Agronomic Parameters of High-Altitude Rice Varieties and their Relation to Temperature at Different Growth Stages

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ABSTRACT

The warm temperate agro-ecozone or high-altitude rice production areas in Bhutan represent a unique agro-ecology that is specific to adaptation needs of rice varieties. A study was undertaken to consolidate the basic agronomic parameters released and popularly cultivated rice varieties of the high-altitude areas. The agronomic parameters were assessed in relation to the weather in the zone. Ten years' weather data (2009-2018) of Paro Dzongkhag was used to relate the agronomic parameters of rice varieties to temperature and rainfall patterns. Seven improved varieties and one traditional variety were used for this study which was conducted at Tsento-Shari ((2450 masl), Paro in 2019 rice season. 50% flowering and days to maturity which are the two most fundamental indicators of adaptation of rice varieties in the warm temperate agro-ecozone were at 162-181 days and 206-236 days respectively. The mean temperatures in the trial site for 10 years during anthesis was 18.5 ºC against the optimum mean temperature requirement for rice (30-33 ºC). The mean temperature at the ripening phase was found to be 16.5 ºC as against the optimum temperature requirement of 20-25 ºC. Despite a relatively low mean temperature during ripening, all the assessed varieties matured and produced good yield indicating good cold tolerance. Rice farmers in the high-altitude areas normally transplant seedlings at about 90 days old when they are hardy enough and can gain some level of physiological maturity to help cope against low mean temperature at ripening. The mean yield of the eight varieties ranged from 2.01 t/acre to 2.98 t/acre which was higher compared to the national average yield of 1.73 t/acre.

Keywords: *Warm Temperate agro-ecozone; Agronomic parameters; 50% Flowering; Days to Maturity; Temperature; Rainfall*

1. Introduction

Rice is the most important crop in the world as more than half of the world's population depend on it as the staple food (IRRI, 2020). Bandumula (2018) reported that eleven countries of Asia contribute about 87% of the global rice production and hence Asia significantly contributes in achieving global food security. However, the rice sector is hit by many abiotic, biotic and socio-economic constraints that hinder its production (Fahad et al., 2019). Among biotic stresses, Sridevi and Chellamuthu (2015) revealed that weather is the most important determinant of growth, yield and production of rice. These challenges are further exacerbated by the decreasing number of rice

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farmers and a fast-growing global population, making it more difficult to meet increasing rice demands (IRRI, 2020). Though the rice area and production in Bhutan is meagre in comparison to the rest of the Asian countries, rice is an indispensable part of the Bhutanese diet as it constitutes a large portion of our daily calorie. Moreover, the majority of the Bhutanese population (57%) depends on agriculture for their livelihood (MoLHR, 2016). Due to the pivotal role it plays in our economy and livelihood, rice is also considered synonymous to the food security of our nation (Chhogyel & Bajgai, 2015). The annual production of rice in 2018 was 63,404.93 MT from a total harvested area of 36,670.21 acres with an average yield of 1.73 t/acre (RSD, 2019).

However, the production from within the country can meet only about 47% of the annual demand and the shortfall of more than 50% is met by importing rice mostly from India (Dema, Tashi, Ghimiray, & Chhogyel, 2019). Bhutan imported 61,467.8 MT of rice in 2018 costing Nu.1884.1 M (RSD, 2019). Rice sector is hit by challenges like drying out of irrigation water, unpredictable precipitation and, potential rice fields being fallowed – all attributed to climate change and global warming (Chhogyel & Bajgai, 2015). Ghimiray (2012) states that limited wetland, use of low yielding traditional varieties, inadequate inorganic fertilizer inputs, insufficient irrigation water and labour shortage are the main factors leading to the low productivity of rice in Bhutan.

Despite numerous constraints, rice is grown in all 20 dzongkhags at elevations ranging from 150 m in the southern lowlands to 2600 m in the north (Chhogyel & Bajgai, 2015). Rice growing agro-ecological zone of the country is categorized into four zones according to elevation and rainfall pattern namely, Wet subtropical (<600 masl), Humid subtropical (600-1200 masl), Dry subtropical (1200-1800 masl) and Warm Temperate (1800-2600 masl) (Ghimiray, Pandhey, & Velasco, 2013).

