficient numbers are presented at the bottom-left diagonal. The intensity of colors of circles and numbers, and the size of the circles indicate the proportion of Pearson's coefficients. DF, days to flowering; DM, days to maturity; PH, plant height; NT, number of tillers; NP, number of panicles; GY, grain yield; BM, biomass; SNU, straw nitrogen uptake; GNU, grain nitrogen uptake; TNU, total nitrogen uptake; WUE, water use efficiency.

4. Discussion

Nitrogen (N) is an important element and the application of nitrogenous fertilizers in upland rice systems is crucial as N significantly impacts rice performance and productivity. Rice yield is significantly influenced by reduced or no N fertilizer application and the overuse of N results in increased agronomic and economic losses, as well as affects soil health. The efficiency of applied N fertilizer is influenced by various rice crop management practices, and sowing time (ST) is one of them. Improper N management and wide sowing windows adopted by small land holders and upland rice growers are major problems affecting the upland rice production in Southern Thailand. Early or late sowing alters the nutrient availability to rice plants due to variations in prevailing climatic conditions and moisture availability. To achieve viable rice productivity, optimal management of nitrogen application rate (NR) with respect to ST is necessary as upland rice performance and yield are significantly influenced by N input under various ST.

The quantity of applied N significantly influences the physiological processes and photosynthesis of plants [44], which ultimately impacts the performance of yield attributes and defines the rice yield potential. Our results indicate that the performance of yield attributes and the yield of upland rice varied significantly under varying NR and N nutrition remarkably improved the overall performance. Additional N supply resulted in increased plant height in both years. An increase in plant height occurred possibly due to the contribution of added N which improved the growth, internode length and overall metabolism. Enhanced N application is well documented in encouraging cell expansion, and it subsequently stimulated stem elongation [45,46]. Results for plant height were supported by the findings of Abbasi et al. [39] and Zhang et al. [44] who reported remarkable improvements in plant height following increased N application rate. Similar results have also been demonstrated by Jahan et al. [47] who described that an increase in N supply to rice genotypes caused a significant increase in the height of rice plants. In the present study, higher nitrogen application resulted in an additional 1–4 tillers as well as panicles per plant. Previous studies have also observed that panicle numbers were increased with an increase in NR [44]. The increase in tillering due to increased NR might be linked to more N availability at the tillering stage which plays a role in cell division. Wang et al. [48] demonstrated that N availability controls rice tiller numbers through the regulation of the nitrate transporter. An elevated nitrogen level in rice plants leads to increased tiller numbers and tiller bud outgrowth [49]. The number of panicles is one of the major contributing factors in rice yield. Cell division triggered by N supply increases the panicle formation at reproductive stages of rice crop. Jahan et al. [47] observed that N fertilization increased the number of tillers m^{-2}, which resulted due to the increased N availability for cell division. In our study, higher N concentration in plants resulted in a higher number of panicles, and similar findings were observed by Manzoor et al. [27] Yield attributes and yield were significantly associated with applied NR. Approximately 19–339% increase in grain yield was observed in our study with increasing NR under different ST. An increase in yield possibly occurred due to the increased performance of yield attributes. Zhang et al. [43] observed that an increase in NR significantly increased grain yield; however, this increase in grain yield was in the limited range of NR. Chen et al. [49] also observed that grain yield and biomass of rice were positively affected by increased NR. An increase in plant biomass ranging from 26 to 127% with increasing NR under different ST indicated a higher performance of biomass contributing traits including plant height and the number of tillers. An increase in plant biomass with N fertilization has also been reported in a rice experimental study by Jahan et al. [47] In our experimental results, it was noticed that grain yield was in an increasing trend up to NR 4.8 g N pot^{-1}, indicating the need for an increase in further levels of NR in future experimentation to observe the curve for better optimization of the N application rate.

Nitrogen application and N uptake by plants significantly influence the physiological processes of rice. Synchronization of crop N requirement and N supply is an important step to enhance N use in rice plants. The ratio between N uptake and N loss regulates plant growth and development, and higher plant biomass is produced if more N is absorbed [7]. However, there are various factors that may influence N utilization and N uptake in rice plants as N is highly susceptible to denitrification, volatilization and leaching losses in rice environments. Higher plant N uptake is desired through efficient N management. In our study, plant and grain N concentrations and N uptake varied among NR. Straw and grain N uptake was increased up to NR 4.8 g N pot^{-1} during both years. Maximum grain N uptake was observed at 4.8 g N pot^{-1} under ST2, and it was decreased under ST3. Variations in the increase in straw and grain N concentrations and N uptake were observed at varying NR under different ST which indicates the impact of ST. Jahan et al. [47] also reported that rice's response to applied NR was associated with growing seasons. An increase in rice straw N, grain N concentration and N uptake was also observed by Chen et al. [49]. Higher N uptake is an indication of the achievement of crop N requirement under ideal NR availability and optimal conditions. It was indicated that an increase in NR under delayed sowing could not increase grain N uptake. Total N uptake was also observed at its maximum under ST2 at 4.8 g N pot^{-1}, indicating that increasing NR under ST2 increased total N uptake. N uptake was also decreased in late sowing as reported by Pal et al. [50] Agronomic efficiency of applied N (NAE) is an important index to record the response of grain productivity in relation to NR. In our study, NAE was increased with increasing NR and it was observed that maximum NAE was achieved at 4.8 g N pot^{-1}. Nitrogen use efficiency (NUE) was also increased with increasing NR, and maximum NUE was achieved at 4.8 g N pot^{-1} under ST2 as well. Enhancing N use efficiencies in upland rice systems is one of the main objectives of N fertilization. We observed that increased NR enhanced the N use efficiencies. Furthermore, water use efficiency (WUE) was also associated with NR, and higher NR 4.8 g N pot^{-1} resulted in higher WUE. The association of NUE and WUE has also been well reported [7,51].

Sowing time critically impacts the utilization of environmental sources including moisture availability during crop growth, and it can influence crop yields [4]. It was observed that ST influenced the performance of Dawk Pa–yawm with respect to applied NR. Maximum grain yield was observed under ST2 and an increase in NR to 4.8 g N pot^{-1} could not cause a significant increase in grain yield under delayed sowing, ST3. This indicated that NR 4.8 g N pot^{-1} was suitable for ST2 while NR 3.2 g N pot^{-1} was suitable for ST3 with respect to N use. Days to flowering and days to maturity were increased under delayed sowing, ST3. Crop yield and biomass [52] are highly correlated with the life cycle. Gomez–Macpherson and Richards [53] stated that phenology is one of the critical aspects of adaptation and enhancement of yield as it regulates the length of critical crop growth stages and change in crop phenology is considered one of the major indicators of climate change impact. Maximum plant height, number of tillers, number of panicles and grain yield were observed under ST2, while biomass was recorded at its maximum under ST3 during 2019–2020. It indicated that conversion of photo-assimilates to grain was decreased under ST3 as an increase in biomass under delayed sowing could not result in increased grain yield. Babel et al. [34], in a climate change impact study, predicted that the delay in ST of Thai rice genotype KDML–105 at Roi Et province (Thailand) with 30 days delay in initial sowing would increase yield by 23% during the 2050s. The predictions of Babel et al. [34] are supporting evidence for this research as it was observed that ST2, which was slightly delayed ST for upland rice, resulted in improved grain yield, N uptake, N efficiencies as well as WUE. The maximum of N use efficiencies including NAE and NUE was achieved at NR 4.8 g N pot^{-1} under ST2 possibly due to the level of N matched with optimal ST and crop N requirement that was attained. Our results are in line with the findings of Yousaf et al. [54] who observed that maximum N efficiencies were observed in rice and oilseed crop rotations when the N level matched the N requirements of crops. Higher N uptake and enhanced N efficiencies under ST2 were favored in improved WUE and resulted in higher WUE under ST2. Results for enhancement in WUE and NUE in adjustment to ST were also supported by previous studies [7].

The findings of the present study indicate the importance of and are the supporting evidence for, the need for proper N management according to various ST for upland rice production in Thailand. Our study indicates that N fertilization and various NR applied under different ST produced significantly improved results for upland rice productivity. Therefore, N application practices [14–18], as well as N fertilizer recommendations based on soil analysis and soil nutrient status [19,20] and location-specific recommendations [21], are needed to be modified and improved according to various ST. However, further investigations in this field are needed to achieve more precise optimization of NR and ST for upland rice in Southern Thailand as, in the present study, soil moisture was constantly and sufficiently supplied whereas climatic conditions and rainfall variability differs under various ST in the field conditions. In addition, N uptake and utilization is not only influenced by prevailing climatic conditions, soil moisture status and NR or N availability but also varies among various genotypes of the same plants [55–58]. It was observed that high genetic variability and variation among agronomic traits prevailed amongst numerous Thai upland rice genotypes [14–17] including the studied genotype Dawk Pa–yawm. Therefore, the authors suggest that it becomes necessary to include other major upland rice genotypes being cultivated in Southern Thailand for future field investigations.

5. Conclusions

Ideal agronomic management of upland rice is an important strategy to enhance productivity and enhance resource input efficiency. The identification and application of optimal NR synchronized with ST are some of the principal elements of this strategy. Results obtained from the current study exhibit the significance of the optimal NR and its synchronization with ST as it was indicated that NR and ST influenced growth, productivity, nitrogen use efficiencies and WUE of upland rice. An increase in NR indicated an increased performance of yield and yield attributes. In addition to grain yield, NR and ST significantly influenced N uptake, NAE, NUE and WUE. Maximum performance for yield, yield attributes and WUE was achieved at 4.8 g N pot^{-1}. However, the highest plant and grain N uptake and N use efficiencies were achieved at 3.2 g N pot^{-1}. Considering the impact of ST, the maximum performance for yield, grain N uptake, N use efficiencies and WUE were achieved under ST2. Based on the findings of this study, and from a practical point of view, the application of 4.8 g N pot^{-1} (90 kg N ha^{-1}) and sowing in the month of September (ST2) would enhance upland rice production. Though field investigations for current study should be considered prior to general recommendations. Furthermore, it is recommended that future experiments should investigate more upland rice genotypes, more NR gradients and ST intervals under field conditions for improved and precise NR optimization according to ST and recommendations.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14041997/s1, Table S1. Mean squares of ANOVA of yield and yield attributes of Dawk Pa–yawm, straw N uptake, grain N uptake, total N uptake and water use efficiency during 2018–2019. Table S2. Mean squares of ANOVA of yield and yield attributes of Dawk Pa–yawm, straw N uptake, grain N uptake, total N uptake and water use efficiency during 2019–2020. Figure S1: Study area at Prince of Songkla University, Songkhla in Southern Thailand (Source: adapted from ArcGIS: *v*10.5).

Author Contributions: Author T.H. and S.D. conceived the idea and T.H. conducted experiments. N.H. helped in experiments and data collection. T.H. analyzed the data and prepared the first draft. C.N., M.A. and S.D. edited the manuscript. S.D. supervised and contributed in finalized version and M.A. proofread the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research is a part of a Ph.D. study supported by "Thailand's Education Hub for Southern Region of ASEAN Countries (TEH–AC)" scholarship from Prince of Songkla University, Thailand. This research was partially funded by Graduate School, Prince of Songkla University and Faculty of Natural Resources, Prince of Songkla University, Thailand.

Data Availability Statement: Data is presented in the article and supplementary materials.

Acknowledgments: Authors are thankful to editors and anonymous reviewers for providing valuable comments for improving manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Muthayya, S.; Sugimoto, J.D.; Montgomery, S.; Maberly, G.F. An overview of global rice production, supply, trade, and consumption. *Ann. N. Y. Acad. Sci.* **2014**, *1324*, 7–14. [CrossRef] [PubMed]
2. Sporchia, F.; Thomsen, M.; Caro, D. Drivers and trade–offs of multiple environmental stressors from global rice. *Sustain. Prod. Consum.* **2021**, *26*, 16–32. [CrossRef]
3. FAO. FAOSTAT (Online). Available online: http://www.fao.org/faostat/en/#home (accessed on 18 August 2020).
4. Varinruk, B. Thailand Rice Production and Rice Research and Development on Climate Change. In Proceedings of the Workshop on Strengthening APEC Cooperation on Food Security and Climate Change, Ha Noi, Vietnam, 19–21 April 2017.
5. USDA. Thailand: Irrigation Shortage Reduces 2015/16 Rice Production. Available online: https://ipad.fas.usda.gov/highlights/2015/10/th/index.htm (accessed on 25 June 2020).
6. Nascente, A.S.; Lanna, A.C.; de Sousa, T.P.; Chaibub, A.A.; de Souza, A.C.A.; de Filippi, M.C.C.N. Fertilizer dose–dependent efficiency of *Serratia* spp. for improving growth and yield of upland rice (*Oryza sativa* L.). *Int. J. Plant Prod.* **2019**, *13*, 217–226. [CrossRef]

7. Ullah, H.; Santiago–Arenas, R.; Ferdous, Z.; Attia, A.; Datta, A. *Improving Water Use Efficiency, Nitrogen Use Efficiency, and Radiation Use Efficiency in Field Crops under Drought Stress: A Review*, 1st ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2019; Volume 156, ISBN 9780128175989.
8. GRiSP. *Rice Almanac*, 4th ed.; International Rice Research Institute: Los Baños, Philippines, 2013.
9. Hussain, T.; Hussain, N.; Ahmed, M.; Nualsri, C.; Duangpan, S. Responses of lowland rice genotypes under terminal water stress and identification of drought tolerance to stabilize rice productivity in Southern Thailand. *Plants* **2021**, *10*, 2565. [CrossRef]
10. Kumar, V.; Ladha, J.K. *Direct Seeding of Rice. Recent Developments and Future Research Needs*, 1st ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2011; Volume 111, ISBN 9780123876898.
11. Nokkoul, R.; Wichitparp, T. Quality of upland rice seed produced during the rainy season in Southern Thailand. *Int. J. Plant Anim. Environ. Sci.* **2013**, *3*, 181–184.
12. Kichey, T.; Hirel, B.; Heumez, E.; Dubois, F.; Le Gouis, J. In winter wheat (*Triticum aestivum* L.), post–anthesis nitrogen uptake and remobilisation to the grain correlates with agronomic traits and nitrogen physiological markers. *Field Crop. Res.* **2007**, *102*, 22–32. [CrossRef]
13. Sinclair, T.R.; Horie, T. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. *Crop Sci.* **1989**, *29*, 90–98. [CrossRef]
14. Suwanasa, C.; Nualsri, C.; Junsawang, N.; Soonsuwon, W. Yield trial of upland rice (*Oryza sativa* L.) in Songkhla Province, Thailand. *Songklanakarin J. Plant Sci.* **2018**, *5*, 1–6.
15. Hussain, T.; Anothai, J.; Nualsri, C.; Soonsuwon, W. Application of CSM-CERES-Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield. *Indian J. Agric. Res.* **2018**, *52*, 140–145. [CrossRef]
16. Hussain, T.; Anothai, J.; Nualsri, C.; Soonsuwon, W. Evaluating performance of sixteen upland rice genotypes uder field conditions for further breeding process. *J. Agric. Sci.* **2018**, *10*, 144. [CrossRef]
17. Islam, S.; Anothai, J.; Nualsri, C.; Soonsuwon, W. Correlation and path analysis of phenological traits of Thai upland rice genotypes. *Songklanakarin J. Plant Sci.* **2020**, *7*, 133–142.
18. CARSR. *Rice Production Status-Highland Farming System*; Center for Agricultural Resource System Research, Faculty of Agriculture, Chiang Mai University: Chiang Mai, Thailand, 2003. Available online: http://www.mcc.cmu.ac.th/agsust/highland_SA/riceproduction_highland.htm?fbclid=IwAR1Mjn6SlS7z2N7cUR_U7F9Bnl4MijMGyFti106tFpo_RYdjoDRmyPxtkHg (accessed on 15 October 2021).
19. DRRD. Division of Rice Research Development. Rice Knowledge Bank, 2016. Available online: https://brrd.ricethailand.go.th/ (accessed on 13 September 2017).
20. Norsuwan, T.; Utasuk, K.; Panyasai, T.; Sangchyoswat, C. Optimization of nitrogen fertilizer application in lowland rice production system of agricultural resource system research station using tailored farm-plot database. *Chiang Mai Univ. J. Nat. Sci.* **2020**, *19*, 333–349. [CrossRef]
21. DRRD. Soil and Fertilizer Management in Rice Fields, Fertilizer Recommendations for Southern Region. Rice Knowledge Bank, Division of Rice Research Development, 2017. Available online: https://webold.ricethailand.go.th/rkb3/title-index.php-file=content.php&id=043.htm#p9 (accessed on 22 December 2021).
22. Choudhury, A.T.M.A.; Khanif, Y.M. Effects of nitrogen and copper fertilization on rice yield and fertilizer nitrogen efficiency: A 15N tracer study. *Pak. J. Sci. Ind. Res.* **2006**, *47*, 50–55.
23. Qiao, J.; Yang, L.; Yan, T.; Xue, F.; Zhao, D. Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area. *Agric. Ecosyst. Environ.* **2012**, *146*, 103–112. [CrossRef]
24. Belder, P. *Water Saving in Lowland Rice Production: An Experimental and Modeling Study*; Wageningen University: Wageningen, The Netherlands, 2005; ISBN 9085042240.
25. Wang, Y.L.; Liu, T.X.; Zhao, P.; Zhang, X.; Tan, J.F.; Li, C.H. Effect of nitrogen fertilizer application on yield, nitrogen absorption and soil nitric N in super–high–yield summer maize. *Sci. Agric. Sin.* **2013**, *46*, 2483–2491.
26. Fang, Q.; Ma, L.; Yu, Q.; Malone, R.W.; Saseendran, S.A.; Ahuja, L.R. Modeling nitrogen and water management effects in a Wheat–Maize double–cropping system. *J. Environ. Qual.* **2008**, *37*, 2232–2242. [CrossRef] [PubMed]
27. Manzoor, Z.; Awan, T.H.; Zahid, M.A.; Faiz, F.A. Response of rice crop (Super Basmati) to different nitrogen levels. *J. Anim. Plant Sci.* **2006**, *16*, 52–55.
28. Farrell, T.C.; Fox, K.; Williams, R.L.; Fukai, S.; Lewin, L.G. Avoiding low temperature damage in Australia's rice industry with photoperiod sensitive cultivars. In Proceedings of the 11th Australian Agronomy Conference, Geelong, VIC, Australia, 2–6 February 2003.
29. Nazir, M. *Crop Production*; Bashir, E., Bantel, R., Eds.; National Book Foundation: Islamabad, Pakistan, 1994; Volume 252.
30. Watcharin, S.; Kanrob, P.; Charassri, N.; Nattapon, J. Improving photoperiod insensitivity of a Thai upland rice variety by marker–assisted foreground selection. *Int. J. Agric. Technol.* **2020**, *16*, 199–206.
31. Takahashi, H.G.; Yasunari, T. A Climatological monsoon break in rainfall over Indochina—A singularity in the seasonal March of the Asian summer monsoon. *J. Clim.* **2006**, *19*, 1545–1556. [CrossRef]
32. Limsakul, A.; Singhruck, P. Long–term trends and variability of total and extreme precipitation in Thailand. *Atmos. Res.* **2016**, *169*, 301–317. [CrossRef]
33. Gajri, P.R.; Prihar, S.S.; Arora, V.K. Interdependence of nitrogen and irrigation effects on growth and input–use efficiencies in wheat. *Field Crop. Res.* **1993**, *31*, 71–86. [CrossRef]

