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# Multiple Stress Tolerant Crop Varieties in India: Scope, Status & A Way Forward

COMPENDIUM



**ICAR-National Institute of Abiotic Stress Management**

**Malegaon Kh, Baramati, Pune**

# MULTIPLE STRESS TOLERANT CROP VARIETIES IN INDIA: SCOPE, STATUS AND A WAY FORWARD

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# FOREWORD

Stress factors include combinations of abiotic and biotic stressors that simultaneously or sequentially affect plants and microbiomes, causing a significant decrease in plant growth, yield, and overall health. Abiotic stresses like drought, salinity, flooding, extreme temperatures, and heavy metal contamination significantly affect crop yields and quality. These stresses are responsible for about 50% of crop yield losses in agriculture. In India, out of approximately 140 million ha of cultivable land, about 120 million ha is affected by drought, salinity, high and low temperature, soil erosion, salinity/alkalinity, soil acidity, water logging, heavy metals, nutrient deficiencies and other edaphic constraints. Further, biotic stresses are also posing serious threats to agricultural productivity. To address these multifaceted challenges, it is very crucial to develop effective management practices and multi stress-tolerant crop varieties (MSTCVs) which can tolerate multiple stresses including both biotic and abiotic stresses. This necessitates smart breeding which integrates both conventional breeding methods and modern biotechnological tools, including transgenics and genome editing. However, several organizations under umbrella of National Agricultural Research System (NARS) developed and released such MSTCVs varieties in different crops developed.

This compendium on "Multiple Stress Tolerant Crop Varieties in India: Scope, Status, and a Way Forward" presents the data on registered germplasm tolerant to different abiotic stresses. Further, authors outlined a smart breeding roadmap for accelerating the development and adoption of multiple stress tolerant crop varieties in India. I hope that this compendium will add valuable information to repository of abiotic stress management. The road map providing actionable scientific and policy insights for the development of climate-smart crop varieties in foreseeable future for sustainable development of Indian agriculture.

**(Himanshu Pathak)**

**Dated the 20th September, 2024**
**New Delhi**

# PREFACE

In the face of a rapidly changing climate and mounting pressures on global food security, managing both abiotic and biotic stresses is crucial to sustain food production to feed over 9.5 billion world population by 2050. Several organizations under umbrella of National Agricultural Research System (NARS) working hard to sustain food production by minimizing the impacts of different stresses on crop production through the agronomic and crop improvement interventions. However, in the recent years, occurrence of combined and multiple stresses has become a new norm dragging the productivity down further. Managing such complex and multifaceted events through agronomic intervention alone may not be effective and economical. Therefore, availability of climate smart crop varieties and matching agronomic packages that can withstand multiple stresses will be the need of the hour. India, with its diverse agricultural landscape and climate, faces unique challenges from both abiotic stresses like drought, salinity, heat, heavy metal contamination and pollution, etc. as well as from biotic stresses such as pests and diseases. The crops may witness these stresses either individually or in combinations and/or often in a sequential manner.

To deal with such adversities, the development and adoption of multi stress-tolerant crop varieties (MSTCVs) will be pivotal in our quest to address the emerging threats to global food and nutritional security. Considering the importance of MSTCVs, in this compendium, '*Multiple Stress Tolerant Crop Varieties in India: Scope, Status, and a Way Forward'* is the collection of all information required to devise effective future strategies to enhance productivity to ensure food and nutritional security. It will also provide a scientific road map for developing climate smart varieties in India.

The authors wish that the information will be utilized by researchers and students for devising strategies for developing multiple stress tolerant crop varieties exploiting the genetic resources described here. Farmers will be equally benefited from the information about the available multiple stress tolerant crop varieties suitable for their agro-climatic regions. Policy makers will gain a clear understanding of the current status and the necessary steps to support the development, popularization and adoption of MSTCVs at a larger scale. The insights and complied information presented herein are intended to empower knowledge of all stakeholders associated with abiotic stress management in agriculture.

We hope that this compendium will not only provide information but also actionable strategies for the development of climate smart varieties and a way forward the agenda of climate resilience in Indian agriculture.

**Authors**

## CONTENT


| Section | Content | Page |
|---|---|---|
| **1** | **Scope: Importance of abiotic and multiple stresses** | 1 |
| 1.1 | The Imperative for Multiple Stress-Tolerant Crop Varieties | 2 |
| 1.2 | Abiotic and Biotic Stresses in Agriculture | 4 |
| 1.2.1 | Important Abiotic Stresses in agriculture and their Multifaceted Impact on Crop Production | 4 |
| 1.2.2 | Biotic Stresses: An Additional Layer of Challenges to Abiotic Stresses in Crops | 14 |
| 1.3 | Advancements and Achievements in Abiotic Stress-Tolerant Crop Varieties | 15 |
| 1.4 | The Emergence of Multi- and Combined Stresses: Moving Beyond Managing Single Stress Challenges in Agriculture | 17 |
| 1.4.1 | Management of Multiple Abiotic Stresses | 22 |
| **2** | **Status: Overview of multiple stress tolerant crop varieties in India** | 26 |
| 2.1 | From Concept to Reality: The Development and Significance of Multi-Stress Tolerant Crops in India | 27 |
| 2.1.1 | Field crops | 27 |
| 2.1.2 | Commercial crops | 34 |
| 2.1.3 | Forage and fodder crops | 39 |
| 2.1.4 | Horticultural crops | 39 |
| **3** | **A Way Forward: Upscaling the Development and Adoption of Multi-Stress Tolerant Crop Varieties** | 57 |
| 3.1 | Strategies for the Development of Multi-Stress Tolerant Crop Varieties | 58 |
| 3.1.1 | Understanding the Response of Crops to Multiple Stresses | 59 |
| 3.1.2 | Designing Climate-Smart Breeding Programs for Development of Multi-Stress Tolerant Crop Varieties | 75 |
| 3.1.3 | Green Super Rice (GSR) varieties: An example for successful breeding strategy for developing multiple stress tolerant varieties | 112 |
| 3.2 | Strategies for Scaling Up Adoption and Cultivation of Climate-Smart Varieties in Stress-Prone Regions: Building resilience at farm level | 113 |
| 4 | **Conclusion** | 118 |
| 5 | **References** | 120 |

## TABLE CONTENT


| Table No. | Title | Page |
|---|---|---|
| 1. | Percent yield reduction (range) in major cereals and millet crops due to different abiotic stresses | 13 |
| 2. | Percent yield reduction in different crops due to various biotic stresses | 14 |
| 3. | Impact of multiple stresses or combined stresses on yield of different crops | 20 |
| 4. | Impact of multiple or combined stresses on quality in different crops | 21 |
| 5. | Multiple stress tolerant varieties of field crops | 29 |
| 6. | Multiple stress-tolerant varieties of important commercial crops | 35 |
| 7. | Multiple stress tolerant varieties of forage and fodder crops | 39 |
| 8. | Multiple stress tolerant varieties of fruit crops | 44 |
| 9. | Multiple stress tolerant varieties of vegetable crops | 49 |
| 10. | Multiple stress tolerant varieties of medicinal, aromatic and plantation crops | 51 |
| 11. | Multiple stresses in maize and their insights or salient findings | 60 |
| 12. | Multiple abiotic and biotic stresses affecting physio-biochemical traits in rice | 62 |
| 13. | Mitigation effect/mechanisms of $eCO_2$ under combined heat and drought in different crops | 64 |
| 14. | Wild species of crops known for different abiotic stress tolerance | 77 |
| 15. | Germplasm of different crops registered for traits associated with different abiotic stress tolerance | 82 |
| 16. | List of genes/QTLs identified to be involved in saline/alkali stress tolerance in plants | 97 |
| 17. | List of some genes/QTLs involved in metal toxicity tolerance in plants | 98 |
| 18. | List of genes/QTL involved in nutrient use efficiency of major nutrients in plants | 99 |

## FIGURES


| Figure No. | Title | Page |
|---|---|---|
| 1 | Climate change and its multifaceted effect on crops and possible strategies to mitigate it thereof | 4 |
| 2 | Effect of heat and hailstorms on fruit crops | 10 |
| 3 | The foxtail millet crop gown under shallow basaltic soils at ICAR-NIASM field showing nitrogen deficiency | 12 |
| 4 | Three main categories of possible types of stresses based on their interaction | 19 |
| 5 | Schematic model illustrating the plant-stress (biotic and abiotic) interactions at the molecular level | 74 |
| 6 | Schematic illustration of breeding design for development of multi-stress tolerant crop variety | 111 |

SECTION 1

# SCOPE: IMPORTANCE OF ABIOTIC AND MULTIPLE STRESSES

## 1.1 The Imperative for Multiple Stress-Tolerant Crop Varieties

Agriculture plays a pivotal role in addressing the intertwined challenges of food and nutritional security, climate change, and the increasing global demand for food. As climate change affects weather patterns and crop productivity, agriculture must adapt through innovative practices and technologies. Climate change challenges efforts to maintain and improve crop production in many regions. Despite elevated carbon dioxide ($eCO_2$) can boost yields for $C_3$ crops like wheat and rice by enhancing photosynthesis and water-use efficiency, this benefit is often overshadowed by the adverse effects of high temperatures, heat and drought. In contrast, $C_4$ crops such as maize, sugarcane, millet, and sorghum may benefit from higher $CO_2$ levels, especially under drought conditions, due to their high temperature and heat tolerance and high photosynthetic efficiency and adapted to hotter and drier climates. However, climate change overall poses significant risks, with simulated crop yield losses ranging from 7% to 23% under severe scenarios and without adaptation (Rezaei *et al*., 2023). Similarly, the yield of the major crops in India may reduce by 9–18% due to climate change (Pathak, 2022).

The impact of climate change on crop production is multi-faceted. Climate change exacerbates abiotic stresses such as water stresses (drought and flood), edaphic stresses (salinity and nutrient or elements imbalance), and atmospheric (cold, heat, elevated $CO_2$) which can impair crop growth and reduce yields by disrupting physiological processes (**Fig. 1**). It also influences biotic stresses by altering pest and disease dynamics, potentially increasing the frequency and severity of infestations and outbreaks that further threaten agricultural productivity and sustainability.

