Moisture stress in upland rice (*Oryza sativa* L.) and measures to overcome it under changing climate: A Review

Abstract

Low yields in upland rice (*Oryza sativa* L.) are frequently linked to poor crop management practices along with a lack of highyielding varieties, abiotic and biotic stressors. Drought (lack of water), overwatering (waterlogging/flooding), extreme temperatures (cold, frost, and heat), etc, all negatively impact crop and other plant growth, development, yield, and seed quality. Drought or moisture stress is the most important factor affecting upland rice under changing climate. Global climate change also exacerbates the vulnerability of upland rice production.Upland rice plants undergo physiological and biochemical alterations as well as morphological changes as a result of moisture stress.Different moisture stress affects the yield of upland rice ranging from 18-97% yield loss. As a result, crop management with broad, integrative and multi-disciplinary methodologies is required to increase productivity and profitability. Different mitigation strategies to overcome moisturestress andincrease upland rice yields have been addressed in this review.

Keywords:ROS, AMF, PPFM, PGPR andSensor.

1. Introduction

Crop plants are subjected to a variety of environmental stresses, many of which impair plant growth and development, reducing crop plant yield (Farooq et al., 2010). Abiotic stress is the most damagingelement to crop growth and yield around the planet. According to research, abiotic stressors are also more detrimental when they occur in mixtures of abiotic stress factors. Drought, salinity and temperature are the most common abiotic stressors that limit agricultural development and productivity around the world. The availability of water is the most critical factor limiting the productive potential of higher plants among the abiotic stressors (Rodriguez et al., 2006). Soil moisture stress is the most harmful of these factors. Global climate change may exacerbate the vulnerability of upland rice production. Abiotic constraints account for a large portion of the difference between yield potential and actual agricultural output, especially in developing nations. Drought stress causes physiological and biochemical changes in upland rice plants, as well as morphological changes which limit upland rice production (Pandey et al., 2007).Barrero et al. (2021) also reported water deficit or surplus during the growing season and temperature extremes associated with climate change are abiotic factors that affect upland rice productivity.

Upland rice production uses less irrigation water and needs less labour. It is suitable for sloping fields that are prone to erosion, as well as drought-prone locations. Upland rice is currently the daily staplediet for about 100 million people. Asia accounts for over two-thirds of the world's upland rice area. Upland rice covers 12 % of the entire rice-growing area in the world. Accordingto recent figures, Asia, Latin America, and Sub-Saharan Africa accounted for 65, 10 %, and 25 % of total upland rice area across 71 nations, respectively, equalling 8.8, 1.2, and 3.2 m ha. In Asia, Latin America, and Africa, upland rice accounted for 6, 19, and 32 % of total rice area, respectively. In most Asian countries, upland rice accounted for less than % of total rice production. It accounts for 13% of India's total rice growing area of 44.71 m ha(Kumar, 2016). Upland rice productivity is extremely low, around 1.0 t ha^{-1}compared to lowland rice output, which is 5-6 t ha^{-1}(Saito et al., 2018).Waterstressisamajorlimitationofuplandriceandmaintainingyieldandnutritionalqualityunderdifferentconditionswillrequireextensiveresearchoncropselectionandmanagement(Ray et al.,2019).

2.*Water/ moisture* stress in upland rice

The major environmental limitation in lowering rice yields is a lack of water. When the water supply to the roots becomes insufficient or the transpiration rate becomes excessive, plants experience water stress. Drought is the maincause of water deficit stress, which is described as a period of excessively dry weather that results in a soil-water deficit and resulted in plant-water deficit (Bray, 2001). Drought is widely regarded as the single most damaging environmental stress, reducing crop yield more than any other factor. Drought is a major limiting factor in crop yields and production around the world, among the several abiotic stress.

2.1 Classification of water/ moisture stress

Hsiao (1973) classified water stress into:

i. Mild stress: plant water potential reduces by -5 to -6 bar, corresponding to an increase of 8-10% in relative water content (RWC) compared to well-watered plants under mild evaporative demand of the atmosphere.

ii. Moderate stress: plant’s water potential lowers by -12 to -15 bar or RWC by 10 to 20 % compared to well-watered plants under low evaporative demand of the atmosphere.

iii. Severe stress: plant water potential declines by more than -15 bar or 20 % RWC compared to well-watered plants grown under low evaporative demand of the atmosphere.

2.2 Effect of drought on morphological characteristics of rice

“Drought stress reduces the number of tillers (Bunnag and Pongthai, 2013), impairs plant height” (Sokoto and Muhammad, 2014) and the germination of rice seedlings.“As a result, a common adverse effect is a reduction in biomass production. Leaf rolling is usually associated with soil water deficit as an effective mechanism to reduce transpiration loss. Rolling rapidly reduces effective leaf area and transpiration, and thisis a useful drought-avoidance mechanism in arid areas” (Clarke, 1986).“High seedling vigour, salt exclusion at the root level, ion compartmentation in structural and older tissues, high tissue tolerance, receptive stomata that close within minutes of exposure to salt stress but partially reopen after acclimatization and upregulation of antioxidant systems are key features for improved performance under salinity. Tolerant genotypes often tend to exclude salt from flag leaves and panicles” (Chakraborty et al., 2019).