The warm temperate or the high-altitude rice production agro-ecology in Bhutan is very unique in that during the rice crop season this environment has a low-high-low temperature pattern similar to that found in Japan, Northern China and Korea (Ghimiray et al., 2008). Considering the very short growing season and a low-high-low temperature pattern, the critical selection parameters established for evaluation and selection of high altitude rice varieties include cold tolerance at the seedling stage, high spikelet fertility, medium maturity (140-160 days), preferred grain quality by farmers, high yield, and tolerance to pest and diseases - specifically rice blast (Ghimiray et al., 2008). The climatic conditions permit only a single crop of rice cultivation. Low temperature is a major constrain at nursery, reproduction and ripening stages. This production zone constitutes roughly 20% of the total rice-growing area in Bhutan, thereby substantially contributing to the country's rice production (Ghimiray et al., 2013). The warm temperate rice production zone is also known for high productivity as compared to other rice production agro-ecology in the country.

Bhutan has a history of an unprecedented blast epidemic that occurred in 1995 caused by the fungus *Pyricularia grisea*. The outbreak was most severe in high altitude regions of Thimphu and Paro though less severe incidences were also reported in mid-altitude areas (Thinlay, Finckh, Bordeos, & Zeigler, 2000). It was reported that most of the high elevation cultivars were found to be blast susceptible which led to the epidemic (Thinlay et al., 2000). Moreover, both Paro and

Thimphu districts experienced unusual weather patterns in 1995 which favoured the outbreak Thinlay et al., 2000). Following the blast outbreak, the government took measures to replace traditional rice varieties with varieties that possess high field tolerance to the rice blast disease, were high yielding with suitable maturity period fitting into the very narrow and specific high-altitude rice-growing environment, and with characters that were ultimately acceptable to the farmers.

With global climatic patterns becoming inconsistent, epidemics more virulent than the blast outbreak of 1995 could put the already threatened rice cultivation at risk in the future. This study was therefore aimed at establishing a minimum baseline for agronomic parameters of high-altitude rice varieties in relation to temperature and rainfall by relating the mean optimum required for rice as against the mean for the warm temperate rice production agro-ecology. The baseline parameters could then serve as a basis for future germplasm introduction, breeding and selection for warm temperate or high-altitude rice agro-ecology in Bhutan.

Eight popular high altitude rice varieties were selected for the trial to examine and establish the agronomic parameters. Ten years' weather data (2009-2018) of Paro Dzongkhag were collected from the National Centre for Hydrology and Meteorology (NCHM) to determine the weather parameters at different growth stages of rice.

2. Materials and Methods

2.1. Experimental site

The study was conducted during the 2019 rice season at Tsento-Shari rice research station in Paro Dzongkhag. The research station was leased in from the Farm Machinery Cooperation Limited (FMCL) in 2017 and is being managed by the Agriculture Research and Development Centre, Yusipang since then. The site is located at an altitude of 2450 masl which falls under “Warm Temperate” agroecological zone. The experimental site is very convenient in carrying out high rice research as most of the popular rice varieties under high altitude region thrive well at the site, and the site is also equipped with adequate field facilities.

2.2. Weather data

Ten years' weather data (2009-2018) of Paro district were collected from the National Centre for Hydrology and Meteorology (NCHM) website, and temperature and rainfall at different growing stages of high-altitude rice were studied. The temperature at high altitude rice-growing zone was also compared with the standard temperature required by rice for its optimum growth and development and the reasons for the differences in temperature between the two were discussed.

Table 1. Ten years weather data of Paro district (2009-2018); Source: NCHM (2018).

Month	Maximum Temperature (°C)	Minimum Temperature (°C)	Mean monthly Temperature (°C)	Maximum Rainfall (mm)	Minimum Rainfall (mm)	Mean Monthly rainfall (mm)
January	13	-3	5	5	2022	1014
February	16	-1	7	12	1768	890
March	18	3	10	20	1890	955
April	21	6	14	31	1789	910
May	22	10	16	64	1873	969
June	24	13	19	62	1911	987
July	24	14	19	101	2134	1117
August	24	14	19	94	2133	1114
September	23	13	18	72	2064	1068
October	21	8	14	40	1989	1014
November	17	3	10	1	1857	929
December	15	-2	7	2	2006	1004

2.3. Design and Layout

The trial was laid out in Randomized Complete Block Design (RCBD), and was replicated three times where the treatments were assigned randomly. There were eight treatments laid out in plots of 5 m x 2 m or 10 m^2. The seedlings were transplanted at plant to plant and row to row spacing of 20 cm x 20 cm.

2.4. Treatments

The treatments were: Yusiray Maap-1, Yusiray Maap-2, Yusiray Kaap-2, Yusiray kaap-3, Yusiray Kathramathra, Khangma Maap, Jakar Ray Naab and Janam, a traditional variety as a standard check. The treatments were chosen based on their popularity in high altitude region especially in Paro and Thimphu Dzongkhags.

