agronomy

MDPI

Article

Impacts of Drought Stress on Water Use Efficiency and Grain Productivity of Rice and Utilization of Genotypic Variability to Combat Climate Change

Tajamul Hussain [1], Nurda Hussain [1], Muhammad Tahir [2], Aamir Raina [3], Sobia Ikram [4], Saliha Maqbool [2], Muhammad Fraz Ali [5] and Saowapa Duangpan [1,6,*]

1 Laboratory of Plant Breeding and Climate Resilient Agriculture, Agricultural Innovation and Management Division, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand
2 Department of Soil, Water & Climate, University of Minnesota, 506 Borlaug Hall, 1991 Upper Buford Circle, St Paul, MN 55108, USA
3 Department of Botany, Aligarh Muslim University, Aligarh 202002, India
4 Institute for Future Farming Systems, Central Queensland University, Building 361, Bruce Highway, Rockhampton, QLD 4701, Australia
5 College of Agronomy, Northwest A&F University, Yangling, Xianyang 712100, China
6 Oil Palm Agronomical Research Center, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand
* Correspondence: saowapa.d@psu.ac.th; Tel.: +66-74-286-138

Abstract: Rice is an important cereal and drought stress is a critical abiotic stress that negatively influences the performance and productivity of rice crop, particularly under a changing climate scenario. The objectives of this study were to evaluate the impacts of drought stress on grain productivity and water use efficiency of rice cultivars and to assess the genotypic variability among the tested cultivars. Two irrigation treatments including a control and drought stress were applied to the experiments during 2018–2019 and 2019–2020. The statistical evaluation included a comparison of means, genotypic and phenotypic coefficients of variation, path analysis, correlation assessment, hierarchical clustering of tested cultivars and principal component analysis. The results indicated that drought stress negatively affected the grain productivity of the rice cultivars. The grain productivity of the cultivars decreased, ranging between 21–45% and 21–52% in the first and second season, respectively. Similarly, water use efficiency was significantly decreased ranging between 7–53% and 21–55% during the first and the second season, respectively. The broad-sense heritability for grain productivity was differed under control and drought stress treatment, indicating that the chances of the transfer of grain-productivity-related traits could be affected during selection for stress tolerance. The correlation assessment indicated that the intensity of association among the evaluated parameters was higher under the control treatment. A maximum direct effect was observed by water consumption (1.76) under control whereas, by water use efficiency (1.09) under drought stress treatment on grain productivity in path analysis. Considering the water use efficiency as a desired trait for selection in path analysis, a maximum direct effect was observed by grain productivity under the control (0.68) and under drought treatment (0.88). Hom Pathum and Pathum Thani−1 were identified as highly tolerant cultivars in the hierarchical clustering and principal component analysis. It was concluded that the results obtained for the assessment of drought stress on grain productivity, water use efficiency and genotypic variability among these cultivars could be utilized in selection program for stress tolerance and the stress tolerant cultivars could be used for sustaining grain productivity to reduce the impacts of climate change.

Keywords: rice; drought stress; path analysis; heritability; principal component analysis

Citation: Hussain, T.; Hussain, N.; Tahir, M.; Raina, A.; Ikram, S.; Maqbool, S.; Fraz Ali, M.; Duangpan, S. Impacts of Drought Stress on Water Use Efficiency and Grain Productivity of Rice and Utilization of Genotypic Variability to Combat Climate Change. *Agronomy* **2022**, *12*, 2518. https://doi.org/10.3390/agronomy12102518

Academic Editor: Guanfu Fu

Received: 30 August 2022
Accepted: 10 October 2022
Published: 15 October 2022

1. Introduction

Climate change has impacted agricultural crop production and water shortages [1], and variations in moisture availability are among the current critical issues. Lowland rice production systems are major rice systems and are crucial to food security. Rain-fed lowland rice production covers 6.2 million hectares globally [2]. Rice is a major cereal crop in Thailand, which critically contributes towards the country's food security and economy [3]. In Southeast Asia, Thailand ranks second in rice production [4]. Rain-fed lowland rice production systems, which are a major production system in Thailand, are highly susceptible to climatic variability [5] and drought stress occurrence. Water shortages and drought stress occurrence have been forecasted in numerous studies to be severe due to the influence of climate change in the future, i.e., Ullah et al. [6], El Sherbiny et al. [7] and Hussain et al. [8]. The occurrence of drought stress due to the impact of climate change affects the crop performance and production potential [9,10]. Rain-fed rice production is achieved during the rainy season in Thailand [5,6,8,11]. The grain productivity of rice is significantly affected by drought stress events at various crop stages caused by seasonal variability of rainfall patterns [5].

Drought stress affects rice plant physiological processes and impacts the performance of agronomic traits, which ultimately results in declined grain productivity [12,13]. Yield losses are dependent upon the duration and intensity of the stress intervals. Rice is very sensitive to drought stress, and if drought stress occurs in midseason or at the flowering stage, it can affect the grain numbers as well as spikelet fertility, causing yield losses up to 92% [14] and severe yield losses can occur if drought prevails at terminal or lateral crop stages [15]. According to Pantuwan et al. [16] and Ovenden et al. [17], drought stress affects source-to-sink distribution and leads to reduced grain productivity. In this scenario, drought-stress-tolerant cultivars can help to sustain grain productivity as they are highly capable of retaining higher productivity under drought stress [18]. Different cultivars demonstrate varying responses to drought stress [19] and the capability of a cultivar to sustain yields or perform well is considered as a principal indicator for the cultivar's stability [20]. According to Blum [21], farmers consider a cultivar as drought tolerant if it has the potential to sustain grain productivity under a reduced water supply. Thus, such types of cultivars are always highly desired, as they also produce better yields as compared to drought-stress-susceptible cultivars. Therefore, exploring the local germplasm subjected to drought stress would help to identify suitable cultivars for enhanced drought stress tolerance and maintain higher yields under a climate change scenario.

Breeding rice crop for drought stress tolerance to avoid or prevent abiotic stresses is an important factor for sustaining rice productivity. The yield assessment and improvement of drought-tolerant cultivars are crucial in rice breeding and selection for drought resistance. It is very important to understand the plant characteristics involved in higher yield production and the effective resistance to drought, which helps to select and develop genotypes with higher water use efficiency for better water management and improved production [22,23]. Water use efficiency is an important indicator that exhibits the response of a specific cultivar under different available irrigation water and soil moisture statuses. Generally, the water use efficiency of plants is decreased under a water deficit and vice versa, but plants maintaining their physiology and rescheduling their water use are specified as exhibiting anti-drought behavior. Water use efficiency is decreased due to a higher rate of transpiration under drought stress and genotypes fail to produce optimum yields. Hu et al. [24] found that the water use efficiency of wheat genotypes was decreased under a water deficit. However, the water use efficiency of a cultivar does not necessarily mean a reduction under drought stress. Hu et al. [24] also found that the water use efficiency of two wheat genotypes was increased under a water deficit at middle level stress as compared to non-stressed conditions, which provided a clue for water saving. A higher or lower reduction in water use efficiency is mainly a characteristic of reduced water use under drought stress than net production [25]. Monclus et al. [26] suggested that producing a high level of drought tolerance requires the ability of a cultivar to increase its water use efficiency.

A number of methods and techniques are being used to evaluate crop cultivars for their improved drought tolerance responses including primary yield trials, field evaluations and modern breeding practices. Maintaining the crop water productivity or water use efficiency of a crop, survival and sustaining the yields under drought stresses are some of complex mechanisms that are regulated by a number of genes [1]. Cultivars exhibiting a higher water use efficiency in relation to water consumption are useful for acquiring drought-tolerant traits. However, water use efficiency alone cannot be considered as an indicator for drought tolerance, as drought tolerance is complex mechanism in which plant root water uptake and other physiochemical process are involved. Thus, water use efficiency provides a preliminary option for selecting cultivars for further screening processes.

The identification and selection of crop cultivars in breeding trials is considered laborious. Thus, initially screening a variety of crop cultivars under different management options for diversity among various agronomic and morphological characteristics is still one of the basic principles of crop breeding. Water use efficiency is one of the critical factors for rice breeders, particularly when selecting and breeding rice for drought tolerance. Rice cultivars can be classified based on plant agronomic and morphological traits by rice breeders [27]. Diversity among the crop population [28,29] for specific or desired attributes, i.e., grain productivity and water use efficiency, is a critical component. In rice breeding programs, evaluating crop productivity under variable drought stress conditions and the investigation of crop water use efficiency both help to identify suitable and stable cultivars. In this regard, exploring correlations among plant traits is highly advantageous. High and positively associated traits can be targeted for further improvements. A correlation determines the association among two attributes or variables, where its value ranges between −1 and +1, whereas a zero exhibits no correlation or association among the tested attributes [30]. A path coefficient analysis, which is a multivariate statistical tool for evaluating linkages among two or more attributes [31], can be used to identify the in-depth direct and indirect impacts of affecting components on desired traits and for the assessment of comparative importance among variables. Direct effects are significant for breeding as they are directly linked to the targeted traits. Path coefficient analysis has been used to observe correlations among yields and yield components in various crops including rice [32,33], cowpea [34], spinach [35], wheat [36], barley [37] and melons [28]. A proportion of phenotypic variance is known as broad-sense heritability (H^2), which is attributable to the effects including the sum of the additive, epistatic and dominance effects, which then can be used predict the probability of an improvement in targeted crop traits [28], and it defines the responses to assortment. Yield components usually have a low heritability, which makes it hard to reach the desired and targeted trait for selection. Hence, crop breeders must select the traits with high heritability indicating a significant correlation with yield components [33]. In the selection process, similarly acting crop cultivars under various applied stresses can be identified using hierarchical clustering and principal component analysis (PCA) based on studied traits [38], which can then be further classified into various groups and subgroups based on the performance of the studied attributes [5].