“Uplandricewasfoundtobeparticularlysensitivetowaterstressduringtheearlyreproductivestages. Stress during this period increased the number of growing degree days required not just to achieve the next developmental stage, but also to attain maturity, affecting the development time from seed to harvest. Whenwaterisretained,thewatercontentinthe0-0.6msoillayerisreducedtoalmost50%ofthewateraccessibletoplantsandthestomatalconductance oftheaxialleafsurfaceandleafareaindexdecreasessignificantly,indicatingseverestress.Farmerswithlimitedirrigationwatercanpreventwaterstressbywateringduringthe panicle initiation (PI)periodandsavingwaterforlaterperiods” (Alou et al., 2018). “Drought stress at the reproductive stage lowered plant height, the number of days to complete heading, flag leaf area, chlorophyll content, and panicles hill by a significant amount” (Mohamed et al., 2019).

Drought before and after heading significantly impacts brown and milled rice rates by lowering quality. It also has an impact on tillering, floret initiation and subsequent spikelet sterility, as well as grain filling and the terminal period of rice cultivation (Table 1.). “Terminal drought is the most destructive abiotic stress factor for rice grain yield. Plant antioxidant responses were altered in several studies on the effects of drought stress and dehydration, showing physiological adaptability” (Kumar et al., 2021).

Table 1: Effect of stress at the reproductive stage on yield of upland rice (Dixit et al., 2012).

S. No.	**Stress**	**Yield loss**
1.	Mild	18–39%
2.	Moderate	70–75%
3.	Severe	80–97%

2.3 Effect on physiological aspects

"Drought stress impacts a variety of physiological systems in plants and causes a variety of physiological responses that enable them to adapt to drought stress. Increased water productivity during water stress necessitates the optimization of various physiological mechanisms" (Serraj et al., 2009). The understanding of rice's physiological reactions to drought should aid ongoing research into developing drought resistance in uplandrice.

a. **Effect on Photosynthesis**: Due to a decrease in Rubisco activity, a Calvin cycle enzyme, severe drought conditions inhibit photosynthesis (Zhou et al., 2007). However, as a protective mechanism, the quantity of Rubiscoactivase increases during drought stress, which rescues Rubisco sites(Ji et al., 2012). The enzymes involved in C4 photosynthesis are more drought-resistant than those engaged in C3 photosynthesis, according to Pandey and Shukla (2015).Overreduction of the photosynthetic electron transport chain may occur if PSII activity exceeds demand, which increases the creation of reactive oxygen species (ROS). As a result, there must be a balance between photochemical activity and photoassimilates demand. Drought drastically reduces PSII activity in rice plant flag leaves, according to Pieters and Souki (2005)."Drought also has a deleterious influence on photosynthesis by affecting photosynthetic pigments. Changes in photosynthetic pigment concentrations are directly linked to plant biomass and yield" (Jaleel et al.,2009). "Other pigment carotenoids play further roles in the structure of chloroplast photosystems, light-harvesting and photoprotection, as well as helping plants to endure drought" (Maisura et al., 2014).

   "Plantsgrownunderwater-deficientconditionshavereducedstomatalconductivitytoconservewater.Duetodecreasedstomatalconductance,carbonmonoxide(IV)fixationisreducedandphotosynthesisratedecreased,resultinginlessanabolicproductionforplantgrowthandyield.Thehigheststomatal conductancewas recorded at 77DASwhilethelowest atDAS of upland rice"(MagwangaandKirungu,2019)

b. **Effect on protein and Lipid synthesis:** Water deficit brings about quantitative and qualitative changes in plant proteins. In general, proteins in the plant decrease during water deficiency due to the suppressed synthesis, more pronounced in C3 than C4. The main proteins synthesized in response to water stress are late embryogenesis abundant (LEA)-type proteins, desiccation stress proteins, proteins that respond to ABA, dehydrins, cold regulation proteins, proteases, enzymes required for the biosynthesis of various Osmoprotectants, the detoxification enzymes (SOD, CAT, APX, POD, GR).

Waterdeprivationaffectsnitrogenmetabolisminplants andwater-deprivedplantshavebeenfoundtoinitiateproteinhydrolysis,resultinginanincreaseinaminoacidsinplanttissues (MagwangaandKirungu,2019).

ABA is a growth regulator, involved in stress tolerance. A dynamic accumulation of ABA in response to water stress has been well studied in rice. It has a role in mediating plant responses against drought stress conditions through a series of signal transduction pathways.