34. Babel, M.S.; Agarwal, A.; Swain, D.K.; Herath, S. Evaluation of climate change impacts and adaptation measures for rice cultivation in Northeast Thailand. *Clim. Res.* **2011**, *46*, 137–146. [CrossRef]
35. Boonwichai, S.; Shrestha, S.; Babel, M.S.; Weesakul, S.; Datta, A. Evaluation of climate change impacts and adaptation strategies on rainfed rice production in Songkhram River Basin, Thailand. *Sci. Total Environ.* **2019**, *652*, 189–201. [CrossRef]
36. Boonwichai, S.; Shrestha, S.; Pradhan, P.; Babel, M.S.; Datta, A. Adaptation strategies for rainfed rice water management under climate change in Songkhram River Basin, Thailand. *J. Water Clim. Chang.* **2021**, 1–18. [CrossRef]
37. Sarfraz, R.; Shakoor, A.; Abdullah, M.; Arooj, A.; Hussain, A.; Xing, S. Impact of integrated application of biochar and nitrogen fertilizers on maize growth and nitrogen recovery in alkaline calcareous soil. *Soil Sci. Plant Nutr.* **2017**, *63*, 488–498. [CrossRef]
38. Hammad, H.M.; Farhad, W.; Abbas, F.; Fahad, S.; Saeed, S.; Nasim, W.; Bakhat, H.F. Maize plant nitrogen uptake dynamics at limited irrigation water and nitrogen. *Environ. Sci. Pollut. Res.* **2017**, *24*, 2549–2557. [CrossRef]
39. Abbasi, M.K.; Tahir, M.M.; Sadiq, A.; Iqbal, M.; Zafar, M. Yield and nitrogen use efficiency of rainfed maize response to splitting and nitrogen rates in Kashmir, Pakistan. *Agron. J.* **2012**, *104*, 448–457. [CrossRef]
40. Zhou, Q.; Ju, C.X.; Wang, Z.Q.; Zhang, H.; Liu, L.J.; Yang, J.C.; Zhang, J.H. Grain yield and water use efficiency of super rice under soil water deficit and alternate wetting and drying irrigation. *J. Integr. Agric.* **2017**, *16*, 1028–1043. [CrossRef]
41. Duangpan, S.; Tongchu, Y.; Hussain, T.; Eksomtramage, T.; Onthong, J. Beneficial Effects of Silicon Fertilizer on Growth and Physiological Responses in Oil Palm. *Agronomy* **2022**, *12*, 413. [CrossRef]
42. Duangpan, S.; Buapet, P.; Sujitto, S.; Eksomtramage, T. Early assessment of drought tolerance in oil palm D × P progenies using growth and physiological characters in seedling stage. *Plant Genet. Resour. Characterisation Util.* **2018**, *16*, 544–554. [CrossRef]
43. Wei, T.; Simko, V. R Package "Corrplot": Visualization of a Correlation Matrix. Available online: https://github.com/taiyun/corrplot (accessed on 10 November 2021).
44. Zhang, J.; Tong, T.; Potcho, P.M.; Huang, S.; Ma, L.; Tang, X. Nitrogen effects on yield, quality and physiological characteristics of giant rice. *Agronomy* **2020**, *10*, 1816. [CrossRef]
45. Millard, P. The accumulation and storage of nitrogen by herbaceous plants. *Plant Cell Environ.* **1988**, *11*, 1–8. [CrossRef]
46. Wu, K.; Wang, S.; Song, W.; Zhang, J.; Wang, Y.; Liu, Q.; Yu, J.; Ye, Y.; Li, S.; Chen, J.; et al. Enhanced sustainable green revolution yield via nitrogen-responsive chromatin modulation in rice. *Science* **2020**, *367*, eaaz2046. [CrossRef]
47. Jahan, A.; Islam, A.; Sarkar, M.I.U.; Iqbal, M.; Ahmed, M.N.; Islam, M.R. Nitrogen response of two high yielding rice varieties as influenced by nitrogen levels and growing seasons. *Geol. Ecol. Landsc.* **2020**, 1–8. [CrossRef]
48. Wang, J.; Lu, K.; Nie, H.; Zeng, Q.; Wu, B.; Qian, J.; Fang, Z. Rice nitrate transporter *OsNPF7.2* positively regulates tiller number and grain yield. *Rice* **2018**, *11*, 1–13. [CrossRef] [PubMed]
49. Chen, Z.; Wang, Q.; Ma, J.; Zou, P.; Jiang, L. Impact of controlled–release urea on rice yield, nitrogen use efficiency and soil fertility in a single rice cropping system. *Sci. Rep.* **2020**, *10*, 1–10. [CrossRef] [PubMed]
50. Pal, R.; Mahajan, G.; Sardana, V.; Chauhan, B.S. Impact of sowing date on yield, dry matter and nitrogen accumulation, and nitrogen translocation in dry–seeded rice in North–West India. *Field Crop. Res.* **2017**, *206*, 138–148. [CrossRef]
51. Lupini, A.; Preiti, G.; Badagliacca, G.; Abenavoli, M.R.; Sunseri, F.; Monti, M.; Bacchi, M. Nitrogen use efficiency in durum Wheat under different nitrogen and water regimes in the Mediterranean Basin. *Front. Plant Sci.* **2021**, *11*, 1–19. [CrossRef] [PubMed]
52. Aslam, M.A.; Ahmed, M.; Stöckle, C.O.; Higgins, S.S.; ul Hassan, F.; Hayat, R. Can growing degree days and photoperiod predict spring wheat phenology? *Front. Environ. Sci.* **2017**, *5*, 1–10. [CrossRef]
53. Gomez–Macpherson, H.; Richards, R.A. Effect of sowing time on yield and agronomic characteristics of Wheat in South–eastern Australia. *Aust. J. Agric. Res.* **1995**, *46*, 1381–1399. [CrossRef]
54. Yousaf, M.; Li, X.; Zhang, Z.; Ren, T.; Cong, R.; Ata–Ul–Karim, S.T.; Fahad, S.; Shah, A.N.; Lu, J. Nitrogen fertilizer management for enhancing crop productivity and nitrogen use efficiency in a rice–oilseed rape rotation system in China. *Front. Plant Sci.* **2016**, *7*, 1–9. [CrossRef] [PubMed]
55. Yi, J.; Gao, J.; Zhang, W.; Zhao, C.; Wang, Y.; Zhen, X. Differential uptake and utilization of two forms of nitrogen in Japonica rice cultivars from North-Eastern China. *Front. Plant Sci.* **2019**, *10*, 1–11. [CrossRef] [PubMed]
56. Song, W.; Makeen, K.; Wang, D.; Zhang, C.; Xu, Y.; Zhao, H.; Tu, E.; Zhang, Y.; Shen, Q.; Xu, G. Nitrate supply affects root growth differentially in two rice cultivars differing in nitrogen use efficiency. *Plant Soil.* **2011**, *343*, 357–368. [CrossRef]
57. Qian, X.; Shen, Q.; Xu, G.; Wang, J.; Zhou, M. Nitrogen form effects on yield and nitrogen uptake of rice crop grown in aerobic soil. *J. Plant Nutr.* **2004**, *27*, 1061–1076. [CrossRef]
58. Koutroubas, S.D.; Ntanos, D.A. Genotypic differences for grain yield and nitrogen utilization in Indica and Japonica rice under Mediterranean conditions. *Field Crop. Res.* **2003**, *83*, 251–260. [CrossRef]

Paper III

Hussain, T., Gollany, H.T., Hussain, N., Ahmed, M. Tahir, M. and Duangpan, S. 2022. Synchronizing Nitrogen Fertilization and Planting Date to Improve Resource Use Efficiency, Productivity and Profitability of Upland Rice. *Frontiers in Plant Science*. **13:** 895811. *doi:10.3389/fpls.2022.895811*.

(This manuscript is accepted in *Frontiers in Plant Science* journal)

frontiers | Frontiers in Plant Science

ORIGINAL RESEARCH
published: xx April 2022
doi: 10.3389/fpls.2022.895811

Synchronizing Nitrogen Fertilization and Planting Date to Improve Resource Use Efficiency, Productivity, and Profitability of Upland Rice

*Tajamul Hussain[1], Hero T. Gollany[2], Nurda Hussain[1], Mukhtar Ahmed[3], Muhammad Tahir[4] and Saowapa Duangpan[1]**

[1] Laboratory of Plant Breeding and Climate Resilient Agriculture, Agricultural Innovation and Management Division, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Thailand, [2] United States Department of Agriculture, Agricultural Research Service (USDA-ARS), Columbia Plateau Conservation Research Center, Pendleton, OR, United States, [3] Department of Agronomy, Faculty of Crop and Food Sciences, Pir Mehr Ali Shah (PMAS)-Arid Agriculture University, Rawalpindi, Pakistan, [4] Department of Soil, Water, and Climate, University of Minnesota, Falcon Heights, MN, United States

OPEN ACCESS

Edited by:
Sajid Fiaz,
The University of Haripur, Pakistan

Reviewed by:
Muhammad Azhar Nadeem,
Sivas University of Science and Technology, Turkey
Farhat Abbas,
South China Agricultural University, China

****Correspondence:***
Saowapa Duangpan
saowapa.d@psu.ac.th

Specialty section:
This article was submitted to Crop and Product Physiology, a section of the journal Frontiers in Plant Science

Received: *14 March 2022*
Accepted: *05 April 2022*
Published: *xx April 2022*

Citation:
Hussain T, Gollany HT, Hussain N, Ahmed M, Tahir M and Duangpan S (2022) Synchronizing Nitrogen Fertilization and Planting Date to Improve Resource Use Efficiency, Productivity, and Profitability of Upland Rice. Front. Plant Sci. 13:895811. doi: 10.3389/fpls.2022.895811

Synchronizing nitrogen (N) fertilization with planting date (PD) could enhance resource use efficiency and profitability of upland rice (*Oryza sativa* L.) production in Thailand. The objective of the study was to assess upland rice responses to four N fertilization rates (NFRs) and three planting dates. Field experiments were conducted during two growing seasons under four NFRs, no N applied (N_0), 30 (N_{30}), 60 (N_{60}), and 90 kg N ha^{-1} (N_{90}), and NFR were applied at the initiation of tillering and panicle emergence stages. The planting dates selected were early (PD1), intermedium (PD2), and late planting (PD3) between September and December of each season. The NFRs and planting dates had a significant influence on N uptake, N use efficiency (NUE), crop water productivity, yield and yield attributes, and profitability of upland rice production. A linear relationship among NFRs, agronomic traits of upland rice, N uptake, and crop water productivity was observed, and a significant seasonal effect was indicated. Fertilization at N_{90} under PD2 enhanced yields, yield attributes, and grain yields, as well as crop water productivity by 56 and 105% during the second and first seasons, respectively. Grain N, total N, and straw N were increased by 159, 159, and 160%, and by 90, 114, and 153%, during the first and second seasons, respectively. Enhanced N efficiencies, including agronomic efficiency, recovery efficiency, partial factor productivity, and N harvest index, at varying NFRs were observed under PD2 during both seasons. Highly significant ($p < 0.001$) and positive associations were observed among agronomic attributes, N uptake, NUE, and crop water productivity of upland rice in correlation assessment. Profitability from grain yields was observed with N fertilization and N_{90} resulted in maximum profit under all the PDs. However, the highest marginal benefit-cost ratio was observed at N_{60} under PD2 during both seasons. The results suggest that the NFR of 90 kg N ha^{-1} and planting at the end of September or start of October would enhance resource use efficiency and productivity, and maximize profitability. Furthermore, long-term field investigations with a range of NFRs and adopting forecasting measures to adjust the planting date for upland rice are recommended.

Keywords: agronomic management, nitrogen uptake, recovery efficiency, crop water productivity, grain yield

INTRODUCTION

Rice is a major cereal crop, is a staple food, and is a source of calories, protein, and nutrients; it significantly contributes to the dietary needs in Thailand. Globally, rice is grown in more than 95 countries (IRRI, 2002). Thailand is the sixth major rice-producing country worldwide and is ranked second in Southeast Asia (FAO, 2020). Upland rice contributes 11% of the world's rice production (Jaruchai et al., 2018), 9% of the total rice production area in Asia (Nascente et al., 2019) and Thailand. It is an important crop, contributing to local food security and economy of upland areas. It is also beneficial, as it is grown under rainfed conditions, and additional irrigation water is seldom applied (Kumar and Ladha, 2011). However, grain production of upland rice is low especially in Thailand because of various factors, including seasonal weather patterns and traditional agronomic management practices.

Upland rice is farmed by small landholders in northern and southern regions of the country during the rainy season (Nokkoul and Wichitparp, 2013). The production potential of upland rice is not yet explored because of its limited production in less fertile soils and drought-prone areas. Upland rice is cultivated on upland soils, foothill plains, and slopy and mountainous areas in Thailand. Northern Thailand consists of high mountains where upland rice is cultivated in highlands and steep river valleys. Swidden agriculture is also practiced in northern Thailand where upland rice is grown in rotation with slashing vegetation, tree regeneration, and shift in cultivation (Champrasert et al., 2020). Comparatively low yield production (0.6–0.9 t.ha^{-1}) of upland rice has been reported in northern Thailand (Karladee et al., 2012). In the southern region, upland rice is cultivated as a sole crop or is intercropped with young rubber, oil palm, and other fruit trees, and is found to be the most favorable crop for intercropping with young rubber, oil palm, and other trees. Because of its feasibility for intercropping, experiments conducted in Songkhla province confirmed that upland rice is a potential option to meet grain needs and is not affecting the young rubber if sufficient fertilizer is applied. Furthermore, a coordinated program between the Rubber Department and Rice Department of Thailand identified two local cultivars, Dawk Pa-yawm and Kho Muang Luang, as the most suitable cultivars for intercropping with young rubber and are recommended for general cultivation (Laosuwan, 1996), which increased the production of upland rice in southern Thailand. However, no further study has been conducted to analyze the impact of seasonal variations in weather patterns on upland rice response to fertilizer recommendations, which have led to continuous traditional agronomic management practices resulting in declined productivity in Thailand.

Stable upland rice production is a significant factor to meet increasing demand and ensuring food security. Climate change has affected rice production because of changes in seasonal variability in rainfall and increases in average temperature. In this scenario, maintaining a higher yield per unit area is a primary objective of upland rice production systems. In comparison to climatic factors, including air temperature, rainfall, solar radiation, soil moisture, and insects, pests, and weeds, planting time (Ferrari et al., 2018) and nitrogen (N) fertilization management are factors that are highly associated with yields and are easy for farmers to adjust and manipulate. Nitrogen is a critical nutrient that affects crop growth (Hameed et al., 2019; Santiago-Arenas et al., 2021), hence, significantly influencing crop productivity. Nitrogen deficiency in rice plants causes yellowing of leaves, reduces leaf size, and leads to low productivity, whereas excessive N fertilization results in agronomic and economic losses. Therefore, it becomes imperative that a sufficient and optimum N dose should be applied to obtain stable grain production. In northern areas of Thailand, the application of 10–75 kg N ha^{-1} by farmers in upland rice fields was reported in a survey conducted by Chiang Mai University, Thailand (CARSR, 2003). Different NFRs have been observed as N fertilization of 61.25 kg N ha^{-1} (Suwanasa et al., 2018), 61.25 kg N ha^{-1} (Hussain et al., 2018a,b), and a basal fertilization of 15 kg N ha^{-1}(Islam et al., 2020) in upland rice farming in southern Thailand. Corresponding to the Division of Rice Research and Development (DRRD) of Thailand (DRRD, 2016; Norsuwan et al., 2020), 48.75–82.5 kg N ha^{-1} based on soil N status was recommended to be used as N fertilization management for rice production. In addition to this, DRRD advised split application of 40–45 kg N ha^{-1}, including 20–45 kg N ha^{-1} as basal dose and remaining dose before heading stage for foothill rice areas (DRRD, 2017). Fertilization of 34–39 kg N ha^{-1} for photoperiod–sensitive and 59–69 kg N ha^{-1} for photoperiod–insensitive was recommended based on photoperiod sensitivity of rice cultivars in Songkhla province (experimental area) of Thailand. Variable ranges of N fertilization prevail in Thailand, and no specific or optimum recommendations have been observed according to different planting times for upland rice production. Therefore, farmers usually practiced fertilization of 10–75 kg N ha^{-1} in upland rice fields. Farmers usually use urea to meet N fertilizer demand. Application of improper dose of urea, which is extremely volatile, results in higher N losses as urea–NUE is lower around 30–40%, in rice production systems, and seldom exceeds 50% (Choudhury and Khanif, 2006). Efficient fertilizer use is also a key component to increase N uptake by rice plants. However, traditional, and inadequate N fertilization practices along with variability in cultivar's efficiency to take up N from soil, existing climatic conditions, including temperature and soil water contents, have affected effective N use. Nitrogen uptake has a direct relationship with NFR. In contrast, higher NFRs result in higher N losses (Zhang et al., 2018) because of increased soil N in the root zone (Belder, 2005). Excessive N use in upland rice may not increase yield as has been observed in numerous studies. Singh and Singh (1976) reported that the upland rice cultivar Bala was responsive up to 90 kg N ha^{-1}. Therefore, optimal nutrient management is necessary (Manzoor et al., 2006) to reduce agronomic and economic losses triggered by reduced or excessive N fertilization. To enhance N use efficiency (NUE) and identification of suitable N fertilizer rate (NFR), estimation of plant nutrient concentrations and N uptake are useful indicators. NUE has also indicated a decreasing trend with an increase in N fertilization rates (Barbieri et al., 2008) due to high levels of N in the soil, and NUE in rice production systems has decreased (Santiago-Arenas et al., 2021). Higher NUE achieved at a certain NFR could be used to identify a suitable NFR for upland rice production.

Ideal PD is a useful agronomic management factor for upland rice, and can ensure maximum use of climatic contributors (i.e., photosynthetic radiation, favorable temperature, and precipitation). Planting date affect rice productivity, as soil water status and environmental conditions differ over time. Upland rice is grown during the rainy season in Thailand (Hussain et al., 2018b), and the rainy season lasts from May to October (Limsakul and Singhruck, 2016; Ullah et al., 2019). High variability prevails in the climate of Thailand, and most rain in the east of southern Thailand occurs from November to February of the subsequent year (Limsakul and Singhruck, 2016). Farmers in Thailand perform early or delayed upland rice planting depending on soil water availability. Upland rice planted too early or late is affected by hot and dry intervals when the rice is at the reproductive stages. Too early or delayed planting results in high plant sterility, and the number of effective tillers is reduced (Nazir, 1994). Grain production is also decreased because of the incomplete development of yield-contributing traits at different crop growth phases. The yield potential of a cultivar depends on tillering that occurs at vegetative stages and panicle density that is achieved at panicle formation stages. Unsuitable planting dates and less precipitation at the reproductive stage of upland rice results in higher yield losses (Hussain et al., 2018b). Planting photosensitive upland cultivars in southern Thailand (Watcharin et al., 2020) is another critical aspect affecting upland rice productivity. The recommendation for development and cultivation of photoperiod-insensitive upland rice cultivars to stabilize rice productivity (Watcharin et al., 2020) is also threatened because of the impact of climate change, as climate change has resulted in high rainfall variability and increased drought occurrence (Ullah et al., 2019; Mansour et al., 2021). In this scenario, photoperiod-insensitive cultivars will also be affected because of seasonal variations in rainfall, which cause drought or flood incidents leading to reduced N availability or removal of N from soil surface during high rainfall events. Farmers apply supplementary irrigation to upland rice during hot and dry intervals which increases input cost, and crop water productivity is also affected.