2.5. Data collection

The trial was monitored regularly and data were collected at different stages of the crop. The traits on which data were collected include plant height, days to 50% flowering, number of tillers per hill, days to maturity and grain yield per plot. The trial was harvested from an area of 5.04 cm^2 after removing the borders. The grain moisture content at harvest ranged between 20-25%. However, plot yield was measured when the grain moisture was reduced to 15% or below.

2.6. Data analysis

The data was analyzed using Statistical Tool for Agriculture Research (STAR) software. Analysis of variance (ANOVA) was done to verify the variation in the traits.

3. Results and Discussion

3.1. Agronomic traits

Data on different agronomic traits were collected and comparisons of different traits were made to provide a general agronomic description of high-altitude rice. The standard check used was a popular a traditional variety Janam with a long history of adaptation to the warm temperate agro-ecozone. The comparison of the agronomic traits of improved varieties with that of the local variety provides strong evidence that the traits are suitable and acceptable to farmers of high-altitude rice-growing areas with very specific climatic requirements.

Table 2. Different agronomic traits of high-altitude rice varieties.

Variety	Plant Height (cm)	Days to 50% flowering	Number of tillers	Days to Maturity	Yield (t/acre)
Jakar Ray Naab	104^{c}	162^{e}	14^{a}	206^{f}	2.01^{b}
Janam	140^{a}	165^{d}	14^{ab}	210^{e}	2.26^{ab}
KhangmaMaap	119^{b}	168^{c}	12^{ab}	215^{d}	2.60^{ab}
Yusiray Kaap-2	120^{b}	170^{c}	11^{ab}	210^{e}	2.48^{ab}
Yusiray Kaap-3	104^{c}	180^{a}	10^{ab}	236^{a}	2.56^{ab}
Yusiray Kathramathra	107^{c}	181^{a}	13^{ab}	235^{a}	2.98^{a}
Yusiray Maap-1	120^{b}	177^{b}	13^{ab}	225^{b}	2.91^{ab}
Yusiray Maap-2	111^{bc}	170^{c}	10^{b}	221^{c}	2.61^{ab}
P-value	0.00	0.05	0.023	0.00	0.04
SE±	3.19	0.55	1.26	0.88	0.26
CV(%)	3.38	0.39	12.84	0.49	12.57

Values in columns followed by different letters in subscript are significantly different at 0.05 % level of significance.

Grain yield

The result (Table 2) show that Yusiray Kathramathra had the highest grain yield (2.98 t/acre) while Jakar Ray Naab had the lowest (2.01 t/acre). Due to slender culms, heavy lodging was observed in Jakar Ray Naab as a result of which the yield was affected.

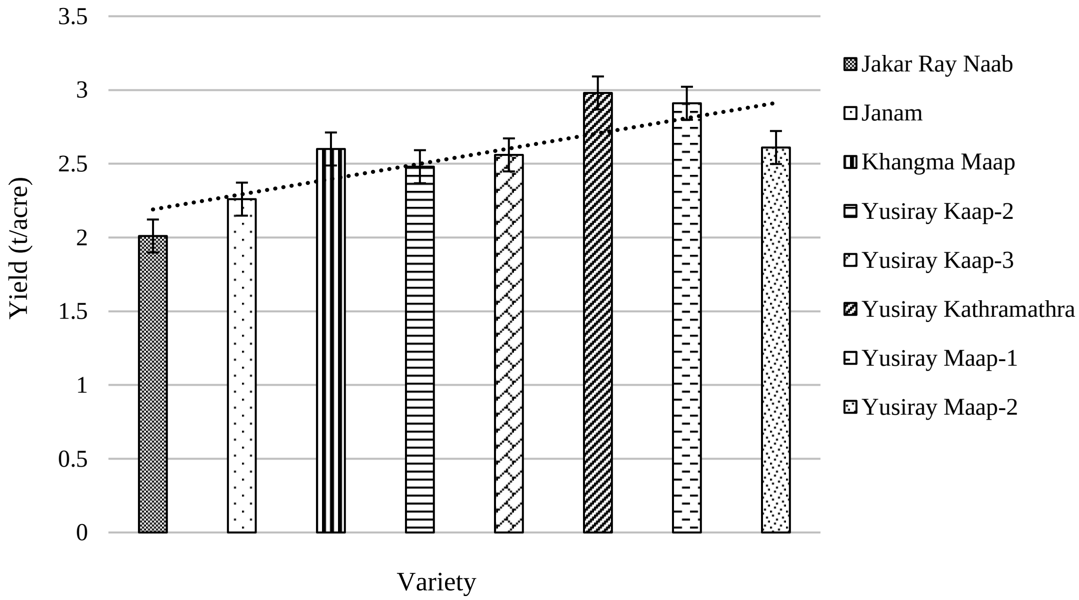

Figure 1. Yield of different high altitude rice varieties.