Drought results in the variation of fatty acids composition. Lipid peroxidation is the well-known effect of drought and many other environmental stresses via oxidative damage.

c. Oxidative stress accompanied by drought stress:“Enzymatic antioxidants are superoxide dismutase (SOD) and peroxide dismutase (POD), while non-enzymatic ones are ascorbic acid and alpha-tocopherol. Superoxide dismutase (SOD) is an enzyme that alternately catalyzes the dismutation (or partitioning) of the superoxide radical into either ordinary molecular oxygen (O_2) or hydrogen peroxide (H_2O_2). Superoxide is produced as a by-product of oxygen metabolism and, if not regulated, causes many types of cell damage” (MagwangaandKirungu,2019). The non-enzymatic plant antioxidants can be classified into two major types:(1) Ascorbic acid AA-like scavengers and (2) pigments such as carotenoids.

“Defence mechanisms in the crop for restricting the damage caused by ROS can be done by increasing antioxidants, either enzymatic or non-enzymatic antioxidants. These antioxidants have a role in protecting the crop from damage due to oxidative stress” (Miller et al., 2010).Boy et al. (2020) observed that “drought induces the production of ROS and antioxidant activity of four local upland rice cultivars in Central Sulawesi, Indonesia. Drought tolerant cultivars of Habo and Sunggul had higher activities of SOD, POD, AAred as well as α-Toch with lower content on free radicals of $O_2^-$and H_2O_2 compared to non-drought tolerant cultivars”.

3. Mitigation strategies for drought stress in upland rice

It includes the use of drought-resistant varieties, tillage, moisture conservation techniques, irrigation scheduling, adjusting the date of sowing, seed priming, use of growth regulators, silicon, antitranspirants, $CaCl_2$, biofertilizers, etc.

3. 1. Varieties

The first drought tolerant, early duration (90-95 days) variety Vandana was developed in 1992 from Central Rainfed Upland Rice Research Station of Central Rice Research

Institute at Hazaribag, using drought tolerant and high yielding indica genotypes. Further efforts led to the development of varieties like Anjali (2002),Virendra (2006), CR Dhan 40 (2008) andSahbhagidhan (2011). lndiraBarani dhan-1 and ShushkSamrat were developed and released simultaneously at IGKV, Raipur, and NDUA&T, Faizabad, respectively. In 2005, DFID (Department for International Development) and Birsa Agricultural University in Ranchi collaborated to develop two popular upland cultivars, BVD109 and BVD110 (Maiti et al., 2018).Pandey and Velasco (2005) listed the characteristics of upland rice varieties such as short duration rice cultivars, modified root systemswith thicker and deep penetrating roots, lodging resistance, early vigour and drought tolerance.

“Rice cv. Tulsi is recommended for Eastern India, for upland ecological cultivationsystems where a crop experiences natural cycles of water deficit and water sufficiency, depending upon the monsoon rains” (Srivalli et al., 2003). Jinsy (2015) compared four different varieties like Aiswarya, Uma, MAS 946 -1 (Sharada) and PMK (R) 3 under flooded and aerobic conditions. The effect of varieties on water productivity, rooting depth and root volume was significant, with MAS 946 –1 (Sharada) recording higher values.Magwanga and Kirungu, (2019) observed “asignificantreductioninyieldfromtwo uplandricevarieties IRAT 109 and Lemontunderwaterdeficit butIRAT109exhibitedarelativelyhigheryieldindexunderwaterdeficit conditions. Theimprovedyieldcouldbeattributedtotheabilityto escape drought conditionsduetoitsabilitytomature early”.

3.2. Tillage

Yoichiro et al. (2005) investigated how upland rice responded to various agronomic approaches and found that harvest index, root length, and grain yield were all higher with deep tillage and straw mulch.While Gopal et al. (2010) reported that “soil structure is improved in upland rice grown under zero tilled direct-seeded rice (ZTDSR) due to reduced compaction from zero tillage”. Zero tillage beds also provide the opportunity for mechanical weed control and improved fertilizer placement as existing weeds are burned down by using herbicides such as paraquat @ 0.5 kg a.i. ha^{-1}or glyphosate @ 1.0 kg a.i. ha^{-1}.

No-till with 100%covered surface with residues stored (122–172 mm) more soil moisture (0–40 cm soil depth) in comparison with that for the conventional tillage with 100% residue incorporation (110–161 mm) and enhanced productivity and profitability of upland rice (Yadav et al. 2018).) Upland rice grown under rice–rapeseed (Brassica campestris Var. Toria) system in rainfed conditions with two tillage systems CsT- conservation and CT- conventional tillage, significantly showed lower bulk density and penetration resistance (0–

15 cm) and higher water infiltration rate under CsT than CT. The soil water holding capacity (WHC) and soil moisture content (SMC) in rapeseed were significantly higher under CsT than those under CT at 0-15 cm and 15–30 cm depths according to Das et al. (2020).