Abiotic stresses alone have the potential to cause ~51%–82% crop yield loss in major food crops of global agriculture (Ashima *et al*., 2024). The abiotic stresses such as water stresses (drought, flood and/or submergence), extreme temperatures (hot and cold), excessive salts (salinity/sodicity), chemical factors (pH and heavy metals), air pollutants (nitrogen and sulfur dioxide and ozone), radiation (UV), and other stressors including nutrient deficiencies pose threats to global food and nutritional security by causing substantial yield and quality losses. Approximately, 90% of the cultivable land is being affected by one or more stressors (Minhas *et al*., 2017), which causes the loss of millions of dollars each year consequent to a decrease in crop productivity and quality. It is estimated that abiotic stresses can reduce yields by up to 80% in major crops depending on intensity and severity (Oshunsanya *et al*., 2019; Lohani *et al*., 2020; Moulick *et al*., *2024*). The percent yield losses due to abiotic stresses are region and crop-specific, which is ultimately associated with weather abnormalities linked to

climate change (Pathak *et al*., 2022). An investigation on the likelihood of yield loss of wheat, maize, rice and soybeans in response to droughts of various intensities in the 10 largest producing countries revealed that wheat production in the USA and Canada faces over 80% probability of falling below average during exceptional droughts, while maize in India and rice in Vietnam and Thailand are particularly at risk. Soybean yield losses are most severe in the USA, Russia, and India, with the risk of yield reduction increasing more sharply with escalating drought severity (Leng and Hall, 2019). Drought alone causes an average annual yield loss of 17% in the tropics, and severe droughts in key food-producing countries have reduced global grain production by 5% or more in some years (Vijayalakshmi, 2018). In Europe, drought and heat waves led to greater yield losses in cereals, with reductions of 9% and 7.3%, compared to non-cereals, which experienced losses of 3.8% and 3.1%, respectively and reported almost more than three times crop yield losses compared to last five decades (Brás *et al*., 2021).

In future, agriculture will need to produce more from areas affected by salinity and drought also to meet the growing demand for food to feed over 9.5 billion world population by 2050. The situation is likely to worsen further with the predicted increase in frequency and intensity of climatic extremes and a drastic reduction in the availability of water for agricultural use unless cultivars equipped with both drought and or salinity tolerance and high water-use efficiency (WUE) become available. Hence, management of abiotic stresses in agriculture is very crucial to minimize such losses. Managing abiotic stresses involves a multifaceted approach that includes genetic improvements, agronomic practices, and technological interventions. Agronomic strategies such as effective water management techniques like drip irrigation (can save up to 40% of water) and rainwater harvesting are essential for effective management and mitigation of drought and salinity, while crop diversification and conservation agriculture can mitigate the water, edaphic and other abiotic stresses besides better utilization of resources. However, genetic augmentation through traditional and or modern breeding tools like Marker Assisted Selection (MAS), genetic engineering and genome editing will remain at the forefront in developing climate-resilient varieties. Additionally, technological interventions, including remote sensing and forewarning systems will provide farmers with timely information to make informed decisions regarding stress management. By integrating these diverse approaches, agriculture can better adapt to the increasing challenges posed by abiotic stresses, ultimately supporting sustainable food production systems in the backdrop of climate change owing to global warming.

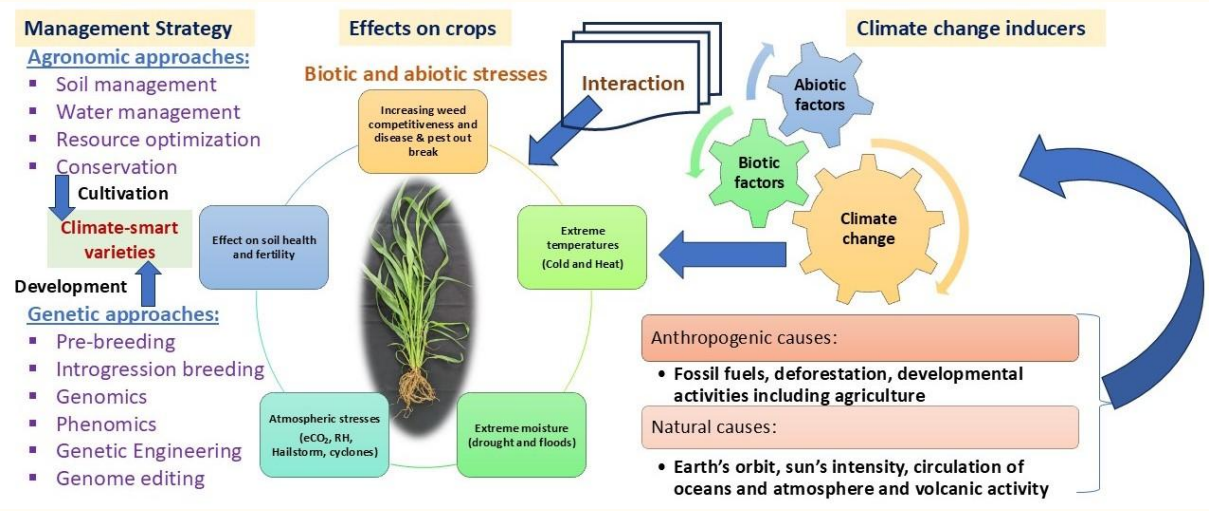



**Figure 1. Climate change and its multifaceted effect on crops and possible strategies to mitigate it thereof.**

This compendium explores the themes, starting with a highlighting of important abiotic stresses and their impact on crop production and the progress made in developing stress-tolerant varieties. Additionally, it also highlights the emerging threat of multiple concurrent stresses and their implications for crop productivity and quality. We have described the importance and status of developing climate-smart varieties equipped with tolerance to various stresses, addressing both the achievements and limitations of current varieties in India. Further, the book will also delve into strategies for advancing the breeding of multiple stress-tolerant crop varieties, including understanding crop responses to combined stresses and the underlying mechanisms of tolerance.

At the end of the book, we also discussed possible comprehensive approaches that integrate conventional and OMICS-based molecular breeding which offers a roadmap for breeding climate-smart varieties with enhanced multiple stress tolerance. The book can be considered as a compendium of Plant Genetic Resources for Multiple Stress-Tolerant Crop Varieties By addressing these diverse challenges, we aim to support sustainable food production systems and guide the future for developing crop varieties for climate resilience.

## 1.2 Abiotic and Biotic Stresses in Agriculture

### 1.2.1 Important abiotic stresses in agriculture and their multifaceted impact on crop production

Abiotic stresses can severely affect crop productivity by affecting physiological processes, reducing yields, and thereby compromising food security. Understanding their impact has

spurred research into developing resilient crop varieties that can thrive under adverse environmental conditions.

**Drought:** Drought significantly impacts crop production, affecting various crops differently and leading to substantial yield losses. For instance, in cereal crops like wheat and maize, drought stress can severely hinder germination, root development, overall growth and biomass gain. Research indicates that drought can reduce wheat yields by 30% to 50%, particularly during critical growth stages such as flowering and grain filling (Chakraborty *et al*., 2023). Similarly, a $C_4$ crop, maize is highly sensitive to water deficits, studies show that yield losses can reach up to 40% under severe drought conditions, primarily due to reduced kernel formation and weight (Boraiah *et al*., 2021)

Leguminous crops, such as chickpeas and lentils, also suffer considerable yield losses due to drought. These crops are particularly vulnerable during the flowering and pod-filling stages, where insufficient water can lead to poor seed set and reduced pod development. Terminal drought and heat stress (exceeding 35°C) during the flowering and grain-filling stages were responsible for approximately 50% of the yield losses in chickpea (Negussu *et al*., 2023). Overall, the adverse effects of drought on plant growth and development, coupled with the resulting yield losses, underscore the urgent need for developing drought-tolerant crop varieties and implementing effective water management strategies to enhance productivity (Singh, 2016).

**Waterlogging/flooding:** Flooding has a profound impact on crop physiology and production, affecting various crops and leading to significant yield losses. Excessive rainfall and waterlogging can severely impede plant growth by causing root oxygen deprivation, stunted root growth, horizontally and vertically, and photosynthesis, which is critical for nutrient uptake and overall plant health. For instance, rice a staple food for millions, is particularly sensitive to flooding. Prolonged inundation can lead to yield reduction of up to 50%, especially during critical growth stages such as flowering and grain filling. Additionally, crops like soybeans and wheat may also suffer under flooded conditions, with studies indicating average yield losses of approximately 3% for rice and 2% for wheat during significant flood events, resulting in losses amounting to billions of dollars globally (Kim *et al*., 2023; Wang *et al*., 2022).

The effects of flooding extend beyond immediate yield losses; they also disrupt the overall growth and development of crops. Waterlogged conditions can lead to the deposition of mud and debris on plants, further hindering photosynthesis and growth (Kaur *et al*., 2020). Moreover, flooding can wash away essential nutrients from the soil, leading to long-term soil degradation and reduced agricultural productivity. In regions prone to flooding, such as the Yangtze River Basin in China, agricultural productivity can decline by 40% due to frequent and prolonged flood events, underscoring the critical need for effective flood management strategies in agriculture (Wang *et al*., 2022). Overall, the adverse effects of flooding on crop production highlight the importance of developing resilient agricultural practices to mitigate these challenges.

**High temperatures:** High temperatures and heat stress significantly impact crop production, leading to reduced growth and substantial yield losses across various crops. For example, wheat and rice are particularly sensitive to heat stress during critical reproductive stages. Research indicated that for every 1°C increase in temperature during the flowering period, wheat yield can decline by approximately 3-4%, while rice production can decrease by about 10%. These losses are primarily due to reduced grain number and weight, as heat stress adversely affects pollen viability and fertilization processes. In extreme cases, heat waves can lead to yield reductions of up to 40% in crops like sunflowers and maize, which are also highly susceptible to elevated temperatures during their reproductive phases.

Additionally, legumes such as chickpea and soybean experience significant stress under high-temperature conditions. Heat stress can lead to poor seed set and reduced pod development, resulting in yield losses of up to 50% in chickpeas during critical growth stages. The physiological effects of heat stress include accelerated leaf senescence, decreased photosynthesis, and impaired water uptake, all of which contribute to stunted growth and diminished crop yields. As global temperatures continue to rise, the frequency and intensity of heat stress events are expected to increase, which will have an impact on stomatal conductance, net photosynthesis, biomass gain and ultimately productivity further necessitating the development of heat-resistant crop varieties and effective management practices to mitigate their impacts. Heat stress causes huge losses in yield and quality in fruit crops (Fig. 2 A&B).

