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A Comprehensive Review of Abiotic Stress Responses in Rice with Special Emphasis on Climate Change and Heavy Metal Toxicity

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Abstract

Micro RNA molecules are one of the millions of biomolecules that control the genetic information in an organism. In general, this food is being equally affected in the yields and production through water rationing due to heat resulting from climate change. Regarding stress response, the rice plant has several types of responses to various stress such as stress due to salinity, heavy metal toxicity or drought stress. It also inclines on the level of polluting rice fields by heavy metals that are potentially damaging to bones of skeleton humans. Another method which may be of some use is what is termed as phytoremediation or else the preservation of the soil in such manner that it becomes unsuitable for the heavy metals to absorb them as rice plants do. Due to the many factors that affect food production, there is a big chance for inter-sectorial endeavor, with policy makers, researchers, producers, and consumers. These pollutants are easily transported from their sources whether natural or industrial into the soil, and impact on the quality of the soil and on its production capacity. Besides human life, presence of the pollutants in the atmosphere is equally a threat to life of all form in a chain of food pyramid. It pollutes water, its concentrated form impacts negatively on plant and other forms of life. The pollutants that are likely to affect rice plants include; arsenic, cadmium, lead and mercury pollutants as discussed above. Almost all the plants develop a way of guarding themselves in case of scenarios where they have to undergo metal chelating processes. It has been involved in controlling gene expression under stress in plants as well as animals. Concerning biotic stress factors, the diseases are likely to affect the Japonica rice whilst for the abiotic stress factors, the rice is sensitive to the effect of heavy metals. Climate conditions and international changes may cause the yield of rice in the end. Various abiotic stresses such as heat stress, cold, drought, salinity, and high level of several heavy metals are commonly reported to reduce yield in indica rice varieties. This brings us to the question of how the stress can be reduced for rice production and this include the sustainable practices that should be practiced in the agricultural sector.

Keywords: Rice (Oryza sativa); Abiotic stress; Climate change; Heavy metal toxicity; Salinity stress; Drought stress; Heat stress; Cold stress; MicroRNAs (miRNAs); Stress-responsive genes; Phytoremediation; Soil contamination; Molecular mechanisms; Antioxidant defense; Gene expression; Climate-resilient rice varieties; Japonica and Indica rice; Food security

Introduction

Some of the activities performed by RNA molecules include regulating the materials held in genes. They possess small base sequences measuring 21-23 and are featured in all plants, animals and some viruses. As the base pairing to the target sequence in the 3' UTR of the mRNAs it binds down regulate and results in mRNA degradation or repression of translation of the genes miRNA. In plants, the functions of miRNAs include but are not limited to the following plant physiological processes: Plant growth and development, hormone biosynthesis and signaling, defense against biotic and abiotic stress, etc. Now these genes have lower expression and consequently regulate the six components involved in growth processes and plant development and stress resistance in a general way. The miRNAs operate in the paths that occur among the various individual cells present in the animal having the specific appearance, which involves growth, differentiation, cell death and immune responses. They also have responsibilities in cancers, heart diseases, and disorders that are associated with neurodegeneration, and in such cases, when duty is imbalanced, it can overload the normal gene and cell processes. In human case, microRNA is employed frequently as molecular markers for diagnostic purpose and as targets for treatment in various diseases. These could be present in many of the body fluids including blood, saliva and urine making the test both useful in diagnosing early and screening tests. MiRNAs in general have been found to be involved in the modulation of gene expression and its patterns in both plant and animal models thus facilitating understanding of functional aspect of microRNAs along with few aspects of disease development and possible treatments.

Therefore, the aim of the current study is to identify the molecular mechanisms through which rice can heat acclimate Using the analysis pipeline which involves assessing the shuttles DEGs on the heat stress related experimentation datasets available at public domain.

Abiotic Stress Response in Rice

Unquestionably, rice is the most vital food crop cultivated on all continents that mainly provides required calories to approximately two thirds of the world's 7 billion population. The proliferating risk regarding rise of abiotic stresses like drought, flooding, salinity, heat and cold has been more by the way of the rice ecosystem where rice is cultivated with plants (Dar et al., 2021). The occurrence rate, scale and time period of these stresses would be even greater because of the causal effects of the progressive impacts of climate change. The greatest abiotic challenge to rice cultivation is certainly drought or non-availability of water in rainfed lowlands. Submersion of rice plants under floodwater in duration of one or two weeks due to sudden monsoons, which is the most prevailing issue in rain fed lowland areas (Koppa & Amarnath, 2021). Most of the endurance cultivation conditions encountered misfortunes of filling early in the phase and then drought during flowering that lead to big yield losses. Furthermore, salinity is another major soil issue which occurs when soluble salts are present in high concentration and control water availability since it is the next most common problem apart from drought and limits rice production globally (Korres et al., 2022). By now, heat stress has fast reared its ugly head as one of the greatest nightmares of rice farming all due to the global climate change. It hampers the plant growth, obstructs its metabolic works and finally the production is hampered. For both temperate regions and high-mountain areas located in tropical and subtropical regions, cool temperature is also an unavoidable obstacle of rice farming. Frost incidence has a significant negative impact on the rice crop during germination, vegetative growth and reproductive phase leading to major yield reduction. The scenario is often that the rice crop is continuously exposed to complex stresses (e.g. salinity along with drought, drought followed by submergence; they cause enormous crop losses. The upgrading combined treatment of several abiotic stresses would dramatically enhance rice productivity with the aim of sustaining water and soil resources (Onyeneke et al., 2021).

Salinity Stress

Plants of rice under salinity stress initiate coordinated pathways at molecular and protein levels to fend off the injury arising from the hazardous effects. Across gene ontology unraveled the activation of traits that defense itself against the stimuli and stressors, showing a clear response to the change. As verification, some genes for example TIFY9 (JAZ5), RAB16B, ADF3, Os01g0124650, and Os05g0142900 were picked for qRT-PCR analysis, which was used to demonstrate precise monitoring of the gene expression changes in response to the stress of salinity. This different expression at genetic level as well as the up-regulation of 422 and down-regulation of 139 genes showed the complicated nature of rice's adaption phenomenon. Besides, weighted co-expression network analysis identified the existence of the different intensively connected modules, some of them having high correlation with genes regulating abiotic stress responses, offering clues about the interrelated regulatory networks controlling how the rice plant responds to salinity stress. Further example is label-free quantitative shotgun proteomics which was employed for in-depth investigating the role of protein function and localization in the special salinity stress response allowed a deeper understanding of the molecular processes behind the specificity of rice's protein stress response to salinity stress. This complex study of rice response to saline stress, however, is key to program not just about strengthening rice resistance to environmental pressure, but also improving world food security ranking (Mirdar Mansuri et al., 2020).

Water Deficit Stress

Genetic mechanisms, in addition to water supply, become the key factor in rice growing, and allow plants to overcome the difficult conditions of dehydration which is a major problem for the plant world. SOS locus 1 is found to be as the predominant gene that encodes the Na1+ transporter in roots in the epidermal cells of roots and xylem parenchyma cells (Foster & Miklavcic, 2019). The absence of the SOS1 takes a plant to much serious salt stress, and it becomes essential in the mechanisms that tolerate salt. In conjunction with SOS1, the SKC1/HKT8 genes mechanize salt tolerance in rice plants through a strategy that directs the movement of Na1 out of the plants and preserves a low K1/Na1 balance in the rice shoots. Rice strains demonstrate salt resistance in a different manner since the most salt resistant cultivar is IR29. However, when rice plants are subjected to the joint effect of drought and salinity stress, they encounter several stumbling blocks including, the disruption of osmosis, higher concentration of salt and the elevated production of reactive oxygen species ROS that produce free radicals which damage cells and organelles. This type of environmental stress initiates apoptosis which badly interrupts physiological and biochemical processes, morphological features of rice also taking away its photosynthetic efficiency. The complex linking between the genetic features and environmental factors generates the requirement for a thorough understanding about the nutrients in the rice grain affected by water constraints and this genomics can offer an amazing option to improve the rice yield and the grain quality under the unfavorable environment (Tiwari et al., 2024).