3.3. Seed priming

It is a viable and instant method for establishing drought tolerance in rice. Seed priming is the process of hardening the protoplasm of seeds. There are many types of priming such as hydro priming, halo priming, osmoprimingand hormonal priming. When compared to non-primed seeds, Sheela (1993) found that seed treatment with water for 12 hours and KCl(2.5 %) for 18 hours produced the highest grain and straw production.Brooks et al. (2020) evaluated the benefit of different seed priming found that seeds primed with 0.05 % $MgCl_2$ were highly effective in improving a variety of attributes such as mean emergence time (MET), emergence index (EI), vigour index (VI), and fresh and dry weight of shoot and root. Under normal, mild drought stress, and severe salinity stress, the METs of hydro primed (control) seed were 1.08, 4.70, and 4.70 days, respectively, but the METs of seed primed with $MgCl_2$ seed were 0.53, 3.40, and 1.63 days. The results demonstrated that osmopriming with 0.05 % $MgCl_2$ is an effective strategy for helping upland rice seedlings resist abiotic stress conditions by improving seed emergence and seedling growth.

3.4. Sowing

Based on weather forecasting, proper planning of sowing time is required. Timely sowing ensures higher rainwater use efficiency. Early or delayed sowing leads to lower rice production. The best time to seed direct-seeded rice (DSR) is about 10-15 days before the monsoon begins to maximize the utilization of monsoon rain (Kamboj et al., 2012).

“Method of sowing includes broadcasting, dibbling and row seeding by using a drum seeder. Broadcasting needs 80-100 kg seeds ha^{-1}. In dibbling seed rate is 80 -90 kg ha^{-1}. Optimal seed rates for row sowing 20 cm apart and broadcast under appropriate management were 300 and 400 seeds m^{-2}(67.5 and 90 kg ha^{-1}for cv. Kalinga III) respectively” (Singh et al., 2017).According to Adigbo (2007) dibbling of “pregerminated seeds resulted in higher growth attributes and yield.To ensure uniform crop establishment, upland rice should not be drilled deeper than 2.5 cm and planting at the optimal time increases total yield by 40-50 % and improves rainwater usage efficiency” (Kamboj et al., 2012).

3. 5. Irrigationscheduling

“Proper irrigation scheduling enables the farmers to schedule water rotation among the various fields to minimize crop water stress and maximize the yield. It reduces the cost of water and labour. The most used irrigation scheduling method is the IW/CPE ratio method i.e. the ratio of irrigation water(IW) applied to cumulative pan evaporation (CPE). Narrower the ratio, the wider the irrigation interval.Higher grain yield, straw yield and biological yield were observed when irrigated at IW/CPE ratio of 1.2" (Jolly, 2017). Aparna (2017) observed higher grain yield, straw yield and HI were observed when irrigated at 3 cm depth at 10 mm CPE.

"Irrigation schedule for rice under limited water sources:For summer rice under limited resources of water, phasic stress irrigation can be practiced to the advantage of saving a substantial quantity of irrigation water without any significant reduction in yield. About 20-30 % more area can be irrigated with the same water resources by adopting one of the following phasic stress irrigations given below. Depending upon the schedule, water-saving ranges from 24-36 % of the requirement for 5 cm continuous submergence throughout the crop growth" (KAU, 2016).

Micro irrigation methods

Nowadays micro-irrigation is gaining popularity among rice farmers. "Sprinkler and drip irrigation methods have the potential to increase irrigation water use efficiency by reducing runoff and deep drainage losses and evaporation. Growth attributes such as plant height and tiller number hill^{-1} were found to be higher under sprinkler irrigation at 125% Epan"(Shahanila, 2015). Anusha et al. (2015) reported that drip irrigation at 2.0 Epanthroughout growth stages recorded higher productive tillers (no hill^{-1}), panicle length, panicle weight, grain and straw yield.

3.6. Moisture conservation methods

Mulching is the oneof moisture conservation methods. It will reduce evaporation losses and therebyincreases soil moisture storage. Organic and polythene mulches are the two types used in upland conditions. Ellilot et al. (2016) reported that rice straw mulch with 3t ha^{-1}recorded higher root biomass, shoot biomass and yield compared with no straw mulch.Yadav et al. (2018)) also observed that "no-till with 100% covered surface with residuesalong with brown manuring (BM) stored (122–172 mm) more soil moisture (0–40 cm soil depth), recorded the lowest weed biomass and density. Therefore, the cultivation of upland rice using no-till along with BM mulching enhanced the productivity and profitability of rice cultivation in Indi"a.