The analysis, however, showed that except between Yusiray Kathramathra and Jakar Ray Naab, no significant difference in yield was observed among other varieties. Though Yusiray Kathramathra had the highest yield, due to its smaller grain size, fewer farmers opted to grow it in their field while Jakar Ray Naab was found to perform better than other varieties at higher elevations (> 2500 masl).

Plant height

The study affirmed that plant heights for high altitude rice regime ranged from 104 cm to 140 cm with Janam being the tallest while Jakar Ray Naab and Yusiray Kaap-3 were the shortest. The experiment showed that Janam was significantly taller than the rest of the varieties depicting that tall stature is a common trait in traditional varieties.

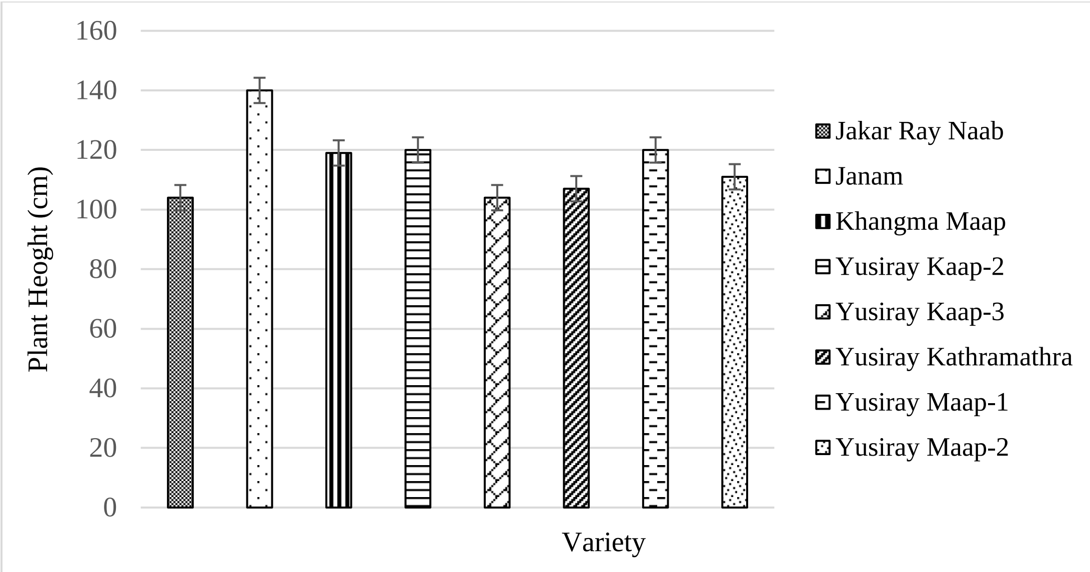

Figure 2. Plant height of different high-altitude rice.

Tillering

Since numbers of tillers per plant are strongly correlated to the number of panicles per plant, high tillering capacity is regarded as an important trait in rice production (Miller, Hill, & Roberts, 1991). Tillering in rice starts 10 days after transplanting and it attains maximum tillering stage 50-60 days after transplanting (Vergara, 1992). Chaudhary and Ghildyal (1970) reported that tillering is positively correlated with rising temperatures between the range of 15-33 ºC, but above 33 ºC, tillering is rendered unfavourable. According to Mahbubal Alam, Islam, and Muhsi (1985), the optimum temperature for tillering is 25-31 °C. The temperature during the tillering stage was observed between 12-24 ºC in high altitude rice-growing region. Though the temperature was found lower than the optimum temperature required, Yoshida (1981) revealed that rice plants have lower threshold temperature (10-13 ºC) during vegetative stage which makes them less sensitive to cold. Satake and Hayase (1970) indicate that decreased tillering, lower stature and yellowing of leaves are the common symptoms of chilling stress observed at the vegetative stage of rice. The experiment (Table 2) shows that Janam and Jakar Ray Naab had the highest numbers of tillers (14) while Yusiray Maap-2 had the lowest (10). The maximum tillering stage was observed in mid to third week of July depending on the variety.