Heat Stress

Rice, a food that constitutes the core of the diet of a majority of the world people being put into the exposure to the heat stress condition faces the challenging task of conquering this condition. We ended up doing detailed researches on commonly grown IR24, IR36, Akita Komachi, Koshihikari and the N22 landrace sorts which were very tolerant to elevated temperatures as well. The QTLs (Quantitative Trait Loci) of heat tolerance of N22 local variety is its main attribute of interest. These QTLs can be enriched into other rice varieties and hence, a variety is developed which can withstand the problems (Kilasi et al., 2018). This study aims to figure out the molecular mechanisms that heat acclimation in rice involves by applying analysis pipeline consisting of differential gene expression analysis on public datasets containing heat stress related experimentation data. Finally, it claims that heat stress responses in rice are induced by genes that upon adaptation cause the organism to create heat stress role. What is contrary to the traditional view, in rice, the genes regulating the tolerance to high temperatures are often epistatic, i.e., they act in a small-effect manner, establishing an extremely complex and multifactorial background for this trait control. Besides this, promising breakthroughs in genome editing such as CRISPR-Cas9 and TILLING increases the pace for reworking rice as heat-adaptable as might quickly change the rice breeding process (Liu et al., 2020). The scientists aim to narrow down the heat stress in rice farming by creating genotypes which carry almost several QTLs by employing the marker-assisted breeding or genomic selection technologies, as well, they provide a solution to the problem by increasing the tolerance rate of plants. Besides these methods, the GWAS and GBS techniques are available and are used in high-throughput phenotyping and genotyping approaches that enable the identification of many more genes responsible for heat tolerance in rice, thus opening the door for researchers to have all kinds of resources to ensure the sustained life of such a sister crop (Pan et al., 2023).

Cold Stress

Besides rice, many other crops being exposed to cold temperatures will set off a chain of response reactions at the physical and molecular levels meant to recoup for the losses incurred at low temperatures. The rice plants experience a couple of changes under cold stress conditions in an effort to sustain themselves in harsher conditions. Physiologically, when it comes to cold stress the cellular membranes get disrupted; subsequently, there is loss of electrolytes and water uptake from the soil becomes a problem (Q. Zhang et al., 2014). In turn this leads to deficiency in symptoms like wilting and reduced growth, which are usually experienced by plants. In response to the limitations of their development, rice plants deploy various molecular mechanisms. To counteract the freezing effect, genes with cold tolerance properties are up regulated; they encode cryoprotective proteins including antifreeze proteins and some LEA proteins. These proteins are responsible for creating a hindrance against the ice formation damage and also regulating the cellular structures in proper manner. Moreover, conditions of cold stress rebuild the production of osmoprotectans including proline and sugars which function as proteins chaperones for the purpose of preserving protein structure and integrity. In addition, as result of cold stress, cells should start producing ROS (reactive oxygen species) that cause damage to organic compounds in cell. To fight back stress, rice plants transcribe more of their genes making antioxidant agents like superoxide dismutase (SOD), catalase (CAT) and peroxidases to degrade excess ROS and make oxidative damage minimum. Generally, the abiotic stress response in rice to cold is quite complex- it's governed by the intricate mechanisms of physiology and molecular biology directed at the normal cellular functioning and preserving the cells from injury by low temperatures. The investigation of the changes presents an essential factor for the creation of cold tolerant varieties of rice that may survive in uneasy environments (Y. Wang et al., 2024).

Heavy Metal Stress

Common heavy metals that induce abiotic stress in rice plants

Heavy metals commonly associated with inducing abiotic stress in rice plants include:

A. ***Arsenic (As):*** Arsenic contamination in rice farming is one of the serious issues in regions which have it in water or soil in the large quantities. Shortage in the water supply can cause a slowdown in the plant growth resulting in the lower yield and quality of the grain.
B. ***Cadmium (Cd):*** The issue of cadmium pollution in the soil frequently may originate from industrial operations, mining or with the use of some fertilizers and pesticides. As cadmium is stored in rice grains it introduces potential health issues to mankind.
C. ***Lead (Pb):*** The sources of soil contamination with lead can vary, including industrial releases, lead-based coatings or urban seepage. When it comes to lead, it is prospect that will accumulate in rice grains so as to pose health hazards.
D. ***Mercury (Hg):*** The anthropogenic processes like water contaminated because of industrial practices and mining and natural sources can cause the mercury to be in rice. It may, consequently, result in the reduction of plants growth and production.
E. ***Nickel (Ni):*** (i) Nickel effects can come about from acidic soils or from nickel extent where nickel is otherwise naturally high. This can affect the overall development process of growth and yield as well.
F. ***Zinc (Zn):*** Whilst zinc plays an critical role as a micro constituent plant growth, when the plant is heavily lubricated, it can induce toxicity condition in rice crops leading to reduced growth and yield. A soil possibly suffers from the excess zinc content from over-application of zinc containing fertilizers (Arif et al., 2019).

These metallic materials could interfere or hamper the physiochemical development of rice plants by inhibiting the growth, yield and health aspects that the plants may need to thrive. Furthermore, they could be filled in the rice grains thereby, when the rice is being eaten, the contamination problem comes up as well in humans.

Response of rice plants towards heavy metal stress at the molecular level

In accordance with heavy metal stress, the rice plant activates complex molecular responses to ensure that the plants maintain their normal condition. The significant finding was generated in a study which evaluated the twofold action of sodium nitroprusside (SNP) on heavy metal stress in Korean rice cultivar Jinbu including exposure to elements such as mercury (Hg), chromium (Cr), copper (Cu) and zinc (Zn). Research has proved that SNP as a tool can boost rice plants resistance levels against different heavy metals, especially lead, by improving their abilities in extreme conditions (Niyoifasha et al., 2023). Furthermore, S-nitroso cysteine (CySNO) insertion into Arabidopsis thaliana elicited extensive alterations at the level of the transcripts numerous of them related to plant protection in different stresses. In the molecular system rice plants deploy multiple mechanisms including biosynthesis of a class of hormones called phytochelatins, metal tolerance proteins, metallothionein, ROS, RNS, and antioxidants. The cross-talk among metal transporters and arsenic detoxifying genes is the way of rice plants to maintain internal balance of metals. Not only rice plants have developed complex mechanisms to bind and retain different metal ions but also, they are capable of segregating and veiling them from vital cell components (Nicolas-Francès et al., 2022). Heavy metals act as a secondary defense line and plants employs chelation, transportation, sequestration and detoxification of metal ions in vacuoles. This strategy is used to counter the stress caused by heavy metals. Besides that, ethylene along with the active forms of Oxygen species also act as internal signals that coordinate metal stress related responses in rice plants at the molecular level. These signaling molecules therefore mediate the complex defense mechanisms that rice plants are so adept at using to guard against metal-induced adverse effects (Steffens, 2014).

Strategies that can be employed to enhance the tolerance of rice plants to heavy metal stress

Across the journey to make rice plants more tolerant of heavy metal stress, a different number of potential strategies have been identified as effective methods. Another strategy is that the production of antioxidants within rice plants makes it possible for the detoxification of ROS to occur and hence the response to heavy metal stress is improved. Hence, furthermore, ion homeostasis and compartmentation are made of the mechanism by which heavy metal stress is prevented in rice plants. Osmo protection through osmolyte regulation is another powerful contributor that can substantially add to the rice plants' tolerance to heavy metal stress (Sarma et al., 2023). Besides, the pretreatments using melatonin have demonstrated effectiveness which increased the non-enzymatic antioxidants activity and bolstered the antioxidant enzymes activity in rice, to benefit stress tolerance. Besides, zinc oxide nanoparticles are able to effectively reduce chilling stress in rice plants, therefore, the plant height and root length of the plants is also increased significantly. When it comes to genetic approaches, genes for example SOS1, HKT1, and SKC1/HKT8 are known to play a crucial role in increasing salt tolerance in rice plants via mechanisms that are responsible for the control of ion transport and homeostasis. Secondly, gene scanning and haplotype breeding are other aids that help to limit the accumulation of arsenic in rice grain thus playing a role in upgrading the tolerance to heavy metal stress. Selective identification and association of allelic variants with low-arsenic content rice grains is a key step to guarantee rice tolerance toward heavy metal stress. The final recommendation would be using rice cultivars with the lowest potential arsenic in the grain as a practical approach of improving the tolerance of heavy metals in rice plants (A. Singh et al., 2022).

Loss of Rice Cultivation Land due to climate shift effects

India Scenario of Climate Change

It is likely that the warming might be more severe in northward India. The dynamism of changing climate will be reflected not only in the heat and cold extremes, but also in the heightened frequency of maximum and minimum temperatures. Some areas may get even more rainfall supplanted by the constantly dry fields in others (Hussain et al., 2023). Punjab and Rajasthan located North West and Tamizh Nadu in the South are displaying decline in an average note. On the other hand, an overall surge of 20% in summer monsoon rainfall in the whole of the Indian area is projected. The number of rainy days may decline in a few parts of India, such as MP. However, the intensity of rain will rise across most of the country, e.g., North East. As water consumption is on the rise, gross per capita water availability is forecasted to shrink from about 1820m3/yr in 2001 to as thin a line as 1140 m3/yr in 2050. Corals of the Indian Ocean will very soon experience extreme temperatures during summer that exceed those in the last two decades. It expected that periodical coral bleaching will become almost certain by 2050. These days, the districts of Jagatsinghpur and Kendrapara in Odisha, Nellore and Nagapattinam in Tamilnadu, and Junagadh and Porabandar districts in Gujarat are the most exposed to the consequences of a greater destructive potential and frequency of cyclones, as is presented in the National Communication (NATCOM) report of 2004.Screenings on the mean sea level along the Indian coast line during last 100 years reveal a 100-year rising trend of about 1.0 mm/yr. While this recent data indicates an increasing trend of 2.5 mm/year in sea level along the coast of India. The sea surface temperature in India near will be rise by around 1.5-2.0°C by the middle of this century, and 2.5-3.5°C by the end of century. Based on the estimated information, 1 meter of sea-level rise will displace about 7.1 million people in India. Also, it is said that 5764 sq km of land will be lost along with 4200 km of roads, according to the NATCOM report in 2004. It is projected that more than 50% of India's forests will undergo a shift in forest types in the near future. This change will have adverse effects on associated biodiversity, regional climate dynamics, and livelihoods that depend on forest products. Additionally, it seems that within the next 50 years, most of India's forest biomass will be highly vulnerable to climate change. Furthermore, it is projected that by 2085, 77% and 68% of India's forested areas will experience a shift in forest types (Mahato, 2014).