Keeping in view the importance of the above, the present study was designed to evaluate the impacts of drought stress on the grain productivity and water use efficiency of rice cultivars. A combination of statistical approaches was used to identify the genotypic variability and classification of cultivars based on their peculiarities in terms of water consumption, water use efficiency and grain productivity. The results obtained for each cultivar provide the basis for their utilization in further breeding processes to enhance their drought stress tolerance and in mitigating the impacts of climate change, particularly in terms of the drought stress intervals occurring at lateral rice crop growth stages.

2. Materials and Methods

2.1. Experimental Setup and Crop Management

The study was conducted in the greenhouse of the Faculty of Natural Resources, Prince of Songkla University, Thailand for two crop seasons during 2018–2019 (first season) and 2019–2020 (second season). Detailed information about crop management and the experimental procedure were provided in our previous study [5]. In brief, famous lowland rice cultivars were selected for evaluation in this study. The germplasm for all twelve cultivars, which included Hom Pathum, Chor Lung, Dum Ja, Sang Yod, Hom Nang Kaew, Hom Chan, Pathum Thani−1, RD−15, Lep Nok, Look Pla, Khao Dawk Mali−105 and Tia Malay Dang, were obtained from the Phatthalung Rice Research Center, Phatthalung province, and farmers in southern Thailand. In both years, fine soil was prepared, and 12 kg soil was uniformly filled in conical-shaped planting pots with a 30 cm top diameter, 19 cm base diameter and 24 cm height with drainage holes at the bottom to allow drainage, whereas the planting pots were placed on pot plates. The soil texture of the soil used in both seasons was sandy clay loam with 65.08%, 10.21% and 21.42% of sand, silt and clay, respectively, and the electrical conductivity of soil was 44.50 µS cm^{-1}. The experimental soil contained 4.73 gkg^{-1} and 4.60 gkg^{-1} organic matter and 0.34 gkg^{-1} and 0.30 gkg^{-1} total nitrogen contents in first and the second season, respectively. The mean daily maximum and minimum temperatures were recorded using WatchDog micro weather station (Series:1000, Model: 1425®) from Spectrum Technologies and are shown in Figure S1. The daily mean maximum and minimum temperatures ranged from 26.3–44.6 °C and 22.2–26.8 °C during the first season, whereas they ranged from 33.3–46.7 °C and 22.8–27.1 °C during the second season, respectively. The direct seeding method was used to plant seeds in the planting pots and extra plants were thinned to maintain three plants per pot at the seedling stage for adequate plant establishment. Two irrigation treatments were imposed on the experiments, which included a control (C) and drought stress (D), and each treatment was replicated three times. Plants were irrigated using an automatic drip irrigation system with a dripper head water discharge capacity of 8 L per hour [5]. Irrigation was applied for specific time durations and on days during the experimental period. The irrigation amount for each cultivar was first summed from the planting to maturity duration of the specific genotype, following which the irrigation amount as liters per pot was calculated by multiplying the irrigation time duration and dripper head water flow capacity. Plants in both treatments were irrigated equally until drought stress was applied after 75 days of planting by holding irrigation in drought stress treatment until temporary wilting was witnessed. Irrigation was restored soon after witnessing temporary wilting in the drought treatment (Figure 1). Recommended crop production practices were performed in both seasons to avoid insect, pest and disease attacks.

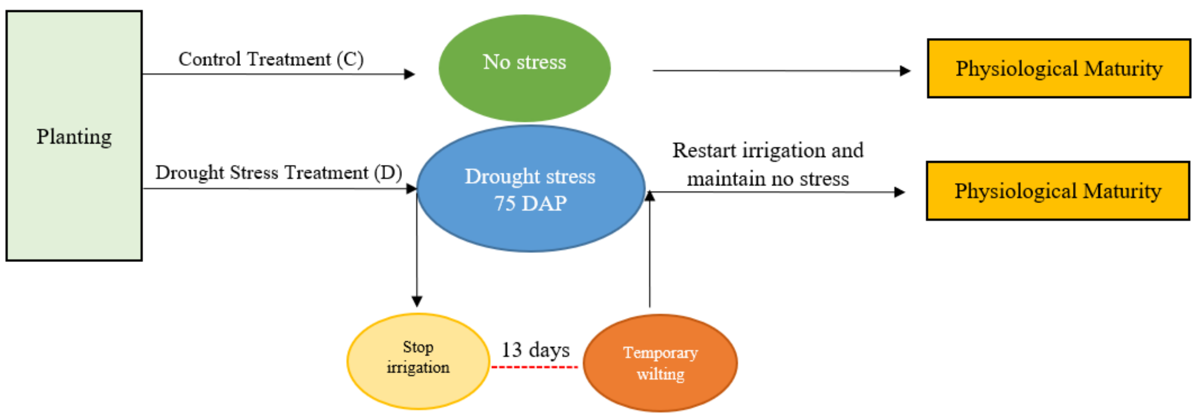

Figure 1. Scheme of irrigation water application in control (C) and drought stress (D) treatments.

2.2. Crop Harvest and Data Collection

Detailed information on the crop harvesting and data collection methods were given in our previous study [5]. When 50% of the plants in each treatment reached physiological maturity, the maturity duration (days) was counted. The maturity duration is linked to our previously published work [5]. Manual harvesting was performed, and the grain productivity was calculated from randomly selected plants for each cultivar in each replication and treatment. The grain productivity was modified to a gram-per-pot basis, and it was determined as the dry grain weight by drying the grain samples in an oven at 70 °C to achieve a constant weight.

2.3. Determination of the Water Use Efficiency

The water use efficiency was computed using Equation (1) as described by Zhou et al. [39] for each cultivar as a relationship between the grain productivity and applied irrigation water.

$$\text{Water use efficiency }(\text{g/L}) = \frac{\text{Grain productivity per pot }(\text{g})}{\text{Applied irrigation water per pot }(\text{L})} \tag{1}$$

2.4. Statistical Analysis

Statistical analysis was performed using the Statistix 8.1 package (Analytical software, Tallahassee, FL, USA) [40]. Analysis of variance was conducted in a factorial design arranged in a completely randomized model for maturity duration, water consumption, grain productivity and water use efficiency observed from three replications for all cultivars in response to the control and drought stress treatments and their interactions in both seasons. The least significant difference was used to compare the means and the significance was studied at p values less than 0.05. Genotypic (G_{CV}) and phenotypic (P_{CV}) coefficient of variations, broad-sense heritability (H^2), genetic advance (GA) and genetic advance as a percentage of the mean (GA_M) for grain productivity, days to maturity, water consumption and water use efficiency of the lowland rice cultivars under the control and drought stress treatments were computed as described by Al-Tabbal and H. Al-Fraihat [41], Covarrubias-Pazaran [42], Teklu et al. [43], Oladosu et al. [44] and Khomphet et al. [28] using the R program [45]. Path analysis to figure out the direct and indirect effects of the studied traits on grain productivity and water use efficiency was performed as used by Krualee et al. [46] and Khomphet et al. [28] using the R program as well [45]. Furthermore, the cultivars were classified according to their responses for grain productivity and water use efficiency under the control and drought stress treatments using the ClustVis software [47] as described by Hussain et al. [5] for hierarchical clustering. The clustering distance for rows and columns was considered based on their correlation and the average was used for the clustering method for rows and columns in a heatmap. A principal component analysis (PCA) biplot was generated using the R program [45].

3. Results

3.1. Irrigation Water Consumption and Crop Duration

The statistical analysis indicated that the irrigation water consumption was significantly different for cultivar (C), treatment (T), seasons (S) and the interactions of C × T, C × S, T × S and C × T × S (Table 1). During the first season, the irrigation water consumption was increased for the cultivars Hom Pathum, Dum Ja, Sang Yod, Hom Nang Kaew, Hom Chan, Pathum Thani−1, Lep Nok, Look Pla and Tia Malay Dang, whereas it decreased for the cultivars Chor Lung, RD−15 and Khao Dawk Mali−105 under drought stress conditions (Figure S2A). In the second season, the irrigation water consumption was increased for all the cultivars under drought stress conditions (Figure S2B). The maturity duration of the cultivars Hom Pathum, Dum Ja, Sang Yod, Hom Nang Kaew, Hom Chan, Pathum Thani−1, Lep Nok, Look Pla and Tia Malay Dang was increased by 4, 5, 14, 7, 10, 8, 4, 5 and 11 days, respectively, whereas it decreased for the cultivars Chor Lung, RD−15 and

Khao Dawk Mali−105 by 19, 11 and 5 days, respectively, during first season. In the second season, the maturity duration of all the cultivars was increased by 4, 4, 8, 8, 4, 6, 4, 3, 3, 7, 4 and 6 days, respectively, for Hom Pathum, Chor Lung, Dum Ja, Sang Yod, Hom Nang Kaew, Hom Chan, Pathum Thani−1, RD−15, Lep Nok, Look Pla, Khao Dawk Mali−105 and Tia Malay Dang (Table 2) [5].

Table 1. Significance and sum of squares obtained from analysis of variance for water consumption, days to maturity, grain productivity and water use efficiency of lowland rice cultivars.

	Water Consumption	Days to Maturity	Grain Productivity	Water Use Efficiency
Cultivar (C)	49929.70 ***	63879.70 ***	1522.47 ***	0.59 ***
Treatment (T)	162.56 ***	564.10 ***	1901.32 ***	0.44 ***
Season (S)	297.56 ***	217.60 **	1490.02 ***	0.11 ***
C × T	702.19 ***	942.20 ***	124.46 ns	0.07 **
C × S	1089.19 ***	1530.40 ***	927.80 ***	0.19 ***
T × S	33.06 ***	52.60 ns	27.78 ns	0.00 ns
C × T × S	375.69 ***	651.00 **	129.17 ns	0.06 ns

***: $p < 0.001$, **: $p < 0.01$, ns: non—significant difference.

Table 2. Maturity duration (days) of lowland rice cultivars under control and drought stress treatments during first season (A) and second season (B) [5].