Budhar and Palaniappan (1996) observed that the application of nitrogen fertilizer increased the number of productive tillers. Yoshida (1981) also mentioned that tillering is dependent on the nitrogen, phosphorus and potassium content in the leaf blades. Wang et al. (2017) found that late-emerging tillers had a lower number of spikelets per panicle and grain filling percentage and hence yield contribution was lower than early emerging tillers.

Maturity

The number of days to maturity was calculated from the date of establishment of nursery to the date of crop harvest. In the warm temperate agro-ecozone farmers establish the nursery by the second fortnight of February when the mean monthly temperature is around 7 °C which then picks up to only 0 °C in March (Table 1). The optimum temperature for germination of rice seed is 25-35 °C. Normally farmers in the warm temperate agro-ecozone transplant about 90 days old seedlings which allows the seedlings to attain the hardiness required to cope with low temperatures. It is also perceived that the rice plants gain some level of physiological maturity in the nursery that helps them tolerate the low mean temperatures at ripening. The days to maturity for the eight varieties ranged from 206 to 236 days from seed to seed. Jakar Ray Naab was observed to be the earliest variety to mature while Yusiray Kaap-3 took the longest duration to mature (Table 2). All the high-altitude varieties can be categorized as long duration varieties.

The optimum temperature for rice at ripening stage is 20-25 ºC with a critical low range of 12-18 ºC (Table 3). High-altitude rice matures in the month of October and harvest has to be completed by last week of October before the onset of early frost. The temperature in October in Paro which represents the warm temperate rice production zone ranged from 8-21 ºC with a mean value of 14 ºC (Table 1) which was within the lowest critical range. Any varieties with longer maturity than the tested varieties will show high spikelet sterility, empty grains and the panicles will not droop due to cold temperature.

3.2. Comparative analysis on temperature at different growth stages/phases of rice

The standard temperature (Table 3) required by rice for its optimum growth and development was compared with the existing temperature at high-altitude rice growing agro-ecology (Table 4) at different growth stages, and the possible causes for the difference in temperature between the two were discussed.

Table 3. Response of the rice plant to varying temperatures at different growth stages. Source: (Yoshida, 1981).

Growth Stage	**Critical temperature (ºC)**		
	Low	**High**	**Optimum**
Germination	10	45	20-35
Seedling emergence and establishment	12-13	35	23-30
Tillering	9-16	33	25-31
Anthesis	22	35	30-33
Ripening	12-18	30	20-25

Table 4. Temperature at different growth stages of high-altitude rice growing agro-ecology.

Growth Stage	Critical temperature (ºC)		
	Low	High	Mean
Germination	5	20	12.5
Seedling emergence and establishment	8	22	15
Tillering	14	24	18.5
Anthesis	13.5	23.5	18.5
Ripening	11	22	16.5

Vegetative Phase

a) Germination and seedling establishment

Farmers generally practice dry bed method of nursery in high altitude region. Rice nursery development begins with the onset of the warm season, i.e., by mid of February to mid-March. Seedling germination takes 3-4 weeks, prolonging the nursery period over 90 days. Dubey, Verma, Goswami, and Devedee (2018) reported that low temperature delays the germination of rice up to one month or longer because plants tend to reduce their physiological response during severe cold stress. Germination of rice seedlings can occur at a temperature range between 10-45 ºC with an optimum temperature range of 20-35 ºC and temperatures below 10 ºC could result in complete failure of germination (Yoshida, 1981). The mean temperature observed (Table 4) in high altitude rice-growing region during the germination stage was 12.5 ºC which is only slightly above the critical minimum temperature. Lou et al. (2007) stated that temperature below 15 ºC makes rice prone to damage by chilling stress, especially during the early seedling growth phase. Yoshida, (1981) reported that stunting is a common symptom of cold injury in rice seedling.

However, to protect the membranes from freezing damage, sucrose and other simple sugars are found to accumulate to acquire cold tolerance in most species (Thomashow, 1999). Cold tolerant rice cultivars were revealed to possess higher content of antioxidant and maintain higher activity of defensive enzymes (Huang & Guo, 2005). It was also indicated that higher gibberellic acid (GA) content in rice seedlings increased cold tolerance in rice cultivars (Naidu, Fukai, & Gunawardena, 2005).

b) Shoot elongation

Nishiyama (1977) stated that the critical minimum temperature for shoot elongation ranged between 7-16 ºC. By the third week of May when rice seedlings attain 2-3 leaf stage at 15-25 cm height, it is ready for transplantation in high altitude rice-growing environment. The temperature during transplantation increases to 17 ºC. A moderate increase in temperature was found to accelerate the emergence of leaf in rice (Gao, Jin, Huang, & Zhang, 1992). There is also adequate rainfall to augment consistent irrigation water supply during transplantation. The monthly rainfall was recorded between 63-1892 mm in May-June month. Sridevi and Chellamuthu (2015) reported that crop stand and the duration of crop growth is affected by variation in rainfall and the height of rice crop was taller when there was high rainfall during active growth period.