3.7. Use of Silicon and $CaCl_2$

"Silicon can alleviate water stress by decreasing transpiration. Transpiration from the leaves occurs mainly through the stomata and partly through the cuticle. As Si is deposited beneath the cuticle of the leaves forming a Si-cuticle double layer, the transpiration through the cuticle may decrease by Si deposition" (Ma, 2011). "Calcium has been shown to ameliorate the adverse effects of water stress on plants and is involved in signalling anti-drought responses. Calcium appears to play a central role in many defense mechanisms that are induced by drought, and Ca^{2+}signalling is required for the acquisition of drought tolerance or resistance. Application of $CaCl_2$ (1 %) as seed treatment helped in mitigating the harmful effect of drought stress" (Devi, 2013).

3.8. Use of biofertilizers and Microorganism

Pink Pigmented Facultative Methylotrophs (PPFM) aremethylobacterium that can reduce drought stress by producing ROS scavenging enzymes, by increased production of proline and production of ACC deaminase which converts ACC to ammonia and alpha-ketobutarate wherein normal reaction ethylene formation occurs. Other biofertilizers like Trichoderma, VAM can be used to mitigate against stress as their colonization in the root reduces drought-induced changes by enhanced root growth, improved acquisition and storage of water in rice.

"Upland rice is a rice ecotype that differs from irrigated ecotype rice; it is adapted to both drought stress and aerobic conditions. Bacteria and fungi were isolated from roots of upland rice in Xishuangbanna, China and the PGP ability of 17 endophytic and 10 rhizospheric isolates from upland rice roots was evaluated under well-irrigated and drought-stress conditions, and 9 fungal strains increased rice seedling shoot length, shoot and root fresh weight, antioxidant capability and proline contents"(Pang et al., 2020).

Management of drought stress through the application of plant growth promoting rhizobacteria (PGPR) is now considered an effective strategy in the present scenario of altered environmental conditions of the world. Karmakar et al. (2021) isolated some potential microbial resources (PGPR) from drought-affected upland rice fieldsrhizospheric soils of South Bengal. Isolate 1 and 6 showing PGP traits were identified as species of Mycobacterium sp. and Bacillussp. and both organisms showed a positive influence (through an increase in germination percentage, root growth, shoot growth, fresh weight and dry weight) on the studied rice growth and development under induced drought. Hence, these two isolates are expected to alleviate drought stress in the upland rice for their nature of plant growth promotion under drought stress.

3.9. Biotechnological approaches

The HRD gene, identified from Arabidopsis mutant hrd-D exhibits drought resistance and salt tolerance. Expression of the Arabidopsis HARDY (HRD) gene in rice improves water use efficiency (Karaba et al., 2007). Balachandran et al. (2014) suggested that "genetically modified rice was engineered with AtDREB1A gene for improved drought stress tolerance.Genome editing with various nucleases enhanced disease resistance, crop productivity and quality and abiotic stress tolerance in rice". The CRISPR/Cas technology allows for genome editing to answer the demand for new, enhanced climate-resilient cultivars (Barrero et al., 2021).

3.10. Sensor

Dursun and Ozden, (2011) conducted"an experiment usinga wireless sensor network for low-cost wireless controlled irrigation solutions and real time monitoring of the water content of soil. Data acquisition is performed by using solar powered wireless acquisition stations for the purpose of control of valves for irrigation. The Base station unit is programmed to read and to evaluate sensors data, to control valves and to communicate with other units. 10 HS coded pre-calibrated Soil Moisture Sensor of Decagon has been used to measure the water content of soil. The sensor unit sends moisture data with sensor number. The Valve unit changes the position (on or off) after receiving the data from Base station unit and the irrigation system start to work. The obtained irrigation system not only prevents moisture stress due to climate change but also diminished excessive water usage, ensuring of rapid growing weeds and derogating salification.Cost effective solar power can be the answer for all our energy needs. Solar powered smart irrigation systems are the answer poor farmer". Similarly, Harishankar *et al.* (2014) performed "a case study on power-efficient water irrigation system using solar power in which the controller was connected to the soil sensor and water supply valve. The water valve was turned ON/OFF based on the water level monitored by the moisture sensor. When the soil moisture content reaches the required value, the valve is fully closed and power to driver circuit is killed and controller is put into sleep mode for low power consumption. Visa vice, when the moisture in the soil is dried due to high temperatures under changing climate. This way the whole system works automatically and helps to mitigate the moisture stress effect on crops under changing climate".

Sensor-based IoT system was used for water irrigation by Kansara et al. (2015) in which the controller controlled the opening and closing of a solenoid valve based on the water level of the soil. A series of weather alerts were sent to the user via a mobile application to update the temperature and humidity of the environment under changing climate, which had a direct influence on the water level of the soil. This way it helps plants to avoid stress conditions. Using ATMEGA 328, a water sprinkler system for smart irrigation was reported by Kumar et al.(2017) using temperature, humidity and soil moisture sensors. The water sprinkler was controlled based on the soil moisture level to save water and thereby, reduce stress conditions.