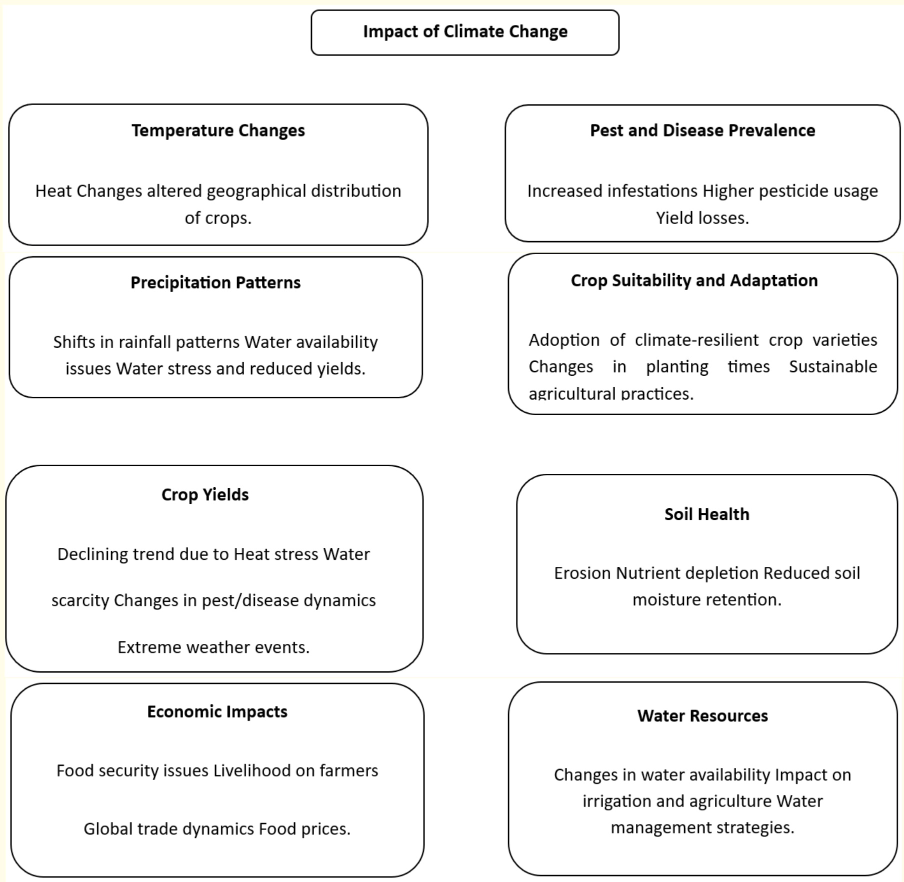

Figure 1: Flow chart Of Impact of Climate Change on Agriculture.

Aspect	***Predicted Effect***	***Effects on Agriculture***	***Reference***
Temperature	Increased average temperatures, leading to heat stress in crops	Changes in growing seasons and crop viability	(Intergovernmental Panel on Climate Change, 2023)
Precipitation	Changes in rainfall patterns, affecting water availability	Altered irrigation requirements and water stress in plants	(Macintyre et al., 2018)
Pests and Diseases	Spread of pests and diseases to new regions	Increased pest pressure and disease outbreaks	(Najafi et al., 2019)

Crop Yields	Variable crop yields due to extreme weather events	Fluctuations in productivity and crop failure risks	(Challinor et al., 2014)
Soil Health	Degradation of soil quality due to erosion and nutrient loss	Reduced soil fertility and increased susceptibility to erosion	(Lal, n.d.)
Water Resources	Increased competition for water resources	Limited water availability for irrigation and livestock	(Bierkens & Wada, 2019)
Food Security	Challenges in ensuring food security for growing populations	Increased food demand and supply chain disruptions	(Wheeler & Von Braun, 2013)

Table 1: Effects of Climate Change on Agriculture in the Coming Decades.

Rice production in India

India plays a dominant role in the production of rice, making a 20% contribution to world rice production. Rice is the most important and very popular crop in many regions of India which is taken as a staple food. While rice is only 23.3% of the gross cropped area and 43% of all food grain production, as well as 46% of whole cereal productions. The history of rice (Oryza sativa L.) production in India from 1950 to 2015, along with the rice growing area and irrigation facility. India is considered to be the nation with the largest rice planting area. Sowing of the kharif rice is done in June July and it is harvested in November-December. These together account for 84% of the rice yield of the country. This is then followed by the summer rice (sown in the period between, Nov-Feb) and harvested in the period, Mar-Jun. This contributes 9% to the rice crop; and, the Autumn rice (sown in May-Aug) and harvested in Sept-Oct that comprises 7% of the rice crop. Rice farming is often regulated by a temperature of about 25º C and an annual rainfall above 100 cm. Even in regions with less rain, irrigation is usually used to grow rice. Contrasting sometimes the rice yield in India goes down due to drought and other extreme events, it goes up to 400% since 1950-2015 in other countries. These years from 2009-10 were to be remembered as terrible rice droughts affected almost half of the country. Climate changes will respond and affect the production of rice in India even in future. Along with the population increase, the challenge for the Indian agriculture sector is to raise rice production while striving for the countermeasures of climate change. Thus, evaluation of how climate change will affect rice productivity in India becomes a crucial necessity (Paidipati & Banik, 2020).

Impact of climate change on rice production

Global warming caused by climate change which will shift temperatures, drive sea-level rises, and alter rainfall patterns all over the planet, will bring serious problems to growth, yield, and the economy of rice farming. The model of DSSAT provides the chances of 12% decrease in rice harvests with the rise in temperature, and changes of precipitation could reduce the yields per area for up to 31.3% till 2030. On the other hand, the rise in the concentration of CO2 in the air might be released a positive effect to the plant growth; as CO2 is one of the most important components for the process of photosynthesis. The CO2 concentration in the atmosphere has a palpable impact on the net photosynthesis rate of C3 plants like the first one ivy. This effect results from the two following processes: an enrichment of substrate CO2 (the starting material of photosynthesis) and an inhibition of photorespiration (a reversal process of the photosynthesis reactions) by high CO2 concentrations. However, there are other potentially harmful effects associated with long-term exposure to high CO2, including, gradually, a limited stimulatory effect on metabolism. Photosynthetic acclimation in rice is related to both the face RuBP carboxylation and the back RuBP regeneration limitations (Naikwade, 2017).

Effect of climate change on rice crops

Rice growth cycle can be divided into three stages: vegetative, reproductive and grain filling (or ripening) state. Different rice strains react differently to heat after reaching various development stages. This period crises arises when occurrences of heat stress and delayed rains (water stress) happen at a particular development stage, and such can lead to no harvest. Tolerance to heat-stress in rice at one developmental stage would not be a guarantee of the same level of tolerance near the other stages. Climate change could have a bearing on freshwater systems and had the data been analyzed, rice production of certain areas in Asia would have been found to be declining as a result of water stress being caused by rising temperature, shorter rainy days, and longer droughts. In India water related stress is most of the time due to droughts. However, there are some rice cultivars that are more drought tolerant and may be more adapted to specific regions.

Temperature Change

The rice crop is tolerant to high temperatures during the vegetative phase, but highly susceptible at the flowering stage during floral (Das et al., 2014). The daily or night time heat stress exerts varied consequences on rice growth and production. The annual mean minimum temperature has shown a relatively rapid increase over the period of last two to three decades compared to the increase in the annual mean maximum temperature. This trend most likely will become the new norm and impact discovery firstly in certain vulnerable areas and then on the whole planet (Impa et al., 2021). According to many rice specialists, 24°C is commonly regarded as the acceptable temperature for rice. If rice plants are put under temperatures which would be 1°C warmer than the normal for several days, rice yield and biomass can drop up to 10% (Hussain et al., 2019). Under the elevated temperature of about 3°C, the phase of the rice crop can be affected, the grain-filling duration can be shortened, and the respirations will possibly be increased. This may affect the yield and inferior grain quality of the rice crops. From the experiments conducted in the rice fields, the result shows that there will be a 12.2% to 35.6% reduction in photosynthesis by an increase of 3.6°C to 7°C. Run the chance of leaning in the planting calendar, from −14 to+14 days, could bring a 12.5% to 25% reduction in yields (Sajid & Hu, 2022).