	First Season (A)		Second Season (B)	
Cultivars	**Control**	**Drought Stress**	**Control**	**Drought Stress**
Hom Pathum	128 ± 3 EF	132 ± 2 D	122 ± 0 G	126 ± 0 F
Chor Lung	170 ± 2 A	151 ± 1 C	171 ± 1 A	175 ± 1 A
Dum Ja	168 ± 3 AB	173 ± 7 A	165 ± 0 C	173 ± 2 AB
Sang Yod	147 ± 1 D	161 ± 1 BC	147 ± 1 F	155 ± 1 E
Hom Nang Kaew	158 ± 5 C	165 ± 6 AB	163 ± 0 C	167 ± 0 CD
Hom Chan	144 ± 2 D	154 ± 4 C	150 ± 1 E	156 ± 0 E
Pathum Thani−1	131 ± 3 E	139 ± 7 D	122 ± 0 G	126 ± 1 F
RD−15	124 ± 1 EF	113 ± 4 E	108 ± 1 I	111 ± 0 H
Lep Nok	168 ± 4 AB	172 ± 2 AB	167 ± 2 B	170 ± 3 BC
Look Pla	161 ± 1 BC	166 ± 3 AB	159 ± 1 D	166 ± 0 D
Khao Dawk Mali−105	124 ± 3 EF	119 ± 1 E	109 ± 0 I	113 ± 1 H
Tia Malay Dang	120 ± 2 F	131 ± 2 D	116 ± 1 H	122 ± 0 G

Means (±standard errors of three replicates) of maturity duration (days) under control and drought stress treatments. Statistical difference (p-value < 0.05) among the means of lowland rice cultivars in each treatment is presented by capital letters.

3.2. Impact of Drought Stress on Grain Productivity

The grain productivity was highly significantly different for cultivars (C), treatments (T) and seasons (S), whereas it was not significantly different for C × T, T × S and C × T × S, as indicated by the analysis of variance (Table 1). There was a significant variation for grain productivity among all the cultivars under the control and drought stress conditions during both seasons (Figure 2). The grain productivity of all the cultivars was affected under drought stress, and the grain productivity of the cultivars Hom Pathum, Chor Lung, Dum Ja, Hom Nang Kaew, Pathum Thani−1, Lep Nok, Look Pla, Khao Dawk Mali−105 and Tia Malay Dang was significantly decreased by 21%, 31%, 23%, 26%, 28%, 36%, 39%, 30% and 45%, respectively, during the first season (Figure 2A), and the grain productivity of all the cultivars including Hom Pathum, Chor Lung, Dum Ja, Sang Yod, Hom Nang Kaew, Hom Chan, Pathum Thani−1, RD−15, Lep Nok, Look Pla, Khao Dawk Mali−105 and Tia Malay Dang significantly decreased by 24%, 21%, 22%, 25%, 43%, 26%, 26%, 36%, 33%, 25%, 52% and 34%, respectively, during the second season (Figure 2B).

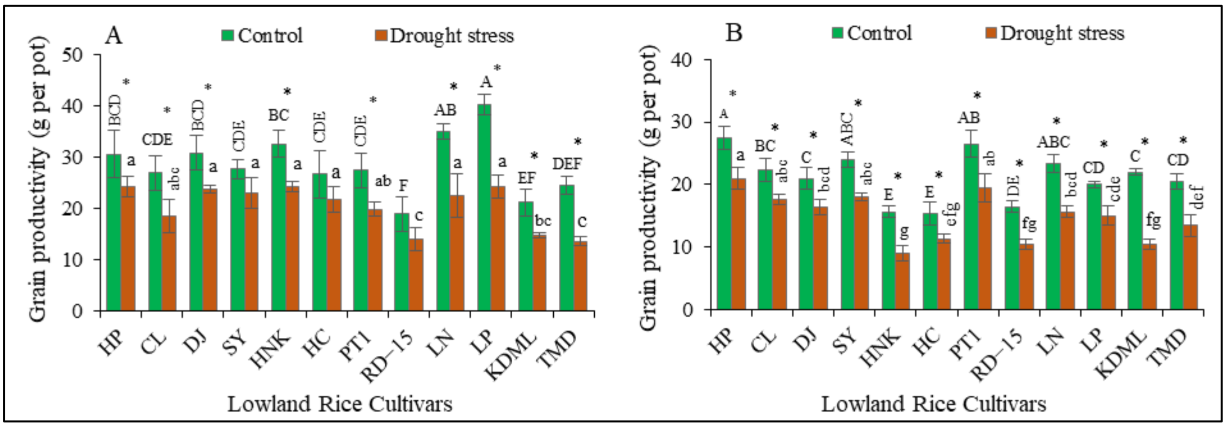

Figure 2. Grain productivity (grams per pot) of twelve lowland rice cultivars under control and drought stress treatments during first season (**A**) and second season (**B**). Means from three replications are presented with ± standard errors. Significance ($p < 0.05$) among cultivars in control treatment is presented using capital letters, whereas significance ($p < 0.05$) among cultivars in drought stress treatment is presented using lower-case letters. Significance among treatments for each cultivar is presented by stars (*). HP: Hom Pathum, CL: Chor Lung, DJ: Dum Ja, SY: Sang Yod, HNK: Hom Nang kaew, HC: Hom Chan, PT1: Pathum Thani−1, LN: Lep Nok, LP: Look Pla, KDML: Khao Dawk Mali−105, TMD: Tia Malay Dang.

3.3. Impact of Drought Stress on Water Use Efficiency

Considering the water use efficiency, highly significant differences were indicated in the statistical analysis for cultivars and treatments, whereas non-significant differences were observed for the interactions of treatment × season and cultivar × treatments × season (Table 1). A significant variability prevailed for the water use efficiency among the tested cultivars and the water use efficiency of all the cultivars was higher in the control treatment, whereas it decreased under the drought stress treatment for the tested cultivars ranging from 7–53% and 21–55% during the first season (Figure 3A) and the second season (Figure 3B), respectively. The water use efficiency of the cultivars Hom Pathum, Dum Ja, Sang Yod, Hom Nang Kaew, Pathum Thani−1, Lep Nok, Look Pla, Khao Dawk Mali−105 and Tia Malay Dang significantly decreased by 24%, 24%, 26%, 27%, 24%, 34%, 36%, 40%, 22% and 53%, respectively, during the first season (Figure 3A), and it significantly decreased for the cultivars Hom Pathum, Chor Lung, Dum Ja, Sang Yod, Hom Nang Kaew, Hom Chan, Pathum Thani−1, Lep Nok, Look Pla, Khao Dawk Mali−105 and Tia Malay Dang by 27%, 21%, 24%, 31%, 43%, 30%, 30%, 33%, 27%, 55% and 40%, respectively, during the second season (Figure 3B).

3.4. Genotypic Variability

The analysis for the genotypic variability of the pooled data from the two seasons indicated that the parameters including the genotypic (G_{CV}) and phenotypic (P_{CV}) coefficient of variations, broad-sense heritability (H^2), genetic advance (GA) and genetic advance as percentage of the mean (GA_M) acted similarly for days to maturity, water consumption and water use efficiency of the lowland rice cultivars under the control and drought stress treatments except for grain productivity, in which the phenotypic (P_{CV}) coefficient of variation and broad-sense heritability (H^2) differed under the control and drought stress treatments (Table 3), which indicated that stress induction had the ability to alter the behavior of the genotypic variability parameters. Under the control treatment, G_{CV} and P_{CV} were categorized as medium for grain productivity (13.72 and 17.17) and days to maturity (15.18 and 15.29), whereas they were high for water consumption (25.68 and 25.68) and water use efficiency (23.48 and 25.34). Under the drought stress treatment, G_{CV} and P_{CV} acted similarly, being categorized as medium for days to maturity (15.19 and 15.42) and high for water consumption (25.35 and 24.35) and water use efficiency (21.65 and

25.62), and in contrast, G_{CV} and P_{CV} were categorized as medium (17.09) and high (22.14), respectively, for grain productivity.

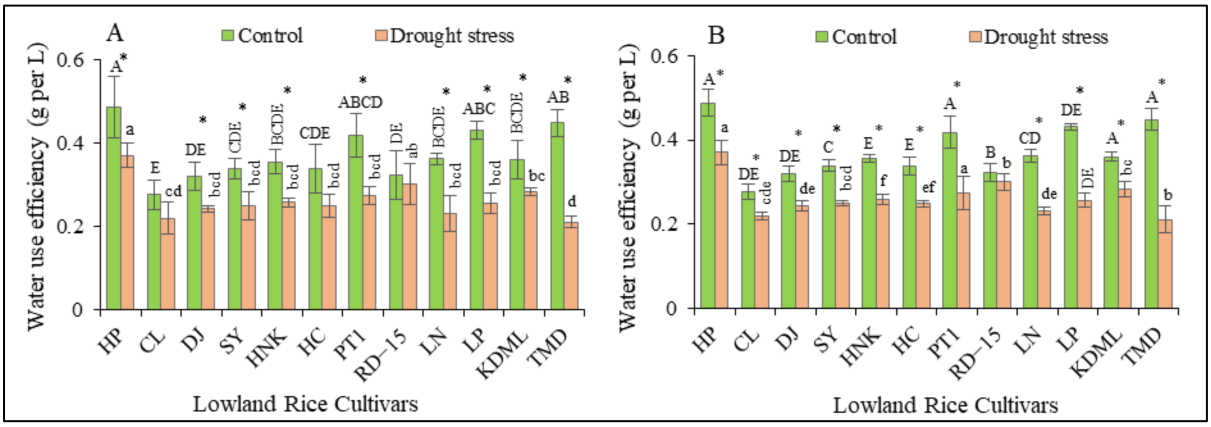

Figure 3. Water use efficiency of twelve lowland rice cultivars under control and drought stress treatments during first season (**A**) and second season (**B**). Means from three replications are presented with ± standard errors. Significance ($p < 0.05$) among cultivars in control treatment is presented using capital letters, whereas significance ($p < 0.05$) among cultivars in drought stress treatment is presented using lower-case letters. Significance among treatments for each cultivar is presented by stars (*). HP: Hom Pathum, CL: Chor Lung, DJ: Dum Ja, SY: Sang Yod, HNK: Hom Nang kaew, HC: Hom Chan, PT1: Pathum Thani−1, LN: Lep Nok, LP: Look Pla, KDML: Khao Dawk Mali−105, TMD: Tia Malay Dang.