3.11. Omic approaches:

"The intrinsic genes for sophisticated abiotic stress in plants may be identified as omics technology advance. Proteomics and metabolomics have been demonstrated to be quickly growing fields, allowing researchers to obtain detailed and precise information on proteins and metabolites produced by plant cells in response to environmental issues. Both of these new locations are predicted to significantly enhance cereal production. Similarly, transcriptomics profiling is particularly valuable in guaranteeing a full understanding of regulatory molecules and networks that are involved in stress tolerance communication" (Kumar et al., 2021).

5. CONCLUSION

The development of high-yielding drought-resistant cultivars is a mandatory component for most rice growers in changing climates. In this regard, many researchers proved to have some scientific way of proper mitigating and management to meet the demands of a rising global population under different climatic changes. Hence, many droughts resistant varieties viz. IRAT-109, CR Dhan-40, Vandana, Tulsi, etc. along with the HRD gene that undergoes SRI (System of Rice Intensification) technique with low/ reduced tillage operation via hormonal priming specially PGPR that are sown at appropriate early dates in the month of May-June using ATMEGA 328, a water sprinkler system for smart irrigation is recommended. In the case of drought sensors, transcriptomics profiling is valued in guaranteeing a full understanding of regulatory molecules and networks that are involved in stress tolerance communication. Application of silica on the rice leaves leads to the formation of cuticle double layer by influencing the reduction of transpiration pull which ultimately enhances the moisture level that makes it tolerable to drought stress.

REFERENCE:

Adigbo, O. S., Ojerinde, O.A., Ajayi, O., and Nwilene, F.E. 2010. Effects of sowing methods on upland rice in lowland rice-vegetables sequence in inland valley. J. Agric. Sci. Tech. 4(3): 119-133.

Alou, I.N., Steyn, J.M., Annandale, J.G. and Van der Laan, M., 2018. Growth, phenological, and yield response of upland rice (Oryza sativa L. cv. Nerica 4®) to water stress during different growth stages. Agricultural Water Management. 198: 39-52.

Anusha, S., Nagaraju, G. B., Mallikarjuna, H., and Kombali, G. 2015. Influence of drip irrigation scheduling on growth and yield of direct seeded rice (Oryza sativa L.). The Ecoscan. 23 (1): 329-332.

Aparna, R.A. 2017. Irrigation scheduling and live mulching in upland rice (Oryza sativa L.). M. Sc. (Ag) thesis, Kerala Agricultural University, Thrissur,101p.

Balachandran, S.M., Ravikumar, G., and Manimaran, P. 2014. GM Rice Engineered with AtDREB1A Gene for Improved Drought Stress Tolerance. ISB News Rep. 4p.

Barrero, L.S., Willmann, M., Craft, E., Manna-Akther, K., Harrington, S.E., Garzon-Martinez, G.A., Glahn, R., Piñeros, M. and Mccouch, S. 2021. Identifying genes associated with abiotic stress tolerance suitable for CRISPR/Cas9 editing in upland rice cultivars adapted to acid soils. pp 1-19.

Boy, R., Indradewa, D., Putra, E.T.S. and Kurniasih, B., 2020. Drought-induced production of reactive oxygen species and antioxidants activity of four local upland rice cultivars in Central Sulawesi, Indonesia.Biodiversitas Journal of Biological Diversity, 21(6).

Bray, E.A. 2001. Plant response to water deficit stress.Encyclopedia of life sciences. 5p. [www.els.net]

Brooks, S., Athinuwat, D. and Chiangmai, P.N. 2020.Enhancing germination and seedling vigor of upland rice seed under salinity and water stresses by osmopriming.Science & Technology Asia.63-74.

Bunnag, S. and Pongthai, P. 2013. Selection of rice (*Oryza sativa* L.) cultivars tolerant to drought stress at the vegetative stage under field conditions. Am. J. Plant Sci. 4: 1701-1708.

Chakraborty, K., Chattaopadhyay, K., Nayak, L. 2019. Ionic selectivity and coordinated transport of Na+ and K+ in flag leaves render differential salt tolerance in rice at the reproductive stage. Planta. 250: 1637-1653

Clarke, J.M. 1986. Effect of leaf rolling on leaf water loss in Triticum spp. Canadian J. Plant Sci., 66(4): 885-891.

Das, A., Jayanta L., Ramkrushna G.I., Savita, B., Rattan L., Krishnappa, R., Yadav, G.S.., Subhash B. and Shishomvanao N. 2020. Conservation tillage and residue management improves soil properties under a upland rice–rapeseed system in the subtropical eastern Himalayas. Land Degradation & Development. 31(14): 1775-1791.

Dixit, S., Swamy, B.P.M., Vikram, P., Ahmed, H.U., Sta Cruz, M.T., Amante, M., Atri, D., Leung, H. and Kumar, A. 2012. Fine mapping of QTLs for rice grain yield under drought reveals sub-QTLs conferring a response to variable drought severities. Theor. Appl. Genet., 125: 155–169.