**Low temperatures:** Low temperatures, including chilling and freezing stress, significantly impact crop production, leading to reduced growth, cell division, photosynthesis, water transport, and substantial yield losses across various crops. For instance, in cereals like wheat

and barley, cold stress can reduce yields by up to 40% if it occurs during critical growth stages such as flowering and grain filling (Soualihou *et al*., 2022). Chilling injury occurs when temperatures fall below 15°C but remain above freezing, often damaging plant membranes and resulting in symptoms like wilting, cellular deposits, and heightened vulnerability to pathogens (Anonymous, 2013). Freezing injury, on the other hand, arises when soil or plant fluids freeze, causing disruptions to structures and functions (Anonymous, 2013).

Legumes like chickpea and soybean are also highly sensitive to low temperatures, with studies indicating yield losses of up to 50% under cold conditions (Soualihou *et al*., 2022). Low-temperature tolerant crops like rye can withstand temperatures as low as 4°C when fully hardened, while more sensitive crops like durum wheat may suffer damage at temperatures below -10°C (Snyder *et al*., 2005). To alleviate the adverse effects of cold stress, crop plants have developed cold-acclimation mechanisms. These include the accumulation of specific proteins, alterations in membrane composition, regulation of signalling pathways, osmotic adjustments, and the production of endogenous hormones (Soualihou *et al*., 2022).

**Salinity**: About 20% of the world's irrigated land is affected by salinity (Munns and Tester, 2008), and if present trend continues, about 50% of irrigated land will come under salinity (Mahajan *et al*., 2008). Soil having an electrical conductivity (EC) of ≥4 dS $m^{-1}$ is referred to as saline soil, corresponding to 40-mM NaCl (Horie *et al*., 2011). Salt stress poses a significant impact on seed germination, root and shoot length, plant height, overall plant growth, biomass gain and fruit development (Liang *et al*., 2014; Sabagh *et al*., 2021). If the pH of the soil is greater than 8 and has a high concentration of soluble salts and an exchangeable sodium percentage (ESP) of more than 15%, then that soil is referred to as saline-alkaline soil. In the native environment, salinity stress is generally caused by chlorides and sulphates of neutral salts of Na, K, Ca and Mg (e.g. NaCl, $Na_2SO_4$, $CaCl_2$, $MgSO_4$), whereas saline-alkali stress is usually driven by basic salts (e.g., $NaHCO_3$, $Na_2CO_3$) (Fang *et al*., 2021). In India, out of 147 million hectares of degraded land, an estimated 6-7 million hectares of soil are damaged by salinity/alkalinity from which roughly 2.0 million hectares of salt-affected land are in the process of reclamation (Kumar and Sharma, 2020). Additionally, it is anticipated that the area under salinity soil is likely to rise to a projected 16.2 million hectares by 2050 (Bishnoi *et al*., 2021).

Salinity is a significant abiotic stress that adversely affects crop production by disrupting plant growth, development, and yield across various agricultural systems. High salt

concentrations in the soil lead to osmotic stress, which hinders water uptake and creates an ionic imbalance that can be toxic to plants. To counter the detrimental effects, plants employ intracellular and extracellular osmoregulation processes that regulate osmotic stress and dehydration (Rivera-Ingraham and Lignot, 2017). These different defence mechanisms can be either monogenic or polygenic, with dependence on different pathways (Gupta and Huang, 2014). In both saline and saline-alkali stress, osmoregulatory substances (e.g., proline, betaine, sugars, and polyamine) are accumulated in plants (Deinlein *et al*., 2014; Guo *et al*., 2015).

In saline or saline-alkaline soils, $Na^+$ is the most prevalent soluble salt. It can enter root cells through ion channels (non-selective cation channels) or $K^+$ transporters. Excessive $Na^+$ is then transported to the shoot through transpiration, which can lead to $Na^+$ toxicity and disrupt cellular functions. To avoid this, plants either maintain $Na^+$ homeostasis in the cytoplasm or reduce $Na^+$ transport to the shoot (Cao *et al*., 2022). Accumulation of $Na^+$ into the vacuoles is another way of lowering the toxicity for the plants, or plants can exclude $Na^+$ transport by physical barriers like casparian strips in roots.

Wheat is particularly sensitive to salinity, with studies indicating that salinity can reduce grain yield by approximately 39% during critical growth stages such as anthesis and grain filling (Kopecká *et al*., 2023). This decline in yield is primarily due to reduced photosynthetic activity, impaired nutrient uptake, and accelerated senescence of reproductive organs, which collectively diminish the plant's ability to produce grain effectively.

Other crops, such as rice and soybean, also experience significant yield losses due to salinity. Rice, for example, can suffer yield reduction of up to 50% in saline conditions, particularly during the flowering stage, which is crucial for grain development (Godoy *et al*., 2021). Similarly, soybean exhibit reduced growth and yield under saline stress, with yield losses reported to be around 30% in saline soils (Kopecká *et al*., 2023). As global salinity levels continue to rise due to factors such as improper irrigation practices, increase in irrigation water salinity, ingression of sea water in coastal areas, erratic rainfall and climate change, developing salinity-tolerant crop varieties and implementing effective management strategies becomes increasingly necessary for sustaining agricultural productivity and ensuring food security in the changing climatic scenarios (Boraiah *et al*., 2023).

**Atmospheric stresses:** Erratic Rains: Erratic rainfall patterns significantly impact crop production by disrupting the water supply essential for plant growth and development. In

regions where crops like maize and rice are cultivated, inconsistent rainfall can lead to both drought and flooding conditions, each detrimental to yield. For instance, maize is particularly sensitive to water scarcity during its flowering stage; insufficient rainfall can result in kernel abortion and reduced grain weight, leading to yield losses of up to 40% (Daryanto *et al*., 2016). Conversely, excessive rainfall can cause waterlogging, impairing root function and nutrient uptake, which can further decrease yield.

**Hailstorms:** Hailstorms can cause severe physical damage to crops, leading to significant yield losses. The impact of hailstorms varies depending on the crop stage at the time of the storm. For example, young seedlings may be destroyed, while mature crops can suffer from bruising and defoliation, leading to reduced photosynthesis and yield. Research indicated that hailstorms can cause yield reduction of up to 50% in crops like wheat and barley, particularly when storms occur during critical growth stages such as flowering or grain filling (Rötter and Geijn, 1999). The immediate effects of hailstorm damage can lead to a decline in crop quality and marketability, compounding the economic losses for farmers and impacting local food supplies. Figure 2 (C-D) shows the damage caused by sudden hailstorms in different crops in the farmers' fields in Maharashtra.

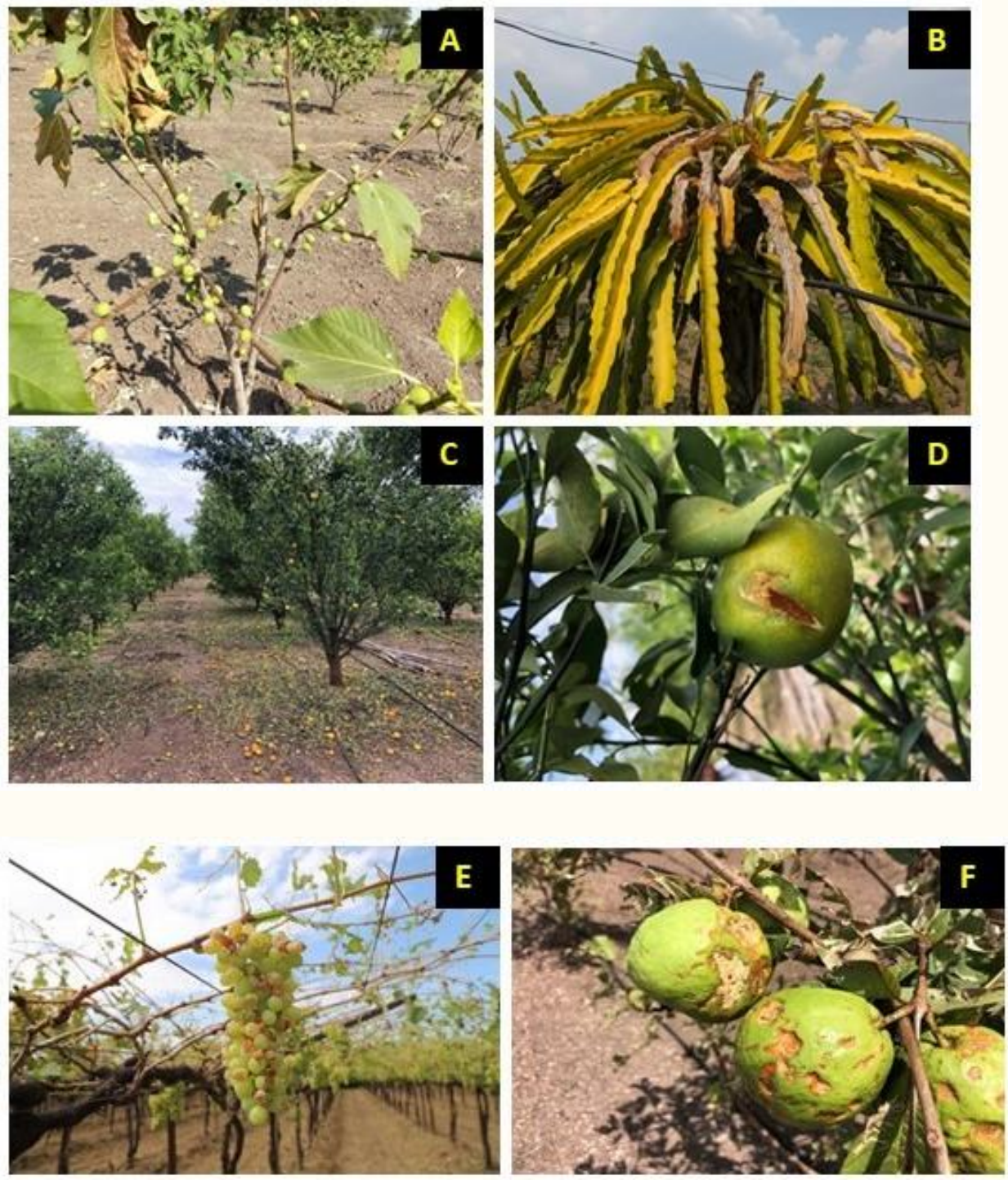



**Figure 2. Effect of heat and hailstorms on fruit crops. high temperature stress in fig (A); sunburning in dragon fruit (B) and hailstorm damage in sweet orange (C&D), grapes (E) and guava (F).**

**Carbon Dioxide Levels**: Elevated atmospheric carbon dioxide ($CO_2$) levels can have mixed effects on crop production. While increased $CO_2$ can enhance photosynthesis and potentially boost growth in some crops in $C_3$ crops such as wheat and soybean by increasing partial pressure of $CO_2$ in mesophyll cells and in and around RUBISCO thus reducing the

photorespiration drastically, the benefits are often offset by other stressors such as higher temperatures and water scarcity. For instance, some studies suggested that elevated $CO_2$ can increase yields by 10-20%, but this is contingent upon optimal growing conditions being maintained (Ainsworth and Long, 2005). Furthermore, higher $CO_2$ levels have been linked to reduced protein and nitrogen content in crops, which can negatively affect crop quality and nutritional value (Myers *et al*., 2014). As a result, while elevated $CO_2$ may enhance growth, the overall impact on food security remains complex and dependent on a multitude of interacting environmental factors.