Rainfall

The recent research has shown that relative humidity plus high temperatures, likely is the cause of a lot of heat-related deaths and discomfort. It has now been seen that higher humidity underlies the levels of moderately high-to-high temperature negatively effect on a much bigger scale compared to the conditions that exhibit lower relative humidity (Baldwin et al., 2023). Based on this interaction, rice cultivation regions in the tropics and subtropics can be classified into two categories: tapping into deserts or tropical savannas. Thus, it seems evident that a cultivation in hot/dry regions, where temperatures can be above 40 °C (as in the cases of Pakistan, Iran and India), has been made possibly through unplanned selection for efficient transpiration cooling- a avoidance mechanism at a sufficient water supply (De Z. Abeysiriwardena & Dhanapala, 2021).

Floods and submergence

Floods and submersion bring an amazing shock especially to the growers of the lowlands in the Southeast and South Asia. Rice plants cannot survive flood condition even for some days as they cannot stand complete submergence and ultimately die. Yield losses due to unpredictable flood events can be classified into three damage categories: the first stage is complete submergence (referred as flash flooding) that leads to mortality of plant after a couple of days then the second stage is partial submergence (a type of stagnant flooding) through prolonged periods of time (which generated many harvest losses). The last one is waterlogging (a flooding taking the shape of ten meters high) that creates anaerobic conditions which in turn h The height and power of flooding during the time of extreme weather events could become much higher than usual according to the featured researchers, probably cause submergence as well as unnatural sea levels (Michael et al., 2023; A. Singh et al., 2017).

Drought stress

Drought stress, which is an obstacle to crop production system dependent on rain, continually continues to challenge the farmers of rice. India frequently faces droughts which can be worst during the summer months. Downey (2002) in India about half of the rice planting area and two hundred and fifty million people were subjected to waters scarcity. Similarly, Thailand is equally prone to drought which brings crop failure and even when the total effect is considered, the aftermath and has social, economic, and highly destructive impact also.

Salinity

Rice production under salinity stress is an interplay between tolerance genes and some rice genotypes can adapt to environments with up to moderately saline levels. The divergence of rice behavior in response to salt stress relies on the corresponding developmental phases as well. The rice is the more tolerant plant species during the germination, vector mode, and maturation; however, it is comparatively either dry or water lack at the early phase of vegetative and reproductive periods (Asch & Wopereis, n.d.). IPCC 2014 report indicates that frequent sea level rise and the coastal floodings events are the main reasons to have the salinity as a great threat for rice continuity due to their is projected to occur within the next 50-100 year (Teng et al., 2016).

Climate-Resilient Rice Varieties	***Rice Varieties with Gene Pyramiding***	***Genes for Overexpression and Modification***	***References***
Swarna-Sub1	IR64+Sub1	Sub1	(A. Singh et al., 2017)
DRR Dhan 42	Swarna-Sub1+Sub1+C2-1	OsSAP16	(A. Singh et al., 2017)
DRR Dhan 45	IR64+Sub1+qDTY12.1	OsDREB1A	(Dixit et al., 2019)
DRR Dhan 49	IR64+Sub1+qDTY12.1+qDTY4.1	OsbZIP23	(Dixit et al., 2019)
Sahbhagi Dhan	Swarna-Sub1+qDTY12.1	OsRMC	(A. Singh et al., 2017)
Sambha Mahsuri	IR64+Sub1+qDTY12.1+qDTY4.1+Pup1	OsEREBP1	(Dixit et al., 2019)
CR Dhan 801	Swarna-Sub1+qDTY12.1+Pup1	OsEATB	(A. Singh et al., 2017)
CR Dhan 802	IR64+Sub1+qDTY12.1+qDTY4.1+Pup1	OsLHY	(Subudhi et al., 2020)

Table 2: Genetic Innovations in Climate-Resilient Rice: Varieties, Gene Pyramiding, and Overexpression/Modification Genes.

Role of Heavy Metal

Effects of heavy metal in plants especially in rice

Metals of heavy elements (they are metallic elements with a high atomic weight and density resulting in them having much heavier weight than lighter metals) are a group of those metals. These include major toxic elements namely bismuth, arsenic, cadmium, lead, mercury, and chromium among others. These elements come from the soils and the Earth’s crust naturally, but they are as a result of the increased industrial processes, mine deposits, and production activities, among others. By existing within high concentrations, heavy metals can have adverse effects on plants, and also rice which is a substantial food for the large percentage of people across the world (Niyoifasha et al., 2023).

Here’s how heavy metals affect plants, with a focus on rice:

A. ***Uptake and Accumulation:*** Plants possess the ability to dilute heavy metals from the soil through the transportation of these substances from their roots to their leaves. Where these metals get deposited inside the plant structure can differ as well. They can for instance get absorbed by the roots, stems, leaves or grains. In the case of rice more of the unhealthy metals may be found in the grain, the part of the plant that people consume (Zakaria et al., 2021).

B. ***Physiological Effects:*** The heavy metals can play a role in the physiological processes and they can be capable of altering the growth and development of plants. These toxic substances play a role of visually hindering photosynthesis and respiration; hence, nutrient absorption becomes difficult and as a result, growth and productivity decreases. Besides, heavy metals are also able to generate reactive oxygen species (ROS), which are toxic and result to damage on membrane, proteins, and DNA (R. Rai et al., 2016).

C. ***Nutrient Imbalance:*** Metal contamination can upset plants’ equilibrium of macro and micro elements that are essential. Such as, cadmium can be the reason behind the poor intake and distribution of iron (Fe), zinc (Zn), and calcium (Ca). Such situations can lead to the decrease in the content of certain nutrients in the soil and thus to make the negative effect upon the plant development even worse (Khan et al., 2015).

D. ***Bioaccumulation and Biomagnification:*** In the rice ecosystem, heavy metals can, in the long run, build up in the soil in particular in paddy fields where anaerobic conditions of flooded fields get an upper hand. As soon as these heavy metals have accumulated in the soil, to can be absorbed by the rice plants and then passed to people and animals via the food chain. The said biomagnification process, however, poses a major health risk since rice is a staple food for more than 3 billion people on planet earth (Schäfer et al., 2015).
E. ***Toxicity and Health Risks:*** If a human consumes rice that is polluted with heavy metals, they are likely to face some serious health problems. Chronic exposure to heavy metals, including cadmium, lead or arsenic, has been proved to be a risk factor in many diseases like neurological disorders, cancer and kidney damages. The effects of the toxic influence of heavy metals on children and pregnant women is so highly crucial (Mohammad Ali et al., n.d.).
F. ***Environmental Contamination:*** The heavy metal pollution of soil and water entities may introduce further larger-scale environmental problems. Use our automatic essay generator and instant proofreading to check your work instantly. Agricultural fields located nearby become affected too with the spread of heavy metals to contaminated water used for irrigation. In addition, runoff from soil which has been polluted can get into water bodies, risking aquatic ecosystems and biological diversity(Mohammad Ali et al., n.d.).
G. ***Remediation Strategies:*** Some remedy solutions to the heavy metal contamination of rice fields have been advocated such as phytoremediation as well as using plant life that would extract, lock or destroy the heavy metals from the soil. Moreover, liming, organic manuring, and phosphate amendments can efficiently reduce the availability of heavy metals in soil, thus limiting their uptake by rice plants. Ultimately, heavy metals contamination has a serious effect on rice crop production, food security and human beings' health. Resolving this matter obliges the policymakers, scientists, growers and consumers to work synchronously with the purpose of implementing sustainable agricultural practices, reducing industrial pollution and guaranteeing the safety of our food chain (Wan et al., 2024).

Effects of heavy metal on soil
Sources of Heavy Metals in Soil

Natural Sources: Heavy metals such as lead, mercury, and cadmium, being components of the rocks/ minerals, come out of their bonds by weathering - the process of deposition of rainwater. This leads to geological processes such as eruptive, destruction and erosion that result in the natural deposition of high loads of heavy metals in the soil.

Anthropogenic Activities:

A. ***Industrial Processes:*** The mining, processing, plate, and manufacturing stages of metal include as well emissions of heavy metal that to pollute the environment. The releases straight from the earth by way of spills, leaks and releasing particles in the air are some of the processes in which these metal pollutants harm the earth.
B. ***Agricultural Practices:*** Besides fertilizers and pesticides, which are inorganic and usually contain heavy metals, the damn water is another problem for soils pollution as well. Additionally, tilling and land application of sewage sludge apart them from natural soil level.
C. ***Waste Disposal:*** Hazardous industrial waste, municipal solid waste, and electronic waste (e-waste) if not disposed off properly can clog the pores and make the soil prime location for heavy metals to accumulate. First, landfills and land dumps are leached to produce the leachate which then goes into the surrounding soils and ground waters.
D. ***Atmospheric Deposition:*** In one way, automobiles are the other huge source of emission of heavy metals and coal combustion and incineration are the other sources. In the long haul these emissions are drifting and get settled on the soil surface through the depositing process via the air (Selvi et al., 2019).