A significant synergy between optimum fertilization, particularly N, and soil water contents is reported in other studies (Santiago-Arenas et al., 2021), which positively influences rice productivity. Adjustment in PD can shift crop period to most favorable period and enable a crop to utilize enough soil water, thus increasing crop water productivity. There is evidence for enhanced NUE with increased crop water productivity under various N applications, and NFR-altered crop water productivity and water input determined NUE (Gajri et al., 1993). Ideal PD is also as important, as it ensures maximum vegetative growth, adjusts the sensitivity of cultivars to difference in temperatures, and enhances grain filling (Farrell et al., 2003). In addition, adjusting the crop growth period according to a suitable PD (Ullah et al., 2019) helps in shifting critical crop growth and developmental phases to the most promising part of the season that ensures maximum use of input resources. Therefore, to reduce and cope with the influence of climate change on upland rice production, proper plant nutrient management and adjustment in PD is essential (Babel et al., 2011; Boonwichai et al., 2019, 2021).

Traditional agronomic practices for N fertilization, general recommendation rates, and prevalence of wide planting windows have led to increased vulnerability of upland rice production. To the best of our knowledge, field evaluations for identifying a suitable NFR alone or synchronized with ideal PDs have not been conducted for upland rice production in Thailand. Therefore, the research was conducted to determine upland rice responses to NFRs and PDs under field conditions. We hypothesized that adjusting PD and application of suitable N rate synchronized with PD assures improved resource use efficiency, enhances productivity, and maximizes profitability of upland rice production.

MATERIALS AND METHODS

Study Site Description

A 2-year experiment was established in the experimental field area of the Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Thailand (7°00'14.5" N, 100°30'14.7" E) during rice growing periods in the 2018–2019 and 2019–2020 crop years. The experimental area is in Songkhla province in the east of Southern Thailand (**Supplementary Figure S1**). The climate of Songkhla is characterized by a hot or dry season (January–May) and a rainy season (June–December). High variability prevails in the climate of Southern Thailand. Maximum precipitation occurs from November to February of next year in the eastern part of Southern Thailand (Limsakul and Singhruck, 2016). The mean minimum and maximum temperatures reach 24.8 and 31.5°C, respectively, with an annual average temperature of 27.9°C and average annual rainfall of 2,066.7 mm (Hussain et al., 2021a; TMD, 2021). The soil at the study area is well-drained sandy clay loam at the 0–30 cm soil depth. Field capacity, permanent wilting point, and available water capacity of the 0- to 30-cm soil layer are 15.06, 9.44, and 5.62%, respectively. Soil chemical properties of pre-plantation soil analysis include pH, organic matter (Walkley and Black, 1934), total N (Kjeldahl, 1883), available phosphorus (Bray and Kurtz, 1945), and available potassium (Thomas, 1982), and are reported in **Supplementary Table S1**.

Treatments and Experimental Setup

The experimental trials consisted of two treatments, namely, nitrogen fertilization rates (NFRs) and planting dates (PDs). The NFRs included the control (N_0) with no applied N and 30 kg N ha^{-1} (N_{30}), 60 kg N ha^{-1} (N_{60}), and 90 kg N ha^{-1} (N_{90}) urea applied. Targeted rice planting windows were last weeks of August, September, and October of each season. However, it was not always possible to perform planting on targeted dates in the second season (2019–2020) and was delayed because of unfavorable field conditions. Planting dates for 2018 were 30 August, 26 September, and 31 October 2018 for the early (PD1), intermedium (PD2), and late (PD3) planting in the first growing season (2018–2019), and 1 September, 6 October, and 3 November for the early (PD1), the intermedium (PD2) and late (PD3) planting dates in 2019 in the second growing season (2019–2020), respectively. The genotype used in experiments was Dawk Pa-yawm, which is a non-glutinous (Suwanasa et al., 2018) Thai upland rice genotype, very popular because of its aromatic fragrance, and is commonly cultivated in upland rice-growing areas of Thailand. Before planting in both seasons, the experimental field was plowed twice using a disc plow and a rotavator (twice). Experimental treatments were arranged in a randomized complete block design with three replicates. Each treatment was designated in an individual plot (3×3 m^2) having 11 rows with 30-cm row-to-row spacing. To reduce the risk of lateral movement of nutrients during high rainfall intervals, all the plots were separated by a 1.5-m buffer space on each side with 0.3-m-high dikes. Drain furrows were made in the center of the surrounding buffer space of each plot, and during heavy rainfall, the dikes were cut to drain excess rainwater from each plot to avoid overflow of rainwater. In both seasons, the recommended basal fertilizer rate (DRRD, 2017) for phosphorus (19 kg P_2O_5 ha^{-1}) and potassium (13 kg K_2O ha^{-1}) was applied equally to all the experimental plots before planting. Five seeds per hill were manually planted at 5-cm soil depth using a hand hoe, maintaining a 25-cm plant-to-plant distance. A sprinkler irrigation system with a sprinkler head (ANT-1401, product code: 351-1401160®), a water discharge capacity of 160 L h^{-1}, and a 3-m diameter of water dispersal range was installed for supplementary irrigation (10–15 mm per event) at the time of planting and during the hot and dry intervals of each growing season. Thinning was performed to maintain a single plant per hill after 20–25 days of germination to attain a uniform plant stand. Urea (46% N) was used as a source of N fertilizer and was applied in two uniform splits by incorporating the fertilizer at ~5 cm soil depth in the plant rows using a hand-operated mini plow in the experimental plots according to the experimental design at the initiation of the tillering and panicle emergence stages. Weeds were manually removed from plots, and recommended cultural practices were used to control insects, pests, and diseases by spraying suitable chemical formulations to reduce yield losses in both seasons. The experimental field was surrounded on each side and covered with a net placed at a height of 2 m in both seasons to avoid crop damage by birds and rodents.

Data Collections and Observations

Daily minimum and maximum temperature (°C), and daily rainfall (mm) data for both seasons were collected from Kho Hong Agrometeorology–Agricultural Information Center, Hat Yai, located 1.8 km from the experimental site. Agronomic data collection and plant sampling for determining N concentrations were performed at maturity during the harvest for each planting date. The number of days to flowering and days to maturity was recorded when 50% of flowering occurred, and 50% of plants reached physiological maturity in each experimental plot. Stem height was recorded from the ground surface to the topmost panicle or leaf. Stem density was counted at the time of maximum stem formation stage, and stems/tillers having at least one visible leaf were included. Plants from a 1-m^2 area in each plot were manually harvested and used to record grain yield and yield components. Eight sample hills were manually harvested from the demarcated area to determine aboveground biomass yield. Plants from border rows were not harvested in each plot to avoid border effect. Rice straw and grain samples were dried in an oven at 65°C at various time intervals until constant weight (Yousaf et al., 2016), and dry weights of samples were obtained to determine grain yield and aboveground biomass.

Nitrogen Concentration, Nitrogen Uptake, and Nitrogen Use Efficiency

Grain and straw samples were collected from each replication and treatment in both seasons. The straw samples were first chopped, and then the straw and grain samples were oven-dried at 65°C to a constant weight (Yousaf et al., 2016). The oven-dried grain and straw samples were ground to 1 mm using a grinder model "Retch Cyclone Mill Twister" (Hussain et al., 2021a). The Kjeldahl method (Kjeldahl, 1883) was used to determine concentrations at the Central Analytical Laboratory of Faculty of Natural Resources, Prince of Songkla University, Thailand. Grain and straw N uptake for each treatment was computed by multiplying grain yield and straw yield with corresponding N concentrations (Abbasi et al., 2012; Hammad et al., 2017). Nitrogen use efficiency (NUE) for agronomic N efficiency [AE_N; increase in grain yield (kg) relative to applied N (kg)] of applied N (Equation 1), nitrogen recovery efficiency (RE_N; N absorbed and used by plant) (Equation 2), partial factor productivity (PFP: ratio between grain yield and amount of fertilizer applied N uptake) (Equation 3), and nitrogen harvest index (Equation 4) were computed as outlined by Wang et al. (2018).

$$AE_N = \frac{\text{grain yield } (N_x) - \text{grain yield } (N_0)}{\text{N fertilizer applied } (N_x)} \quad (1)$$

$$RE_N = \frac{\text{N uptake } (N_x) - \text{N uptake } (N_0)}{\text{N fertilizer applied } (N_x)} \times 100 \quad (2)$$

$$PFP = \frac{\text{grain yield}}{\text{N fertilizer applied}} \quad (3)$$

$$NHI = \frac{\text{grain N content}}{\text{total plant N uptake}} \quad (4)$$

Water Input and Crop Water Productivity

Irrigation water data for each PD were recorded with the amount of water applied using a sprinkler irrigation system. Daily rainfall data were collected from Kho Hong Agrometeorology–Agricultural Information Center, Hat Yai, Office of the Thai Meteorological Department. Irrigation water and rainfall received during each PD were added to calculate the total water input. Crop water productivity (kg m^{-3}) was computed by dividing grain yield (kg) by total water input (m^3) using Equation (5) as described by Liu et al. (2019) and Zhou et al. (2017).

$$\text{Crop water productivity (kg m}^{-3}\text{)} = \frac{\text{Grain yield}}{\text{Total water input}} \quad (5)$$

Economic Assessment

Economic assessment for profitability based on grain yield (kg ha^{-1}) obtained from N fertilization relative to non-N fertilized plots was performed. Urea was used as a N fertilizer source, and N application cost for NFR was computed based on the prevailing market price (800 Thai Baht = US$ 23.76 per 50-kg bag) of urea fertilizer. Dawk Pa-yawm rice product selling price of $ 1.78 per kg (Thai Baht 60 = US$ 1.78 per kg.) was taken from farmer's market, and used in an economic assessment. Marginal benefit-cost ratio (MBCR), which provides the marginal assessment of economic returns of various treatments, was computed (Equation 6) (Rahman et al., 2011; Anwar et al., 2021):

$$\text{MBCR} = \frac{\text{Gross return}_{\text{N added}} - \text{Gross return}_{\text{control}}}{\text{Gross cost}_{\text{N added}} - \text{Gross cost}_{\text{control}}} \quad (6)$$

Statistical Analysis

The analysis of variance (ANOVA) function of statistical package Statistix 8.1 (Tallahassee, FL, United States) (Duangpan et al., 2022) was used for statistical analysis and to evaluate the effects of applied N treatments, PDs, seasons, and their interactions. Least significant difference (LSD) was used for mean comparisons at a 5% probability level. The relationship among applied NFRs, agronomic attributes of upland rice, N uptake, and crop water productivity was evaluated by regression analysis using Statistix 8.1 and Microsoft Excel (Santiago-Arenas et al., 2021). A correlation analysis was performed to determine the association among the studied attributes, and the "Corrplot" package (Wei and Simko, 2021) of the R program (Core Team, 2021) was utilized to compute Pearson's correlation coefficients and visuals. The "ggplot2" package (Wickham, 2016) was used for the graphical output of boxplots for computed NUEs.

RESULTS

Weather

Mean daily maximum and minimum temperatures ranged from 24 to 37 and 21 to 26°C during the first season and 27–37 and 22–26°C during the second season, respectively (**Figure 1**). The mean maximum and minimum temperatures were similar within respective PDs during both seasons. However, the mean maximum and minimum temperatures were slightly different from planting to flowering and from flowering to maturity during each PD in both seasons. Mean maximum temperature was higher in the first season, and minimum temperature was comparatively higher in the second season for PD3 (**Table 1**). The highest total rainfall received during PD1 was 1,152 mm during the first season and 1,061 mm during the second season, whereas PD2 and PD3 received 997 and 652 mm during the first season and 823 and 444 mm during the second season, respectively (**Figure 1**). However, the rainfall distribution from planting to flowering and from flowering to the physiological maturity period of each planting date was highly variable. Early planting (PD1) received 921- and 1,060-mm rainfall during the planting to flowering period of the first and second seasons, respectively. Intermediate planting (PD2) received 966- and 777-mm rainfall during the sowing to flowering period of the first and second seasons, respectively. Late planting (PD3) received 652- and 443-mm rainfall, comparatively less than PD1 and PD2 during the sowing to flowering period of the first and second seasons, respectively. From flowering to physiological maturity, PD1 received 231 mm as the highest rainfall during the first season. However, during the second season, PD1 received only 1-mm rain because of delayed planting, while PD2 received 31- and 46-mm rainfall from the flowering to physiological maturity period during the first and second seasons, respectively. During the flowering to physiological maturity period in the first season, delayed planting at PD3 did not receive any rainfall, and in the second season, only 1-mm rainfall occurred (**Table 1**). High temperatures and most dry spells occurred during the growing period of delayed planting on PD3 in both seasons.

Crop Performance and Effect of Season

The statistical analysis indicated that various NFRs, under the effect of seasons (S) and in the interaction of NFR × planting date (PD), NFR × S, and NFR × PD × S, did not significantly affect days to flowering. However, PD alone and in the interaction with the seasons (PD × S) significantly influenced day to flowering, whereas the interactions of NFR and PD were not significantly different. Similarly, N fertilization under various NFRs alone and in the interaction of NFR, PD, and S did not significantly affect days to maturity. However, days to maturity was significantly influenced under the effect of PD, S, NFR × PD, NFR × S, and PD × S. Stem height, stem density, and panicle density acted similarly and were significantly affected under NFR, PD, S, and in the interaction of NFR × S, whereas they were not significantly influenced under NFR × PD, PD × S, and NFR × PD × S. Grain yield and aboveground biomass acted similarly and were affected significantly under NFR, PD, S, NFR × PD, NFR × S, and; PD × S, whereas they were not influenced under the combined interaction of NFR, PD, and S (**Table 2**). The effect of season was significantly different in both seasons (**Table 2**). Rainfall occurrence and distribution were higher and comparatively suitable in the first season (**Figure 1**). Crop growth and maturity duration were extended (**Figure 2**); therefore, the upland rice performed better in the first season than in the second season (**Figure 3**).

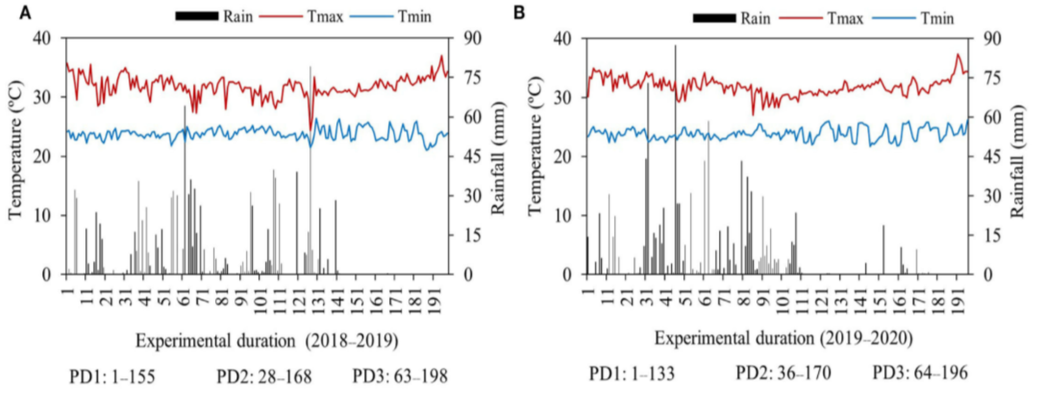


FIGURE 1 | Mean daily maximum (Tmax), minimum temperature (Tmin), and daily rainfall during the experimental growing period (days) of the first season, **(A)** 2018–2019, and the second season, **(B)** 2019–2020. PD: planting date. (data source: Kho Hong; Hat Yai Agrometeorology–Agricultural Information Center: Thai Meteorological Department, Thailand).

TABLE 1 | Mean maximum temperature (Tmax), minimum temperature (Tmin), and total rainfall from planting to flowering and flowering to physiological maturity of each planting date (PD) during the growing seasons of 2018–2019 and 2019–2020.

Duration	Planting date	Tmax (°C)		Tmin (°C)		Rainfall (mm)		Irrigation (mm)	
		2018–2019	2019–2020	2018–2019	2019–2020	2018–2019	2019–2020	2018–2019	2019–2020
Planting to flowering	PD1	31.8	31.8	23.8	23.8	921	1060	75	75
	PD2	31.4	31.2	23.9	23.8	966	777	55	135
	PD3	31.1	31.2	24.0	23.9	652	443	155	245
Flowering to physiological maturity	PD1	30.8	31.0	23.9	24.1	231	1	30	20
	PD2	31.4	31.9	24.1	23.4	31	46	40	20
	PD3	33.5	33.4	23.3	24.5	0	1	50	60

Phenology

Phenology was not significantly influenced by N fertilization. However, flowering in PD1 during the first season crop under N_{90} occurred 4 days earlier than under N_0; whereas maturity was delayed 2–4 days under N fertilization compared to N_0. PD significantly affected phenology, and days to flowering and maturity were decreased by 6–11 and 15–20 days, respectively, under PD2 and PD3 at various NFRs except for days to maturity during the second season (**Figures 2A–D**). Crop duration was relatively shorter in the second season than in the first season possibly because of prevailing climatic conditions.

Stem Height

NFR and PD significantly affected stem height during both seasons. Stem height was increased with an increase in NFR, and maximum stem height was observed at N_{90} under all the PDs during both seasons. Increase in stem height under the effect of N addition ranged 33–40% under PD1, 18–26% under PD2, and 23–36% under PD3 during the first season and 11–25% under PD1, 7–23% under PD2, and 10–19% under PD3 during the second season. Under the influence of PDs, maximum stem height was observed in PD2 at all NFRs during both seasons. Stem height increased by 15, 4, 3, and 4% for N_0, N_{30}, N_{60}, and N_{90}, respectively, under PD2 during the first season, while it was increased by 8, 4, 8, and 6% for N_0, N_{30}, N_{60}, and N_{90}, respectively, under PD2 during the second season. Delayed planting (PD3) resulted in a decline in stem height by 15, 12, 6, and 8% for N_0, N_{30}, N_{60}, and N_{90}, respectively, under PD3 during the first season, and by 11, 8, 19, and 15% for N_0, N_{30}, N_{60}, and N_{90}, respectively, under PD3 during the second season (**Figures 2E,F**). PD alone had a significant positive impact on stem height.

Stem and Panicle Density

Stem density was positively influenced by N addition and N fertilization at the initiation of tillering stage, resulted in increased number of secondary stems and stem density (m^{-2}) in both seasons (**Figures 3A,B**). Maximum stem density was observed at N_{90} under all the PDs during both seasons. The increase in stem density under the effect of N fertilization ranged from 44 to 62% under PD1, 34–59% under PD2, and 53–73% under PD3 during the first season and were 31–79% under PD1, 27–50% under PD2, and 35–76% under PD3 during the second season. Maximum stem density was observed under PD2 at all the NFRs during both seasons and increased by 11, 3, 10, and 9% in the N_0, N_{30}, N_{60}, and N_{90} treatments, respectively, during

TABLE 2 | F-values and significance obtained from the combined analysis of variance for days to flowering, days to maturity, stem height, stem density, panicle density, grain yield, aboveground biomass, straw nitrogen (N) content, grain N content, total plant N uptake, and crop water productivity of upland rice (genotype: Dawk Pa-yawm) as influenced by various N fertilization rates (NFRs) and planting dates.