**Low and High Relative Humidity (RH):** Relative humidity levels can significantly influence crop health and yield. Low humidity can lead to increased transpiration rates, causing water deficit stress in crops such as tomatoes and peppers, which are sensitive to moisture levels. This stress can result in wilting, reduced fruit size, and ultimately yield losses of up to 30% under prolonged and intense low RH conditions (Dieleman *et al*., 2019). Conversely, high humidity can create favourable conditions for fungal diseases, such as powdery mildew in cucumbers and grapes, which can lead to significant yield losses and reduced fruit quality. High RH levels can also interfere with pollination processes in crops like corn and soybean, leading to poor seed set and reduced yields (Hatfield and Prueger, 2015). Therefore, maintaining optimal humidity levels is crucial for maximizing crop productivity in varying climatic conditions.

**Nutrient stresses:** Nutrient stresses represent a significant category of abiotic stresses that contribute to yield losses in crops. When plants experience deficiencies or imbalances in essential nutrients, such as nitrogen, phosphorus, or potassium, their growth, development, and overall productivity can be severely affected. These nutrient imbalances can lead to poor plant health, reduced photosynthesis, and lower resistance to diseases and pests. For instance, nitrogen deficiency often results in stunted growth and yellowing of leaves (Figure 3), while phosphorus deficiency can impair root development and energy transfer within the plant. Such deficiencies not only diminish crop yields but also affect the quality of the harvested produce. Further, the potential role of deficiency or excess nutrients in a plant's defence status against other biotic (pests and diseases) and abiotic stresses via nutrient sensing and signalling mechanisms in plants cannot be underestimated. Primary nutrients (nitrogen, phosphorus, and potassium), secondary nutrients (calcium, magnesium, and sulphur), micronutrients (zinc,

boron, iron, and copper), and beneficial nutrients (cobalt, selenium, and silicon) are essential for helping crop plants cope with abiotic stress (Kumari *et al*., 2022).



**Fig. 3. The foxtail millet crop gown under shallow basaltic soils at ICAR-NIASM field showing nitrogen deficiency**

Nutrient imbalance significantly impacts both crop yield and quality, leading to substantial agricultural losses. Nitrogen deficiency, which is common in many agricultural soils, can cause reduced plant growth and lower yields due to impaired photosynthesis and chlorophyll production. At the same time excess N application under suboptimal conditions or abiotic stresses like drought can cause significant yield losses. For instance, due to low and excess N application in maize, 3-75 % yield losses were reported (Boraiah *et al*., 2022). Similarly, phosphorus deficiency negatively affects root development and energy transfer, which can reduce crop yields and quality, particularly in staple crops like wheat and maize. Published estimates indicate that 30–32% of cropland and 43% of grassland suffer from soil phosphorus deficiency. In contrast, Europe and North America have the largest areas with excess phosphorus. France and the United States have the highest amounts of this excess in their respective regions. On the other hand, Asia shows the greatest phosphorus deficiency, with India having the highest proportion of deficiency among countries (McDowell *et al*., 2024). Potassium deficiency often results in poor fruit development and increased susceptibility to diseases, as seen in tomatoes and potatoes (Marschner, 2012). Metals toxicity adds another complexity to balanced nutrition and stresses in plants which is gaining more importance in recent years (Narendrula-Kotha *et al*., 2020). As the majority of the cultivable soils are deficient in one or more nutrients, identification of nutrient use efficient genotypes and improving nutrient use efficiency of externally applied nutrients will be useful in enhancing nutrient availability and uptake in crop species for sustaining productivity. Hence, managing

nutrient stress should be considered an important strategy in mitigating other stresses as individual or combined.

**Yield loss estimates due to abiotic stresses:**

The extent of yield losses due to abiotic stresses varies depending on the crop's inherent tolerance, the growth stage of the crop, its sensitivity, and the intensity of the stress. Major abiotic stresses, including extreme temperatures, drought, and nutrient deficiencies or toxicities, can lead to annual crop yield losses ranging from 51% to 82% globally (Oshunsanya *et al*., 2019). Pathak *et al*. (2022) have compiled data on the percentage of yield losses across different crops resulting from various abiotic stresses at different stages. The range of yield reduction in important crops due to different stresses is presented in Table 1**.**

**Table1. Percent yield reduction (range) in major cereals and millet crops due to different abiotic stresses**

| **Crops** | **Stresses** | **Yield reduction (%)** | **References** |
|---|---|---|---|
| Rice | Drought | 22-70 | Pathak *et al*. (2022) |
| | Submergence | 30-70 | |
| | Heat | 6-30 | |
| | Cold | 9-29 | |
| | Salinity | 50-75 | |
| Wheat | Drought | 50–60 | Zhao *et al*. (2020) |
| | Submergence | 50–70 | Olgun *et al*. (2008) |
| | Heat | 4-15% | Sidhu (2023) |
| | Cold | 3-86 | Hongting *et al*. (2017) |
| | Salinity | 13-45 | Sabagh *et al*. (2021) |
| Maize | Drought | 13-90 | Boraiah *et al*. (2022) |
| | Waterlogging | 7-76 | |
| | Heat | 1-90 | |
| | Heat + Drought | 100 | |
| | Cold | 8-75 | |
| | Salinity | 10-34 | |
| | Low N | 3-22 | |
| | High N | 19-75 | |
| Little millet | Drought | 62-81 | Basavaraj *et al*. (2022) |
| Foxtail millet | | 19-52 | |
| Bajra | | 31-72 | |
| Proso millet | | Up to 55 | |
| Tef | | 69-72 | |
| Finger millet | | Up to 100 | |

### 1.2.2 Biotic Stresses: An additional layer of challenges to abiotic stresses in crops

Plant diseases and pest outbreaks, exacerbated by climate change, global food trade, and evolving pathogens and insects, pose a significant threat to food security and health. Biotic stress encompasses the damage inflicted on plants by living organisms such as parasites, weeds and pathogens, including viruses, bacteria, fungi, nematodes, and insects. Plants are persistently subjected to biotic stress, resulting in alterations to their metabolism and physiological damage, which ultimately reduces their productivity. Losses due to pests and disease may be direct and indirect. For instance, Cerda *et al*. (2017) predicted through modelling that pests and diseases result in 26 % primary yield losses (26%) and also 38% secondary yield losses in coffee.

Globally, pests and diseases account for an estimated one-sixth of farm produce losses annually. These losses are particularly severe in Asia and Africa, where they significantly impact smallholder farmers' ability to feed their families (Sharma *et al*., 2021). Almost all the crops are notably affected by one or more biotic factors. Yield losses caused by diverse biotic stresses in major crops are presented in Table 2. Every year, up to 40 per cent of global crop production is lost due to plant pests and diseases. Each year, these losses cost the global economy over USD 220 billion (FAO, 2024). Savary *et al*. (2019) documented global yield losses in major crops attributable to biotic stresses associated with 137 pathogens and pests. The reported losses were as follows: wheat (21.5%, with a range of 10.1% to 28.1%), rice (30.0%, ranging from 24.6% to 40.9%), maize (22.5%, with a range of 19.5% to 41.1%), potato (17.2%, ranging from 8.1% to 21.0%), and soybean (21.4%, with a range of 11.0% to 32.4%). In India, biotic stresses alone cause a loss of about 25-30% of the extant value of the commodity annually (Vision document, NIBSM).

**Table 2. Percent yield reduction in different crops due to various biotic stresses**

| Crops | Biotic stresses | Yield reduction (%) | References |
|---|---|---|---|
| Rice | Blast disease | 70-80 | Simkhada *et al*. (2022) |
| | Bacterial Blight | 14.9-47.4% | Ansari *et al*. (2018) |
| | | 70% | http://www.knowledgebank.irri.org/ |
| | Rice tungro | 100 | |
| | Weed | 12–22 | Savary *et al*. (2012) |
| | Stem borer | 1.9–5.8 | |
| | Combined disease and pests | 25–43 | |
| Maize | Weeds | 34 | Constantine *et al*. (2020) |

| | | | |
|---|---|---|---|
| | Animal pests | 18 | |
| | Disease | 16 | |
| Wheat | Fungal diseases | 15–20 | Figueroa *et al*. (2018) |
| | Pests and pathogens | 4.84- 16.29 | Zhang *et al*. (2022) |
| | Wheat stem | 50-100% | Kayim *et al*. (2022) |
| | Stripe rust | 10 -70% | |
| | Powdery mildew | 5-62% | |
| | Karnal bunt | up to 40% | |
| | Flag smut | 5-20% | |
| | Septoria disease | 30–50% | |
| | Tan spots | 5-50% | |
| | Root rot | 5.7% | |
| | Crown root rot | 35% | |
| | Black point | up to 90% | |
| | Wheat mosaic virus | up to 90% | |
| | Wheat spindle streak mosaic virus | 30% | |
| Blackgram | Cyst nematode | 26–78% | Singh *et al*. (2024) |
| | Powdery mildew | up to 90% | Boraiah *et al*. (2022b) |