Effects of Heavy Metals in Soil

Soil Degradation

Exposure of soil to toxic metals affect the process which maintain the physicochemical properties that determines the soil productiveness, and thus the soil quality drops significantly. The soil gets worn down and the water drainage rate goes down as well as erosion and soil, which have no recovery power.

Reduced Nutrient Availability

As a result, the surplus of metal adversely affects the capacity of plants to obtain proper nutrition through lowering the number and activation of only useful plant nutrients. As cadmium is an antagonist element of plants to zinc, a nutrient deficiency occurs and the plant growth is suppressed by the increase in cadmium in the plant.

Toxicity to Plants

The soil composed of a high amount of metallic elements could even be fatal to plants. The process is completed by presenting with all the results which includes the symptoms like chlorosis or necrosis, and dwarfs the plant. Harmful metals like Lead and Mercury which tends to concentrate in the tissues of plants are alike harmful or worse for humans and animals through ingesting such crops.

Bioaccumulation and Biomagnification

Briefly, bioaccumulation of heavy metals can occur in soil creatures, e.g., earthworms, insects, and microbe populations. Oftentimes, these pollutants accumulate in the food web such that in the long run, they are at the risk of exposing other organisms in this food web besides humans.

Groundwater Contamination

Hosting these heavy metals may possibly penetrate through the successive layers of soil in effect, the groundwater shall be contaminated. If the depth of aquifers and sediments are shallow, aquifers and aquatic species may be greatly impacted.

Human Health Risks

Farmers spray pesticides, fungicides, and herbicides on the plants themselves trying to fight off any infestation or weed. These chemicals penetrate the soil when they encounter it and are finally discharged into the groundwater which undefined eventually gets into the irrigation systems. The long-lasting effect of heavy metal toxins on expecting mothers and children who have not realized their fundamentals of development takes the cake (Jiwan & Ajay, 2011).

Morphological, Physiological, Biochemical changes observed in rice plants grown under heavy metal stress

The heavy metal pollution may be the vital problem that would be responsible for the damage of the plants as well as ecosystems through soil and water. It may be that produce such supply turns out to be over- or under-proportionate to the demand on the market. The rice crops , beside other ones , could build up a supreme amount of heavy metals like arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg) . In some countries of the world these kind sources can be a significant intake of heavy metal for the people. Those metals are which are just translocated from the soil to the plant body and then into human food are a critical issue not only for better to agriculture practice but also for public health. The third metals could undergo the reactions and ultimately trigger the production of ROS and $OH^{\cdot}$ along with water formation. Being reasonatively reactive with vast attraction radicals can cause break down and loss of vital components of the cell such molecules e.g. carbohydrates, amino acid, lipids and DNA. Therefore, the importance of learning not only the adverse effects of heavy metals on rice species as a whole but also at the level of a cell or the characteristics of the plant itself needs to be stressed. This determination should be followed by the study of the ways in which these plants should be protected from the effects of pollutants.

Morphological and Physiological Responses to Heavy Metal
Arsenic

Arsenic is a metal whose oxidation states range from different forms and the most abundant is arsenides which [As3−] form, arsenites which [As3+] form and arsenates which [As5+] form. Rice plant may be contaminated by arsenic, an inorganic toxicant. The latter is still much more dangerous than the organic poisons. The most researched and significant inorganic forms of arsenic that are the main ones found in the rice plant are As5+ and As3+. Likewise, MMA and DMA are the most predominant molecular species which usually are present in rice plants. The depressing part here is that an organic As3+ has the most toxicity when it comes to immobilization of As5+ that is flush-out of the body system as the As3+ cannot be degraded it gets accumulate in the body tissue. It can be based on the involvement (engagement) of methyl groups via the inorganic arsenic either basic or acid (by oxidation states). Arsenic biomethylation, a newly born pathway, operates when arsenic species are converted into an organic compound in the rice paddy soil. This process is lower in organic arsenic species than inorganic arsenic species. Reducing agents or processes generating As3+ dominance rather than As5+ domination were seen in aquatic rice paddies, whereas oxidation agents or processes, As5+ dominated aerated rice soil fields.

As a result of the larger arsenic absorption the plants could be more vulnerable to stunted growth. Arsenic in rice plants can cause both reduced and lower seed germination rates; plant growth becomes impaired; photosynthetic rates are lower and the yield goes down due to reproductive failure; volume of biomass is lower; and the disease called “straight head” appears. The disease is represented by symptoms like the damaged apex of the spike, led to poor pollination, the loss of grain fill and the extreme situation of not having heads or panicles at all. Degradation in the photosynthesis and chloroplasts is due to the change in the the membrane structure brought about by arsenic. Arsenic disrupts the body’s metabolism process of proteins, lipids, and carbohydrates. First of all, arsenic can very well increase ROS (reactive oxygen species) production that stand higher than can be scavenge, resulting to naked proteins and other vital cell components. When the rices seedlings are exposed to As5+, reactive oxygen species H2O2 was generated, whereas As3+ was demonstrated to produce superoxid an O2−and H2O2 leading to the peroxidation of lipid. With the As5+ APX (ascorbate peroxidase) activity increases in the root of seedlings, they grow normally reducing the H2O2 level ascorbate-glutathione regime. Also, the enzymatic antioxidants’ concentration such as CAT, SOD, GPO, CAT-P, GR, and MDHAR was increased to pick the ROS coming about in the case of As3+ exposure.

Cadmium

Cd is a secondary ingredient, that is not essential for plant growth, but it is rather abundantly found in the environment. Several human practices, for example, smelting, mining, urbing wastes and using the artificial fertilizers containing Pb result in exposure of the Cd to the environment and leads to the vulnerable health risks in humans. Lately, it is been found out that, paddy soil pollution with Cd may cause rice quality issues. Rice plants can take up Cd from the soil, and at later stages in the production process, these metal elements may accumulate in the grain products. The rice plant absorbs Cd from the soil through the roots, moves it into the shoots by xylem pumps at the root-to-shooting nodes, and redistributes it with remobilization at the leaf nodes. Citrate, tartaric acid and histidine are strong chelators and their biological function appears to enhance the translocation of Cd from shoots to roots in the xylem during the whole translocation process. Indica varieties usually carry larger percentages of Cd accumulated in their shoots and grains in comparison to regular japonica types. Nothing works in a silo; low levels of cadmium in plants cause abnormal decreases in leaf water content, vitals minerals, water soluble proteins, non-enzyme antioxidants, and enzymic antioxidants. Cd poisoning not only reduces rice output but also deteriorates quality of grains, whereby yield components, such as the number of panicles, their spikelets per panicle and the setting percentage, all deteriorate. The supply of necessary photosynthetic pigments is altered by the excess Cd that the plants take up with it and which drastically hinders the electron transport systems of the chloroplasts and the complexes between the Chl and proteins. This stress imposes a dysfunction of the enzymes involved in Chl biosynthesis, and the Calvin cycle, together with a water balance impairment. Cd leads to the aggregation of rice seedlings enzyme δ-aminolevulinic acid dehydratase, which is responsible for chlorophyll synthesis and thereby blocks the formation of chlorophyll. Cd in medium increase by This implies that elevated Cd in the medium is an important element of the enhanced Cd accumulation in the seeds and TBARS (thiobarbituric acid reactive substances) amount. It also noticeably depletes the percentage of rice kernel germination, shoot length, product weight, and moisture of the rice too.

Lead

The element lead (Pb) is not beneficial to plants and any amount if absorbed by the plants may cause harm to plant metabolism. It undermines roots' absorption process of minerals from the soil and can go through the roots of rice plants by being passive to the move water that might be running through the soil at that time. Pb is translocated from the soil as a result of contact between the epidermal cells of the root and the xylem vessels into the other organs of the plant. In rice cultivars, a shoot is subjected to a heavy level of Pb (1.2 mM) concentration shows a significant decrease in plant height, tiller number, and spikelet number per panicle. Lead poisoning not only changes the primary structure of chloroplast, but also affects the production of carotenoids and plastoquinones as well as the electron chain transport too. Moreover, a deficiency of CO2 happens and, consequently, the stomata close, causing a reduction in the enzyme activity in the Calvin cycle. A study by Khan et al argues that Pb (lead) contamination has no impact on the root growth, while facilitates significant decrease of shoot length and biomass of rice when compromised by the low nutrition reserves of nitrogen or phosphorus. Plants yield a surplus of a type of oxygen radicals named reactive oxygen species (ROS), and antioxidant enzymes activity is unstable in the presence of Pb toxicity.