Traits	**Nitrogen fertilization rate (NFR)**	**Planting date (PD)**	**Season (S)**	**NFR x PD**	**NFR x S**	**PD x S**	**NFR x PD x S**
Days to flowering	1.59^{ns}	173.55***	0.22^{ns}	0.79^{ns}	1.56^{ns}	19.09***	1.80^{ns}
Days to maturity	0.73^{ns}	249.87***	901.71***	2.93*	3.71*	267.98***	1.32^{ns}
Stem height	147.51***	58.88***	181.63***	0.90^{ns}	12.27***	0.02^{ns}	1.94^{ns}
Stem density	416.23***	106.10***	1,141.89***	0.34^{ns}	14.64***	1.46^{ns}	1.93^{ns}
Panicle density	424.2***	108.95***	1,122.01***	0.61^{ns}	13.98***	1.20^{ns}	1.50^{ns}
Grain yield	216.73***	194.00***	212.01***	12.58**	27.77***	6.25**	1.88^{ns}
Above ground biomass	602.11***	271.30***	1,046.98***	8.87**	35.13***	8.00**	1.47^{ns}
Straw N content	1,211.02***	958.70***	1,927.22***	29.97***	101.56***	44.06***	3.24**
Grain N content	447.25***	909.10***	404.46***	34.16***	41.66***	38.43***	3.93**
Total plant N uptake	1,129.38***	1,491.77***	1,393.23***	50.28***	99.25***	64.95***	3.62**
Crop water productivity	228.78***	246.59***	53.31***	12.80***	21.61***	3.01^{ns}	1.93^{ns}

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, ns, non-significant at $p \geq 0.05$.

the first season, and increased by 27, 23, 8, and 7 in N_0, N_{30}, N_{60}, and N_{90}, respectively, during the second season. Delayed planting (PD3) resulted in decline in stem density by 19, 8, 13, and 12% in N_0, N_{30}, N_{60}, and N_{90}, respectively, during the first season, and by 29, 25, 19, and 17% in N_0, N_{30}, N_{60}, and N_{90}, respectively, during the second season. Similarly, panicle density was positively influenced by N addition. Nitrogen fertilization resulted in increased panicle density (m^{-2}) in both seasons (**Figures 3C,D**). Maximum panicle density was observed at N_{90} under all the PDs during both seasons. The increase in panicles under the effect of N fertilization ranged from 46 to 63% under PD1, 38–65% under PD2, and 51–76% under PD3 during the first season, and ranged from 37 to 87% under PD1, 27–60% under PD2, and 34–79% under PD3 during the second season. Under the influence of PDs, maximum panicle density (m^{-2}) was observed under PD2 and at all the NFRs during both seasons, and it increased by 10, 5, 12, and 11% for N_0, N_{30}, N_{60}, and N_{90}, respectively, during the first season, whereas it was increased by 24, 15, 6, and 6% in N_0, N_{30}, N_{60}, and N_{90}, respectively, during the second season. Delayed planting (PD3) resulted in decline in panicle density (m^{-2}) by 18, 11, 15, and 13% in N_0, N_{30}, N_{60}, and N_{90}, respectively, during the first season, and by 27, 23, 22, and 19% in N_0, N_{30}, N_{60}, and N_{90}, respectively, during the second season. PD significantly impacted stem density and panicle density (**Figures 3A–D**). Both attributes were increased under PD2 and decreased under PD3 with N_0. Maximum increase under PD2 and maximum decrease under PD3 in stem density were observed with N_0 during both seasons. Maximum increase in stem density and panicle density was observed with N_0 in both seasons.

The regression analysis for stem density (**Figures 4A,B**) and panicle density (**Figures 4C,D**), and NFR under all the PDs indicated a highly significant linear relationship between both seasons and stem density, as well as panicle density, continued to increase with increase in NFR.

Grain Yield and Aboveground Biomass

Grain yield was positively affected by varying N additions on all the planting dates, and maximum grain yield was obtained with N_{90} in both seasons (**Figures 3E,F**). Grain yield was increased by 25–75% at PD1, 30–105% at PD2, and 38–94% at PD3 during the first season and by 12–32% at PD1, 11–56% at PD2, and 5–41% at PD3 during the second season. Maximum grain yield was obtained in PD2 at all the NFRs in both seasons, and it was increased by 14, 18, 53, and 33% in N_0, N_{30}, N_{60}, and N_{90}, respectively, under PD2 during the first season, whereas it was increased by 14, 14, 32, and 34% for N_0, N_{30}, N_{60}, and N_{90}, respectively, under PD2 during the second season. A decline in grain yield was observed because of delayed planting at PD3 as compared to PD2, and grain yield was decreased by 25, 20, 41, and 29% for N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD3 during the first season, whereas it was decreased by 22, 26, 31, and 29% for N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD3 during the second season. Similarly, aboveground biomass was also positively influenced by N addition, and N fertilization resulted in increased aboveground biomass in both seasons (**Figures 3G,H**). Maximum aboveground biomass was observed at N_{90} at all the PDs during both seasons. Nitrogen addition increased aboveground biomass by 28–73% at PD1, 45–81% at PD2, and 40–83% at PD3 during the first season, and by 22–59% at PD1, 29–64% at PD2, and 21–50% at PD3 during the second season. A decline in aboveground biomass was also observed because of delayed planting at PD3 as compared to PD2, and it was decreased by 19, 22, 27, and 19% in N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD3 during the first season, whereas it was decreased by 15, 20, 24, and 22% for N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD3 during the second season.

The effect of PD was considerable on grain and aboveground biomass yields under all the NFRs. Grain yield and aboveground biomass were increased at PD2 and decreased under delayed planting, PD3. The regression analysis for grain yield (**Figures 4E,F**) and aboveground biomass (**Figures 4G,H**),

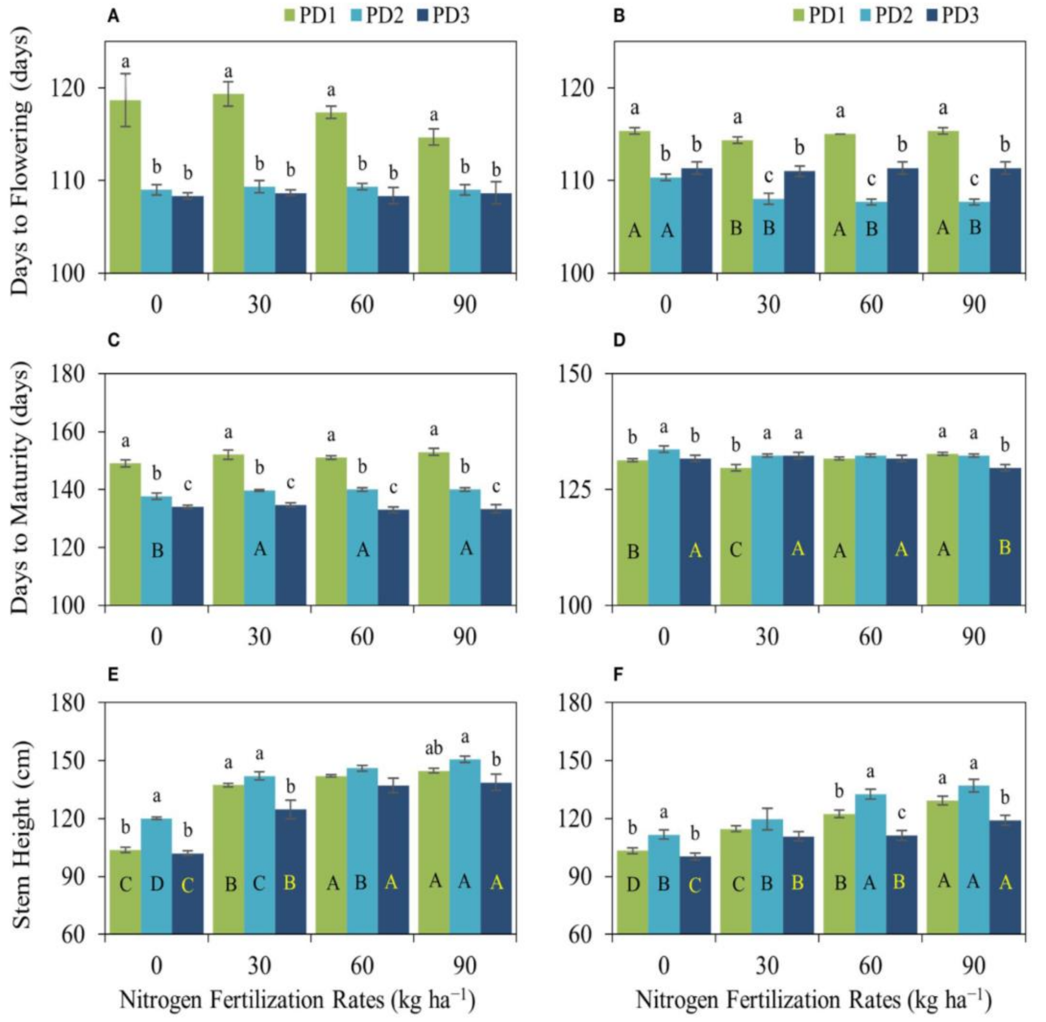


FIGURE 2 | Impact of nitrogen (N) fertilization rates and planting dates on **(A,B)** days to flowering, **(C,D)** days to maturity, and **(E,F)** stem height of upland rice during the first season, **(A,C,E)** 2018–2019, and the second season, **(B,D,F)** 2019–2020. Significance ($p < 0.05$) for the means (± standard errors of 3 replicates) of traits under various N fertilization rates within each planting date is indicated by uppercase letters inside the respective bars. Significance ($p < 0.05$) for the means (± standard errors of 3 replicates) of traits under various planting dates within each N fertilization rate is indicated by lowercase letters above the bars. Bars without letters refer to a non-significant difference ($p \geq 0.05$).

and NFRs under all the PDs indicated a highly significant linear relationship between in both seasons and grain yield, as well as aboveground biomass, continued to increase with increase in NFR in this assessment.

Nitrogen Uptake

Rice straw N content, grain N content, and total plant N uptake significantly ($p < 0.001$) differed under the effect of treatments and their interactions, including NFR, PD, S, NFR × PD, NFR × S, PD × S, and NFR × PD × S (**Table 2**). A significant increase in straw, grain and total N uptake was observed with increase in NFR under all the PDs during both seasons (**Figure 5**). The effect of N fertilization on rice straw N content ranged from 59 to 181% at PD1, 69 to 160% at PD2 and 54 to 186% at PD3, and 45 to 140% at PD1, 55 to 153% at PD2, and 60 to 129% at PD3 during the first and the second seasons, respectively (**Figures 5A,B**). Under the influence of PDs, maximum straw N content was observed at PD2 and all the NFRs during both seasons. Straw N uptake increased at PD2 by 43, 52, 38, and 32%, whereas it increased by 30, 39, 51, and 37% for N_0, N_{30}, N_{60}, and N_{90} during the first and second seasons, respectively, when compared to PD1. Delayed planting (PD3) resulted in decline in straw N content

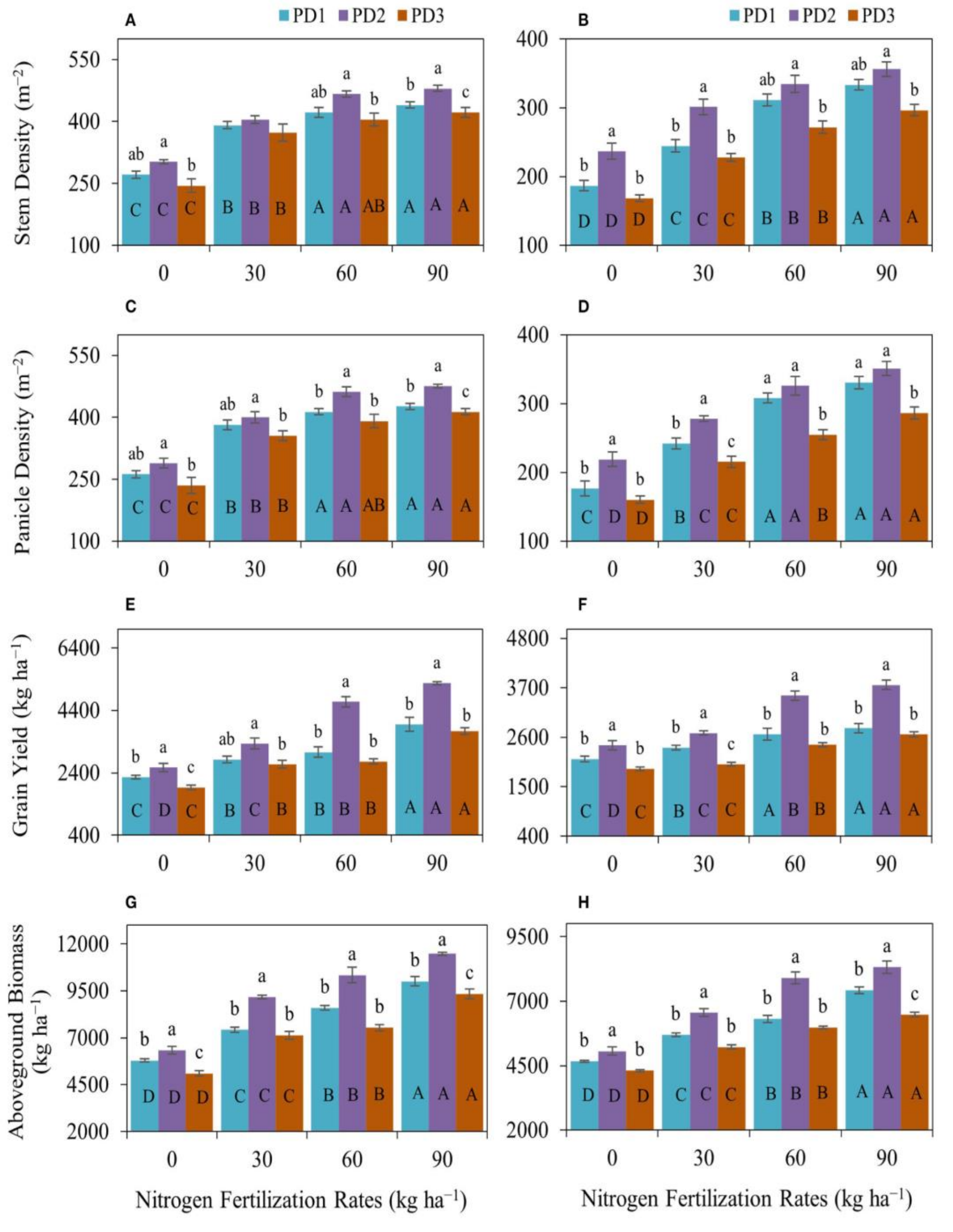


FIGURE 3 | Impact of nitrogen (N) fertilization rates and planting dates on **(A,B)** stem density, **(C,D)** panicle density, **(E,F)** grain yield, and **(G,H)** aboveground biomass of upland rice (genotype: Dawk Pa-yawm) during the first season, **(A,C,E,G)** 2018–2019, and the second season, **(B,D,F,H)** 2019–2020. Significance ($p < 0.05$) for the means (± standard errors of 3 replicates) of traits under various N fertilization rates within each planting date is indicated by uppercase letters inside the respective bars. Significance ($p < 0.05$) for the means (± standard errors of 3 replicates) of traits under various planting dates within each N fertilization rate is indicated by lowercase letters above the bars.

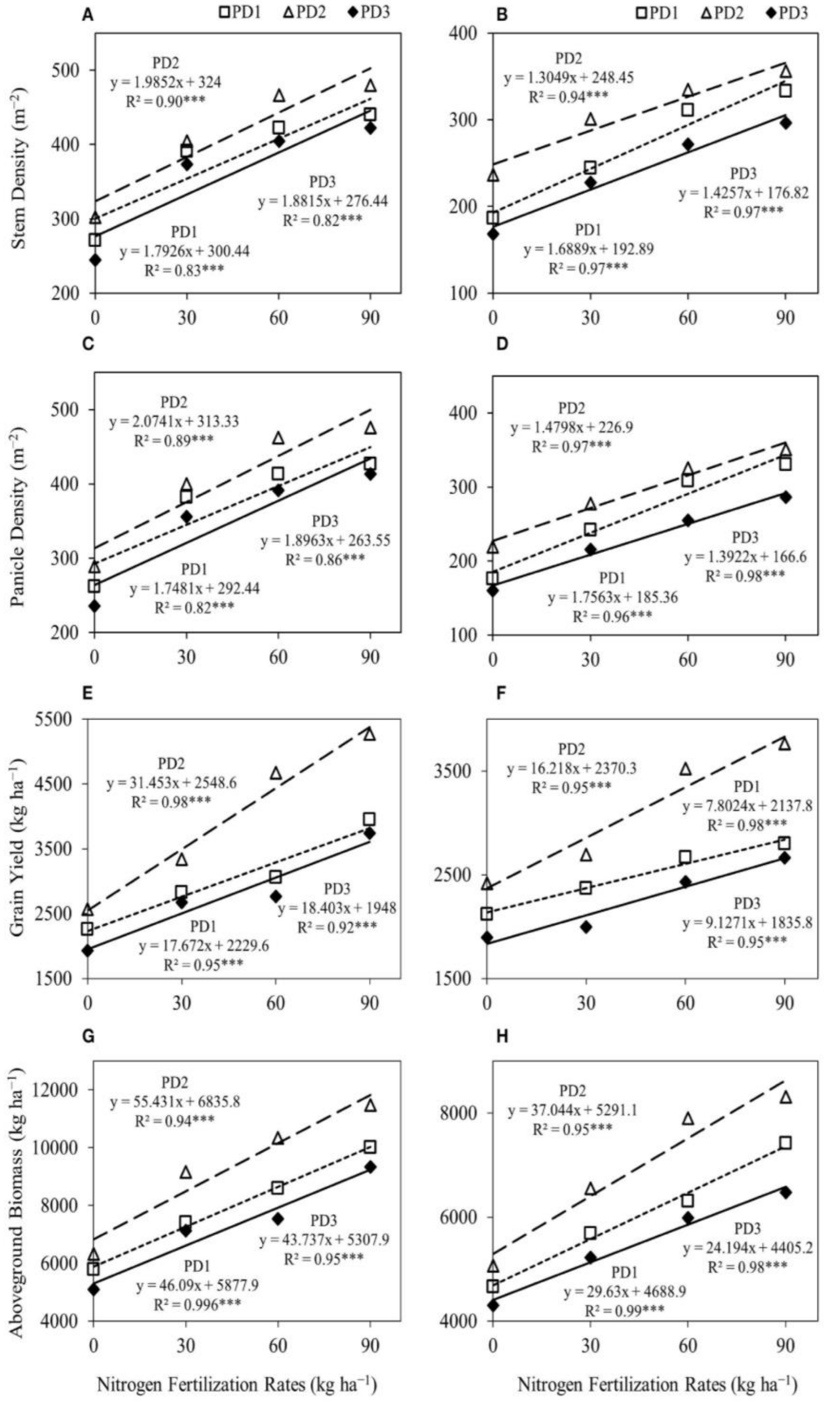


FIGURE 4 | Linear regression relationships **(A,B)** between nitrogen (N) fertilization rates and stem density, **(C,D)** between N fertilization rates and panicle density, **(E,F)** between N fertilization rates and grain yield, and **(G,H)** between N fertilization rates and aboveground biomass for upland rice obtained from the first season, **(A,C,E,G)** 2018–2019, and the second season, **(B,D,F,H)** 2019–2020, data. *** Significant at $p < 0.001$.

by 43, 48, 46, and 37% and by 42, 40, 46, and 48% for N_0, N_{30}, N_{60}, and N_{90} at PD3 as compared to PD2 during the first and second seasons, respectively. A significant linear relationship was indicated between NFR and straw N content for all the planting dates in both seasons (**Figures 6A,B**).