*Note: The yield loss range is based on different studies*

## 1.3 Advancements and Achievements in Abiotic Stress-Tolerant Crop Varieties

Abiotic stress-tolerant crop varieties (ASTCVs) play a significant role in minimizing yield losses in agriculture, particularly in India, where diverse agro-climatic conditions often lead to significant crop failures due to stresses like drought, salinity, and extreme temperatures. The cultivation of ASTCVs is considered one of the best strategies to cope with climate change and abiotic stresses (Boraiah *et al*., 2021; 2023). Research and development efforts by organizations like the Indian Council of Agricultural Research (ICAR) and state agricultural universities (SAUs) have led to the release of various high-yielding and stress-resilient varieties of crops such as rice, wheat, pulses, and oilseeds, which are essential for sustaining agricultural productivity to face vagaries of climate variability (Singh, 2016). For instance, ICAR-NRRI, Cuttack, Odisha has evaluated, identified, and developed several rice varieties/genotypes tolerant to submergence, stagnant flooding, aerobic conditions, and high temperatures (Boraiah *et al*., 2021). The adoption of ASTCVs has been shown to enhance agricultural productivity and resilience to climate change. For example, the introduction of drought-tolerant rice varieties has benefited approximately 700,000 farmers in India, particularly in states like Odisha, where these varieties have led to yield increases of up to 872 kg per hectare, translating to significant economic benefits for farmers. Similarly, the development of salt-tolerant

varieties has opened new opportunities to reclaim salinized lands, further contributing to food security and nutritional security (Boraiah *et al*., 2021).

However, the non-availability of quality seeds, low genetic yield potential and susceptibility to biotic stresses are affecting the widespread adoption of these varieties. By integrating ASTCVs into farming systems, India can bolster its resilience to climate variability, ensuring a stable and equitable food supply while also supporting the livelihoods of millions of farmers. The ongoing efforts to develop and disseminate these resilient varieties are crucial for achieving long-term agricultural sustainability in the country (Boraiah *et al*., 2021; 2023)

Developing crop varieties with enhanced tolerance to multiple abiotic stresses—such as drought, flooding, extreme temperatures, salinity, and mineral toxicity—is essential for sustaining and improving crop yields in the face of changing climate scenarios (Lohani *et al*., 2020). Researchers worldwide have undertaken significant efforts to breed climate-resilient crop varieties that can withstand various abiotic stresses. This work has led to the identification of quantitative trait loci (QTLs) and genes associated with abiotic stress tolerance in numerous crops, utilizing advanced genomic tools and statistical methods (Boraiah *et al*., 2021; Kaur *et al*., 2023). Additionally, screening diverse plant genetic resources has uncovered trait-specific genetic stocks exhibiting tolerance to different abiotic stresses. Notable achievements include the development of rice varieties that thrive in submergence-prone areas and can endure high temperatures (Boraiah *et al*., 2021). Various salinity-tolerant varieties of different crops have also been developed and released by National Agricultural Research Systems (NARS) in India.

However, the increasing frequency and intensity of climate extremes, such as simultaneous or sequential occurrences of drought and salinity or extreme temperatures, pose significant challenges to global agriculture, threatening food security, nutritional security, and overall crop productivity. Traditional breeding methods have typically focused on single stress tolerance, yet the simultaneous manifestation of multiple stresses necessitates the use of modern genetic tools to develop resilient crops. To address these challenges, researchers are emphasizing an integrated approach that leverages advanced breeding techniques, genomic tools, and biotechnological innovations to incorporate multiple stress-resilient traits or QTLs into key crops with high-yielding backgrounds. Considerable progress has been made in identifying QTLs, genes, biomolecules, and pathways linked to multiple stress tolerance. For example, the recently released molecular-bred chickpea variety, Chickpea 10216, exhibits tolerance to both abiotic stresses (drought) and biotic stresses (fusarium wilt and dry root rot)

in India (Bharadwaj *et al*., 2021). Accelerating its adoption by farmers is crucial to validate its potential under multiple stress conditions.

Transgenic approach is another promising tool to accelerate the development of climate smart crop varieties. A notable example of successful commercialization in this area is Monsanto's DroughtGard™ maize, launched in the United States in 2013. This genetically modified crop features a transgene encoding cold shock protein B (CSPB) derived from the bacterium *Bacillus subtilis*. CSPB acts as an RNA chaperone, helping to maintain physiological performance during stress by ensuring normal RNA function. Research indicates that DroughtGard™ maize outperforms wild-type maize in terms of grain yield under water stress conditions (Moglia and Portis, 2016).

Considering the fact that we need to produce more from decreasing cultivable areas to feed over 9.5 billion estimated world population by 2050 in the backdrop of an increase in frequency and intensity of climate extremes owing to climate change, in this compendium we will briefly discuss about the strategies need to be adopted to develop climate-smart varieties with sustainable yield and equipped with multiple stress tolerance to ensure sustainable global food and nutritional security.

## 1.4 The Emergence of Multi- and Combined Stresses: Moving Beyond Managing Single Stress Challenges in Agriculture

Due to global warming and its associated climate abnormalities, crops are increasingly facing a combination of abiotic and biotic stresses, which significantly impact their growth and yield. The simultaneous occurrence of abiotic stresses, such as drought and heat, drought, and waterlogging and sometimes combinations of more than two stresses like drought, heat and salinity or flooding is also being witnessed in field conditions, which is reported to be more detrimental to crop production compared to these stresses occurring separately at different growth stages. Abiotic stress conditions like extreme moisture, extreme temperatures, and salinity also influence the spread and evolution of pathogens, insects, and weeds, with these stresses potentially transforming minor pests into significant threats. Furthermore, stresses like drought and nutrient deficiency conditions enhance competitive interactions between weeds and crops, as many weeds exhibit better water and nutrient use efficiency than crops.

The effects of combined stress factors on crops are not always additive, as the outcomes depend on the interactions between these stress factors. Plants adapt their responses to these combined stresses, displaying both unique and common responses. Understanding these interactions is crucial to comprehensively assessing their impact. Recent research has utilized frameworks such as stress matrices to map the interactions among various abiotic and biotic stresses, revealing that these combinations can have both negative and positive effects on plants. Developing crop varieties with improved tolerance to such combined stresses necessitates identifying relevant physio-morphological traits.

Before understanding response and the detrimental impact of multiple stresses in crops, it is very crucial to know the different kinds of stresses based on their occurrence. Stresses affecting plants can be categorized into three main types based on their interactions: single, multiple individual, and combined stresses **(Figure 4)**. A single stress involves only one stress factor impacting plant growth and development. Multiple individual stresses occur when two or more stresses impact plants at different times without overlap, whereas combined stresses occur concurrently with some degree of overlap. For example, drought and heat stress during summer are examples of combined abiotic stresses, while simultaneous attacks by bacterial and fungal pathogens represent combined biotic stresses. Additionally, a sequential stress scenario might involve one stress factor influencing the plant's response to a subsequent one, as seen when drought predisposes *Sorghum bicolor* to *Macrophomina phaseolina* a causal agent of charcoal root rot (Goudarzi *et al*., 2011). Similarly, the occurrence of wilt and rot diseases in several crops due to high moisture or flooding conditions is the most common example of sequential stress.

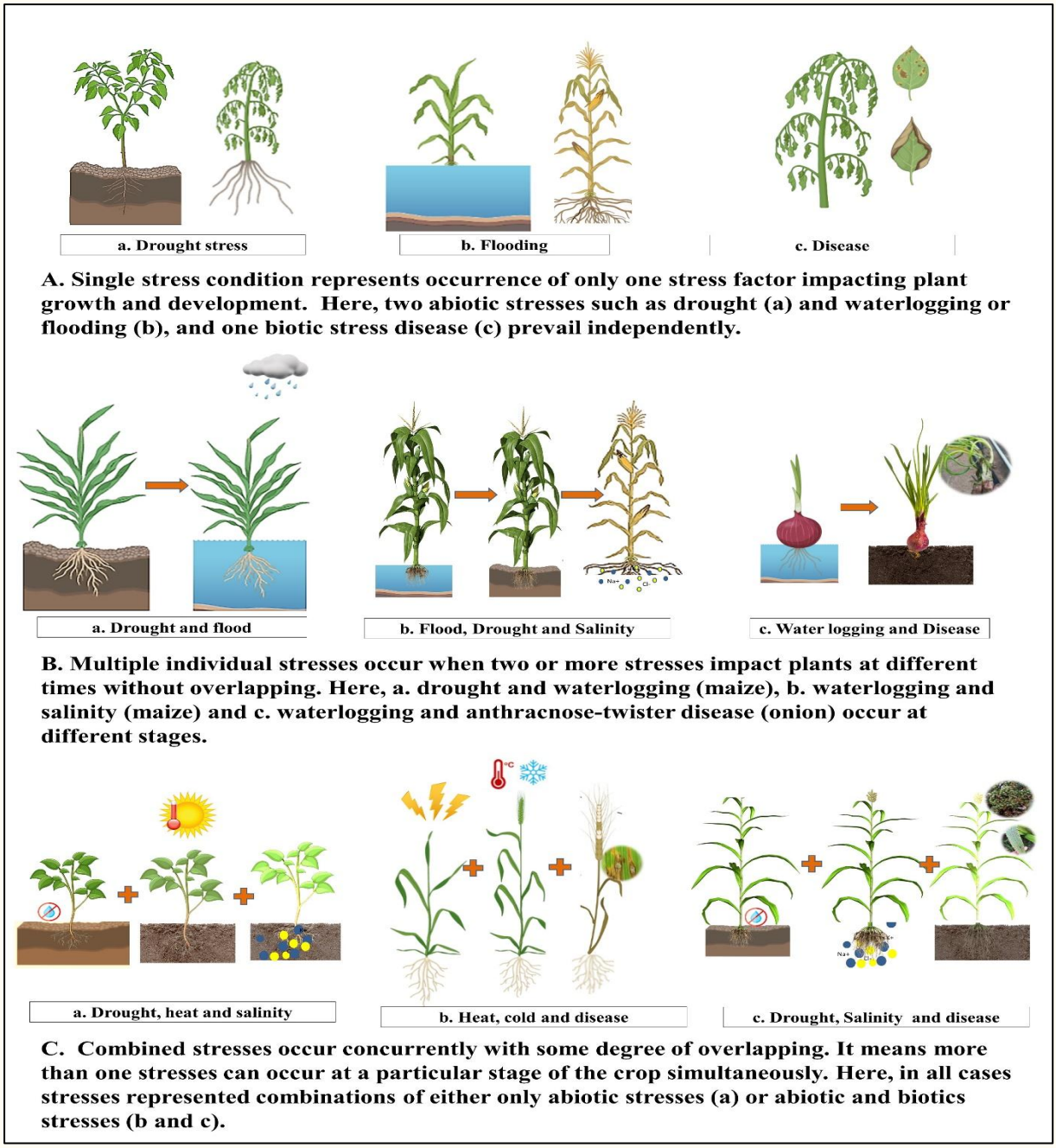



**Figure 4. Three main categories of possible types of stresses based on their interaction viz. Single (A), multiple individual (B), and combined stresses (C). Additionally, a sequential stress scenario may occur as a result of one (prior) stress as shown in the example of twister disease of onion (c) under multiple individual stress (B).**