Table 3. Genotypic (G_{CV}) and phenotypic (P_{CV}) coefficient of variations, broad-sense heritability (H^2), genetic advance (GA) and genetic advance as percentage of mean (GA_M) among grain productivity, days to maturity, water consumption and water use efficiency of lowland rice cultivars under control and drought stress treatments.

		Grain Productivity		**Days to Maturity**		**Water Consumption**		**Water Use Efficiency**	
Control Treatment	G_{CV}	13.72	M	15.18	M	25.68	H	23.48	H
	P_{CV}	17.17	M	15.29	M	25.68	H	25.34	H
	H^2	63.93	H	98.51	H	100.00	H	85.88	H
	GA	5.62	L	44.50	H	40.31	H	0.15	L
	GA_M	22.60	H	31.05	H	52.89	H	44.83	H
Drought Stress Treatment	G_{CV}	17.09	M	15.19	M	25.35	H	21.65	H
	P_{CV}	22.14	H	15.42	M	25.35	H	25.62	H
	H^2	59.60	M	97.13	H	100.00	H	71.40	H
	GA	4.79	L	45.45	H	40.80	H	0.09	L
	GA_M	27.17	H	30.84	H	52.23	H	37.68	H

L: Low, M: Medium, H: High.

The broad-sense heritability (H^2) was high for all the attributes including grain productivity (63.93), days to maturity (98.51), water consumption (100.00) and water use efficiency (85.88) under the control treatment, whereas, in contrast, under the drought stress treatment, it was medium for grain productivity (59.60) and high for days to maturity (97.13), water consumption (100.00) and water use efficiency (71.40) (Table 3).

The genetic advance (GA) acted similarly under the control and drought stress treatments, and it was categorized as low for grain productivity (5.62) and water use efficiency (0.15) and high for days to maturity (44.50) and water consumption (40.31) under the control treatment, whereas it was classified as low for grain productivity (4.79) and water use efficiency (0.09) and high for days to maturity (45.45) and water consumption (40.80) under the drought stress treatment. The genetic advance as percentage of the mean (GA_M) acted similarly and was classified as high for grain productivity (22.60 and 27.17), days to maturity (31.05 and 30.84), water consumption (52.89 and 52.23) and water use efficiency (44.83 and 37.68) for the control and drought stress treatments, respectively (Table 3).

3.5. Correlation Study

The correlation analysis indicated a similar trend for correlation among the studied traits. However, the degree of association varied among the studied attributes under the control (Figure 4A) and drought stress treatments (Figure 4B). The highest significant and positive associations were observed among the maturity duration and water consumption, with values of 1.00 and 0.99, respectively, and grain productivity and water use efficiency, with values 0.46 and 0.54, respectively, for the control and drought stress treatments. In contrast, significant negative correlations were observed among the maturity duration and water use efficiency, with a value of −0.71, and water consumption and water use efficiency, with a value of −0.71 under the control treatment, and among the maturity duration and water use efficiency, with a value of −0.56, and water consumption and water use efficiency, with a value of −0.55 under the drought stress treatment.

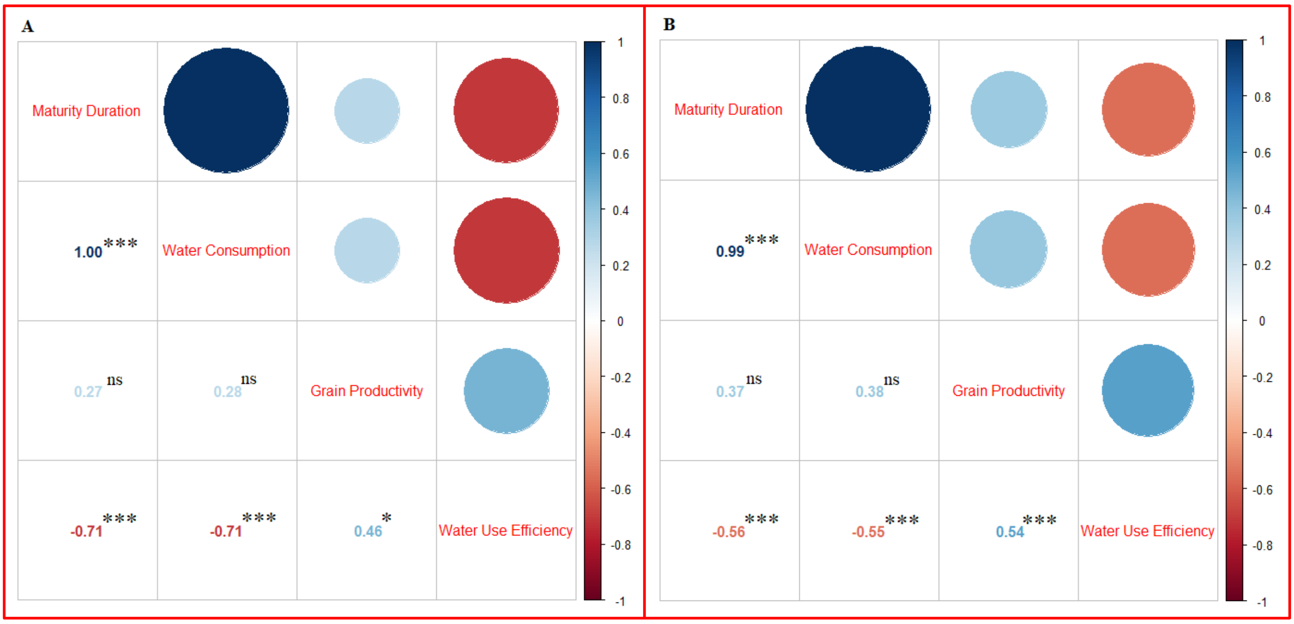

Figure 4. Correlation among maturity duration, water consumption, grain productivity and water use efficiency obtained under control (**A**) and drought stress treatment (**B**). Blue and red color indicates positive and negative correlation, respectively. Higher or lower correlation among parameters is linked to the color intensity and the size of the circles. ***: $p < 0.001$, *: $p < 0.05$, ns: non-significant difference.

3.6. Path Analysis

The path analysis conducted with the preferred traits including grain productivity and water use efficiency indicated a direct and indirect influences of the affecting attributes. For the direct effect under the control treatment, the water consumption (1.76) and water use efficiency (1.46) had a direct positive impact on grain productivity, whereas the days to maturity (−0.24) had a direct negative impact on grain productivity. On the other hand, the water use efficiency had the highest positive indirect effect (0.18), and the water consumption had the highest negative indirect effect (−1.14) on grain productivity via the days to maturity and water use efficiency, respectively (Table 4). However, the highest total positive indirect effect was observed for the days to maturity (1.52) via the water consumption on grain productivity (Figure 5), whereas the highest total negative indirect effect was observed for the water use efficiency (−2.52) via the water consumption on the grain productivity under the control treatment. The residual effect in the path analysis for the grain productivity under the control treatment was 0.005, which exhibited that only a 0.5% effect occurred due to other possible reasons (Table 4). Under the drought stress treatment, the maximum direct effect was observed for the water use efficiency (1.09) on the grain productivity followed by the water consumption (0.79) and days to maturity (0.34). Conversely, the highest positive indirect effect was observed by the water consumption via the days to maturity (0.33) and the highest negative indirect effect was observed by the days to maturity via the water use efficiency (−0.67) followed by the water consumption via the water use efficiency (−0.66), water use efficiency via the water consumption (−0.48) and water use efficiency via the days to maturity (−0.20). However, for the drought stress treatments, the highest total positive indirect effect was observed for the days to maturity (1.11) via the water consumption and the highest negative indirect effect was observed for the water use efficiency (−1.14) via the water consumption (Figure 5). The residual effect in the path analysis for the grain productivity under the drought stress treatment was 0.026, which exhibited that a 2.6% effect occurred due to other possible reasons (Table 4).

Table 4. Path analysis for the direct and indirect effects of studied traits including days to maturity (DM), water consumption (WC) and water use efficiency (WUE) on the grain productivity (GP) of lowland rice cultivars under control and drought stress treatments.

Control					**Drought Stress Treatment**				
Traits	DM	WC	WUE	CC.GP	Traits	DM	WC	WUE	CC.GP
DM	**−0.24**	1.75	−1.14	0.37	DM	**0.34**	0.78	−0.67	0.45
WC	−0.23	**1.76**	−1.14	0.39	WC	0.33	**0.79**	−0.66	0.47
WUE	0.18	−1.38	**1.46**	0.27	WUE	−0.20	−0.48	**1.09**	0.41
Residual effect = 0.005					Residual effect = 0.026				

CC.GP = correlation coefficient with grain productivity; bold diagonal values indicate direct effects, whereas the rest of values stand for indirect effects in relation to grain productivity.