Rice grain N content increased by 31–125% at PD1, 52–159% at PD2, and 48–152% at PD3 during the first season, and by 19–73% at PD1, 18–90% at PD2, and 13–88% at PD3 during the second season (**Figures 5C,D**). Under the influence of PDs, maximum grain N content was observed at PD2 at all the NFRs during both seasons. Grain N uptake increased by 55, 80, 98, and 78% during the first season, whereas it was increased by 57, 55, 83, and 71% for N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD2 during the second season when compared to PD1. Delayed planting (PD3) resulted in decline in rice grain N content by 50, 51, 59, and 51% during the first season, and by 48, 51, 53, and 49% during the second season for N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD3 when compared to PD2. Grain N content continued to increase with increase in NFR under all the PDs, and a linear relationship was observed (**Figures 6C,D**).

A similar trend was observed for total plant N uptake (**Figures 5E,F**). Total plant N uptake was increased by 44–152, 60–159, and 51–168% during the first season and by 30–102, 32–114, and 32–105% during the second season at PD1, PD2, and PD3, respectively. Under the influence of PDs, maximum total plant N uptake was observed in PD2 at all the NFRs during both seasons. Total plant N uptake was increased by 49, 65, 65, and 54% during the first season, whereas it was increased by 45, 48, 68, and 54% during the second season in N_0, N_{30}, N_{60}, and N_{90}, respectively, when PD2 compared to PD1. Delayed planting (PD3) resulted in decline in total plant N uptake by 20, 35, 50, and 51% during the first season, and by 46, 46, 50, and 48% during the second season in N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD3 as compared to PD2. The regression analysis for total plant N uptake and NFR under all the PDs also indicated a highly significant linear relationship during both seasons (**Figures 6E,F**).

Nitrogen Use Efficiencies

Nitrogen fertilization influenced N use efficiencies, including agronomic efficiency (AE_N), recovery efficiency (RE_N), partial factor productivity (PFP), and N harvest index (NHI), and all varied under varying NFRs. Maximum AE_N (kg kg^{-1}) was as follows: 18.8 in N_0 and N_{90} at PD1, 35 in N_{60}, at PD2, and 24.7 in N_0 at PD3 during the first season, and 9.1 in N_{60} at PD1, 18.4 in N_{60} at PD2, and 9 at N_{60} at PD3 during the second season (**Figures 7A,B**). Significant variability in AE_N was observed under the influence of PD, and maximum AE_N was observed at PD2 at all the NFRs. Agronomic efficiency was increased by 36, 162, and 60% for N_{30}, N_{60}, and N_{90}, respectively, during the first season, and it was increased by %, 102 and 97 for N_{30}, N_{60}, and N_{90}, respectively, during the second season. Delayed planting (PD3) resulted in decline in AE_N by 4, 60, and 30% during the first season, and by 63, 51, and 43% during the second season in N_{30}, N_{60}, and N_{90} at PD3 as compared to PD2, respectively.

Recovery efficiency varied under N fertilization, and maximum RE_N of 50% in N_{90}, 88% in $N_{30,}$ and 44% in N_{90} during the first season, and 27% in N_{60}, 48% in $N_{60,}$ and 22% in N_{60} during the second season was observed, respectively, at PD1, PD2, and PD3 (**Figures 7C,D**). Significant variation in RE_N was observed under the influence of PD, and maximum RE_N was observed at PD2 at all the NFRs. RE_N was increased by 101, 82, and 57% during the first season, and by 56, 106, and 63% during the second season in the N_{30}, N_{60}, and N_{90}, respectively. Delayed planting (PD3) resulted in decline in RE_N by 55, 59, and 43% during the first season, and by 46, 55, and 50% in N_{30}, N_{60} and N_{90}, respectively, under PD3 as compared to PT2 during the second season.

Partial factor productivity (PFP) gradually decreased with increase in NFR, and the maximum observed during the first season were 94.2, 111.4, and 89.1 kg kg^{-1}, and 79 kg kg^{-1}at PD1, 89.8 kg kg^{-1} at PD2, and 66.6 kg kg^{-1} at PD3 during the second season (**Figures 7E,F**). PFP varied among the planting dates, and maximum PFP was also observed under PD2 at all the NFRs. PFP increased by 18, 53, and 33% during the first season, and by 14, 32, and 34% during the second season in N_{30}, N_{60} and N_{90}, respectively. PFP declined by 20, 41 and 29% during the first season and by 26, 31, and 29% during the second season in N_{30}, N_{60}, and N_{90}, respectively, at PD3 as compared to PD2.

N harvest index (NHI) differed under N fertilization, and maximum NHI observed were 47% in N_{30} and N_{90} at PD1, 54% in N_{60} and N_{90} at PD2, and 50% in N_{30} at PD3 during the first season, and 53% in N_{30} and N_{60} at PD1, 57% in N_{60} at PD2, and 55% in N_{90} at PD3 during the second season (**Figures 7G,H**). NHI varied among the PDs, and maximum NHI was also observed at PD2 and all the NFRs. Nitrogen harvest index increased by 9, 20, and 16% during the first season and increased by 5, 9, and 11% during the second season, respectively, with the N_{30}, $N_{60,}$ and N_{90} treatments. Nitrogen harvest index also declined by 3, 13, and 12% during the first season, and by 8, 7, and 1% during the second season with N_{30}, $N_{60,}$ and N_{90}, respectively, under PD3 as compared to PD2.

Crop Water Productivity

Crop water productivity was significantly ($p < 0.001$) different under the effect of NFR, PD, S, NFR × PD, and NFR × S, whereas no significant interaction was observed for PD × S and NFR × PD × S (**Table 2**). Crop water productivity was highly influenced by seasons. An increase in crop water productivity was observed with increase in NFR, and maximum crop water productivity was at N_{90} under all the PDs during both seasons (**Figure 8**). The increase in crop water productivity ranged from 25 to 75, 30 to 105, and 38 to 94% during the first season, and 12–32, 11–56, and 5–41% during the second season at PD1, PD2, and PD3, respectively, under the effect of N addition. Maximum crop water productivity was observed at PD2 in all the NFRs during both seasons. Crop water productivity increased by 33, 36, 74, and 54% during the first season, and by 33, 34, 56, and 58% during the second season in N_0, N_{30}, N_{60}, and N_{90}, respectively, at PD2. Delayed planting (PD3) resulted in decline in crop water productivity by 4, 3, 26, and 10% during the first season, and by 4, 4, 11, and 8% during the second season in N_0, N_{30}, N_{60}, and N_{90}, respectively, under PD3 as compared to PD2. The regression analysis between NFR and crop water productivity under all the

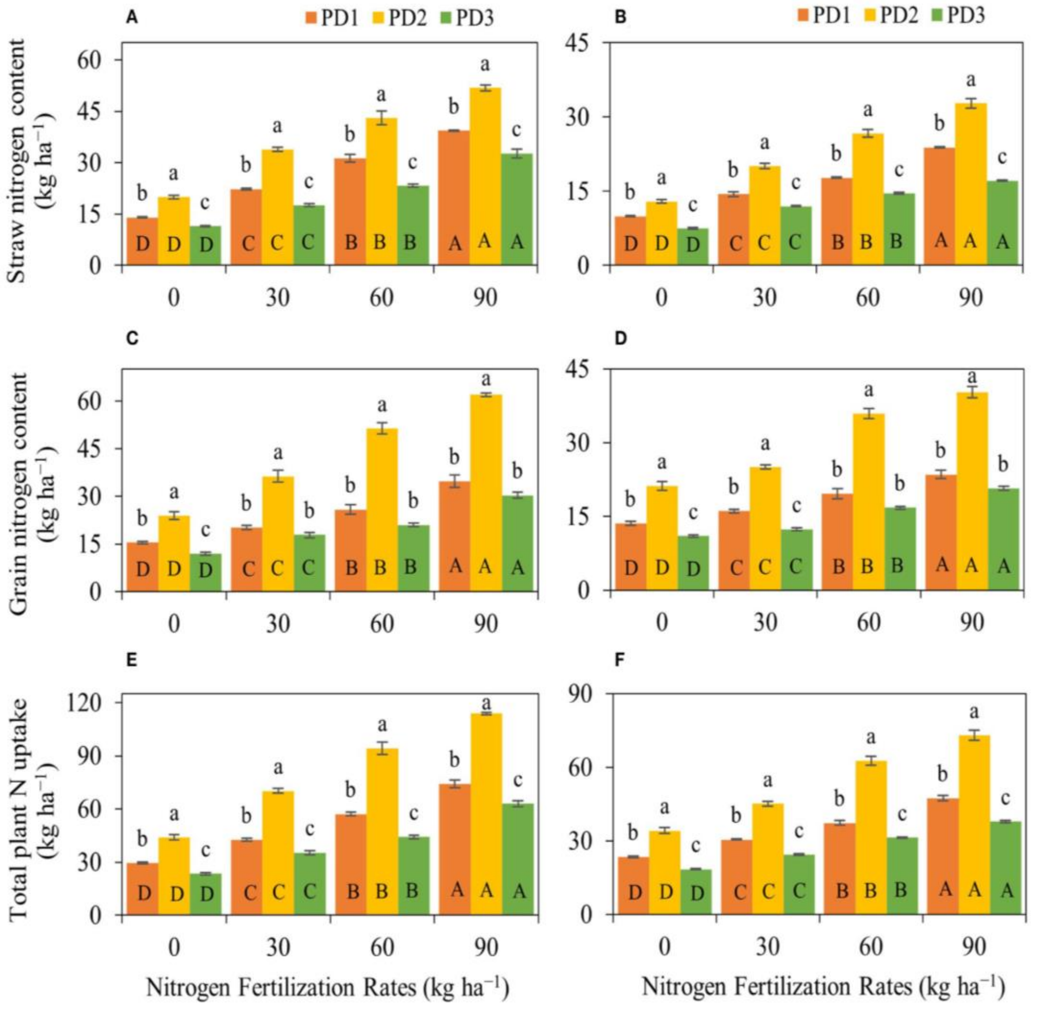


FIGURE 5 | Impact of nitrogen (N) fertilization rates and planting dates on **(A,B)** rice straw N content, **(C,D)** rice grain N content, and **(E,F)** total plant N uptake of upland rice during the first season, **(A,C,E)** 2018–2019, and the second season, **(B,D,F)** 2019–2020. Significance ($p < 0.05$) of the means (± standard errors of 3 replicates) with respective attribute under various N fertilization rates within each planting date is indicated by uppercase letters inside the respective bars. Significance ($p < 0.05$) of the means (± standard errors of 3 replicates) with respective attribute under various planting dates within each N fertilization rate is indicated by lowercase letters above the bars.

PDs showed a highly significant linear relationship during both seasons (**Figures 9A,B**).

Pearson's Correlation

Pearson's correlation assessment of pooled data for studied agronomic traits of upland rice indicates a strong correlation among agronomic traits, N uptake, NUE, and crop water productivity (**Figure 10**). N uptake, NUE, and crop water productivity indicated the highest significant positive association between grain N content (GN) and total plant N uptake (TPNU) of 0.99. The correlation between TPNU and straw N content (SN), grain yield (GY) and TPNU, and aboveground biomass (AGB) and SN was 0.98. Correlation between stem height (SH), and panicle density = GY, and SN = GY, and GN (0.97) > SH and stem density (0.96) > GY. Furthermore, correlation of AGB = TPNU (0.95) > and AGB = SH (0.94) > SD and AGB (0.93) > AGB and GN. In contrast, the highest negative association was observed between days to flowering and crop water productivity (−0.68), and days to maturity and N harvest index (−0.6).

Economic Assessment and Profitability

The economic analysis for Dawk Pa-yawm grain productivity per hectare indicated that increase in NFR of up to 90 kg N ha^{-1} provided the highest economic benefit for all the PDs during both seasons (**Table 3**). Maximum additional profits for PD1, PD2, and PD3 were 3,005.95, 4,809.15, 3,222.42 US$ ha^{-1} during the

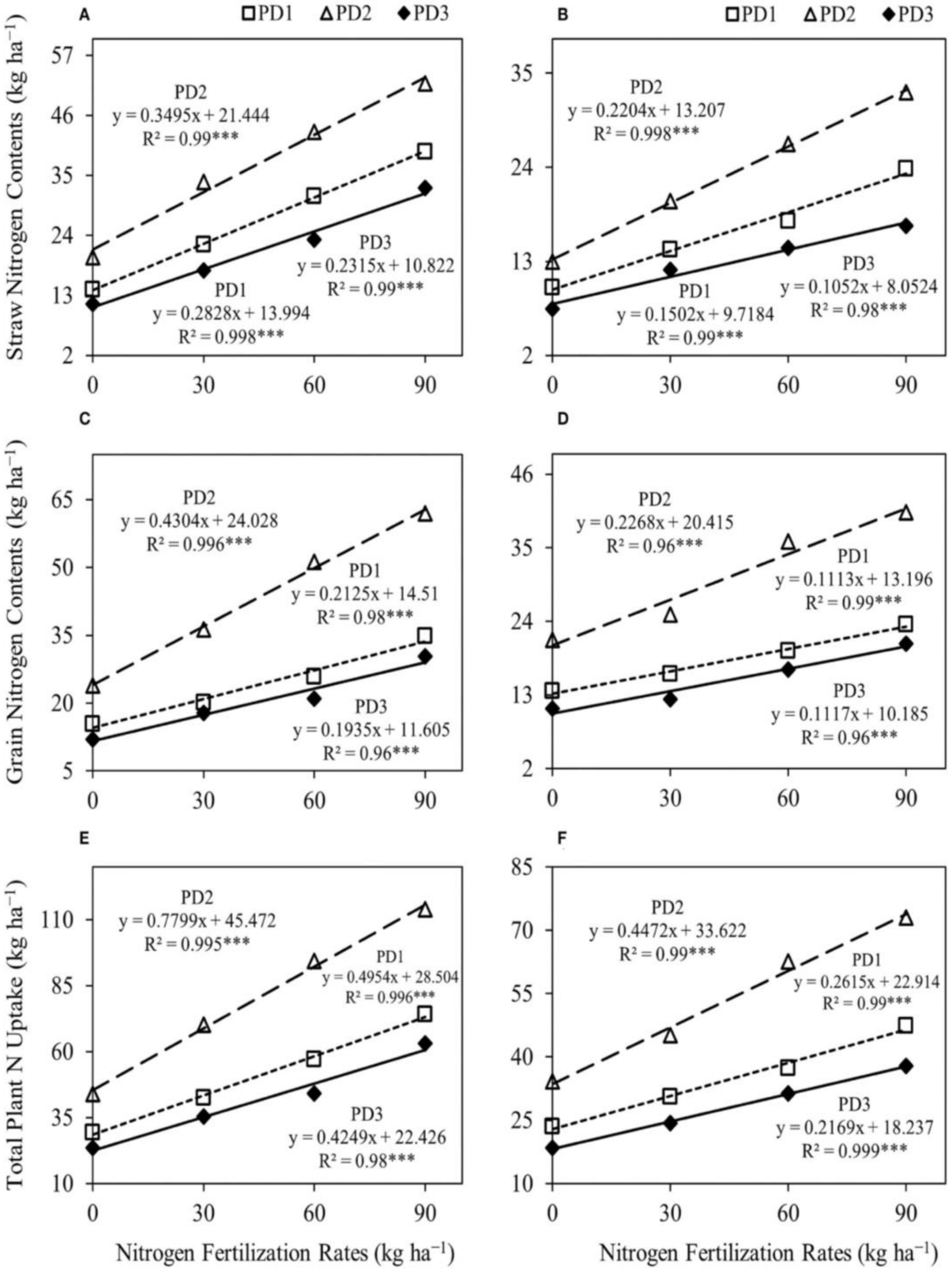


FIGURE 6 | Linear regression relationships **(A,B)** between nitrogen (N) fertilization rates and straw N contents, **(C,D)** between N fertilization rates and grain N contents, and **(E,F)** between N fertilization rates and total plant N uptake for upland rice obtained from the first season, **(A,C,E)** 2018–2019, and the second season, **(B,D,F)** 2019–2020, data. *** Significant at $p < 0.001$.

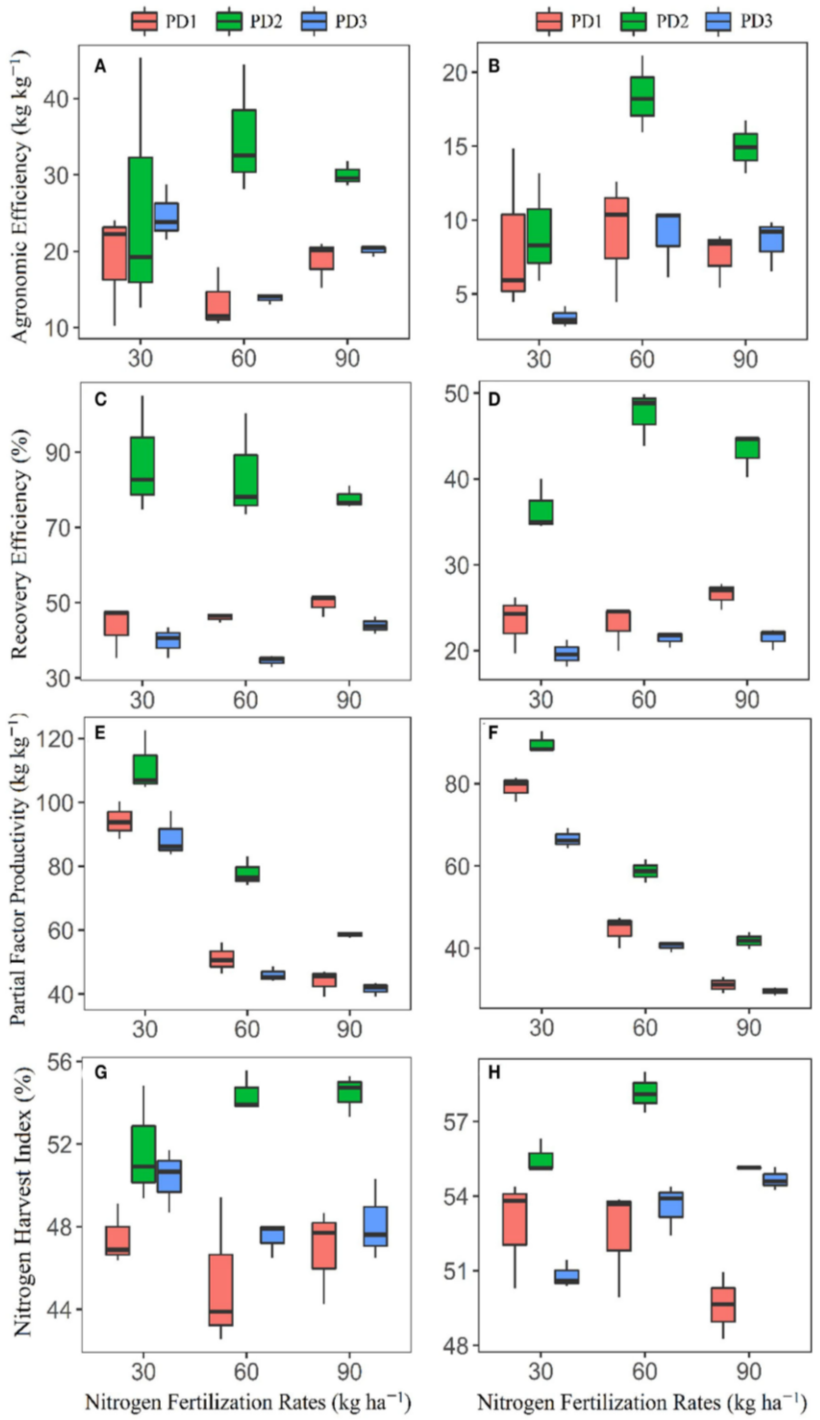


FIGURE 7 | Box plots for **(A,B)** agronomic efficiency, **(C,D)** recovery efficiency, **(E,F)** partial factor productivity, and **(G,H)** nitrogen harvest index of applied nitrogen fertilizer for upland rice (genotype: Dawk Pa–yawm), as influenced under different planting dates during the first season, **(A,C,E,G)** 2018–2019, and the second season, **(B,D,F,H)** 2019–2020. Means are presented with black horizontal lines within the box plots for each planting date, whereas the upper and lower boundaries of box plots indicate 75th and 25th percentiles of data, respectively. The upper and lower whiskers indicate maximum and minimum data points.