3.3. Reproductive phase (flowering)

The opening and closing of spikelet (floret) are referred to as anthesis and it lasts for about 1-2.5 hours. Anthesis normally occurs between 8:00 AM to 1:00 PM. Flowering in rice plant can occur between a temperature range of 22-35 ºC with the optimum temperature ranging between 30-33 ºC (Yoshida, 1981). In high altitude rice-growing region, the temperature during flowering time ranged between 13.5-23.5 ºC with a mean temperature of 18.5 ºC. The flowering stage of rice is most sensitive to high temperature (Tian, Tsutomu, Li, & Lin, 2007) followed by low temperature after booting. Temperature exceeding 35 ºC for more than 1 hour caused heavy spikelet sterility (Yoshida, 1981) while low-temperature range between 10-15 ºC was critical for spikelet fertility (Tinarelli, 1989). High temperature leads to incomplete splitting of anther, wilting of stigma and pollen desiccation causing fertilization failure (Osada et al., 1973) while low temperature interferes with the pollen grain formation (Tinarelli, 1989). The experiment showed that Jakar Ray Naab was the first to attain 50% flowering in 162 days while Yusiray Kathramathra was the last to attain 50% flowering in 181 days. The rainfall during flowering time was found to range between 83-2099 mm. Vijayakumar (1998) mentioned that continuous rainfall for three days would impact proper anthesis in rice. Heavy rainfall was found to result in a large number of empty spikelets (Sreenivasan, 1985).

3.4. Ripening Phase

The experiment showed that Jakar Ray Naab was the earliest to mature (206 days) while Yusiray Kaap-3 (236 days) took the longest duration. The temperature requirement for ripening phase ranges from 12-30 ºC with an optimum range between 20-25 ºC (Yoshida, 1981). The temperature at ripening/maturity stage in high altitude rice-growing zone ranged from 11-22 ºC with a mean temperature of 16.5 ºC. (Tashiro & Wardlaw, 1989) found that lower temperature during maturity/ripening stage resulted in the heavy shattering of grains and also lengthened the ripening period as translocation of photosynthates to the grains are slowed down. When the temperature drops below 10 ºC for several days, the ripening process is found to stop and due to cold stress maturity is largely delayed (UAS, 2018). On the other hand, high temperature during grain filling period triggers photorespiration (Khan, Kumar, Hussain, & Kalra, 1999) and high temperature is also found to cause decreased grain weight due to the inability of the spikelets to serve as a sink during temperature stress (Oh-e, Saitoh, & Kuroda, 2004).

4. Conclusion

Constituting approximately 20% of the total rice-growing region in the country, the warm temperate high-altitude agroecology has a very essential role in achieving the nation’s food security. Moreover, our rice farmers face challenges like drying up of irrigation water sources, conversion of wetland to dryland due to developmental activities, paddy fields getting fallowed over time, multifold increase in wages and the younger generation not taking up farming. Moreover, with climate and weather patterns becoming more unpredictable, a need to evaluate and establish the agronomic parameters of rice varieties for the warm temperate rice–ecozone in relation to temperature and water availability at different growth stages has become very critical.

This study on agronomic parameters of high-altitude rice varieties gives a very broad indication that temperature range during the growing season falls in the lowest critical range and rice varieties require very specific adaptation features. The 10-year weather data used in this experiment clearly indicate that the temperature range in the warm temperate rice growing environment is much lower compared to the optimum temperature required by rice plant for optimum growth and development. Lower soil, air and irrigation water temperatures lead to a long and extended maturity period in high altitudes. Nursery period in the warm temperate region was found to be very lengthy (about 90 days) due to prevailing low temperature during those months (February to April). Rapid seedling growth was observed only by April when maximum temperature was recorded at 20ºC. The temperature at flowering stage was also found to play a very critical role as very low temperature interferes with pollen grain formation. Continuous rainfall during flowering also leads to a large number of empty spikelets, ultimately hampering production. Due to the cold low-high-low temperature pattern in warm temperate agro-ecozone, all rice varieties have to possess specific agronomic parameters, mainly cold tolerance at the seedling stage, medium maturity duration, high spikelet formation, preferred grain quality by farmers, and high yield and tolerance to pest and diseases. Future studies have to take into consideration long term climate data and its correlation to specific agronomic parameters of high-altitude rice varieties that help them perform under such a production environment. This will help rice breeders to develop more climate-resilient varieties suitable for the warm temperate agro-ecozone.