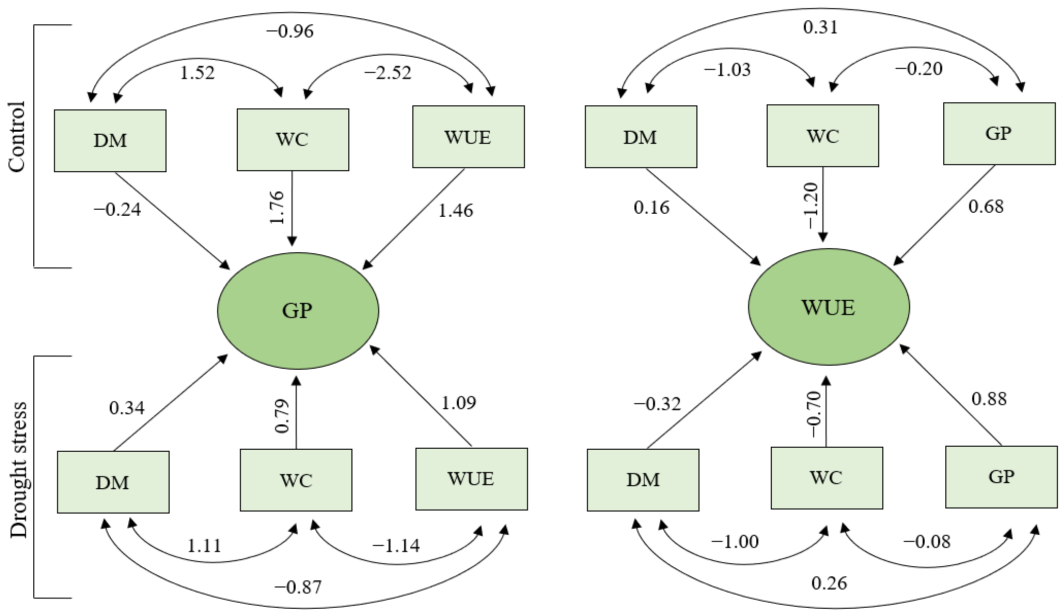

Figure 5. Path diagram indicating total direct and indirect effects of computed attributes on the grain productivity (GP: left) and water use efficiency (WUE: right) from control and drought stress treatments. DM: days to maturity, WC: water consumption, WUE: water use efficiency.

Considering the water use efficiency, for the direct effect under control treatment, the grain productivity (0.68) and days to maturity (0.16) had a direct positive impact on the water use efficiency, whereas the water consumption (−1.20) had a negative direct impact on the water use efficiency. On the other hand, the days to maturity (0.25) and water consumption (0.27) had the highest positive indirect effects on the water use efficiency via the grain productivity. In contrast, the grain productivity (−0.47) had the highest negative indirect effect on the water use efficiency via the water consumption (Table 5). However, the highest total positive indirect effect was observed for the grain productivity (0.31) via the days to maturity on the water use efficiency (Figure 5), whereas the highest total negative indirect effect was observed for the days to maturity (−1.03) via the water consumption on the water use efficiency under the control treatment. The residual effect in the path analysis for the water use efficiency under the control treatment was 0.002, which exhibited that only a 0.2% effect occurred due to other possible reasons (Table 5). Under the drought stress treatment, the maximum direct effect was observed for the grain productivity (0.88) on the water use efficiency followed by the negative direct effects of water consumption (0.70) and days to maturity (0.32). Conversely, the highest positive indirect effect was observed by the days to maturity via the grain productivity (0.40) and the highest negative indirect effect was observed by the days to maturity via the water consumption (−0.69) followed by the grain productivity via the water consumption (−0.33), water consumption via days to maturity (−0.31) and by grain productivity via days to maturity (−0.14) (Table 5). However, for the drought stress treatment, the highest total positive indirect effect was observed for the days to maturity (0.26) via the grain productivity and the highest negative indirect effect was observed for the water consumption via the days to maturity (−1.00) (Figure 5). The residual effect in the path analysis for the water use efficiency under the drought stress treatment was 0.021, which exhibited that a 2.1% effect occurred due to other possible reasons (Table 5).

Table 5. Path analysis for the direct and indirect effects of studied traits including days to maturity (DM), water consumption (WC) and grain productivity (GP) on the water use efficiency (WUE) of the lowland rice cultivars under control and drought stress treatments.

Control					**Drought Stress Treatment**				
Traits	DM	WC	GP	CC.WUE	Traits	DM	WC	GP	CC.WUE
DM	**0.16**	−1.19	0.25	−0.78	DM	**−0.32**	−0.69	0.40	−0.61
WC	0.16	**−1.20**	0.27	−0.78	WC	−0.31	**−0.70**	0.41	−0.60
GP	0.06	−0.47	**0.68**	0.27	GP	−0.14	−0.33	**0.88**	0.41
Residual effect = 0.002					Residual effect = 0.021				

CC.WUE = correlation coefficient with water use efficiency; bold diagonal values indicate direct effects whereas, the rest of values stand for indirect effects in relation to water use efficiency.

3.7. Classification of Cultivars Using Hierarchical Clustering and Principal Component Analysis

The cultivars were classified into two clusters (A and B) through hierarchical clustering based on grain productivity and water use efficiency under the control and drought stress treatments (Figure 6). Similarly acting cultivars were classified into the same clusters. The first cluster (A) consisted of six cultivars including Chor Lung, Pathum Thani−1, Sang Yod, Hom Chan, Hom Pathum and Dum Ja, whereas the second cluster (B) also included six cultivars including, Khao Dawk Mali−105, Tia Malay Dang, Hom Nang Kaew, RD−15, Lep Nok and Look Pla (Figure 6). The classification of the clusters indicated that, in terms of the grain productivity and water use efficiency under the control and drought stress treatments, the cultivars in their respective groups acted similarly for producing grain yields and maintaining water use efficiency. The cultivars in cluster (A), including Chor Lung, Pathum Thani−1, Sang Yod, Hom Chan, Hom Pathum and Dum Ja, produced a better grain yield and a reduced decline in water use efficiency under the drought stress treatment, whereas the cultivars in cluster (B), including Khao Dawk Mali−105, Tia Malay

Dang, Hom Nang Kaew, RD−15, Lep Nok and Look Pla, indicated a comparatively higher decline in grain yield and water use efficiency under the drought stress treatment and were among the vulnerable and affected cultivars under the drought stress treatment in terms of grain productivity and water use efficiency.

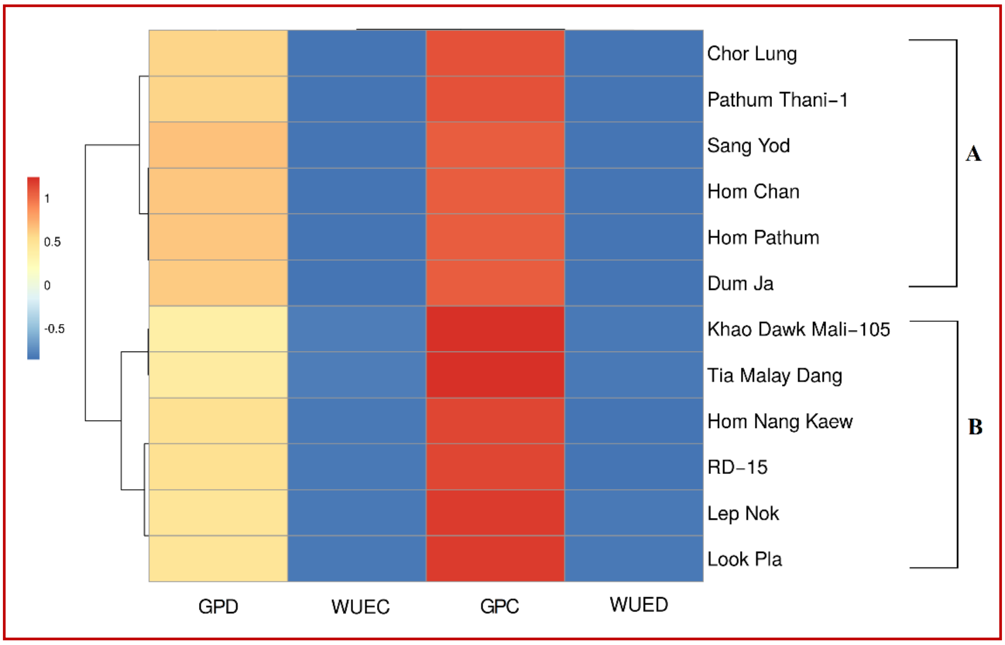

Figure 6. Heatmap of grain productivity under drought stress (GPD), water use efficiency under control (WUEC), grain productivity under control (GPC) and water use efficiency under drought stress (WUED) among twelve lowland rice cultivars. Cultivars are classified into two groups (A and B), and each group is comprised of similarly acting cultivars. Higher association is indicated by dark colors, whereas light colors indicate lower association among cultivars and attributes.

The principal component analysis (PCA) was executed to assess the cultivars based on grain productivity and water use efficiency under control and drought stress treatments (Figure 7). Considering the PCA results from grain productivity and water use efficiency under control and drought stress treatments, PC1 and PC2 contributed 51.18% and 42.19% of the total variation (93.37), respectively. In PC1, all traits contributed almost equally and were significantly positively correlated. In PC2, the water use efficiency in both the treatments was positively correlated and the water use efficiency under the drought stress treatment contributed higher than the control treatment. In contrast, the grain productivity under the control and drought stress treatments contributed almost equally and was negatively correlated. The cultivars Hom Pathum, Pathum Thani−1, Look Pla, Sang Yod and Lep Nok exhibited higher positive values in PC1, respectively, whereas the cultivars Dum Ja, Khao Dawk Mali−105, Tia Malay Dang, Chor Lung, Hom Nang Kaew, RD−15 and Hom Chan exhibited higher negative values in PC1, respectively. In PC2, the cultivars RD−15, Khao Dawk Mali−105, Tia Malay Dang, Hom Pathum and Pathum Thani−1 exhibited higher positive values, respectively, whereas the cultivars Hom Chan, Sang Yod, Hom Nang Kaew, Chor Lung, Dum Ja, Look Pla and Lep Nok exhibited higher negative values, respectively. The cultivars were classified into two groups. The first group included the cultivars Hom Pathum, Pathum Thani−1, RD−15, Khao Dawk Mali−105 and Tia Malay Dang, whereas the second group included the cultivars Sang Yod, Lep Nok, Look Pla, Dum Ja, Chor Lung, Hom Nang Kaew and Hom Chan.