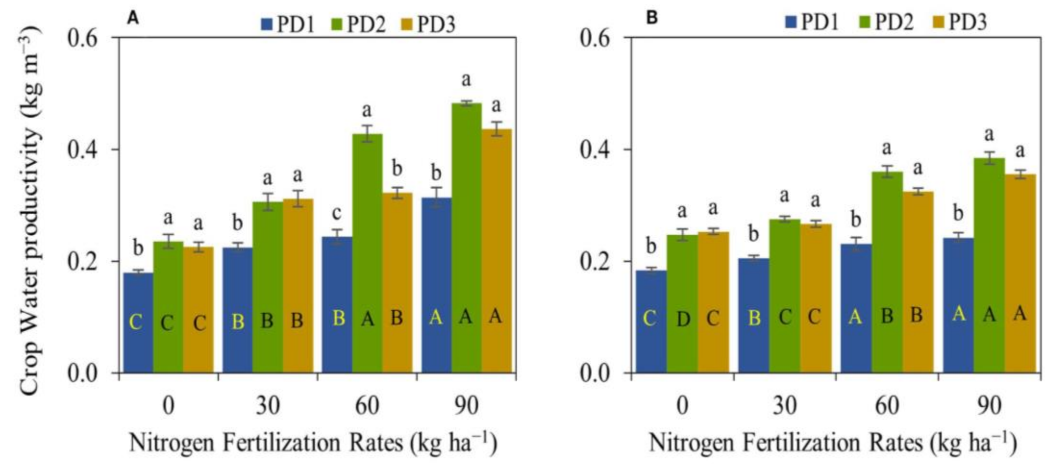


FIGURE 8 | Crop water productivity of upland rice (genotype: Dawk Pa-yawm), as affected by nitrogen (N) fertilization rates and planting dates during the first season, **(A)** 2018–2019, and the second season, **(B)** 2019–2020. Significance ($p < 0.05$) for the means (± standard errors of 3 replicates) of crop water productivity under various N fertilization rates within each planting date is indicated by uppercase letters inside the respective bars. Significance ($p < 0.05$) for the means (± standard errors of 3 replicates) of crop water productivity under varying planting dates within each N fertilization rate is indicated by lowercase letters above the bars.

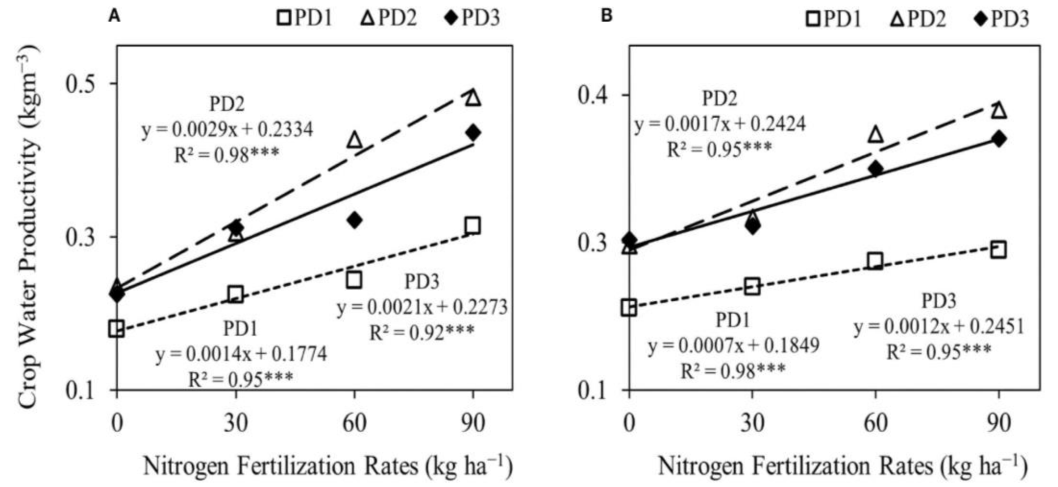
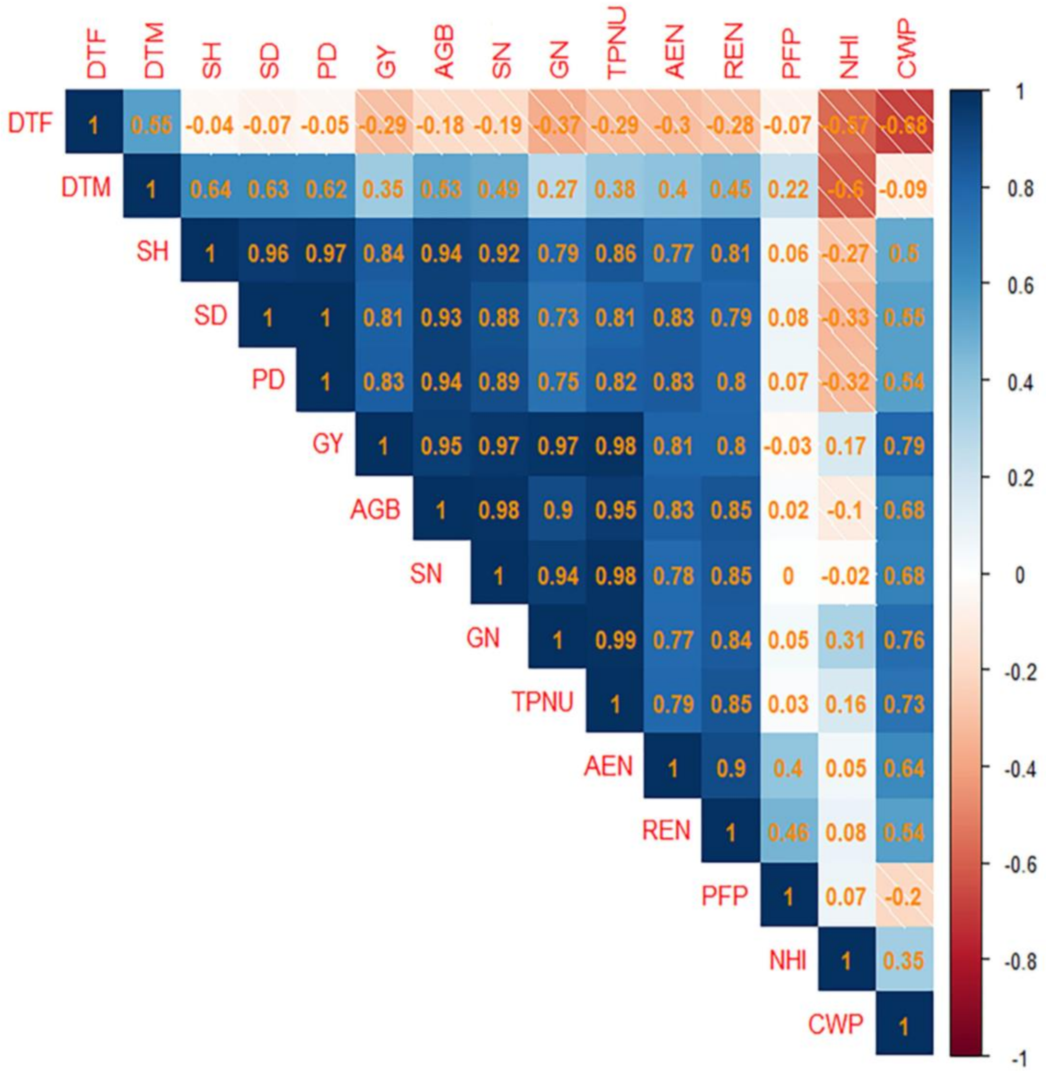


FIGURE 9 | Linear regression relationships between nitrogen fertilization rates and crop water productivity **(A,B)**, of upland rice obtained from the first season, **(A)** 2018–2019, and second the season, **(B)** 2019–2020 data. *** Significant at $p < 0.001$.

first season and 1,213.03, 2,393.62, 1,366.33 US\$ ha^{-1} during the second season (**Table 3**). Considering the impact of planting date, profitability from applied N as compared to control was influenced by the highest gross return, and gross profit margins were observed at PD2 with N_{90} during both seasons. The highest additional profit obtained were 1,373.63, 3,741.95, and 4,809.15 US\$ ha^{-1} during the first season, and 486.78, 1,966.28, and 2,393.62 US\$ ha^{-1} during the second season in N_{30}, N_{60}, and N_{90}, respectively, compared to N_0, at PD2 (**Table 3**). If the Marginal benefit-cost ratio (MBCR) is considered, maximum MBCR was also observed at PD2 and it was valued at 44.32, 60.37, and 51.73 for the first season, and 15.71, 31.72, and 25.75 for the second season in N_{30}, N_{60} and N_{90}, respectively. An increase in grain yield productivity and profitability with an increase in nitrogen rate up to N_{60} at PD2 indicated the highest MBCR with values of 60.37 and 31.72 for the first and second season, respectively.

DISCUSSION

Identification of suitable N fertilizer rate and agronomic management of N fertilizer application synchronized with ideal planting date is critical for enhancing rainfed upland



	DTF	DTM	SH	SD	PD	GY	AGB	SN	GN	TPNU	AEN	REN	PFP	NHI	CWP
DTF	1	0.55	-0.04	-0.07	-0.05	-0.29	-0.18	-0.19	-0.37	-0.29	-0.3	-0.28	-0.07	-0.57	-0.68
DTM		1	0.64	0.63	0.62	0.35	0.53	0.49	0.27	0.38	0.4	0.45	0.22	-0.6	-0.09
SH			1	0.96	0.97	0.84	0.94	0.92	0.79	0.86	0.77	0.81	0.06	-0.27	0.5
SD				1	1	0.81	0.93	0.88	0.73	0.81	0.83	0.79	0.08	-0.33	0.55
PD					1	0.83	0.94	0.89	0.75	0.82	0.83	0.8	0.07	-0.32	0.54
GY						1	0.95	0.97	0.97	0.98	0.81	0.8	-0.03	0.17	0.79
AGB							1	0.98	0.9	0.95	0.83	0.85	0.02	-0.1	0.68
SN								1	0.94	0.98	0.78	0.85	0	-0.02	0.68
GN									1	0.99	0.77	0.84	0.05	0.31	0.76
TPNU										1	0.79	0.85	0.03	0.16	0.73
AEN											1	0.9	0.4	0.05	0.64
REN												1	0.46	0.08	0.54
PFP													1	0.07	-0.2
NHI														1	0.35
CWP															1

FIGURE 10 | Correlation plot of Pearson's correlation analysis among the studied traits of upland rice (genotype: Dawk Pa–yawm). Blue and orange shaded squares indicate positive or negative associations among attributes. Computed Pearson's correlation coefficients are reported in the squares. The intensity of color shades is proportional to the computed coefficients. DTF, Days to flowering; DTM, days to maturity; SH, stem height; SD, stem density; PD, panicle density; GY, grain yield; AGB, aboveground biomass; SN, straw nitrogen content; GN, grain nitrogen content; TPNU, total plant nitrogen uptake; AEN, agronomic efficiency of applied nitrogen; REN, recovery efficiency of applied nitrogen; PFP, partial factor productivity; NHI, nitrogen harvest index; CWP, crop water productivity.

rice productivity. Inadequate N fertilization during improper planting date the rice crop growth period leads to reduced N utilization efficiency and ultimately affects the productivity and profitability of upland rice production. Traditional practices of N fertilization and planting date adopted by small landholders growing upland rice needs to be adjusted according to the soil nutrient status, upland rice N fertilizer demand, and favorable climatic conditions. Water availability during the rainfed upland rice growth period is a crucial element that can significantly influence the utilization efficiency of fertilization. Therefore, agronomic management of suitable N fertilization rate synchronized with ideal planting date is essential to enhance resource use efficiency, productivity, and profitability.

In the experimental location, the average maximum and minimum temperatures during the experimental growth period ranged from 24 to 37°C and 21 to 26°C for the first season and 27–37 and 22–26°C for the second season, respectively. According to Acquaah (2007) and Buddhaboon et al. (2011),

TABLE 3 | Grain yield production, nitrogen fertilization cost, and economic return of upland rice (genotype: Dawk Pa–yawm) calculated for various nitrogen fertilization rates as affected by planting dates.

Growing season	Nitrogen fertilization rate kg ha^{-1}	Planting dates	Grain yield t ha^{-1}	Gross return US$ ha^{-1}	Nitrogen fertilization cost US$ ha^{-1}	Additional profit over control US$ ha^{-1}	Gross margin over control US$ ha^{-1}	MBCR[a]
2018–2019	0	PD1	2.26	4,024.64	–	–	–	–
		PD2	2.57	4,574.72	–	–	–	–
		PD3	1.93	3,436.05	–	–	–	–
	30	PD1	2.83	5,031.19	30.99	1,006.55	975.56	32.48
		PD2	3.34	5,948.35	30.99	1,373.63	1,342.64	44.32
		PD3	2.67	4,755.62	30.99	1,319.57	1,288.58	42.58
	60	PD1	3.06	5,450.21	61.98	1,425.58	1,363.60	23.00
		PD2	4.67	8,316.67	61.98	3,741.95	3,679.96	60.37
		PD3	2.76	4,915.69	61.98	1,479.64	1,417.66	23.87
	90	PD1	3.95	7,030.59	92.97	3,005.95	2,912.98	32.33
		PD2	5.27	9,383.87	92.97	4,809.15	4,716.18	51.73
		PD3	3.74	6,658.50	92.97	3,222.42	3,129.48	34.66
2019–2020	0	PD1	2.12	3,770.95	–	–	–	–
		PD2	2.42	4,306.48	–	–	–	–
		PD3	1.89	3,372.24	–	–	–	–
	30	PD1	2.37	4,219.25	30.99	448.30	417.30	14.47
		PD2	2.69	4,793.26	30.99	486.78	455.79	15.71
		PD3	2.00	3,554.68	30.99	182.44	151.45	5.89
	60	PD1	2.67	4,746.65	61.98	975.70	913.72	15.74
		PD2	3.52	6,272.76	61.98	1,966.28	1,904.30	31.72
		PD3	2.43	4,329.57	61.98	957.33	895.34	15.45
	90	PD1	2.80	4,983.99	92.97	1,213.03	1,120.06	13.05
		PD2	3.76	6,700.11	92.97	2,393.62	2,300.65	25.75
		PD3	2.66	4,738.57	92.97	1,366.33	1,273.36	14.70

[a] *MBCR, marginal benefit-cost ratio.*

the optimal temperature for rice growth is 27°C. The average temperature that prevailed during the rice growth period in both seasons was higher than the optimal temperature range of 25–30°C (Sparks, 2009). The average maximum and minimum temperatures were similar within respective PDs during both seasons. However, the mean maximum and minimum temperatures were different from planting to flowering and from flowering to maturity during each PD in both seasons. The mean maximum temperature was decreased with delay in planting date, whereas the mean minimum temperature was increased from the planting to flowering period. In contrast, the mean maximum temperature was increased with delay in planting date, while the mean minimum temperature was not significantly different from flowering to physiological maturity. The highest mean maximum temperature from flowering to physiological maturity was observed at PD3 during both seasons, which indicated that most hot intervals prevailed during PD3. Temperature difference significantly impacts crop growth duration, and PD regulates the use of environmental resources influencing crop performance (Varinruk, 2017). High and low temperatures occurring under changing climate affect plant growth and development (Aslam et al., 2022). Grain and biomass productivity was highly correlated to life cycle (Aslam et al., 2017). In general, crop growth duration decreased with increase in temperature because of a higher crop growth rate (Yoshida, 1973; Ahmed et al., 2014). We observed that days to flowering and days to maturity were decreased significantly in both seasons, as the temperature from flowering to physiological maturity increased under PD2 and PD3.

Rainfall distribution was different and highly variable among PDs and seasons. Maximum rainfall and high rainfall intervals occurred during PD1 in both seasons. All the PDs received maximum rainfall from planting to flowering. PD2 received a suitable distribution of rainfall during the growth period as compared to PD1 and PD3; therefore, supplementary irrigation was reduced at PD2. Due to less rainfall from planting to flowering and from flowering to physiological maturity, at PD3, supplementary irrigation was increased. As PD1 received the highest rainfall from planting to flowering and particularly from flowering to maturity, crop duration was increased because of extended plant growth and developmental phases in the first season. Previous research has confirmed that rice crop growth duration can be delayed on rainy days or during the occurrence of low temperatures in the terminal stages, and that sunny or hot days may shorten crop growth duration (GRiSP, 2013). In the second season, PD1 received maximum rainfall during the planting to flowering period and received only 1 mm from flowering to physiological maturity accompanied by higher average temperatures; hence, crop growth duration was significantly decreased.

The difference in temperature and rainfall distribution influenced crop duration and supplementary irrigation. We observed that PD1 received the highest rainfall; thus, maximum runoff and flash events occurred during PD1, whereas PD2 received a moderate distribution of rain, which was favorable as compared to PD1 and PD3. Therefore, to enhance the utilization of rainwater, slight delays in planting would be advantageous, which not only prevent heavy runoff events but also causes better rainwater distribution for plants. Luo et al. (2022) reported similar results in crop water requirement and irrigation demand for rice. The early rice required less irrigation frequency and may not require additional irrigation, while middle and late rice planting required increased water demand. In addition, an assessment of climate change impact predicted that a 30-day delay in planting of the Thai rice KDML−105 cultivar would enhance yield by 23% in the 2050s (Babel et al., 2011). The results from our study and findings of Luo et al. (2022) and Babel et al. (2011) strongly support that adjustment in PD would help to enhance natural resource use efficiency, particularly the optimal use of rainfall, with the benefit of reduced or even no supplementary irrigation.