Repetitive or recurrent stresses involve intermittent or recurring exposures to single or multiple stresses, such as multiple spells of high temperatures or recurrent drought during different plant growth stages. For instance, the prevalence of intermittent downpours and dry spells of hot days results in multiple occurrences of floods, drought, and high temperatures at different phenological stages of plants representing repetitive stresses. Pandey *et al*. (2017) narrated different kinds of combinational stresses occurring in nature along with examples.

Like multiple abiotic stresses plants frequently witness multiple biotic stresses either simultaneously or sequentially, with infections by combinations of fungi, bacteria, and viruses leading to more severe disease symptoms than infections by individual pathogens. For instance, the interaction of these biotic stresses along with their impact on plants is well-documented by several studies (Lamichhane and Venturi, 2015 and Pandey *et al*., 2017).

However, the more complex and combinational stress seldom plants face both biotic and abiotic stresses concurrently. The "disease triangle," a concept that emphasizes the interaction between environmental factors, plant hosts, and pathogens, highlights how abiotic stressors like drought and salinity can influence plant susceptibility to various diseases. Specific examples include the effect of drought or salinity on the susceptibility of plants to pathogens causing various kinds of rusts, wilts, rots, and mildews (Pandey *et al*., 2017). Furthermore, environmental stresses like drought, high temperatures, and cold have been shown to increase the competitiveness of weeds over crops fuel the problem of the non-availability of labourers for weeding. Probably this is one of the most challenging problems for adopting Direct seeded rice (DSR).

Hence, under circumstances of increasing global warming and changing weather conditions considering the concurrent occurrence of multiple stressors in crops has emerged as a critical issue in contemporary agriculture. Crops today often contend with a combination of biotic stresses, such as pathogens and pests, alongside abiotic factors like drought and nutrient deficiencies. The interaction between these stressors can exacerbate their individual effects, resulting in significantly greater yield losses and compromised quality in different agricultural crops and also reported to affect forestry species (Teshome *et al*., 2020). For instance, a crop subjected to both a fungal pathogen and water scarcity may experience cumulative damage that surpasses the impact of each stressor in isolation. Tables 3 and 4 show the impact of combined stresses on yield and quality in selected crops.

**Table 3. Impact of multiple stresses or combined stresses on yield of different crops**

| **Crop** | **Stresses** | **Yield losses (%)** | **References** |
|---|---|---|---|
| Rice | DT+HT+ $CO_2$ | 20-21 | Mariem *et al*. (2021) |
| Wheat | DT+HT | 33 | Tack *et al*. (2014) |
| | DT+HT | 9.2 | Matiu *et al*. (2017) |

| | | | |
|---|---|---|---|
| | 50% water deficit stress and elevated $O_3$ (+ 20 ppb) | 43.6 | Ghosh *et al*. (2020) |
| Maize | DT+HT | 11.6 | Matiu *et al*. (2017) |
| | | Up to 100 | Heiniger (2001) |
| | DT+HT (for each excess degree day) | 1.7 | Lobell *et al.* (2011) |
| | High N + drought | 19 | Bennett *et al*. (1989) |
| | High N under rainfed condition | 75 | |
| Soybean | DT+HT | 12.4 | Matiu *et al*. (2017) |
| Sorghum | DT+HT | 87 | Craufurd and Peacock (1993) |
| Banana | DT+HT | 46 | Chaudhari *et al*. (2023) |

**Note:** DT- Drought; HT: Heat/high temperature/ warming-; LT: Low temperature/cold/chilling; SL: Salinity; WL: Waterlogging; HAT: High air temperature

**Table 4. Impact of multiple or combined stresses on quality in different crops**

| Crop | Stresses | Quality | References |
|---|---|---|---|
| Barley | DT+HT | Reduced grain endosperm starch content | Worch *et al.* (2011) |
| Rice | DT+HT+ $CO_2$ | Decreased starch content, reduced baking quality | Mariem *et al*. (2021) |
| Tomato | Water stress + Nematode | Decrease in carotenoid levels of lycopene and β-carotene; Increase flavonoid levels, and chlorogenic acid sugar levels. | Atkinson *et al.* (2011) |
| Grape | DT+HT | Increased berry pH, decreased total acids, particularly organic acid content. | Hewitt *et al.* (2023) |

As a tropical country, India faces a complex array of multiple and combinable stresses, including frequent and severe droughts, floods, land degradation, and extreme temperatures (Ranjan *et al*., 2024). Abiotic stresses, which contribute to over 50% of crop productivity losses, pose significant threats to food and nutritional security for an additional 0.4 billion people in India by 2050. These issues are further compounded by biotic stresses, which alone account for annual losses of about 25-30% of the value of agricultural commodities. With

climate change expected to intensify both biotic and abiotic stresses, maintaining the efficiency of agroecosystems becomes a critical task. Addressing these challenges requires a multifaceted approach, including bridging knowledge gaps related to tolerance mechanisms in crop plants, and managing the frequent occurrence of multiple stresses.

The increasing complexity of agricultural challenges has highlighted the emergence of multi-stress environments, where crops are simultaneously exposed to a combination of biotic and abiotic stressors. This new dimension of stress, which includes interactions between pathogens, pests, drought, and nutrient deficiencies, far exceeds the impact of individual stressors alone. Traditional approaches that address single-stress conditions are becoming insufficient as these compounded stress scenarios lead to more severe crop damage and reduced yields. Understanding and managing multi-stress conditions is now crucial for advancing agricultural resilience. Researchers and practitioners must focus on developing crop varieties that can withstand and adapt to these complex stress interactions. This shift in perspective is essential for improving crop productivity and ensuring food security in the face of increasingly unpredictable environmental and biological challenges

### 1.4.1 Management of multiple abiotic stresses

Managing multiple abiotic stresses requires integrated approaches involving genetics, physiology, and agronomy. Techniques such as marker-assisted breeding, genomic selection, genome editing and precision agriculture are being leveraged to enhance stress tolerance and resilience in crops. Effective management strategies are essential for mitigating the impacts of these stresses, and they can be broadly categorized into agronomic approaches and crop improvement strategies.

#### 1.4.1.1 Agronomic approaches to manage multiple stresses

Agronomic practices play a crucial role in managing multiple abiotic stresses in crop production. One effective strategy is the implementation of conservation agriculture, which includes practices such as reduced tillage, cover cropping, and crop rotation. These practices improve soil health, enhance water retention, and reduce erosion, making crops more resilient to drought and salinity. For example, cover crops can improve soil structure and increase organic matter, which enhances water infiltration and retention, thereby mitigating the effects of drought (Vijayalakshmi, 2018).

Additionally, precision agricultural technologies, including soil moisture sensors and remote sensing, allow farmers to monitor crop conditions and apply water and nutrients more efficiently. This targeted approach can significantly reduce water use and improve crop resilience to stress. Research has shown that precision irrigation can increase water use efficiency by 20-50%, leading to better crop yields under drought conditions (Zhang *et al.*, 2017). Furthermore, integrated nutrient management, which combines organic and inorganic fertilizers, can enhance soil fertility and improve crop resilience to salinity and nutrient deficiencies (Kumar *et al*., 2020).

Another important agronomic practice is the use of mulching, which helps to conserve soil moisture by reducing evaporation, regulating soil temperature, reducing weeds, etc. Studies have demonstrated that mulching can reduce soil temperature fluctuations and minimize moisture loss, thereby enhancing crop performance under both high-temperature and drought conditions (Kumar *et al*., 2020). Overall, these agronomic strategies not only improve crop resilience to multiple stresses but also promote sustainable agricultural practices.

#### 1.4.1.2 Crop improvement approaches

Crop improvement strategies are essential for developing varieties that can withstand multiple abiotic stresses. Traditional breeding methods, along with modern biotechnological approaches, have made significant strides in enhancing stress tolerance in crops. For instance, the identification and incorporation of quantitative trait loci (QTLs) associated with drought and salinity tolerance have led to the development of improved varieties of rice and wheat that can perform better under stress conditions (Zhang *et al*., 2017).

Molecular breeding techniques, such as marker-assisted selection (MAS) and genomic selection, enable breeders to select specific traits associated with stress tolerance more efficiently. Recent advancements in genome editing technologies, such as CRISPR/Cas9, have also shown promise in creating stress-tolerant varieties. For example, researchers have successfully edited genes in rice to enhance salt tolerance, resulting in improved growth and yield under saline conditions (Zhou *et al*., 2020).

The development of multi-stress-tolerant varieties is particularly important, as many crops face multiple stresses simultaneously. Breeding programs that focus on combining traits for drought, salinity, and heat tolerance can lead to the creation of resilient varieties that maintain productivity under challenging conditions. Research has indicated that the adoption

of such multi-stress tolerant varieties can lead to a yield increase of 20-30% in stressed environments, significantly benefiting farmers and contributing to overall food security (Daryanto *et al*., 2016).

The importance of developing and promoting stress-tolerant varieties cannot be overstated. These varieties not only withstand adverse conditions but also maintain productivity, ensuring food security for growing populations. Tolerant varieties often require fewer inputs, such as water and fertilizers, thereby reducing environmental impacts and promoting sustainable farming practices. Furthermore, the use of these varieties can enhance farmers' resilience to climate variability, providing them with a buffer against the economic impacts of crop failures due to abiotic stresses.