References

Bandumula, N. (2018). Rice production in Asia: key to global food security. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 88*(4), 1323-1328.

Budhar, M. N., & Palaniappan, S. P. (1996). Effect of Integration of Fertilizer and Green Manure Nitrogen on Yield Attributes, Nitrogen Uptake and Yield of Lowland Rice (Oryza sativa L.). *Journal of Agronomy and Crop Science., 176*(3), 183-187.

Chaudhary, T., & Ghildyal, B. (1970). Influence of Submerged Soil Temperature Regimes on Growth, Yield, and Nutrient Composition of Rice Plant 1. *J Agronomy Journal, 62*(2), 281-285.

Chhogyel, N., & Bajgai, Y. (2015). Modern rice varieties adoption to raise productivity: A case study of two districts in Bhutan. *SAARC Journal of Agriculture, 13*(2), 34-49.

Dema, Y., Tashi, S., Ghimiray, M., & Chhogyel, N. (2019). Morpho-agronomic Analysis of New Rice Germplasm at Agriculture Research and Development Centre, Bajo. *Bhutanese Journal of Agriculture, II*(1), 13-25.

Dubey, A. N., Verma, S., Goswami, S. P., & 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*(11), 129-136.

Fahad, S., Adnan, M., Noor, M., Arif, M., Alam, M., Khan, I. A., . . . Jamal, Y. (2019). Major constraints for global rice production. In M. F. Mirza Hasanuzzaman, Kamrun Nahar, Jiban Krishna Biswas, (Ed.), *Advances in rice research for abiotic stress tolerance* (pp. 1-22). Cambridge: Woodhead Publishing.

Gao, L., Jin, Z., Huang, Y., & Zhang, L. (1992). Rice clock model—a computer model to simulate rice development. *Agricultural and Forest Meteorology, 60*(1-2), 1-16.

Ghimiray, M. (2012). An analysis of rice varietal improvement and adoption rate by farmers in Bhutan. *Journal of Renewable Natural Resources Bhutan, 8*(1), 13-24.

Ghimiray, M., Dorji, K. D., Katwal, T. B., Penjore, U., Dorji, S., Pem, S., . . . Pradhan, K. (2008). *Rice in Bhutan - A Source Book*. Thimphu: Council for RNR Research of Bhutan (CoRRB). Ministry of Agriculture, Bhutan.

Ghimiray, M., Pandhey, S., & Velasco, M. L. (2013). *Tracking of Improved Varieties in South Asia: Bhutan Report on Rice Estimating adoption rate of modern rice varieties in Bhutan*. RNRRC-Bajo (Wangdue): Department of Agriculture, Ministry of Agriculture Forests, Royal Government of Bhutan

Huang, M., & Guo, Z. (2005). Responses of antioxidative system to chilling stress in two rice cultivars differing in sensitivity. *Biologia Plantarum*, *49*(1), 81-84. doi:10.1007/s00000-005-1084-3

IRRI. (2020). *IRRI Annual Report 2019*. Los Baños (Philippines): International Rice Research Institute (IRRI).

Khan, S. A., Kumar, S., Hussain, M. Z., & Kalra, N. (1999). Climate Change, Climate Variability and Indian Agriculture: Impacts Vulnerability and Adaptation Strategies. In Y. P. Abrol & S. Gadgil (Eds.), *Climate Change and Crops*. Switzerland: Springer.

Lou, Q., Chen, L., Sun, Z., Xing, Y., Li, J., Xu, X., . . . Luo, L. (2007). A major QTL associated with cold tolerance at seedling stage in rice (*Oryza sativa* L.). *Euphytica*, *158*(1), 87-94.

Mahbubal Alam, S. M., Islam, M. T., & Muhsi, A. A. A. (1985). Effect of light and night temperature on some cultivars of rice (*Oryza sativa* L.). *Indian Journal of Plant Physiology*, *28*(4), 385-394.