In this study, the agronomic performance of upland rice was positively influenced by N fertilization. According to Zhang et al. (2020), N addition positively impacts plants' photosynthesis and physiological mechanisms, which determines yield. We observed that upland rice was responsive to NFR and N fertilization at various NFRs, resulted in increased stem height under all the PDs in both seasons. The synergy between NFR and stem height was well reported (Millard, 1988; Wu et al., 2020) because of the effective role of N fertilization in cell growth and enhancement of stem enlargement. Zhang et al. (2020) also found that increase in N fertilization positively influenced the stem height of rice plants. Similar findings were also reported by Jahan et al. (2020). They stated that the stem height of rice plants was enhanced by increased N fertilization. Stem height, under the influence of PD, was negatively affected, and lowest stem height was observed at PD3 at all the NFRs during both seasons. This was possibly due to higher temperatures and low rainfall during PD3, as most of the hot and dry intervals occurred during PD3. Rice is highly vulnerable and sensitive to water stress (Singh et al., 2017), and the decline in stem height of rice is well-documented under water stress (Ichsan et al., 2020; Hussain et al., 2021a,b). A positive correlation prevails among NFR, stem density, and panicle density of rice. We observed that N fertilization positively influenced stem density and panicle density under all the PDs in both seasons. According to Chen et al. (2020), high N input resulted in increased stem buds' growth, which increased stem density. Stem density and increased tillering contribute and determine panicle density. Nitrogen fertilization increased panicle density, and results were supported by the findings of Jahan et al. (2020), who confirmed in their study that higher N availability triggered cell division and caused increase in panicle density (m^{-2}). In contrast, stem density and panicle density were decreased at PD3 under the influence of PD. A decline in stem density, as well as panicle density, possibly occurred because of the overall less rainfall (planting to maturity) and high temperature (particularly from flowering to maturity) that prevailed during PD3. Prevalence of slightly higher temperature above the ambient temperature results in triggered growth of rice, higher stem height, and stem density (Yoshida, 1973; Dubey et al., 2018). However, if higher temperature prevails during active stem formation stages, it results in decline in panicle density (Dubey et al., 2018). In addition, limited rainfall occurrence during PD3 possibly resulted in low soil water status, which might have induced mild water stress. The decline in stem density (Zain et al., 2014) and particularly panicle density (Davatgar et al., 2009) of rice under water stress is also well explored (Hussain et al., 2021b). Increase in stem height and stem density contributes to aboveground biomass (Hussain et al., 2021a), while increase in panicle density contributes to grain yield (Dubey et al., 2018). Nitrogen addition increased the performance of yield attributes, consequently increased grain yield and aboveground biomass. An increase in grain yield with increased NFR was also reported by Zhang et al. (2020), while Chen et al. (2020), as well as Jahan et al. (2020), also reported similar results for increase in grain yield as well as aboveground biomass under increased N supply.

Pearson's correlation assessment also revealed significant, strong, and positive associations among stem height, stem density, panicle density, grain yield, and aboveground biomass indicating that enhanced performance of contributing attributes positively affected grain yield and aboveground biomass production. A strong positive relationship between grain yield and aboveground biomass was also observed because of enhanced sink capacity, since grain productivity can be attributed to development of greater sink capacity (Zhou et al., 2019) and increased biomass productivity (Zheng et al., 2020). In contrast, planting date altered grain yield and aboveground biomass production, causing decline at PD3, possibly because of high temperature and less rainfall. Reduction in rice grain yield, as well as aboveground biomass production, was observed under reduced water supply or water stress, and prevalence of hot intervals is also well documented (Zain et al., 2014; Torres and Henry, 2018; Hussain et al., 2021b).

Reducing the gap between rice crop N requirement and N fertilization ensures enhanced efficiency of plant physiological mechanisms enabling higher N utilization plants. According to Ullah et al. (2019), the relationship between plant N uptake and N loss determines rice plant performance, and high N uptake results in increased dry matter production. Improved N management results in enhanced N uptake and utilization in plants. However, N uptake and N use in rice plants are complex mechanisms, as multiple factors, including climatic, genotypic ability to uptake N, soil properties, N volatilization, N leaching, and denitrification affect N dynamics. Increased NFR resulted in enhanced straw and grain N contents and total plant N uptake, possibly because of increased N availability. Jahan et al. (2020) noted that NFR resulted in increased rice straw and grain N contents and total plant N uptake, and the seasonal impact was significant. Planting date influenced straw and grain N contents and total plant N uptake because of high rainfall events at PD1 and low rainfall events at PD3. Nutrient availability to plant roots is linked to soil water status. We observed that PD2 received better rainfall distributions, thus the maximum straw and grain N contents and total plant N uptake. Crop water productivity indicated a significant and positive association with straw N, grain N content, and total plant N uptake. The reduced N uptake at PD3 resulted in reduced grain yield and was highly correlated with straw N, grain N contents, and total plant N uptake. Reduced source to sink activity resulted in reduced performance of upland rice. Similar results were also reported by Pal et al. (2017). Crop water productivity also indicated an increasing trend with N fertilization, and it was positively associated with plant N uptake and grain yield. An increasing trend in crop water productivity is usually accompanied by high grain yield with high N supply (Santiago-Arenas et al., 2021). However, crop water productivity was not significantly different at PD3 as compared to PD2 in both seasons in comparison to the response of other assessed attributes, particularly grain yield. Grain yield at PD2 was statistically different than at PD3, while it was statistically similar in PD1 and PD3 for N_{60} and N_{90}. The contrasting trend of increase in crop water productivity was not dependent upon grain yield, as grain yield declined at PD3. Thus, this trend occurred because of decline in grain yield as well as decreased water input at PD3. NUEs, including AE_N, RE_N, and NHI, varied among the NFRs, while PFP decreased under increased NFR. NUE is decreased under higher N supply (Barbieri et al., 2008) in rice production systems because of high concentrations of N in the soil (Santiago-Arenas et al., 2021). Our results for PFP were in line with the finding of Santiago-Arenas et al. (2021), that the PFP and AE_N, of direct-seeded rice decreased with increase in NFR. Variation and decline in AE_N, RE_N, and NHI under increased N supply possibly occurred because of increased N fertilization and low grain yield compared to control and vice versa. Thus, we observed improved N use efficiencies under N fertilization. The effect of PD differentiated the performance of N use efficiencies indicating maximum AE_N, RE_N, PFP, and NHI at PD2. Maximum N efficiencies at PD2 occurred because of favorable environmental conditions and improved performance of upland rice at PD2. Maximum efficiencies were reached when the NFR matched with crop N demand. Yousaf et al. (2016) also observed a similar trend for NUE in a rice and oilseed crop rotation. Crop water productivity was also associated with NUE. Furthermore, AE_N, RE_N, and NHI were significant and positively associated with crop water productivity, and higher crop water productivity results in enhanced NUE (Ullah et al., 2019; Lupini et al., 2021).

Our results indicate the impact of N fertilization and improvement in productivity with N fertilization according to various PDs. We have determined that the N fertilizer recommendations for upland rice production (DRRD, 2016, 2017; Norsuwan et al., 2020) and N fertilizer application rate practiced in Thailand (CARSR, 2003; Hussain et al., 2018a,b; Suwanasa et al., 2018; Islam et al., 2020) are not adequate. Another study conducted under partially controlled conditions in sheds also exhibited comparable results (Hussain et al., 2022). Hence, there is a need to adjust the current range (10–75 kg N ha^{-1}) of N fertilization. A significant seasonal impact has been indicated in our findings; hence, modification of NFR as well as PD is necessary to enhance resource use efficiency. The profitability of crop production is always a concern for the farming community. In this study profitability from grain yield with N fertilization was indicated with proper PD. If the benefit-cost ratio considered fertilization with N_{90} ranked first for PD2 while considering MBCR, fertilization with N_{60} might be a suitable NFR. Thus, it should be noted that a linear relationship was indicated among agronomic traits of upland rice, N uptake and crop water productivity, and NFR. Therefore, fertilization with 90 kg N ha^{-1} is recommended for upland rice grown at PD2.

CONCLUSION

Suitable N fertilizer rate (NFR) and ideal planting date (PD) increased and improved source-to-sink relationship and dry matter accumulation, which is a component for increasing the grain yield and profitability of upland rice. Agronomic adjustment in N fertilization and PD would enhance resource use efficiency. We found that N fertilization positively influenced resource use efficiency, upland rice productivity, and profitability; however, variation in PD significantly altered the results. Therefore, synchronization of NFR according to PD is necessary. We found that fertilization with 90 kg N ha^{-1} at PD2 (end of September or start of October) improved the yield and performance of yield attributes. Grain yield and crop water productivity were increased by 56 and 105% during the second and first seasons, respectively. Maximum increase in straw N, grain N content, and total plant N uptake was also observed with 90 kg N ha^{-1} for PD2 by 160, 159, and 159% during the first season, and by 153, 90, and 114%, respectively, during the second season. Variations in NUE were observed at all the NFRs in both seasons. However, maximum N efficiencies, including agronomic efficiency (AE_N), recovery efficiency (RE_N), partial factor productivity (PFP), and N harvest index (NHI) at varying NFRs, were observed at PD2 during both seasons. Highly significant and positive associations were found among agronomic attributes, N uptake, NUE, and crop water productivity for upland rice in a correlation assessment, indicating a direct positive impact of N fertilization. The impact of N fertilization on grain yield and profitability was observed, and application of 90 kg N ha^{-1} resulted in maximum profit at all PDs. However, the highest marginal benefit-cost ratio (MBCR) was observed with N_{60} at PD2 during both seasons. Based on the results, it was suggested that 90 kg N ha^{-1} should be applied, and that upland rice should be planted at the end of September or start of October for enhancing resource use efficiency, improving productivity, and maximum profitability. Furthermore, since a linear relationship among NFRs, agronomic traits of upland rice, N uptake, and crop water productivity was observed, and a significant seasonal effect was indicated, long-term field investigations considering a range of NFRs and adoption of forecasting measures, i.e., rainfall forecasting and yield prediction using crop simulation and modeling techniques to adjust seasonal PD, are recommended for upland rice cultivation in Thailand.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

TH conducted and maintained the experiments and contributed to data collection and curation, investigating, methodology, visualization, formal analysis, writing the original draft, writing, reviewing, and editing the manuscript. NH conducted and maintained the experiments and contributed to data collection. HG contributed to writing, reviewing, and editing the manuscript. MA contributed to technical guidance. MT contributed to technical guidance and writing, reviewing, and editing the manuscript. SD contributed to supervision and acquiring funds, project administration, formal analysis, writing original draft, writing, reviewing, and editing the manuscript. All the authors contributed to the article and approved the final version.

FUNDING

The study was supported by the Thailand's Education Hub for the Southern Region of ASEAN countries' (TEH-AC) scholarship from Prince of Songkla University, Faculty of Natural Resources, Prince of Songkla University, and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and the Global Research Alliance on Agricultural Greenhouse Gases (GRA) through their Climate, Food and Farming Global Research Alliance Development Scholarship (CLIFF-GRADS) program. CCAFS capability building objectives are carried out with support from CGIAR Trust Fund and through bilateral funding agreements. For details, please visit https://ccafs.cgiar.org/donors. Thank you to the U.S. Department of Agriculture-Agricultural Research Service for hosting the first author and to the Government of New Zealand for providing financial support. Mention of trade names or commercial products in this publication does not imply recommendation or endorsement by the U.S. Department of Agriculture-Agricultural Research Service. USDA is equal opportunity provider and employer.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Faculty of Natural Resources, Prince of Songkla University for providing research facilities and also they would like to give sincere appreciation to Pajaree Sonsungsan, researcher, Program in Bioinformatics and Computational Biology, Graduate School, Chulalongkorn University, Bangkok, Thailand, for her help in R program.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpls.2022.895811/full#supplementary-material

REFERENCES

Abbasi, M. K., Tahir, M. M., Sadiq, A., Iqbal, M., and Zafar, M. (2012). Yield and nitrogen use efficiency of rainfed maize response to splitting and nitrogen rates in Kashmir, Pakistan. *Agron. J.* 104, 448–457. doi: 10.2134/agronj2011.0267

Acquaah, G. (2007). *Principles of Plant Genetics and Breeding*. 2nd Edn. Oxford: Blackwell Publishing Ltd.

Ahmed, S., Humphreys, E., Salim, M., and Chauhan, B. S. (2014). Optimizing sowing management for short duration dry seeded aman rice on the High Ganges River Floodplain of Bangladesh. *Field Crops Res.* 169, 77–88. doi: 10.1016/j.fcr.2014.09.009

Anwar, M., Zulfiqar, F., Ferdous, Z., Tsusaka, T. W., and Datta, A. (2021). Productivity, profitability, efficiency, and land utilization scenarios of rice cultivation: an assessment of hybrid rice in Bangladesh. *Sustain. Prod. Consump.* 26, 752–758. doi: 10.1016/j.spc.2020.12.035

Aslam, M. A., Ahmed, M., Hassan, F.-U., Afzal, O., Mehmood, M. Z., Qadir, G., et al. (2022). "Impact of temperature fluctuations on plant morphological and physiological traits," in *Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective*, eds W. N. Jatoi, M. Mubeen, A. Ahmad, M. A. Cheema, Z. Lin, and M. Z. Hashmi (Cham: Springer International Publishing), 25–52.

Aslam, M. A., Ahmed, M., Stöckle, C. O., Higgins, S. S., ul Hassan, F., and Hayat, R. (2017). Can growing degree days and photoperiod predict spring wheat phenology? *Front. Environ. Sci.* 5, 57. doi: 10.3389/fenvs.2017.00057

Babel, M. S., Agarwal, A., Swain, D. K., and Herath, S. (2011). Evaluation of climate change impacts and adaptation measures for rice cultivation in Northeast Thailand. *Clim. Res.* 46, 137–146. doi: 10.3354/cr00978

Barbieri, P. A., Echeverría, H. E., Saínz Rozas, H. R., and Andrade, F. H. (2008). Nitrogen use efficiency in maize as affected by nitrogen availability and row spacing. *Agron. J.* 100, 1094–1100. doi: 10.2134/agronj2006.0057

Belder, P. (2005). *Water Saving in Lowland Rice Production: An Experimental and Modeling Study*. Available online at: http://edepot.wur.nl/121681 (accessed October 20, 2021).

Boonwichai, S., Shrestha, S., Babel, M. S., Weesakul, S., and Datta, A. (2019). Evaluation of climate change impacts and adaptation strategies on rainfed rice production in Songkhram River Basin, Thailand. *Sci. Total Environ.* 652, 189–201. doi: 10.1016/j.scitotenv.2018.10.201

Boonwichai, S., Shrestha, S., Pradhan, P., Babel, M. S., and Datta, A. (2021). Adaptation strategies for rainfed rice water management under climate change in Songkhram River Basin, Thailand. *J. Water Clim. Change* 12, 1–18. doi: 10.2166/wcc.2021.220

Bray, R. H., and Kurtz, L. T. (1945). Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.* 59, 39–45. doi: 10.1097/00010694-194501000-00006

Buddhaboon, C., Jintrawet, A., and Hoogenboom, G. (2011). Effects of planting date and variety on flooded rice production in the deepwater area of Thailand. *Field Crops Res.* 124, 270–277. doi: 10.1016/j.fcr.2011.06.019

CARSR (2003). *Rice Production Status-Highland Farming System*. Center for Agricultural Resource System Research, Faculty of Agriculture, Chiang Mai University, Thailand. Available online at: http://www.mcc.cmu.ac.th/agsust/highland_SA/riceproduction_highland.htm?fbclid=IwAR1Mjn6SlS7z2N7cUR_U7F9Bnl4MijMGyFti106tFpo_RYdjoDRmyPxtkHg (accessed October 15, 2021).

Champrasert, P., Sampattagul, S., Yodkhum, S., and Wangpakapattanawong, P. (2020). Assessment of carbon footprint of upland rice production in Northern Thailand. *Chiang Mai Univ. J. Nat. Sci.* 19, 427–446. doi: 10.12982/CMUJNS.2020.0028

Chen, Z., Wang, Q., Ma, J., Zou, P., and Jiang, L. (2020). Impact of controlled-release urea on rice yield, nitrogen use efficiency and soil fertility in a single rice cropping system. *Sci. Rep.* 10, 10432. doi: 10.1038/s41598-020-67110-6

Choudhury, A. T. M. A., and Khanif, Y. M. (2006). Effects Of nitrogen and copper fertilization on rice yield and fertlizer nitrogen efficiency: A 15N tracer study. *Pak. J. Sci. Ind. Res.* 47, 50–55.

Core Team, R. (2021). *R: A Language and Environment for Statistical Computing.* Available online at: https://www.r-project.org/ (accessed September 16, 2021).

Davatgar, N., Neishabouri, M. R., Sepaskhah, A. R., and Soltani, A. (2009). Physiological and morphological responses of rice (*Oryza sativa* L.) to varying water stress management strategies. *Int. J. Plant Prod.* 3, 19–32. doi: 10.22069/ijpp.2012.660

DRRD (2016). *Division of Rice Research Development. Rice Knowledge Bank.* Available online at: https://brrd.ricethailand.go.th/ (accessed September 13, 2017).

DRRD (2017). *Soil and Fertilizer Management in Rice Fields, Fertilizer Recommendations for Southern Region.* Rice Knowledge Bank, Division of Rice Research Development. Available online at: https://webold.ricethailand.go.th/rkb3/title-index.php-file=content.php&id=043.htm#p9 (accessed December 22, 2021).

Duangpan, S., Tongchu, Y., Hussain, T., Eksomtramage, T., and Onthong, J. (2022). Beneficial effects of silicon fertilizer on growth and physiological responses in oil palm. *Agronomy* 12, 413. doi: 10.3390/agronomy12020413

Dubey, A. N., Verma, S., Goswami, S., and Devedee, A. K. (2018). Effect of temperature on different growth stages and physiological process of rice crop-a review. *Bull. Environ. Pharmacol. Life Sci.* 7, 129–136.

FAO (2020). *FAOSTAT* (Online). http://www.fao.org/faostat/en/#home. Available online at: http://www.fao.org/faostat/en/#home (accessed August 18, 2021).

Farrell, T. C., Fox, K., Williams, R. L., Fukai, S., and Lewin, L. G. (2003). "Avoiding low temperature damage in Australia's rice industry with photoperiod sensitive cultivars," in *Proceedings of the 11th Australian Agronomy Conference.* Deakin University, Geelong (Feb. 2_6.) (Victoria, Australia).

Ferrari, S., Pagliari, P., and Trettel, J. (2018). Optimum sowing date and genotype testing for upland rice production in Brazil. *Sci. Rep.* 8, 1–8. doi: 10.1038/s41598-018-26628-6

Gajri, P. R., Prihar, S. S., and Arora, V. K. (1993). Interdependence of nitrogen and irrigation effects on growth and input-use efficiencies in wheat. *Field Crops Res.* 31, 71–86. doi: 10.1016/0378-4290(93)90051-N

GRiSP (2013). *Rice Almanac,* 4th Edn. Los Baños: International Rice Research Institute.