Dursun, M. and Ozden, S. 2011.A wireless application of drip irrigation automation supported by soil moisture sensors. Scientific Research and Essays, 6(7): 1573-1582.

Ellilot, R.D., Ampofo, E., and Sintondji, O.L. 2016. Tillage, rice straw mulch, and nitrogen fertilization effects on upland rice yield in Northern Benin. J. Nat. Sci. Res., 6(2): 107-115.

Farooq, M., Kobayashi, N., Ito, O., Wahid, A., and Serraj, R. 2010. Broader leaves result in better performance of Indica rice under drought stress. J. Plant Physiol., 167(13): 1066–1075.

Gopal, R., Jat, R.K., Malik, R.K., Kumar, V., Alam, M.M., Ja,t M.L., Mazid, M.A., Saharawat, Y.S., McDonald, A. and Gupta, R. 2010. Direct dry seeded rice production technology and weed management in ricebased systems. Technical Bulletin, International Maize and Wheat Improvement Center, New Delhi, India 28 p.

Harishankar, S., Kumar, R.S., Sudharsan, K.P., Vignesh, U. and Viveknath, T. 2014. Solar powered smart irrigation system. *Advance in electronic and electric engineering*, 4(4): 341-346.

Jaleel, C.A., Manivarnan, P., Wahid, A., Farooq, M., Al-Juburi, H.J., Somasundaram, R. and Panneerselvam, R. 2009. Drought stress in plants: A review on morphological characteristics and pigments composition. Int J. Agric Biol., 11: 100–105.

Ji, K.X., Wang, Y.Y., Sun, W.N., Lou, Q.J., Mei H W, Shen, S.H., and Chen, H. 2012. Droughtresponsive mechanisms in rice genotypes with contrasting drought tolerance during reproductive stage. J. Plant Physiol., 169(4): 336–344.

Jinsy, V.S., Pillai, S.P., and Jacob, J. 2015. Productivity analysis of aerobic rice in the lowlands of southern Kerala. J. Trop. Agric., 53: 1-7.

Jolly, G.E., Bhale, V.M., and Chirde, P.N. 2018. Response of upland irrigated rice (*Oryza sativa* L.) varieties to irrigations. J. Pharmacognosy Phytochemistry. 7(4): 2908-2913.

Kamboj, B.R., Kumar, A., Bishnoi, D.K., Singla, K., Kumar, V., Jat, M.L., Chaudhary N., Jat, H.S., Gosain, D.K., Khippal, A., Garg, R., Lathwal, O.P., Goyal, S.P., Goyal, N.K., Yadav, A., Malik, D.S., Mishra, A. and Bhatia, R. 2012. Direct seeded rice technology in western indo-gangetic plains of India: CSISA Experiences. CSISA, IRRI and CIMMYT.16 p.

Karaba, A., Dixit, S., Greco, R., Aharoni, A., Trijatmiko, K.R., Marsch-Martinez, N., Krishnan, A., Nataraja, K.N., Udayakumar, M. and Pereira, A. 2007. Improvement of water use efficiency in rice by expression of HARDY, an Arabidopsis drought, and salt tolerance gene. In: Proceedings of National Academic Science, U S A. 2007 September 25, 104(39): 15270-15275.

Karmakar, J., Goswami, S., Pramanik, K., Maiti, T.K., Kar, R.K. and Dey, N. 2021. Growth promoting properties of Mycobacterium and Bacillus on rice plants under induced drought. Plant Science Today. 8(1): 49-57.

KAU (Kerala Agricultural University) 2016. Package of Practices Recommendations: Crops (15th Ed.). Kerala Agricultural University, Thrissur, 360p.

Kumar, B. D., Srivastava, P., Agrawal, R. and Tiwari, V. 2017. Microcontroller based automatic plant Irrigation system. Int. Res. J. Eng. Tenchnol. 4: 1436–1439.

Kumar, M., Kumar, P., Singh, A.G. and Jukanti, A.K. 2021. Abiotic Stress Tolerance in Rice: Insight in Climate Change Scenario. In Integrative Advances in Rice Research.IntechOpen. 342p.

Kumar, S. M. 2016. Performance of upland rice (*Oryza sativa* L.) as influenced by NK levels and FYM substitution.M.Sc.(Ag) thesis, Kerala Agricultural University, 82p.

Kumar, S.N. 2017. Improving crop adaptations to climate change: Contextualizing the strategy. In Abiotic Stress Management for Resilient Agriculture. pp. 277-298.

Ma, J. F. 2011.Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Sci Pl Nutrition, 50(1): 11-18.

Magwanga, R.O. and. Kirungu, J.N. 2019.Physiological and developmental response of selected upland rice genotypes to water and nutrient stress condition. International Journal of Plant Science and Horticulture, 1(1): 22-39.