Managing multiple abiotic stresses in crop production requires a multifaceted approach that combines agronomic practices and crop improvement strategies. The development and adoption of stress-tolerant varieties are crucial for enhancing agricultural resilience and ensuring food security in a rapidly changing climate. Continued research and investment in these areas are essential for building a sustainable agricultural future. However, current abiotic stress-tolerant varieties often exhibit limited scope, focusing primarily on individual stresses. Overcoming this challenge involves developing varieties with broader tolerance spectra, addressing multiple stresses simultaneously without compromising yield potential or nutritional quality.

Single abiotic stress-tolerant varieties have been developed to address specific environmental challenges such as drought, salinity, and extreme temperatures. While these varieties have shown effectiveness in improving crop yields under targeted stress conditions, they exhibit significant limitations when it comes to managing multiple stresses simultaneously. For instance, drought-tolerant maize varieties can maintain productivity in water-scarce environments; however, their performance may decline when exposed to additional stresses such as high salinity or extreme heat. This suboptimal use of single-stress tolerant varieties is primarily due to their narrow genetic focus, which often does not account for the complex interactions between different abiotic stresses that crops may encounter in real-world agricultural settings (Vijayalakshmi, 2018).

The effectiveness of single-stress tolerant varieties is further complicated by the fact that many crops experience multiple abiotic stresses concurrently. For example, a rice variety developed for salinity tolerance may not perform well under drought conditions, as the

physiological mechanisms that confer salinity tolerance often differ from those that enhance drought resistance. Research indicated that abiotic stresses can interact synergistically, leading to greater yield losses than would be expected from the individual effects of each stress (Zhang *et al.*, 2017). Consequently, the reliance on single-stress tolerant varieties can result in suboptimal agricultural productivity, particularly in regions increasingly affected by climate change and unpredictable weather patterns.

Given these limitations, there is a pressing need for the development of multiple stress-tolerant varieties that can withstand a combination of abiotic stresses. Breeding programs should focus on pyramiding multiple tolerance traits through conventional breeding techniques or advanced biotechnological approaches such as CRISPR/Cas9 gene editing. For instance, the development of rice varieties that combine drought tolerance (*DTY*), salinity tolerance (*Saltol*), and submergence tolerance (*SUB1*) has shown promising results in maintaining yield under diverse stress conditions (Daryanto *et al.*, 2016). Such multi-stress tolerant varieties are essential for ensuring food security in a rapidly changing climate, as they can help farmers adapt to the increasing variability of environmental conditions.

In conclusion, while single abiotic stress-tolerant varieties have made significant contributions to crop production, their limitations in managing multiple stresses highlight the urgent need for the development of multi-stress-tolerant varieties.

SECTION 2

# STATUS:

# OVERVIEW OF MULTIPLE STRESS TOLERANT CROP VARIETIES IN INDIA

## 2.1 From Concept to Reality: The Development and Significance of Multi-Stress Tolerant Crops in India

The importance of developing crop varieties tolerant to multiple abiotic stresses cannot be overstated. These varieties offer resilience against unpredictable climatic conditions, ensuring stable yields and safeguarding global food production amidst environmental uncertainties. Abiotic stresses such as drought, salinity, extreme temperatures, and erratic rainfall pose significant threats to global agriculture, causing substantial yield losses. In India alone, it is estimated that abiotic stresses can reduce crop yields by up to 50% annually (Vijayalakshmi, 2018). The development of abiotic stress-tolerant crop varieties is crucial for mitigating these challenges and ensuring food security in the backdrop of climate change.

The development and promotion of multiple abiotic stress-tolerant varieties are crucial for enhancing agricultural resilience and ensuring food and nutritional security in India and globally. These varieties not only withstand adverse conditions but also maintain productivity, requiring fewer inputs and promoting sustainable farming practices. In India, where agriculture is highly vulnerable to diverse climatic challenges, efforts are underway to develop and deploy multiple stress-tolerant crop varieties. Initiatives by agricultural research institutions and private sectors have led to the release of promising varieties adapted to varied agro-climatic zones.

Pinpointing the crucial role of MSTCVs in managing multiple stresses, we have attempted to gather information on multiple stress-tolerant varieties of field crops, commercial crops and horticultural crops including vegetable crops, fruit crops, medicinal aromatic and plantation crops developed in India.

### 2.1.1 Field crops:

Field crops are crucial for global food security as they provide essential staples like grains, legumes and oilseeds that form the foundation of human diets. Under a changing climate, these crops face challenges such as altered precipitation patterns and increased extremities of temperatures accelerating the occurrence of multiple stresses that can affect yields and quality. Ensuring the resilience of field crops through sustainable practices and innovative agricultural techniques is vital for maintaining food availability and nutritional quality in the backdrop of these climatic shifts.

Field crops and horticultural perennials exhibit different degrees of sensitivity to stresses due to their distinct biological and physiological characteristics and requirements. Field crops, which are typically annuals, have relatively shorter life cycles and are often bred for high productivity over a single growing season. This makes them more vulnerable to acute stressors, such as extreme temperatures, drought, salinity, submergence, flooding, etc., which can disrupt critical reproductive processes and lead to significant yield losses. Their sensitivity is influenced by the frequency and intensity of stresses, which can adversely impact seed-set and overall crop growth and productivity. For example, field crops have specific optimum and critical temperature thresholds for successful reproduction. When temperatures exceed these thresholds, various morphological and physiological processes that influence seed set are negatively impacted, resulting in substantial yield losses. The level of damage caused is based on crop sensitivity, duration and intensity of stress and stage of crop growth. This is evidenced form variations in the yield losses of different crops due to diverse stresses (Pathak *et al*., 2022). The impact of combined stresses or the occurrence of multiple stresses simultaneously is more pronounced compared to single stress and may be additive in most of the cases (Tables 3 and 4).

Mitigating stresses in field crops is crucial for ensuring stable yields and food security, especially in regions prone to environmental challenges. Zahra *et al*., (2021) observed differential responses of wheat genotypes for combined stresses of heat and drought indicating the potential opportunity to bred varieties for multiple stressors. In India, a number of varieties of field crops have been developed through conventional and molecular breeding approaches. For instance, developing and adopting stress-tolerant varieties like Swarna-Sub1 rice, which can endure complete submergence for up to two weeks, significantly benefits farmers in flood-prone areas of India and Bangladesh by maintaining productivity despite frequent flooding (Daryanto *et al*., 2016). Similarly, the wheat variety, Kharchia 65, which can tolerate both drought and salinity, has been instrumental in breeding programmes aimed at improving crop resilience in arid and semi-arid regions of India (Gupta *et al*., 2017). Groundnut variety ICGV 91114, known for its tolerance to drought, has proven reliable in maintaining stable yields under harsh conditions (Varshney *et al*., 2019). These examples highlight the importance of breeding stress-tolerant varieties to safeguard agricultural productivity and support farmers in managing the impacts of climate variability and environmental stresses. The information on the field crop varieties with multiple stress tolerance is given in Table 5.

**Table 5. Multiple stress tolerant varieties of field crops**

| Crop | Variety | Year | Organization | Area of adoption/ state | Multiple stresses | Biotic stress | Other features |
|---|---|---|---|---|---|---|---|
| Rice | Kalinga 1 | 1973 | ICAR-NRRI, Cuttack | All India | DT+LT | - | - |
| | Sabour Shree | 2015 | BAU, Ranchi | BH | DT+WL | Highly resistant to BPH, GLH and SB | |
| | DRR Dhan 47 | 2018 | ICAR-IIRR, Hyderabad | TS, AP, KA, KL, PY | DT+HT | - | Early maturity |
| | DRR Dhan 50 | 2018 | | AP, TS, TN, KA, BI, OR, CH, UP, MP | DT+WL | - | - |
| | CR Dhan 801 | 2019 | ICAR-NRRI, Cuttack | AP, TS, OR, UP and WB | DT+WL | Tolerant to BL, NB, BLB, SB, LF | |
| | CO 53 | 2020 | TNAU, Coimbatore | TN | DT | moderately resistant leaf blast, neck blast, sheath rot, brown spot and RTD | |
| | CR Dhan 308 | 2020 | ICAR-NRRI, Cuttack | | HT | resistance False smut, and Rice Tungro disease | |
| | CR Dhan 313 | 2020 | | | HT | Resistant to false smut, moderately resistant to BLB, Neck Blast, Leaf Blast. Tolerant to Gall midge, leaf folder, whorl maggot and rice thrips | |
| | CR Dhan 410 | 2020 | ICAR-NRRI, Cuttack | Odisha | WL | Resistant to neck blast, BLB, sheath rot and brown spot diseases. Resistant to stem | |

| Crop | Variety | Year | Organization | Area of adoption/ state | Multiple stresses | Biotic stress | Other features |
|---|---|---|---|---|---|---|---|
| | | | | | | borer, leaf hopper and leaf hopper insect pests. | |
| | Nagina 22 (N22) | - | - | - | DT+HT | - | - |
| Wheat | HD 2160 | 1998 | CSAUA&T, Kanpur | NEPZ | DT+HT | Resistant to BR | |
| | KRL-213 | 2012 | ICAR-CSSRI, Karnal | AS, BH, DL, HR, UP, RJ, PB, WB, UK | DT+SL, tolerant to to alkalinity | Karnal bunt | |
| | KRL 19 | 2011 | ICAR-CSSRI, Karnal | All India | WL+SL | | |
| | KRL 210 | 2012 | | BH, DL, HR, UP, RJ, PB, WB, UK | WL+SL | Resistant to rust and Karnal bunt | |
| | KRL 283 | 2018 | | UP | WL+SL | Resistant to Karnal bunt and LB | |
| Bajra | GHB-538 | 2005 | JAU, Jamnagar | GJ | DT+HT+LT | Resistant to Downey Mildew | Tolerant to lodging |
| Pigeon pea | Maruti | 1986 | AICRP and ICRISAT | MP, AP, KA | DT+WL | Wilt and Sterility mosaic (SMD) virus | |
| | Asha | 1993 | | KA, AP, CG | DT+WL | Wilt | |
| | MAL 13 | 2005 | BHU, Varanasi | UP, WB | DT+WL+SL | - | - |
| | Bahar | 1986 | RAU, Pusa | NEPZ | HT+LT | SMD | |
| Chickpea | JG-315 | 1984 | JNKV, Jabalpur | MP, CG | DT+HT | Wilt | |
| | Pant G 186 | 1996 | GBPUAT, Pantanagar | UK | DT+HT | Wilt, grey mold | |
| | JG-11 | 1999 | JNKV, Jabalpur | MP, CG | DT+HT | Wilt | |
| | JG -6 | 2006 | JNKV, Jabalpur | MP, CG | DT+HT | Wilt | |