Mercury

Hazardous is a term that perfectly defines mercury (Hg) among all the elements in the environment. Under concentrated levels of Me, it becomes possible for plants to fail and cells to get interfered with. Hg is typically localized at the root system of plants causing the most injury there and then. Rice root systems are very sensitive to Hg and may suffer from different scales of damages to the structure of the roots. At Hg stress, proteins expression in the roots may change. People who consume rice from mercury-polluted fertile lands absorb the substance because rice contains a large amount of mercury which is dangerous to human health.

There are three types of mercury: methylmercury, inorganic mercury (Hg2+), and Hg (0). The most bioaccumulative type of Hg is MeHg, which has the most severe neurotoxic effects for both humans and animals. The complete MeHg production in the rhizosphere soil is highly stimulated with medium soil Hg content (3 mg kg^{-1}). MeHg creation peak out when the rice field is blooming or nearing maturity stage but its antioxidant system hardly seems to be affected.

The biggest hunk of Hg2+ located in a rice grain is normally determined from the hull and bran. The white rice, on the other hand, is rich in glycine (a form of MeHg that is more potent). MeHg is likely bound to cysteine present in bran as a form of transport within the seed as it ripens, actively passing to the endosperm. The levels of Hg in rice roots elevating result in increase in ROS, MDA content, and lipoxygenase activity that interrupts a many cellular processes including the growth and development of rice plants (*Effect of Heavy Metals on Plants: An Overview International Journal of Application or Innovation in Engineering & Management (IJAIEM)*, n.d.; Kumar Sharma & Agrawal, n.d.; Sarma et al., 2023).

Biochemical Responses Heavy Metal

This occurring when the amount of heavy metals - As, Hg, Pb, and Cd - spreads in enough volume to form ROS, leads to oxidative stress- an abnormal production of these kinds of cells. Under the influence of the strain, the membrane system loses its integrity, and the metabolism as well as physiological response of rice turn out to be less stable. Therefore, plants of rice counteracted the latter by activating the antioxidant defense system, regulating ion homeostasis, accumulating oncoming substances, regulating osmotic pressure, and generating more signal molecules. In fact, heavy metals and metalloids stress-induced PC-production (thiol-rich peptides) also take place in rice. Mechanism of As-PC formation in rice leaves that complexing of As3+ may give less As-enriched grains. The same as well below the Cad stress in roots and leaves of rice the SOD, POD, CAT, GPX, and APX expressions are stronger. While rice cultivating under CD stress also show the increased levels of non-protein thiols as well as PCs and GSH which are responsible for preventing the hazardous free radicals. Two assays also showed rice was responsive to Pb toxicity favoring CAT and POD activity. Likewise the amassing of proline was high while the level of sucrose raise with the increase of Pb concentrations.

Exposure of the plants to non-ideal conditions trigger glutamate (Glu) which is responsible for mediating their responses to abiotic stress. Through the use of glutamate as a supplement for rice plants, researchers were able to show that the extra element drastically improved the over-all antioxidant activity of the plants which was then able to handle the Cd induced oxidative stress. This, consequently, triggered the downward trend of MDA, H202, OH-, Pro, GABA, Arg and it simultaneously caused the upward trend of CAT, POD, and SGTP. Besides, the dose-dependent suppression of Cd-introduced genes OsNramp1, OsNramp5, OsIRT1, OsIRT2, OsHMA2 and OsHMA3 in the roots of Cd-induced plants was reached under the Glu administration. Through S-itectome approach, protein profiling of 21 proteins involved in defense and detoxification, redox homeostasis and germination activities of rice plants under Cd toxicity could be identified by Ahsan et al. Regarding Hg stress, the protein had increased level of Phe and Trp as different genes which are connected to aromatic amino acids were also upregulated. The rice plants that were externally provided with Phe and Trp tested showed response to high concentration of Hg and had less ROS caused by Hg. Overall, the formation of plaque on the rice roots was illustrated to function as a preventive barrier limiting rice root digestion of Cd and As (JORJANİ & PEHLİVAN KARAKAŞ, 2024).

Molecular Response

Plants' specific communication routes are usually triggered in case there is a high dosage of toxic metals in the environment. The pathways in question are represented by Ros signaling, Calcium-mediated signaling, MAPK signaling and hormonal signaling. These routes induce a release of the stress-gene-responsive genes and transcription factors that in turn help the plants detoxify the heavy metals. The calmodulins (CaM), calmodulin-like proteins, calcineurin B-like proteins, and CDPK can be considered equally important as Ca2+ signaling sensors, and they detect changes in the content of Ca2+ and participate in stress response mechanism. Besides activating MAPK cascade, the signaling molecules too phosphorylate NAC, MYC, MYB, bZIP, DREB and ABRE transcription factors which lead to the alteration of expression of stress-responsive genes. Along with other phytohormonal signaling pathways, such as ethylene, auxin and JA, are also modified by ROS, and the change in phytohormone levels leads to alteration of plant reactions towards metal stress too. Therefore, we need to learn in detail how the signal pathways which metal stress is mediated in plants may interconnect and how the general picture of metal stress signaling in plants can be formed. Therefore, a number of researches have been conducted on the reactions of rice plants to high level of heavy metals, while they aim at enhancing the performances of the existing rice species to be heavy metal-resistant. Go through table 6 that gives an overview of important genes related to heavy metal resistance in rice (Roychowdhury et al., 2018).

Heavy metal stressed induced genes that can be used as biochemical markers

Plants under the effect of heavy metal stress are going through distinctive biochemical reactions which we can measure through certain markers. Metallothioneins (MTs) are proteins that have a great affinity to heavy metal ions - such as cadmium, copper, and zinc. To respond to this heavy metal stress, plants synthesize higher levels of MTs. The elevated levels of MTs act as signposts of the stress buildup. In this sense, the glutathione (GSH), an antioxidant compound of plants, is also influenced in its concentration by the heavy metal stress. While under stress, GSH levels tend to drop as glutathione is consumed by the detoxification processes.

Another biochemical marker widely applied is proline, which is a non-essential amino acid that might accumulate in plants as a consequence of different abiotic stresses, including a heavy metal contamination. The concentration of proline represents the protective mechanism provided to the plant by the heavy metals. The Sod enzyme together with Catalase and Peroxidase also have important functions in relieving heavy metal stress. These enzymes are responsible for removing ROS in excess which are the oxygen reactive species produced in producer plants due to heavy metal exposure, that causes oxidative stress in plants.

Also, MDA that is a byproduct of lipid peroxidation is usually a marker for damage caused by heavy metals which is oxidative in nature. An increasing MDA accumulation shows higher amounts of lipid peroxidation and oxidative stress in the plant cells. In addition, alterations of chlorophyll content and photosynthetic process traits are noticed with heavy metal stress. The decrease in chlorophyll content, besides the changing measurable parameters like the rate of photosynthesis, stomatal conductance, and quantum yield, indicates the unfavourable role of heavy metals on the plant physiological processes. Together, these biochemicals strips allow us to assess the severity of heavy metals stress in plants as well as observe the coping tactics needed for the reduction of stress damages (Ghori et al., 2019; Hasan et al., 2017; Jalmi et al., 2018).

Molecular expression of various metabolic pathways and associated genes in rice under heavy metal stress

According the Cd, As, Pb and Hg concentration in the rice roots, the plant triggered the biological defense mechanism of detoxification that starts at the instance of metal mobilization. Several metabolic pathways simultaneously get started by their gene expression which is envisioned as the stress caused to your body by the heavy metals. The other method is based on the encapsulation of metal ions through the process of biosynthesis here the phytochelatin and PCS enzymes are such to be used. The PCs coordinate the removal of the toxic effects of heavy metal ions by raising their electrical charge. Secondly, rapeseed responds to the ROS (metal stress) by the antioxidant system, which has SOD, CAT, and POD enzymes which have the capability of removing the ROS molecules.

Besides the above in mind, the hallmark of metal-induced transcriptional activator genes including the metal transporters and detoxification genes is the life-saving purpose of the process. GSTs and MTs in turn, show higher copper quantity as a result of copper sequestering and copper evacuation through the mechanisms of copper's bondages and elimination. In addition, the genes for osHAMA2 and osHAMA3 showing relatedness to the transportation of ions in the cell, are greatly expressed for efficient zinc uptake in plants. The two-fold system activation and the connected genes which are supposed to benefit the plant by limiting the accumulation as well as oxidative stress will help in anti-metal stress (Faizan et al., 2024; Rajput et al., 2021).

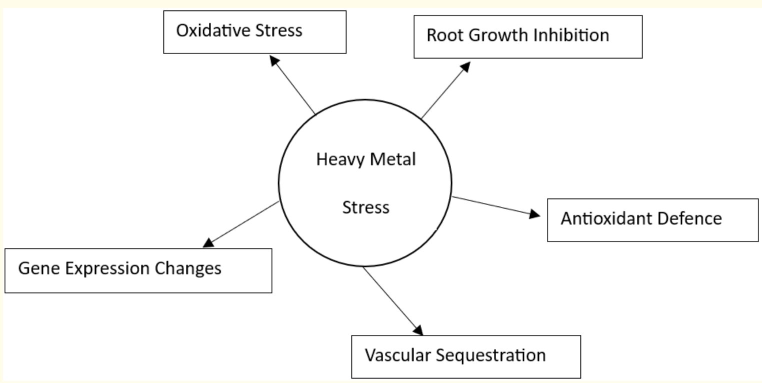

Figure 2: Different types of stress that the rice plants experience in the presence of heavy metals.