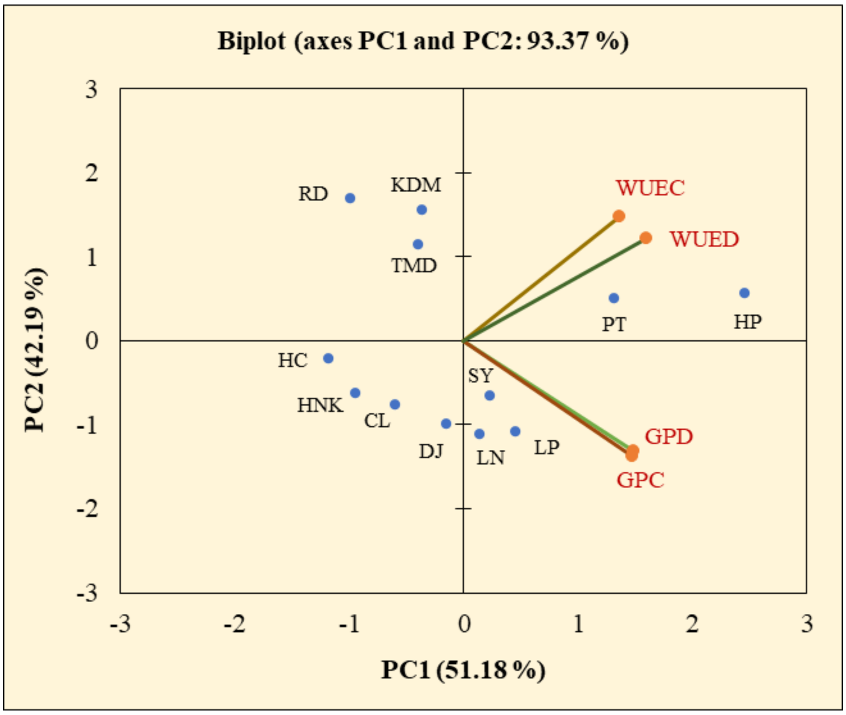

Figure 7. Principal component analysis (PCA) biplot of grain productivity under control (GPC), grain productivity under drought stress (GPD), water use efficiency under control (WUEC) and water use efficiency under drought stress (WUED) for twelve lowland rice cultivars. RD: RD−15, KDM: Khao Dawk Mali−105, TMD: Tia Malay Dang, PT: Pathum Thani−1, HP: Hom Pathum, HC: Hom Chan, HNK: Hom Nang Kaew, CL: Chor Lung, DJ: Dum Ja, SY: Sang Yod, LN: Lep Nok, LP: Look Pla.

4. Discussion

Climate change has negatively influenced the performance of rice cropping systems and seasonal variations in rainfalls has increased the chances of drought stress occurrence [48–57]. Climatic variability has posed a huge threat to worldwide food security [58]. Due to the extreme sensitivity of rice to drought stress [29,59], rice productivity is particularly affected under drought stress at lateral crop stages. Various crop cultivars respond differently under different agro-climatic conditions hence exploring the existing diversity of local germplasm for various attributes is an important component of sustainable agriculture [60]. The agronomic performance and water use efficiency of different types of cultivars varies depending upon the sensitivity of the cultivars to drought stress, which ultimately determines the grain productivity. Hence, the statistical evaluation of the water use efficiency as it is an important physiological attribute [61,62] and grain productivity of various cultivars under drought stress conditions will help to identify the suitable cultivars with improved water use efficiency and grain productivity to sustain yields and to tackle the negative impacts of climate change.

In our study, we observed that the daily mean maximum and minimum temperatures ranged from 26.3–44.6 °C and 22.2–26.8 °C during the first season, whereas it ranged from 33.3–46.7 °C and 22.8–27.1 °C during the second season, respectively. The average temperature observed during the experimental duration was higher than the optimum temperature required for rice crops. Fluctuations in temperature influence the growth of rice plants and affects crop phenology. Under a climate change scenario, a higher or lower temperature occurrence affects plant growth and development [63] by affecting the life cycle of the crop. In our results, an increase in the irrigation water consumption of the rice cultivars under drought stress conditions was observed, which was possibly related to the increase in the maturity duration of those cultivars. The water consumption was also significantly different and was affected under the influence of cultivars (C), treatments (T) and seasons (S). Rice cultivars are considered extremely vulnerable to drought stress, and stress occurrence at lateral stages causes a delay in the flowering and maturity duration of rice cultivars. In our results, the maturity duration was significantly different under the effects of C, T, S, and interactions of C × T, C × S and C × T × S, except for T × S, which possibly occurred due to the uniform experimental conditions in the greenhouse and partially controlled environment. A delay in the maturity duration of rice cultivars under drought stress has also been observed in numerous studies [5,64–67]. Therefore, increased water consumption could be associated with an increased maturity duration of such cultivars. Furthermore, the water consumption was highly associated with the maturity duration under both the control (1.00) and drought stress treatments (0.99). Consequently, the irrigation water consumption amount was decreased for the cultivars Chor Lung, RD−15 and Khao Dawk Mali−105 under drought stress conditions (Figure S2), which was possibly due to their decreased maturity duration. Early maturity and plant senescence under the drought stress conditions in the rice cultivars possibly resulted in the decreased irrigation water consumption of those cultivars. In addition, the maturity duration and water use efficiency were negatively associated under the control (−0.71) and drought stress treatments (−0.56), which indicated that an increase in the maturity duration resulted in a decline in the water use efficiency.

The grain productivity of rice cultivars is greatly affected, as drought stress influences the performance of physiological processes and yield attributes, and less chance of recovery occurs due to the short duration reaching crop to maturity. Our results indicated that a significant variability prevailed among the tested cultivars under the control and drought stress conditions. The performance in terms of grain productivity was significantly affected under drought stress except for the interactions of C × T, T × S and C × T × S, which were not significantly different, which might be because of the partially controlled conditions in the greenhouse. Rice is considered extremely vulnerable to drought stress. Verulkar et al. [68] stated that rice yield was significantly reduced even with a medium stress at the reproductive stage. Similar results and a decline in the grain productivity of rice cultivars has been well reported in a number of studies [62,67,69–71]. The water use efficiency of rice cultivars is affected under limited or reduced water availability and various cultivars respond differently depending on the available water status. The water use efficiency was not significantly different for the interactions of T × S and C × T × S, possibly because of the uniform conditions and due to the effects of grain productivity, as it was computed through grain productivity. In our study, the water use efficiency was reduced for all the cultivars in both seasons, however, it was not significantly decreased for some of the cultivars. The decline in water use efficiency might not linked to the lower performance of the physiological mechanisms, but it was possibly linked to a higher water consumption and low grain productivity, as the water use efficiency was negatively correlated to the water consumption under both the control and drought stress treatments. However, this negative correlation was high with a coefficient value –0.71 under the control and was moderate with a coefficient value of –0.55 under the drought stress treatment (Figure 4). Blum [25] also stated that a higher water use efficiency is mainly a characteristic of reduced water use under drought stress than of net grain production. There was a positive association between the water consumption and grain productivity (0.53) and between the grain productivity and water use efficiency (0.59) (Figure 4), indicating that the cultivars with a higher water use efficiency resulted in a reduced water consumption and better grain productivity under drought stress conditions.

The genotypic (G_{CV}) and phenotypic (P_{CV}) coefficients of variation, broad-sense heritability (H^2), genetic advance (GA) and genetic advance as percentage of mean (GA_M) among the grain productivity, days to maturity, water consumption and water use efficiency of the lowland rice cultivars differed between the control and drought stress treatments. We found that the P_{CV} for grain productivity was medium under the control, whereas it was higher in the drought stress treatment, which indicated that the applied treatments influenced the phenotypic variation for grain productivity. This showed that during the selection process, a pooled analysis for the coefficients of variation and heritability might be misleading for specific trait selection. Hence, it is of high importance that treatment influence should be considered in selection programs. P_{CV} was greater than G_{CV} for grain productivity, days to maturity and water use efficiency under both treatments, indicating that the environment had a greater impact on the expression of these traits, whereas P_{CV} and G_{CV} were equal for water consumption under both treatments. According to the findings of Chuchert et al. [27], P_{CV} was also greater than G_{CV} for most of the agronomic traits of upland rice. H^2 ranged from 63.93% to 100% for the studied traits under the control treatment, whereas it ranged from 59.60 to 100% under the drought stress treatment. The higher H^2 of the studied traits indicated that genetic variation in studied traits was higher as compared to the environmental differences, hence, breeding for selective traits including higher grain productivity, desired short or long days to maturity, low water consumption and higher water use efficiency of lowland rice cultivars could be an effective approach. Similar findings and conclusions for agronomic traits with high H^2 have also been reported by Chuchert et al. [27], Poehlman [72] and Sari et al. [73]. A higher H^2 of the studied traits indicated the greater selection efficiency of these important traits. In contrast, a medium H^2 for grain productivity under drought stress treatment and a higher H^2 for water use efficiency under both control and drought stress treatment indicated that the selection for water use efficiency will be more effective compared to a medium H^2 for grain productivity for selection purposes under stressed environments. The days to maturity and water consumption indicated higher GA under both treatments. A higher H^2 and high GA of days to maturity and water consumption exhibited that these traits were controlled by additive gene impacts, and similar findings for the agronomic traits of rice crops have also been reported by Chuchert et al. [27], Sumanth et al. [74] and Vange [75].

Path analysis was used to determine the direct and indirect effects of the studied traits on the preferred grain productivity and water use efficiency. The path analysis performed for the control and drought stress treatments separately indicated that the direct and indirect impacts of attributes were variable on the desired traits including grain productivity and water use efficiency. It indicated that it was necessary to evaluate the direct and indirect impacts of the affecting attributes on the desired traits separately under optimal and stressed conditions as we observed variations in both treatments. The maximum direct impact, which was observed for water consumption on grain productivity, indicated that water consumption was a major component in influencing the grain yield under optimal conditions, whereas, under drought-stressed conditions, the water use efficiency was the major component in inducing the maximum direct impact on grain productivity. While preferring the water use efficiency of lowland rice cultivars, the grain productivity was the major component in inducing the highest direct impact under optimal as well as under stressed conditions. Our findings indicated the relationship among grain productivity and water use efficiency as well as the importance of the traits for their preferences in the selection process of rice crop breeding programs for drought tolerance and improving water use efficiency to combat the negative impacts of climate change.