Miller, B. C., Hill, J. E., & Roberts, S. R. (1991). Plant population effects on growth and yield in water-seeded rice. *Agronomy Journal, 83*(2), 291-297. doi:https://doi.org/10.2134/agronj1991.00021962008300020006x

MoLHR. (2016). *Labour Force Survey Report 2016*. Thimphu: Department of Employment and Human Resources, Ministry of Labour and Human Resources (MoLHR), Royal Government of Bhutan.

Naidu, B. P., Fukai, S., & Gunawardena, T. (2005). *Increasing Cold Tolerance in Rice: By Selecting for High Polyamine and Gibberellic Acid Content: a Report for the Rural Industries Research and Development Corporation*. Kingston, Canberra: Rural Industries Research and Development Corporation.

NCHM. (2018). *Climate Data Book*. Thimphu: National Centre for Hydrology & Meteorology (NCHM), Royal Government of Bhutan.

Nishiyama, I. (1977). Decrease in germination activity of rice seeds due to excessive desiccation in storage. *Japanese Journal of Crop Science, 46*(1), 111-118. doi:https://doi.org/10.1626/jcs.46.111

Oh-e, I., Saitoh, K., & Kuroda, T. (2004). Effects of rising temperature on growth, yield and dry-matter production of rice grown in the paddy field. In T. F. Neil Turner (Ed.), *Proceedings of the 4th International Crop Science Congress*. Australia: Crop Science

Osada, A., Sasiprapa, V., Rahong, M., Dhammanuvong, S., & Chakrabindu, H. (1973). Abnormal occurrence of empty grains of indica rice plants in the dry, hot season in Thailand. *Japanese Journal of Crop Science, 42*(1), 103-109.

RSD. (2019). *RNR Census of Bhutan*. Thimphu: Renewable Natural Resources Statistics Division (RSD), Ministry of Agriculture and Forests, Royal Government of Bhutan.

Satake, T., & Hayase, H. (1970). Male sterility caused by cooling treatment at the young microspore stage in rice plants: V. Estimations of pollen developmental stage and the most sensitive stage to coolness. *Japanese Journal of Crop Science, 39*(4), 468-473.

Sreenivasan, P. S. (1985). Agro-climatology of rice in India. In *Rice Research in India* (pp. 203-230). New Delhi: Indian Council of Agricultural Research.

Sridevi, V., & Chellamuthu, V. (2015). Impact of weather on rice–A review. *International Journal of Applied Research, 1*(9), 825-831.

Tashiro, T., & Wardlaw, I. F. (1989). A comparison of the effect of high temperature on grain development in wheat and rice. *Annals of Botany, 64*(1), 59-65.

Thinlay, X., Finckh, M. R., Bordeos, A. C., & Zeigler, R. S. (2000). Effects and possible causes of an unprecedented rice blast epidemic on the traditional farming system of Bhutan. *Agriculture, Ecosystems Environment, 78*(3), 237-248.

Thomashow, M. F. (1999). PLANT COLD ACCLIMATION: Freezing Tolerance Genes and Regulatory Mechanisms. *Annual Review of Plant Physiology and Plant Molecular Biology., 50*(1), 571-599. doi:10.1146/annurev.arplant.50.1.571

Tian, X., Tsutomu, M., Li, S., & Lin, J. (2007). High temperature stress on rice anthesis: research progress and prospects. *The journal of applied ecology, 18*(11), 2632-2636.

Tinarelli, A. (1989). Climate and Rice. In J. E. Hill & B. Hardy (Eds.), *Proceedings of the Second Temperate Rice Conference*. Los Baños, Philippines: Inernational Rice Research Institute.

UAS. (2018). *Rice Production Handbook*. Little Rock, Arkansas: The University of Arkansas (UAS).

Vergara, B. S. (1992). *A farmer's primer on growing rice*. Los Baños International Rice Research Institute, Philippines.

Vijayakumar, C. (1998). Hybrid rice seed production technology–theory and practice. In S. S. Virmani, E. A. Siddiq, & K. Muralidharan (Eds.), *Advances in Hybrid Rice Technology: Proceedings of the 3rd International Symposium on Hybrid Rice (Hyderabd, November 1996)* (pp. 52-55). Los Baños International Rice Research Institute

Wang, Y., Lu, J., Ren, T., Hussain, S., Guo, C., Wang, S., . . . Li, X. (2017). Effects of nitrogen and tiller type on grain yield and physiological responses in rice. *AoB Plants, 9*(2).

Yoshida, S. (1981). *Fundamentals of rice crop science* Los Baños International Rice Research Institute, Philippines.