Maisura.,Chozin, M.A., Lubis, I., Junaedinand, A. and Ehara, H. 2014. Some physiological character responses of rice under drought conditions in a paddy system. J. Int. Soc. Southeast Asian Agric. Sci., 20(1): 104–114.

Maiti, D., Mandal, N.P., Singh, C.V., Prasad, S.M., Bhagat, S., Roy, S., Banerjee, A. and Verma, B.C. 2018. Climate resilient production technologies for rainfed upland rice systems. 512-527.

Miller, G., Suzuki.N., Ciftci-Yilmaz, S. and Mittler, R. 2010. Reactive oxygen species homeostatic and signalling during drought and salinity stresses. Plant Cell Environ., 33: 453-467.

Mohamed, A., Sedeek, S., Galal, A. and Alsakka, M. 2019.Effect of water deficiency as abiotic stress on the reproductive and ripening stage of rice genotypes. Int. J. Plant Sci. Agric., 2(1): 13-19.

Pandey, S. and Velasco, L.E. 2005.Trends in crop establishment methods in Asia and research issues. In: Rice is Life: Scientific Perspectives for the 21st Century, Proceedings of the World Rice Research Conference, 4-7 November 2004, Tsukuba, Japan. 45: 178-81.

Pandey, S., Bhandari, H.S. and Hardy, B. 2007. Economic costs of drought and rice farmers' coping mechanisms: a cross-country comparative analysis. Int. Rice Res. Inst.203p.

Pandey, V. and Shukla, A. 2015. Acclimation and tolerance strategies of rice under drought stress. Rice Sci., 22(4): 147-161.

Pang, Z., Zhao, Y., Xu, P. and Yu, D. 2020.Microbial diversity of upland rice roots and their influence on rice growth and drought tolerance. Microorganisms, 8(9):1329.

Pieters, A.J. and Souki, S.E. 2005. Effects of drought during grain filling on PSII activity in rice. J. Plant Physiol., 162(8): 903–911.

Ray, D.K., West, P.C., Clark, M., Gerber, J.S., Prishchepov, A.V. and Chatterjee, S. 2019. Climate change has likely already affected global food production. PloS one, 14:1–18.

Rodríguez, M., Canales, E., Borroto, C.J., Carmona, E., Lopez, J., Pujol, M. and BorrásHidalgo, O. 2006. Identification of genes induced upon water-deficit stress in a droughttolerant rice cultivar. J. Plant Physiol., 163(5): 577-584.

Saito, K., Asai, H., Zhao, D., Laborte, A.G. and Grenier, C. 2018. Progress in varietal improvement for increasing upland rice productivity in the tropics. Plant Production Science, 21(3): 145-158.

Serraj, R., Kumar, A., McNally, K.L., Slamet-Loedin, I., Bruskiewich, R., Mauleon, R., Cairns, J. and Hijmans, R.J. 2009.Improvement of drought resistance in rice. Adv. Agron., 103: 41–98.

Shahanila, P.P. 2015. Fertigation in sprinkler irrigated upland rice (*Oryza sativa* L.). M. Sc. (Ag) thesis, Kerala Agricultural University, Thrissur, 145p.

Sheela, K. R. 1993. Agronomic evaluation of rice cultivars for rainfed conditions of Kerala. M. Sc. (Ag) thesis, Kerala Agricultural University, Thrissur, 59p.

Singh, C.V., Mandal, N.P. and Maiti, D. 2017. Upland rice technologies: A brief overview. ICAR Central Rainfed Upland rice research station (NRRI), Hazaribag, Jharkhand, India.,48 p.

Sokoto, M.B. and Muhammad, A. 2014. Response of rice varieties to water stress in Sokoto, Sudan Savannah, Nigeria. J. Biosci. Med., 2(1): 68–74.

Srivalli, B., Sharma, G. and Khanna- Chopra, R., 2003. Antioxidativedefense system in an upland rice cultivar subjected to increasing intensity of water stress followed by recovery. PhysiologiaPlantarum, 119(4): 503-512.

Yadav, G. S., Anup, D., Rattan, L., Subhash, B., Ram, S.M., Somanagouda, B., Poulami, S., and Mrinmoy, D. 2018. Conservation tillage and mulching effects on the adaptive capacity of direct-seeded upland rice (*Oryza sativa* L.) to alleviate weed and moisture stresses in the North Eastern Himalayan Region of India. Archives of Agronomy and Soil Science, 64 (9): 1254-1267.

Yoichiro, K., Kamoshita, A., Abe, J., and Yamagishi, J. 2005. Improvement of rice (*Oryza sativa* L.) growth in upland conditions with deep tillage and mulch. Soil Till. Res., 92: 30-44.

Zhou, Y., Lam, H.M., and Zhang, J. 2007. Inhibition of photosynthesis and energy dissipation induced by water and high light stresses in rice. J. Exp. Bot., 58(5): 1207–1217.