The hierarchical clustering indicated an identical performance of the assessed cultivars, and the obtained clusters were similar to the classification obtained in a previous study for drought stress tolerance for these cultivars conducted by Hussain et al. [5]. The cultivars Hom Pathum and Pathum Thani−1 were among the superior cultivars in group A in the hierarchical clustering as well as in the biplot of the principal component analysis, where they were on the positive axis of PC1 and PC2. However, some of the cultivars were not in the similar groups of previous evaluations when assessed based on grain productivity and water use efficiency. Such cultivars indicated a better water use efficiency, though this might be due to the reason that a higher water use efficiency was not obtained due to the higher grain productivity under drought stress, but possibly due to the reduced water consumption. Such trends of higher water use efficiency or crop water productivity have also been observed, where water use efficiency was higher due to reduced water consumption and due to other crop management factors instead of higher grain productivity with less water consumption [3,76]. Hence, the results for the obtained water use efficiency should be carefully considered during selection process, as our study highlighted the importance of water use efficiency and its direct and indirect impacts on other agronomic traits. Our results suggest that the findings from the current study about grain productivity and water use efficiency as well as previous investigations [5] could be combined for further exploration for improving drought stress tolerance and for improved water use efficiency and higher grain productivity during the cultivar selection process based on these desired traits.

5. Conclusions

The grain productivity and water use efficiency of Thai lowland rice cultivars were negatively influenced under drought stress conditions as compared to control. The grain productivity of the cultivars decreased ranging from 21–45% and 21–52% in the first season and the second season, respectively. Similarly, the water use efficiency was significantly decreased, ranging from 7–53% and 21–55% during the first season and the second season, respectively. The analysis for genotypic variability coefficients indicated that the broad-sense heritability for grain productivity was differed under the control and drought stress treatments, indicating that the chances of a transfer of grain-productivity-related traits could be affected during the selection for stress tolerance. The correlation assessment indicated that there was a similar trend for association among the water consumption and maturity duration, among the water consumption and grain productivity, between the grain productivity and water use efficiency and the between water consumption and water use efficiency under the control and drought stress treatments. In contrast, the intensity of association among the parameters was comparatively higher under the control treatment. The maximum direct effect was observed with the water consumption under the control, whereas it was observed with the water use efficiency under the drought stress treatment on the grain productivity in the path analysis. Considering the water use efficiency as a desired trait for selection, the maximum direct effect was observed with grain productivity under the control and under drought stress treatment on the water use efficiency in the path analysis. The cultivars Hom Pathum and Pathum Thani−1 were identified as highly tolerant cultivars in the hierarchical clustering and principal component analysis. It was concluded that results obtained about grain productivity, water use efficiency and genotypic variability for stress tolerance about these cultivars could be utilized in further exploration for improving drought stress tolerance and could be used for sustaining grain productivity to reduce the negative impacts of climate change.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy12102518/s1. Figure S1: Mean daily maximum (Tmax) and minimum temperature (Tmin) during the experimental growing period (days of crop duration) of the first season and second season. Figure S2: Irrigation water consumption (Litter per pot) for twelve lowland rice cultivars under control and drought stress treatments during first season (A) and second season (B).

Author Contributions: Authors T.H. and N.H. conducted experiments and collected data under the supervision of S.D., T.H. and N.H. analyzed the data and prepared the first draft. S.D., M.T. and A.R. provided technical guidance for experimentation. S.M., A.R., S.I. and M.F.A. edited and improved the manuscript. All authors proofread the manuscript, contributed to the article and approved the submitted version. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the National Science, Research and Innovation Fund (NSRF) and Prince of Songkla University (Grant No: SCI6505179b). The research was also supported by the Postdoctoral Fellowship from Prince of Songkla University, Thailand to Tajamul Hussain.

Data Availability Statement: The data presented in study are available in this article and Supplementary Materials and the data not already included in the article that support the findings of this study are available on request from the first author (T.H).

Acknowledgments: Authors are thankful to editors and anonymous reviewers for providing valuable comments and suggestions for the improvement of the manuscript.

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

References

1. Latif, M.; Bukhari, S.A.H.; Alrajhi, A.A.; Alotaibi, F.S.; Ahmad, M.; Shahzad, A.N.; Dewidar, A.Z.; Mattar, M.A. Inducing Drought Tolerance in Wheat through Exopolysaccharide-Producing *Rhizobacteria*. *Agronomy* **2022**, *12*, 1140. [CrossRef]
2. 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).
3. Hussain, T.; Gollany, H.T.; Hussain, N.; Ahmed, M.; Tahir, M.; Duangpan, S. Synchronizing Nitrogen Fertilization and Planting Date to Improve Resource Use Efficiency, Productivity, and Profitability of Upland Rice. *Front. Plant Sci.* **2022**, *13*, 895811. [CrossRef] [PubMed]
4. FAO. FAOSTAT. 2020. Available online: http://www.fao.org/faostat/en/#home (accessed on 18 August 2021).
5. 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] [PubMed]
6. Ullah, H.; Mohammadi, A.; Datta, A. Growth, yield and water productivity of selected lowland Thai rice varieties under different cultivation methods and alternate wetting and drying irrigation. *Ann. Appl. Biol.* **2018**, *173*, 302–312. [CrossRef]
7. El Sherbiny, H.A.; El-Hashash, E.F.; Abou El-Enin, M.M.; Nofal, R.S.; Abd El-Mageed, T.A.; Bleih, E.M.; El-Saadony, M.T.; El-Tarabily, K.A.; Shaaban, A. Exogenously Applied Salicylic Acid Boosts Morpho-Physiological Traits, Yield, and Water Productivity of Lowland Rice under Normal and Deficit Irrigation. *Agronomy* **2022**, *12*, 1860. [CrossRef]
8. Hussain, T.; Anothai, J.; Nualsri, C.; Soonsuwon, W. Evaluating performance of sixteen upland rice genotypes under field conditions for further breeding process. *J. Agric. Sci.* **2018**, *10*, 144. [CrossRef]
9. 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]
10. 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.
11. 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.
12. Ahmadikhah, A.; Marufinia, A. Effect of reduced plant height on drought tolerance in rice. *3 Biotech* **2016**, *6*, 221. [CrossRef] [PubMed]
13. 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] [PubMed]
14. Lafitte, H.R.; Yongsheng, G.; Yan, S.; Li, Z.K. Whole plant responses, key processes, and adaptation to drought stress: The case of rice. *J. Exp. Bot.* **2007**, *58*, 169–175. [CrossRef] [PubMed]
15. 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*, 1. [CrossRef] [PubMed]
16. 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]
17. 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]
18. 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] [PubMed]
19. 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]
20. Kandel, B.P.; Joshi, L.P.; Sharma, S.; Adhikari, P.; Koirala, B.; Shrestha, K. Drought tolerance screening of rice genotypes in mid-hills of Nepal using various drought indices. *Acta Agric. Scand. Sect. B Soil Plant Sci.* **2022**, *72*, 744–750. [CrossRef]
21. Blum, A. Drought adaptation in cereal crops. In *Drought Adaptation in Cereals*; Ribaut, J.-M., Ed.; Haworth Food Products Press: New York, NY, USA, 2006; pp. 301–333.
22. Haefele, S.M.; Kato, Y.; Singh, S. Climate ready rice: Augmenting drought tolerance with best management practices. *Field Crops Res.* **2016**, *190*, 60–69. [CrossRef]
23. Lal, R.; Delgado, J.A.; Gulliford, J.; Nielsen, D.; Rice, C.W.; Van Pelt, R.S. Adapting agriculture to drought and extreme events. *J. Soil Water Conserv.* **2012**, *67*, 162–166. [CrossRef]
24. Hu, Y.C.; Shao, H.B.; Chu, L.Y.; Gang, W. Relationship between water use efficiency (WUE) and production of different wheat genotypes at soil water deficit. *Colloids Surf. B Biointerfaces* **2006**, *53*, 271–277. [CrossRef]
25. Blum, A. Drought resistance, water-use efficiency, and yield potential—Are they compatible, dissonant, or mutually exclusive? *Aust. J. Agric. Res.* **2005**, *56*, 1159–1168. [CrossRef]