Role of MicroRNA in Abiotic stress response in rice with special reference to Heavy metal toxicity stress

Introduction of MicroRNA

miRNAs, small RNA molecules, take part in the regulation of genetic information. They have 21-23 nucleotide sequences that are ubiquitous in plants, animals, and some viruses (Voinnet, 2009). MiRNA regulates genes by base pairing to the 3' UTR of mRNAs which binding down-regulate and leads to degradation or translational repression (Cai et al., 2009). In plants, miRNAs affect many physiological processes including, but not limited to, plant development, hormone signaling pathways, both biotic and abiotic stress responses as well as other processes. These genes now express lower and as a result affect plant growth, development, and the stress resistance in general (S. Verma & Sarkar, 2022). In the animal kingdom, the miRNAs function among the different cells in processes including, growth, cell specialization, programmed cell death and immune responses (Z. Li et al., 2018). They also possess roles in the illness of cancer, heart disease and disorders that affect neurodegeneration where being out of balance can turn down the normal gene activity and cell process (Junn & Mouradian, 2012). In the case of humans microRNA are used highly as biomarkers for diagnosis as well as a targets for treatment of various diseases. These smaller molecules could be found in many fluids like blood, saliva and urine and this is an important tool for early diagnosis as well screening (Saini et al., 2021). In general miRNAs play a role in controlling gene expression, in plants and animals offering insight into biological functions disease pathways and potential treatment approaches (B. Zhang et al., 2006).

How MicroRNA is different from other RNAs

MicroRNA that is also commonly referred to as miRNA is a small RNA molecule, the length of which is typically 21 to 23 nucleotides. It is too involved in regulating some of genes after transcription (Rupaimoole & Slack, 2017). This is possible by recognizing different patterns of base sequencing on the mRNA. Cut mRNA down or get it translated less frequently so the amount of a protein of interest is reduced (Scherer & Rossi, 2003). Through processing of pri miRNA in the nucleus to pre miRNA, and mature miRNA in the cytoplasm, the richly known molecules called miRNA are made (Macfarlane & Murphy, 2010). On contrary small nuclear RNA (snRNA) is involved in RNA splicing, a process, which is essential for excising introns and connecting exons in pre mRNA to yield mature mRNA (Lee & Rio, 2015). Usually, snRNAs are about 150 nucleotides long. These are small nuclear ribonucleoprotein particles (spliceosome) components that, for instance, assist with the assembly of spliceosomes and performing splicing processes within the cell nucleus (Delpu et al., 2015). Heterogeneous nuclear RNA (hnRNA) refers to RNA transcripts that are considered precursors (pre mRNA) before undergoing processes such as capping, splicing and polyadenylation to transform into mRNA (J. Wang et al., 2022). HnRNA tends to be longer and more variable in length compared to miRNA and snRNA serving as the transcript of genes that proteins (Ying et al., 2008). While miRNA, snRNA and hnRNA play roles in regulating gene expression and RNA processing, small interfering RNA (siRNA) has a function, in RNA interference (RNAi) (Hung & Slotkin, 2021). siRNA, typically consisting of 20-25 nucleotides facilitates the breakdown of target mRNA. Hinders its translation. It is commonly utilized in research or therapeutic applications to silence genes (Hu et al., 2020). In that case, miRNA decides the level of gene expression while snRNA performs splicing of RNA, hnRNA comes under the process of making mRNA and siRNA is involved in RNA interference, all of them have their role which determine cell function (Lam et al., 2015).

Involvement of MicroRNA in abiotic and biotic stress in plants as well as its role in animals and human species

miRNAs are the important elements in the active functionality network of plants and animals and they are the critical participants in responding to stimuli in the environment and have numerous roles regarding essential biological reactions (H. Zhang et al., 2016). By regulating various molecular response mechanisms to abiotic stresses (like drought, salinity, cold, and heat) in plants, plant miRNAs govern signal transduction and gene expression machinery. They control the accessibility of genes that yields gene products involved in regulation of stress conditions such as osmotic adjustments, ion manipulations and development of antioxidant enzymatic activities (Raza et al., 2023). Consequently, they enable plants to manage differences between their current conditions and surroundings and endure even in extreme conditions. In addition to that key feature of plant miRNA is that they are part of the plants defence against biotic stress which includes pests and pathogens (Basso et al., 2019). Through inhibiting gene expression of plant defence this miRNA has a critical role in the instruction of plant defence responses correctly so the plant can defend against the pathogen attacks (Yang et al., 2021). Among the most unique and necessary non-coding RNAs, microRNAs (MiRNAs) are crucial in animal and humans life, in all the biologically active forms (Bhatti et al., n.d.). Developmentally, miRNA regulates the expression of genes which are vital in creating the difference of cell types, organ and the overall growth (Shivdasani, 2006). Mature human adult mir-50467 miRNAs contribute to planning signaling pathways and process fine-tuning core cellular function such as cell cycle progression, apoptosis and metabolism (Rolle et al., 2016). In terms of external and internal challenges, miRNAs play a major role the in adaptive mechanisms that allow animal to deal with various types of stress and disruptions (P. Singh et al., 2021). MiRNAs control the gene networks involved in reactions to stress, such as oxidative stress, inflammation, hormonal signaling and immunity responses, in which the resulting stress-resistant traits are often genetically programmed (Ibáñez-Cabellos et al., 2023). As matter of fact, it is not just reflection of miRNAs that help to connect different animals and human beings. There is an additional aspect that is critical involvement of miRNAs in diseases. Dysregulated expression of many miRNAs tends to be related to the development of different cancerous, cardiovascular diseases, some brain disorders and some diseases that affect both brain and development, metabolic syndromes, as well as some immunity-related cases (Rivera-Barahona et al., 2017). MiRNAs, which belong to the first group, contribute not only to the carcinogenesis process but accelerate metastasis; on the contrary, second type of miRNAs plays a role of a tumor suppressor that hampers abnormal cell proliferation and restores proper DNA repair mechanisms (Kim et al., 2018). However, a detailed analysis of both ail and non specific aspects of miRNAs therapy would have a substantial power in the capacity of biomedical tools which is essential for advances in diagnosis and focused therapy in future (Ouyang et al., 2019),(Ghamlouche et al., 2023).

Name of Genes	***Function***	***References***
DREB1A/CBF3	Regulates cold and drought stress responses	(Haake et al., 2002)
RD29A	Responsive to dehydration and ABA signalling	(Yamaguchi-Shinozakiaib & Shinozaki, 1994)
SOS1	Involved in salt tolerance	(Shi & Zhu, 2002)
HSP70	Heat shock protein, aids in heat tolerance	(Y. Wang et al., 2015)
ABF3	ABA-responsive element binding factor	(Fujita et al., 2013)
APX	Ascorbate peroxidase, ROS scavenging	(Foyer & Shigeoka, 2011)
LEA	Late embryogenesis abundant protein	(Park et al., 2011)
P5CS	Delta-1-pyrroline-5-carboxylate synthase	(Szabados & Savouré, 2010)
RD22	Responsive to drought and salt stress	(Yamaguchi-Shinozaki & Shinozaki', 1993)

Table 3: Genes which are involved in abiotic stress and their functions.

MicroRNAs are vital players in controlling gene expression in abiotic stress conditions in plants. Also, post-transcriptional regulators of 20-24 nucleotides micrometers in length, miRNAs suppress target mRNA expression by degradation or inhibition of translation by complementary binding (Z. Ma & Hu, 2023). As a result of abiotic stress, i.e., drought, salt, cold or heat, and heavy metals, miRNAs are critical for promoting specific gene expression in modulated mechanisms for plants to adapt to stress conditions (B. Zhang, 2015). Furthermore, miRNAs target genes encoding stress response transcription, ion channel, as well as enzyme-related stress signaling and tolerance pathways generates optimal expression for plants stress reactions by providing stable protection the body without producing body damage or wasting energy (Pagano et al., 2021a). In addition, miRNAs act as the bridges of connections between diverse stress-responding pathways (Pagano et al., 2021b). They facilitate growth and survival of plants under the continuous pressure from the negative environmental factors from all the sides. Moreover, this role extends to that of hormone signaling, which includes the control of abscisic acid (ABA) or jasmonic acid (JA) related paths- both essential for the stress response to be effective (V. Verma et al., 2016). Even more, during epigenetic control, miRNAs are involved in initiating chromatin changes or methylation these patterns in plants that are exposed to abiotic stress (Salgado et al., 2021). Therefore we only have to conclude from this entire network of communication mechanisms which demands are made on plants by the environment: Micro-RNAs (MiRNAs) are the main factors in the survival and normal function of the organism during long space missions in harsh conditions. Overall, the miRNAs are like the knots in a network that connects all plant responses and adaption to abiotic stress: they are the key in its survival and growth in adverse conditions or frobic environments (Dong et al., 2022).