Hameed, F., Xu, J., Rahim, S. F., Wei, Q., Khalil, A., ur, R., et al. (2019). Optimizing nitrogen options for improving nitrogen use efficiency of rice under different water regimes. *Agronomy* 9, 39. doi: 10.3390/agronomy9010039

Hammad, H. M., Farhad, W., Abbas, F., Fahad, S., Saeed, S., Nasim, W., et al. (2017). Maize plant nitrogen uptake dynamics at limited irrigation water and nitrogen. *Environ. Sci. Pollut. Res.* 24, 2549–2557. doi: 10.1007/s11356-016-8031-0

Hussain, N., Ahmed, M., Duangpan, S., Hussain, T., and Taweekun, J. (2021a). Potential impacts of water stress on rice biomass composition and feedstock availability for bioenergy production. *Sustainability* 13, 10449. doi: 10.3390/su131810449

Hussain, T., Anothai, J., Nualsri, C., and Soonsuwon, W. (2018a). Application of CSM-CERES-Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield. *Indian J. Agric. Res.* 52, 140–145. doi: 10.18805/IJARe.A-321

Hussain, T., Anothai, J., Nualsri, C., and Soonsuwon, W. (2018b). Evaluating performance of sixteen upland rice genotypes under field conditions for further breeding process. *J. Agric. Sci.* 10, 144. doi: 10.5539/jas.v10n3p144

Hussain, T., Hussain, N., Ahmed, M., Nualsri, C., and Duangpan, S. (2021b). Responses of lowland rice genotypes under terminal water stress and identification of drought tolerance to stabilize rice productivity in southern Thailand. *Plants* 10, 2565. doi: 10.3390/plants10122565

Hussain, T., Hussain, N., Ahmed, M., Nualsri, C., and Duangpan, S. (2022). Impact of nitrogen application rates on upland rice performance, planted under varying sowing times. *Sustainability* 14, 1997. doi: 10.3390/su14041997

Ichsan, C. N., Basyah, B., Zakaria, S., and Efendi, E. (2020). Differences of water status and relationship with roots growth and yield of rice under water stress. *Syst. Rev. Pharm.* 11, 611–618.

IRRI (2002). *Rice Almanac: Source Book for the Most Important Economic Activity on Earth.* 3rd ed. Oxon: CABI.

Islam, S., Anothai, J., Nualsri, C., and Soonsuwon, W. (2020). Correlation and path analysis of phenological traits of Thai upland rice genotypes. *Songklanakarin J. Plant Sci.* 7, 133–142.

Jahan, A., Islam, A., Sarkar, M. I. U., Iqbal, M., Ahmed, M. N., and Islam, M. R. (2020). Nitrogen response of two high yielding rice varieties as influenced by nitrogen levels and growing seasons. *Geol. Ecol. Landsc.* 6, 24–31. doi: 10.1080/24749508.2020.1742509

Jaruchai, W., Monkham, T., Chankaew, S., Suriharn, B., and Sanitchon, J. (2018). Evaluation of stability and yield potential of upland rice genotypes in North and Northeast Thailand. *J. Integr. Agric.* 17, 28–36. doi: 10.1016/S2095-3119(16)61609-X

Karladee, D., Boonsit, P., Suriyong, S., and Jamjod, S. (2012). Population heterogeneity of upland rice in northern Thailand. *Thai J. Agric. Sci.* 45, 99–104.

Kjeldahl, J. G. C. (1883). Neue methode zur bestimmung des stickstoffs in organischen Körpern. *Fresenius J. Anal. Chem.* 22, 366–382. doi: 10.1007/BF01338151

Kumar, V., and Ladha, J. K. (2011). *Direct Seeding of Rice. Recent Developments and Future Research Needs.* 1st ed. London: Academic Press, Elsevier Inc. doi: 10.1016/B978-0-12-387689-8.00001-1

Laosuwan, P. (1996). Intercropping of young rubber. *Suranaree J. Sci. Technol.* 3, 171–179. doi: 10.1016/0266-3538(95)00141-7

Limsakul, A., and Singhruck, P. (2016). Long-term trends and variability of total and extreme precipitation in Thailand. *Atmos. Res.* 169, 301–317. doi: 10.1016/j.atmosres.2015.10.015

Liu, H., Zhan, J., Hussain, S., and Nie, L. (2019). Grain yield and resource use e fficiencies of upland and lowland rice cultivars under aerobic cultivation. *Agronomy* 9, 591. doi: 10.3390/agronomy9100591

Luo, W., Chen, M., Kang, Y., Li, W., Li, D., Cui, Y., et al. (2022). Analysis of crop water requirements and irrigation demands for rice: Implications for increasing effective rainfall. *Agric. Water Manage.* 260, 107285. doi: 10.1016/j.agwat.2021.107285

Lupini, A., Preiti, G., Badagliacca, G., Abenavoli, M. R., Sunseri, F., Monti, M., et al. (2021). Nitrogen use efficiency in durum wheat under different nitrogen and water regimes in the mediterranean basin. *Front. Plant Sci.* 11, 607226. doi: 10.3389/fpls.2020.607226

Mansour, E., Desoky, E. S. M., Ali, M. M. A., Abdul-Hamid, M. I., Ullah, H., Attia, A., et al. (2021). Identifying drought-tolerant genotypes of faba bean and their agro-physiological responses to different water regimes in an arid Mediterranean environment. *Agric. Water Manage.* 247, 106754. doi: 10.1016/j.agwat.2021.106754

Manzoor, Z., Awan, T. H., Zahid, M. A., and Faiz, F. A. (2006). Response of rice crop (super basmati) to different nitrogen levels. *J. Anim. Plant Sci.* 16, 52–55.

Millard, P. (1988). The accumulation and storage of nitrogen by herbaceous plants. *Plant Cell Environ.* 11, 1–8. doi: 10.1111/j.1365-3040.1988.tb01769.x

Nascente, A. S., Lanna, A. C., de Sousa, T. P., Chaibub, A. A., de Souza, A. C. A., and de Filippi, M. C. C. (2019). N fertilizer dose-dependent efficiency of Serratia spp. for improving growth and yield of upland rice (*Oryza sativa* L.). *Int. J. Plant Prod.* 13, 217–226. doi: 10.1007/s42106-019-00049-5

Nazir, M. (1994). *Crop Production*, eds E. Bashir and R. Bantel (Islamabad: National Book Foundation). p. 252.

Nokkoul, R., and Wichitparp, T. (2013). Quality of upland rice seed produced during the rainy season in southern Thailand. *Int. J. Plant Anim. Environ. Sci.* 3, 181–184.

Norsuwan, T., Utasuk, K., Panyasai, T., and Sangchyoswat, C. (2020). Optimization of nitrogen fertilizer application in lowland rice production system of agricultural resource system research station using tailored farm-plot database. *Chiang Mai Univ. J. Nat. Sci.* 19, 333–349. doi: 10.12982/CMUJNS.2020.0022

Pal, R., Mahajan, G., Sardana, V., and Chauhan, B. S. (2017). Impact of sowing date on yield, dry matter and nitrogen accumulation , and nitrogen translocation in dry-seeded rice in North-West India Field Crops Research Impact of sowing date on yield , dry matter and nitrogen accumulation , and nitrogen translocati. *Field Crops Res.* 206, 138–148. doi: 10.1016/j.fcr.2017.01.025

Rahman, M., Islam, M., Jahiruddin, M., and Haque, M. (2011). Economics of fertilizer use in the Maize-Mungbean/Dhaincha-T.aman rice cropping pattern. *J. Bangladesh Agric. Univ.* 9, 37–42. doi: 10.3329/jbau.v9i1.8741

Santiago-Arenas, R., Dhakal, S., Ullah, H., Agarwal, A., and Datta, A. (2021). Seeding, nitrogen and irrigation management optimize rice water and nitrogen use efficiency. *Nutr. Cycling Agroecosyst.* 120, 325–341. doi: 10.1007/s10705-021-10153-6

Singh, B., Reddy, K. R., Redoña, E. D., and Walker, T. (2017). Screening of rice cultivars for morpho-physiological responses to early-season soil moisture stress. *Rice Sci.* 24, 322–335. doi: 10.1016/j.rsci.2017.10.001

Singh, R. A., and Singh, U. N. (1976). Response of direct seeded upland rice to levels and methods of nitrogen application under dryland conditions. *Riso* 25, 283–287.

Sparks, D. L. (2009). *Advances in Agronomy*. San Deigo: Elsevier Academic Press.

Suwanasa, C., Nualsri, C., Junsawang, N., and Soonsuwon, W. (2018). Yield trial of upland rice (*Oryza sativa* L.) in Songkhla Province, Thailand. *Songklanakarin J. Plant Sci.* 5, 1–6.

Thomas, G. W. (1982). "Exchangeable Cations. Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties", 2nd Edn, in A. L. Page, editor. *Agronomy*. (Madison. WI: America Society of Agronomy and Soil Science of America), p. 159–165.

TMD (2021). *Climatological Center, Thai Meteorological Department Report*. Available online at: http://climate.tmd.go.th/ (accessed August 19, 2021).

Torres, R. O., and Henry, A. (2018). Yield stability of selected rice breeding lines and donors across conditions of mild to moderately severe drought stress. *Field Crops Res.* 220, 37–45. doi: 10.1016/j.fcr.2016.09.011

Ullah, H., Santiago-Arenas, R., Ferdous, Z., Attia, A., and Datta, A. (2019). *Improving Water Use Efficiency, Nitrogen Use Efficiency, and Radiation Use Efficiency in Field Crops Under Drought Stress: A Review*. 1st ed. Amsterdam: Elsevier Inc.

Varinruk, B. (2017). "Thailand rice production and rice research and development on climate change," in *Workshop on Strengthening APEC Cooperation on Food Security and Climate Change, Ha Noi, Vietnam,19-21 April.* Available online at: http://103.95.217.9/mddb.apec.org/Documents/2017/PPFS/WKSP1/17_ppfs_wksp1_008.pdf (accessed July 8, 2020).

Walkley, A., and Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29–38. doi: 10.1097/00010694-193401000-00003

Wang, L., Xue, C., Pan, X., Chen, F., and Liu, Y. (2018). Application of controlled-release urea enhances grain yield and nitrogen use efficiency in irrigated rice in the yangtze river basin, China. *Front. Plant Sci.* 9, 1–13. doi: 10.3389/fpls.2018.00999

Watcharin, S., Kanrob, P., Charassri, N., and Nattapon, J. (2020). Improving photoperiod insensitivity of a Thai upland rice variety by marker-assisted foreground selection. *Int. J. Agric. Technol.* 16, 199–206.

Wei, T., and Simko, V. (2021). *R package "corrplot": Visualization of a Correlation Matrix*. Available online at: https://github.com/taiyun/corrplot (accessed November 10, 2021).

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. New York, NY: Springer-Verlag. Available online at: https://ggplot2.tidyverse.org (accessed January 10, 2022).

Wu, K., Wang, S., Song, W., Zhang, J., Wang, Y., Liu, Q., et al. (2020). Enhanced sustainable green revolution yield via nitrogen-responsive chromatin modulation in rice. *Science* 367, eaaz2046. doi: 10.1126/science.aaz2046

Yoshida, S. (1973). Effects of temperature on growth of the rice plant (*Oryza sativa*L.) in a controlled environment. *Soil Sci. Plant Nutr.* 19, 299–310. doi: 10.1080/00380768.1973.10432599

Yousaf, M., Li, X., Zhang, Z., Ren, T., Cong, R., Ata-Ul-Karim, S. T., et al. (2016). Nitrogen fertilizer management for enhancing crop productivity and nitrogen use efficiency in a rice-oilseed rape rotation system in China. *Front. Plant Sci.* 7, 1496. doi: 10.3389/fpls.2016.01496

Zain, N. A. M., Ismail, M. R., Puteh, A., Mahmood, M., and Islam, M. R. (2014). Impact of cyclic water stress on growth, physiological responses and yield of rice (*Oryza sativa* L.) grown in tropical environment. *Ciência Rural* 44, 2136–2141. doi: 10.1590/0103-8478cr20131154

Zhang, D., Wang, H., Pan, J., Luo, J., Liu, J., Gu, B., et al. (2018). Nitrogen application rates need to be reduced for half of the rice paddy fields in China. *Agric. Ecosyst. Environ.* 265, 8–14. doi: 10.1016/j.agee.2018.05.023

Zhang, J., Tong, T., Potcho, P. M., Huang, S., Ma, L., and Tang, X. (2020). Nitrogen effects on yield, quality and physiological characteristics of giant rice. *Agronomy* 10, 1816. doi: 10.3390/agronomy10111816

Zheng, H., Chen, Y., Chen, Q., Li, B., Zhang, Y., Jia, W., et al. (2020). High-density planting with lower nitrogen application increased early rice production in a double-season rice system. *Agron. J.* 112, 205–214. doi: 10.1002/agj2.20033

Zhou, C., Huang, Y., Jia, B., Wang, S., Dou, F., Samonte, S. O. P. B., et al. (2019). Optimization of nitrogen rate and planting density for improving the grain yield of different rice genotypes in Northeast China. *Agronomy* 9, 555. doi: 10.3390/agronomy9090555

Zhou, Q., Ju, C., xin, Wang, Z., qin, Zhang, H., Liu, L., jun, Yang, J., et al. (2017). Grain yield and water use efficiency of super rice under soil water deficit and alternate wetting and drying irrigation. *J. Integr. Agric.* 16, 1028–1043. doi: 10.1016/S2095-3119(16)61506-X

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

VITAE

Name	Mr. Tajamul Hussain
Student ID	6110630006

Educational Attainment

Degree	**Name of Institution**	**Year of Graduation**
Bachelor of Science (Agronomy)	PMAS, Arid Agriculture University	2015
Master of Science (Plant Science)	Prince of Songkla University	2017
Doctor of Philosophy (Plant Science)	Prince of Songkla University	2022

Scholarship Awards during Enrolment

- 2020: CLIFF–GRADS research award for research collaboration with USDA–Agricultural Research Service, Soil and Water Conservation Research Unit, USA, through “Consultative Group on International Agricultural Research” (CGIAR) research program on “Climate Change, Agriculture and Food Security” (CCAFS) and the “Global Research Alliance on Agricultural Greenhouse Gases (GRA)” administrated by Ryan Institute of National University of Ireland Galway (NUI Galway)
- 2019: Scholarship and travel grant from the Food Security Center of the University of Hohenheim, under “EXCEED” program of German Academic Exchange Service (DAAD), supported by German Federal Ministry for Economic Cooperation and Development (BMZ) for summer school on

“Transformative Changes in Agriculture and Food Systems” held at SEARCA Headquarters, Los Baños, Laguna, Philippines, 9–27 September 2019

- 2019: Scholarship and travel grant from Agrotechnology Innovation Center, Universitas Gadjah Mada (UGM) for summer school on “Smart Integrated Farming for Sustainable Agriculture” held at Agrotechnology Innovation Center, Universitas Gadjah Mada (UGM), Yogyakarta, Indonesia, 15–24 July 2019
- 2019: Thesis research grant for the degree of Doctor of Philosophy in Plant Science from the Faculty of Natural Resources and the Graduate School, Prince of Songkla University
- 2018−2021: Scholarship award for the degree of Doctor of Philosophy in Plant Science from Thailand’s Education Hub for Southern Region of ASEAN Countries (TEH−AC)
- 2017: Thesis research grant for the degree of Master of Science in Plant Science from the Faculty of Natural Resources and the Graduate School, Prince of Songkla University
- 2016−2017: Scholarship award for the degree of Master of Science in Plant Science from Thailand’s Education Hub for Southern Region of ASEAN Countries (TEH−AC)
- 2011−2015: Scholarship award for the degree of Bachelor of Science in Agriculture from the Higher Education Commission (HEC) of Pakistan

List of Publications

Hussain, T., Gollany, H.T., Hussain, N., Ahmed, M. Tahir, M. and Duangpan, S. 2022. Synchronizing nitrogen fertilization and planting date to improve resource use efficiency, productivity, and profitability of upland rice. *Frontiers in Plant Science* 13: 895811. doi:10.3389/fpls.2022.895811. (Q1: Impact Factor: 5.753)

Hussain, T., Hussain, N., Ahmed, M. Nualsri, C. and Duangpan, S. 2022. Impact of nitrogen application rates on upland rice performance, planted under varying sowing times. *Sustainability* 14: 1997. doi: 10.3390/su14041997. (Q1: Impact Factor: 3.251)

Duangpan, S., Tongchu, Y., Hussain, T., Eaksomtramage, T. and Onthong, J. 2022. Beneficial effects of silicon fertilizer on growth and physiological responses in oil palm. *Agronomy* 12:413. doi:10.3390/agronomy12020413 (Q1: Impact Factor: 3.417)

Hussain, T., Hussain, N., Ahmed, M. Nualsri, C. and Duangpan, S. 2021. Responses of lowland rice genotypes under terminal water stress and identification of drought tolerance to stabilize rice productivity in southern Thailand. *Plants* 10: 2565. doi: 10.3390/plants10122565. Q1. Impact Factor: 3.935.

Hussain, T., Anothai, J., Nualsri, C. and Soonsuwon, W. 2022. Evaluation of drought tolerance in Thai upland rice (*Oryza sativa* L.) landraces using DSSAT–CSM–CERES–RICE model. Submitted in Philippine Agricultural Scientist.

Hussain, N., Ahmed, M., Duangpan, S., Hussain, T., Taweekun, J. 2021. Potential impacts of water stress on rice biomass composition and feedstock availability

for bioenergy production. *Sustainability* 13: 10449. doi:10.3390/su131810449. (Q1: Impact Factor: 3.251)

Hussain, T., Anothai, J., Nualsri, C. and Soonsuwon, W. 2018. Application of CSM–CERES–Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield. Indian Journal of Agricultural Research. 52: 140–145.

Hussain, T., Anothai, J., Nualsri, C. and Soonsuwon, W. 2018. Evaluating performance of sixteen upland rice genotypes under field conditions for further breeding process. Journal of Agricultural Science. 10(3):144–150.

Ali, W., Hussain, T., Muqadas, M. and Gillani, S.S.M. 2016. Climate change implications for global food security. Technology Times. Islamabad, Pakistan. 7:03. (January 04–January 10, 2016).

Batool, S., Hussain, T., Mubeen, S., Shamim, A. 2015. Impacts of climate change on crop production in Pakistan, future challenges and mitigation strategies. Technology Times. Islamabad, Pakistan. 6: 03. (March 30–April 05, 2015).

Hussain, T., Mubeen, S., and Aslam, M.A. 2015. Can food security be insured through crop modeling under changing climate? The Veterinary News and Views. Faisalabad, Pakistan. 13: 07. (01–07 February 2015).

Hussain, T. 2015. Crop simulations and modeling: a tool for sustaining food security. Technology Times. Islamabad, Pakistan. 6: 03 (5–11 January 2015).

Book Chapters

Aslam, M.A., Ahmed, M., Hassan, F.U., Afzal, O., Mehmood, M.Z., Qadir, G., Asif, M., Komal, S. and Hussain, T. 2022. Impact of temperature fluctuations on plant morphological and physiological traits. *In*: Jatoi, W.N., *et al.* (eds.), Building Climate Resilience in Agriculture. Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-79408-8_3.

Oral Presentations

Hussain, T., Anothai, J., Nualsri, C., Junsawang, N. Soonsuwon, W. 2017. Yield assessment of Dawk Pa–yawm under different water regimes. Presented in 4th Plant Science Symposium at Department of Plant Science, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Thailand, (17–18 August 2017).

Aslam, M.A., Ahmed, M., Hassan, F.U. and Hussain, T. 2014. Optimization of physiology and yield of rainfed wheat under changing climate through nitrogen management. Presented in International conference on Agriculture, Food Security and Climate Change. Faculty of Agriculture, the University of Poonch Rawalakot AJ&K, (9–11 Sep 2014)

Khan, S., Ahmed, M., Hassan, F.U., Shabbir, G., Aslam, M.A. and Hussain, T. 2014. Root signaling of wheat under water regimes. Presented in International Conference on Agriculture, Food Security and Climate Change. Faculty of Agriculture, the University of Poonch Rawalakot AJ&K, (9–11 Sep 2014)