26. Monclus, R.; Dreyer, E.; Villar, M.; Delmotte, F.M.; Delay, D.; Petit, J.M.; Barbaroux, C.; Le Thiec, D.; Bréchet, C.; Brignolas, F. Impact of drought on productivity and water use efficiency in 29 genotypes of *Populus deltoides* x *Populus nigra*. *New Phytol.* **2006**, *169*, 765–777. [CrossRef]
27. Chuchert, S.; Nualsri, C.; Junsawang, N.; Soonsuwon, W. Genetic diversity, genetic variability, and path analysis for yield and its components in indigenous upland rice (*Oryza sativa* L. var. glutinosa). *Songklanakarin J. Sci. Technol.* **2018**, *40*, 609–616. [CrossRef]
28. Khomphet, T.; Intana, W.; Promwee, A.; Islam, S.S. Genetic Variability, Correlation, and Path Analysis of Thai Commercial Melon Varieties. *Int. J. Agron.* **2022**, *2022*, 7877239. [CrossRef]
29. 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.
30. Schober, P.; Schwarte, L.A. Correlation coefficients: Appropriate use and interpretation. *Anesth. Analg.* **2018**, *126*, 1763–1768. [CrossRef] [PubMed]
31. Lleras, C. Path Analysis. In *Encyclopedia of Social Measurement*; Kempf-Leonard, K., Ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2005; pp. 25–30.
32. Sari, W.K.; Nualsri, C.; Junsawang, N.; Soonsuwon, W. Path analysis for yield and its components in F1 upland rice hybrids and their parental lines. *Songklanakarin J. Sci. Technol.* **2019**, *41*, 1419–1425.
33. 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.
34. Raina, A.; Laskar, R.A.; Wani, M.R.; Jan, B.L.; Ali, S.; Khan, S. Gamma Rays and Sodium Azide Induced Genetic Variability in High-Yielding and Biofortified Mutant Lines in Cowpea [*Vigna unguiculata* (L.) Walp.]. *Front. Plant Sci.* **2022**, *13*, 911049. [CrossRef] [PubMed]
35. Rashid, M.; Yousaf, Z.; Din, A.; Munawar, M.; Aftab, A.; Riaz, N.; Younas, A.; Alaraidh, I.A.; Okla, M.K.; AbdElgawad, H. Assessment of Mineral Nutrient Efficiency in Genetically Diverse Spinach Accessions by Biochemical and Functional Marker Strategies. *Front. Plant Sci.* **2022**, *13*, 889604. [CrossRef] [PubMed]
36. Shamuyarira, K.W.; Shimelis, H.A.; Mathew, I.; Tsilo, T.J. Correlation and path coefficient analyses of yield and yield components in drought-tolerant bread wheat populations. *South Afr. J. Plant Soil* **2019**, *36*, 367–374. [CrossRef]
37. Arpali, D.; Yagmur, M. The Determination of Selection Criteria Using Path Analysis in Two Rowed Barley (*Hordeum vulgare* L. Conv. Distichon). *Turkish J. Agrci. Nat. Res.* **2015**, *2*, 248–255.
38. 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]
39. 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]
40. 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]
41. Al-Tabbal, J.A.; Al-Fraihat, A.H. Genetic Variation, Heritability, Phenotypic and Genotypic Correlation Studies for Yield and Yield Components in Promising Barley Genotypes. *J. Agric. Sci.* **2011**, *4*, 193–210. [CrossRef]
42. Covarrubias-Pazaran, G.E. Heritability: Meaning and Computation. Optimizing Breeding Schemes Manual. 22 June 2021.
43. Teklu, D.H.; Alamerew, K.S.; Gebremichael, D.E. Assessment of genetic variability, genetic advance, correlation and path analysis for morphological traits in sesame genotypes. *Asian J. Agric. Res.* **2014**, *8*, 181–194. [CrossRef]
44. Oladosu, Y.; Rafii, M.Y.; Magaji, U.; Abdullah, N.; Miah, G.; Chukwu, S.C.; Hussin, G.; Ramli, A.; Kareem, I. Genotypic and phenotypic relationship among yield components in rice under tropical conditions. *BioMed Res. Int.* **2018**, *2018*, 8936767. [CrossRef]
45. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2021.
46. Krualee, S.; Sdoodee, S.; Eksomtramage, T.; Sereeprasert, V. Correlation and path analysis of palm oil yield components in oil palm (*Elaeis guineensis Jacq*.). *Kasetsart J.* **2013**, *47*, 528–533.
47. 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] [PubMed]
48. 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]
49. 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]
50. Chowdhury, M.K.; Hasan, M.A.; Bahadur, M.M.; Islam, M.R.; Hakim, M.A.; Iqbal, M.A.; Javed, T.; Raza, A.; Shabbir, R.; Sorour, S.; et al. Evaluation of drought tolerance of some wheat (*Triticum aestivum* L.) genotypes through phenology, growth, and physiological indices. *Agron.* **2021**, *11*, 1792. [CrossRef]
51. Ahmad, A.; Aslam, Z.; Naz, M.; Hussain, S.; Javed, T.; Aslam, S.; Raza, A.; Ali, H.M.; Siddiqui, M.H.; Salem, M.Z.; et al. Exogenous salicylic acid-induced drought stress tolerance in wheat (*Triticum aestivum* L.) grown under hydroponic culture. *PloS ONE* **2021**, *16*, e0260556. [CrossRef]

52. Islam, M.R.; Sarker, B.C.; Alam, M.A.; Javed, T.; Alam, M.J.; Zaman, M.S.U.; Azam, M.G.; Shabbir, R.; Raza, A.; Habib-ur-Rahman, M.; et al. Yield stability and genotype environment interaction of water deficit stress tolerant Mung Bean (*Vigna radiata* L. Wilczak) genotypes of Bangladesh. *Agron.* **2021**, *11*, 2136. [CrossRef]
53. Shabbir, R.; Javed, T.; Hussain, S.; Ahmar, S.; Naz, M.; Zafar, H.; Pandey, S.; Chauhan, J.; Siddiqui, M.H.; Pinghua, C. Calcium homeostasis and potential roles to combat environmental stresses in plants. *South Afr. J. Bot.* **2022**, *148*, 683–693. [CrossRef]
54. Singhal, R.K.; Fahad, S.; Kumar, P.; Choyal, P.; Javed, T.; Jinger, D.; Singh, P.; Saha, D.; Bose, B.; Akash, H.; et al. Beneficial elements: New Players in improving nutrient use efficiency and abiotic stress tolerance. *Plant Growth Regul.* **2022**, 1–29. [CrossRef]
55. Bukhari, M.A.; Yousaf, M.; Ahmad, Z.; Rafay, M.; Shah, A.N.; Abbas, A.; Shah, A.A.; Javed, T.; Afzal, M.; Ali, S.; et al. Enhancing drought stress tolerance in Camelina (*Camelina sativa* L.) through exogenous application of potassium. *Physiol. Plant.* **2022**, *10*, e13779. [CrossRef]
56. Balbaa, M.G.; Osman, H.T.; Kandil, E.E.; Javed, T.; Lamlom, S.F.; Ali, H.M.; Kalaji, H.M.; Wróbel, J.; Telesiñski, A.; Brysiewicz, A.; et al. Determination of morpho-physiological and yield traits of maize inbred lines (*Zea mays* L.) under optimal and drought stress conditions. *Front. Plant Sci.* **2022**, *13*, 959203. [CrossRef]
57. Ahmad, A.; Aslam, Z.; Hussain, D.; Bellitürk, K.; Javed, T.; Hussain, S.; Bashir, S.; Raza, A.; Alotaibi, S.; Kalaji, H.M.; et al. Rice straw vermicompost enriched with cellulolytic microbes ameliorate the negative effect of drought in wheat through modulating the morpho-physiological attributes. *Front. Environ. Sci.* **2022**, *10*, 902999. [CrossRef]
58. Ali, A.; Altaf, M.T.; Nadeem, M.A.; Shah, A.N.; Azeem, H.; Baloch, F.S.; Karaköy, T.; Hussain, T.; Duangpan, S.; Aasim, M. Recent advancement in OMICS approaches to enhance abiotic stress tolerance in Legumes. *Front. Plant Sci.* **2022**, *13*, 952759. [CrossRef]
59. 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]
60. Haldhar, S.M.; Kumar, R.; Corrado, G.; Berwal, M.K.; Gora, J.S.; Thaochan, N.; Samadia, D.K.; Hussain, T.; Rouphael, Y.; Kumar, P.; et al. A field screening of a pomegranate (*Punica granatum*) ex-situ germplasm collection for resistance against the false spider mite (*Tenuipalpus punicae*). *Agriculture* **2022**, *12*, 1686. [CrossRef]
61. Ali, M.F.; Ali, U.; Bilal, S.; Zulfiqar, U.; Sohail, S.; Hussain, T. Response of sorghum and millet to poultry and farmyard 782 manure–based biochar treatments. *Arabian J. Geosci. 2022.15*, 1–12. [CrossRef]
62. Wu, B.; Lin, X.; Ali, M.F.; Wang, D. Development of an irrigation regime for winter wheat to save water resources by avoiding irrigation at anthesis stage. *J. Agron. Crop Sci.* **2022**, *00*, 1–16. [CrossRef]
63. Aslam, M.A.; Ahmed, M.; Hassan, F.-U.; Afzal, O.; Mehmood, M.Z.; Qadir, G.; Asif, M.; Komal, S.; Hussain, T. Impact of temperature fluctuations on plant morphological and physiological traits. In *Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective*; Jatoi, W.N., Mubeen, M., Ahmad, A., Cheema, M.A., Lin, Z., Hashmi, M.Z., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 25–52.
64. 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]
65. 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]
66. 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]
67. 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]
68. Verulkar, S.B.; Mandal, N.P.; Dwivedi, J.L.; Singh, B.N.; Sinha, P.K.; Mahato, R.N.; Dongre, P.; Singh, O.N.; Bose, L.K.; Swain, P.; et al. Breeding resilient and productive genotypes adapted to drought-prone rainfed ecosystem of India. *Field Crops Res.* **2010**, *117*, 197–208. [CrossRef]
69. 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]
70. 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]
71. 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]
72. Poehlman, J. *Breeding Field Crops*; The Avi Publishing Company, Inc.: Westport, CT, USA, 1979.
73. Sari, W.K.; Nualsri, C.; Junsawang, N.; Soonsuwon, W. Combining ability and heritability for yield and its related traits in Thai rice. *Agric. Nat. Resour.* **2020**, *54*, 229–236.
74. Sumanth, V.; Suresh, B.G.; Ram, B.J.; Srujana, G. Estimation of genetic variability, heritability and genetic advance for grain yield components in rice (*Oryza sativa* L.). *J. Pharmacogn. Phytochem.* **2017**, *6*, 1437–1439.
75. Vange, T. Biometrical studies on genetic diversity of some upland rice (*Oryza Sativa* L.) accessions. *Nat. Sci.* **2009**, *7*, 21–27.
76. Santiago-Arenas, R.; Dhakal, S.; Ullah, H.; Agarwal, A.; Datta, A. Seeding, nitrogen and irrigation management optimize rice water and nitrogen use efficiency. *Nutr. Cycl. Agroecosystems* **2021**, *120*, 325–341. [CrossRef]