To cope with abiotic stresses rice shows the positive influence of multiple environmental stress factors by the mediation of miRNA which is considered an important link in these mechanisms of stress tolerance. Many miRNAs in rice have been discovered that trigger reactions in saprophytic pathways (Feng et al., 2021; K. Kumar et al., 2022). MiR156 is a typical example which functions by targeting the SQUAMOSA PROMOTER BINDING PROTEIN - LIKE (SPL) genes that control almost all development and stress responses of the plant. Upon experiencing drought stress, miR156 mechanism of SPLs downregulation can lead to an increase in drought tolerance through both the regulation of stomatal closure and the expression of genes that control stress responses (Xie et al., 2006; L. L. Zhang et al., 2022). Also, an important miRNA is miR319, which is involved in the regulation of TCP transcription factors responsible for leaf development and stress responses (Fang et al., 2021). When drought and salinity are added to rice, the expression of miR319 is induced as a result which results in the repression of TCP genes and reorganization of stress-responsive pathways. miR319, besides this, can regulate genes which remove the reactive oxygen species (ROS). This consequently helps rice plants that are undergoing abiotic stresses to avoid oxidative stress (Zhou et al., 2013; Zhou & Luo, 2014). Besides, miR164 is one of the miRNAs associated with abiotic stresses in rice. It succeeds against NAC transcription factors that act as coordinators of different stress-related signaling pathways. In response to drought and salinity conditions, miR164 obtains the NAC genes in the regulation and leads to the reform of root structure, water uptake, and stress tolerance mechanisms in rice. Apart from that, miR164 has been found to be implicated in the regulation of genes related to ABA signaling adding more evidence of its function in stress resistance (Fang et al., 2014). In addition, miR396 has been showed over and over again to be a major the growth and stress responses both coordinator and the trait mediator of many other physiological processes in rice. The possible interaction could be the reduction of mitotic cell factors (GRFs) when the plant suffer the enemy attack by the triggering of the plant developmental programs which is the drug targets (Chandran et al., 2019; H. Wang et al., 2023). While subjected to rice abiotic stress period, molecular mechanisms were very intricate. This is because miR396 as the main factor accounting for the inhibition of GRFs is believed to be behind the root elongation, nutrient uptake enhancement, and expression of many genes that protect against abiotic stress resulting to the rice tolerance to abiotic stress (Yuan et al., 2019).

Names of MicroRNA	***Function***	***References***
miR156	Regulates developmental transitions	(Huang et al., 2009)
miR159	Targets MYB transcription factors	(Reyes & Chua, 2007)
miR166	Involved in leaf polarity and shoot meristem	(Kelsell et al., 2005)
miR167	Regulates auxin signalling	(Ren et al., 2006)
miR169	Targets NF-YA transcription factors	(L. Li et al., 2012)
miR172	Controls flowering time	(Llave, 2004)
miR319	Regulates TCP transcription factors	(Schommer et al., 2012)
miR396	Targets GRF transcription factors	(Jones-Rhoades, 2012)
miR398	Involved in response to oxidative stress	(Zeng et al., 2014)

Table 4: Some of the microRNAs and their functions found in plants other than in rice plants.

Role of Abiotic Stress of Japonica Rice Species

Japonica type of the dry subspecies of rice that is known for excellent grain quality and its ability to tolerate temperate climates is subject to biotic stress, and the result is the decline in plant growth and development (Pacleb et al., 2021). The heavy metal stress includes the cadmium, lead, or mercury deposition which thus require absolute ecological requirements for growing japonica rice, and it further leads to soil and water systems contamination. These metals get accumulated in the plants, organisms and hinder different metabolic procedures like photosynthesis, digestion, and cell division (P. K. Rai et al., 2019). So, the plant becomes poisonous. Along with this, cadmium results in a competition between nutrients which consequently affect the photosynthesis process and enzyme activities that degrade the growth, yield, and grain quality of japonica rice (Wu et al., 2024). Water stress such as reduced water intake also inhibits photosynthesis, translocation of nutrients and general growth of the plant. High salinity strains the plants, causes ion toxicity, reduces the cell metabolism, and finally reduces their yields. At very high temperatures and heat stress, cells may have trouble and, as a result, the process is disrupted, the gene expression is changed, and the quality and the output of the grain are decreased. Those species lacking nitrogen or phosphorus are weak and cannot be successful in their growth and reproduction processes (Zampieri et al., 2023). As to japonica rice that is seen to have a broad spectrum of stress response mechanisms. In order to respond to poisonous metals, japonica rice activates different systems. Those include metal root barriers which are planted at the plant sites where metals may not develop and penetrate tissues (NaziaTahir et al., 2021). Biosorption is a process of immobilization of metal cations with vacuoles or cell wall of plants or microorganisms to avoid the disruption of their cellular operations (Y. Ma et al., 2016). Examples might contain deep roots or water regulation using stomata is the case of drought. The processes that are salt tolerant depend on the ability to retain ions out of the cells and also on metabolic compartmentalization. As a result, heat shock proteins and antioxidants are activated which are supposed to protect the cellular structure against damages. The stress factor is removed by the changes in physiology like root morphology and higher nutrient uptake efficiency which come up as the adjustment processes (Mansour & Salama, 2019). Moreover, plant breeding as well as genetic modification techniques are used to enable the japonica rice types to fight against challenges such as abounds of heavy metals, drought, saltiness and heat. Besides a series of agricultural techniques such as soil renovation, plant based remediation, water tapering and nutrient enrichment are introduced to deal with the stresses and help japonica rice to grow for long in soil (Shaheen et al., 2023).

Role of Abiotic Stress on Indica Species Rice

One of the challenges for Indica varieties which have good reputation for being stable in warm and humid tropical climate with high productivity is the stresses induced by abiotic factors. Experts have stated that drought, salinity, temperature extremes, nutrient deficiency and heavy metal stress are the main factors for the drop in Indica rice yield (Latha et al., 2019). The negative effect of drought stress is a serious aspect of Indica rice varieties, as it leads to the deterioration of water conditions for growth and development. It provides a disrupted photosynthesis, a lack of mineral intake, and eventually a reduced plant growth which in turn result in yield losses. The problem of salinity of soil or water and negative reaction of Indica rice type is connected with the salinity stress that tends to decrease ability of water absorption and to cause ion toxicity. This, in its turn, results in impaired rice growth and loss of productivity (Bhandari et al., 2023; Muhammad et al., 2024). Indica rice responds to both heat and cold stress as their cellular processes and gene expression wreck and yields are affected together with grain quality. Overheating causes heat stress and furthermore turns into heat-based hypertrophy that leads to generally poor development and low yield while cold stress slows down plant development and growth in the coolest regions (Dasgupta et al., 2020). The severity of nutrient deficiencies trigger problems related to plants growth, plant metabolism and at last result in the lowest yield when adequate management is not undertaken (Yadav, 2010). Further, the lead, cadmium and other toxic metals' stress as a consequence can show up as a poisoning, make the nutrient intake difficult and most ultimately affect this Indica rice variety (Nawab et al., 2022). Indica rice species makes a use different strategy as response to environmental conditions. The adaptation is done by physical means that for example involve modifications in root morphology and the use of osmotic adjustment and antioxidant defense mechanisms to counteract the consequences of stress (Dingkuhn et al., 2017). Since the breeding programs concentrate in developing promising Indica rice varieties which possess specific traits such as drought tolerance, salinity tolerance, heat resistance, nutrient use efficiency and heavy metal removal targets, strategies and mechanisms, then should the focus should be where (Basu et al., 2010). The agronomic management in Indica rice cultivation is based on several practices that one need to consider very carefully. These methods encompass irrigation, soil conditioning, crop rotation, and cultivation of stress-tolerant crops by using sustainable agricultural science to have the farm that will make it strong and fruitful even in unfavourable environments (N. Kumar et al., 2022; Sun et al., 2024).

Conclusion

More than 50 percent of the India's forests is likely to experience the transition of forest types in the near future. At times it compares the rice yield in India decreases because of events like droughts and other calamities, whereas it has risen as much as 400 percent during 1950-2015 in other countries. The model of DSSAT shows the probabilities of 12% decline in the rice harvests with the increase in the temperature, while changes in the precipitation may reduce the yields per area by 31. 3% till 2030. When rice plants are exposed to temperatures that will be about 1°C higher than normal for several days, then the yield and biomass of rice may be reduced by as much as 10%. From the experiments conducted in the rice fields, it is evident that there will be a 12 percent saving in costs. 2% to 35. 6% decrease in photosynthesis the rate of which increases by 3. 6°C to 7°C. Running the chance to incline in the planting calendar from −14 to +14 days could afford a 12. even 5% to 25% declines in yields were reported.

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