| Crop | Variety | Year | Organization | Area of adoption/ state | Multiple stresses | Biotic stress | Other features |
|---|---|---|---|---|---|---|---|
| | JAKI 9218 | 2006 | JNKV, Jabalpur | MP | DT+HT | Resistant to root rot, collar rot and wilt | |
| | GNG 1581 | 2008 | ARS, Sriganganagar | NWPZ | DT+WL | Semi erect habit | |
| Moth bean | CAZRI MOTH-1 | 1999 | ICAR-CAZRI, Jodhpur | RJ, GJ | DT+HT | Blight | - |
| | RMO-225 | 1999 | ARS, Bikaner | RJ, GJ, MS | DT+HT | - | - |
| Lenti | Kota Masoor 3 | 2020 | AU, Kota | RJ | DT+HT | - | - |
| Peanut | Kadiri-3 | 1978 | APAU, Kadiri | AP | DT+HT | Early maturity, tolerant of LLS | |
| | ICGV-87128 | 1988 | ICRISAT, Hyderabad | GJ, AP, KA, OR, TN | DT+HT | Tolerant of ELS, PBND virus | |
| | ICGV-86031 | 1991 | ICRISAT, Hyderabad | AP | DT+HT | resistances to *Spodoptera*, leaf miner, jassids, thrips, PBND | Photoperiod insensitive and resistant to iron deficiency chlorosis |
| | Vemana | 1995 | APAU, Kadiri | AP and TN | DT+HT | Tolerant to leaf spots, PBND | |
| | ICGS-76 | 1989 | ICRISAT, Hyderabad | MS, KA | DT+HT | Resistant of ELS | |
| Soybean | JS-335 | 1994 | JNKVV, Jabalpur | GJ, RJ, MP, parts of MS, | DT+HT | Resistant to bacterial pustules, bacterial blight, GMV & ALS, moderately susceptible to pod blight jassids | |
| | NRC-37 | 2001 | ICAR-IISS, Indore | MP, MS, UP, RJ | DT+WL | Moderately resistant to collar rot, bacterial pustule, pod | |

| Crop | Variety | Year | Organization | Area of adoption/ state | Multiple stresses | Biotic stress | Other features |
|---|---|---|---|---|---|---|---|
| | | | | | | blight and bud blight, stem fly and leaf miner | |
| Linseed | Jawahar-552 (R-552) | 1980 | JNKVV, Jabalpur | CT plains zone | DT+HT | Resistant to wilt; Moderately susceptible to rust and PMD | - |
| | Indira Alsi-32 (RLC-81) | 2005 | JNKVV, Jabalpur | CH, MH, OR | DT+HT | Resistant to PMD, | - |
| | Deepika (RLC-78) | 2006 | | CT plains zone | DT+HT | Moderately resistant to rust, wilt and alternaria blight. Resistant to PMD | - |
| | RLC 92 (IC 555926) | 2008 | | MS, CH, OR, KA | DT+HT | Moderately resistant to linseed bud fly | - |
| Sesame | CUMS-17 (Suprava) | 2018 | IAS, Uni. of Calcutta | WB | DT+HT | - | - |
| Rape seed & mustard | Divya-33 | 2013 | M.R. Seeds Pvt. Ltd., Sriganganagar | DL, HR, PB, JK, RJ | DT+HT+SL | Tolerant to white rust and alternaria. | - |
| | Pusa mustard 25 (NPJ 112) | 2010 | IARI, New Delhi | DL, HR, PB, J&K, RJ, UP | HT+SL | - | - |
| | NRCDR 601 (DMR 601) | 2010 | DRMR, Bharatpur | DL, HR, PB, RJ | HT+SL | - | - |
| | RGN 229 | 2011 | RAU,ARS, Sriganganagar | DL, HR, PB, J&K, RJ | HT+SL | - | - |
| | RGN 236 | 2011 | RAU, ARS, Sri Ganganagar | DL, HR, PB, J&K, RJ | HT+SL | - | - |
| | Pusa Vijay (NPJ 93) | 2008 | IARI, New Delhi | DL | HT+SL | | - |
| | Pusa Mustard 22 (LET - 17) | 2008 | | Delhi | HT+SL | Low incidence of white rust, *sclerotinia* stem rot, downy and powdery mildew. | - |

| Crop | Variety | Year | Organization | Area of adoption/ state | Multiple stresses | Biotic stress | Other features |
|---|---|---|---|---|---|---|---|
| | NRCDR-02 | 2007 | ICAR-DRMR, Bharatpur | RJ, HR, PB, DL | HT+SL | tolerant to white rust, *sclerotinia* rot and *alternaria,* DM | |
| | Pusa MUSTARD 29 (LET - 36) | 2013 | IARI, New Delhi | DL, HR, J, PB, RJ | HT+SL | | |
| | Pusa Mustard 30 (LES-43) | 2013 | | UP, UK, MP, RJ | HT+SL | | |
| | RH 0406 | 2013 | CCSHAU, Hissar, | HR, PB, DL, RJ | HT+SL | Less severity against white rust and *Alternaria* blight | |

**Note: HT=High temperature; DT= Drought tolerant; SL= Salinity tolerant; LT= Low temperature tolerant; WL= Water-logging tolerant**

### 2.1.2 Commercial crops:

The commercial crop sector in India is rapidly growing as agriculture increasingly aligns with agribusiness principles. India holds a leading position in the production and export of high-value crops such as chilli, turmeric, and castor, and ranks second in tobacco production (Reddy *et al*., 2023). Despite this prominent status, the productivity of these crops in India lags behind that of other major producing nations. This productivity gap is partly due to the various stresses these crops face, including pests, diseases, and environmental conditions. Recently, these crops have witnessed the frequent occurrence of more than one stress simultaneously. For instance, chilli crops are often affected by fungal infections and drought, turmeric suffers from soil-borne diseases and excessive moisture, and castor is challenged by the occurrence of pests and diseases and occurrence of irregular and uneven rainfall. Similarly, tobacco cultivation encounters issues with tobacco mosaic virus and fluctuating weather patterns. Addressing these stresses through location-specific research and technological advancements is crucial for improving crop productivity and bringing climate resilience. Enhancing crop resilience and adopting advanced agricultural practices will help to bridge the productivity gap, ensuring that India can leverage its position in the global commercial crop market more effectively.

The development of resilient varieties against diverse biotic and abiotic stresses is the most effective strategy to mitigate the impact of these high-value crops. Several organizations under the NARS umbrella are developing multiple stress-tolerant varieties of different commercial crops. The multiple stress-tolerant varieties of important commercial crops developed in India are given in Table 6.

**Table 6. Multiple stress-tolerant varieties of important commercial crops**

| Crop | Variety | Year | Abiotic Stress | Area of Adoption | Other Features | References |
|---|---|---|---|---|---|---|
| Sugarcane | Co 8371 (Bhima) | 2000 | WL, DT, SL | GJ, MS, MP, KA, AP, TN, KL | Thick cane. High cane yield, Resistant to smut | https://sugarcane.icar.gov.in/ |
| | Co 87025 (Kalyani) | 2000 | DT and WL | GJ, MS, MP, KA, AP, TN, KL, Chandigarh | Resistance to smut, tolerant to red rot | https://iisr.icar.gov.in/ |
| | Co 87268 (Moti) | 2000 | DT + WL | Eastern UP, BH, WB, North East regions of North Central and North East Zones | Early, Resistance to red rot | https://sugarcane.icar.gov.in |
| | Co 89029 (Gandak) | 2000 | WL + DT | Eastern UP, Eastern UP, BH, WB, North East regions of North Central and North East Zones | Early, High tillering, non-lodging cane | https://sugarcane.icar.gov.in |
| | BO 128 (Pramod) | 2001 | WL + SL | Eastern UP, BH, WB, JH | Mid-late, Moderately Tolerant to red rot, smut, tolerant to shoot borer | https://iisr.icar.gov.in/ |
| | Co 94008 (Shyama) | 2004 | DT + SL | GJ, MH, MP, KA, Interior AP, TN, KL | Early, Resistant to red rot and smut | https://sugarcane.icar.gov.in |

| Crop | Variety | Year | Abiotic Stress | Area of Adoption | Other Features | References |
|---|---|---|---|---|---|---|
| | Co 99004 (Damodar) | 2007 | DT + SL | GJ, MH, MP, KA, Interior AP, TN, KL | Midlate, moderately resistant to red rot, Erect canes, non-flowering | |
| Sugarcane | CoH 119 (Haryana Ganna 119) | 2007 | DT + Sodicity | PB, HR, RJ, Central and Western UP, UK | Moderately Resistance to red rot, resistance to GSD, smut & tolerant to top borer, shoot borer | https://iisr.icar.gov.in/ |
| | CoLk 94184 (Birendra) | 2008 | WL + DT | Eastern UP, BH, WB JH | Early, Moderately Resistance to red rot, | |
| | Co 0232 (Kamal) | 2009 | WL + early DT | Eastern UP, Bihar, West Bengal, Jharkhand | Early, Moderately Resistance to red rot, tolerant to top borer, | |
| | Co 0233 (Kosi) | 2009 | WL + early DT | Eastern UP, Bihar, West Bengal, Jharkhand | Moderately Resistance to red rot | |
| | Co 2001-15 (Mangal) | 2009 | DT + SL | GJ, MH, KA, KL, TN, AP, MP | Moderately resistance to red rot, smut, tolerant | https://iisr.icar.gov.in/ |
| | Co 0218 (Shreyas) | 2009 | DT + SL | GJ, MH, KA, KL, TN, AP, MP | Mid- late, Moderately resistance to red rot, smut, tolerant, good ratooner, good jaggery quality | |

| Crop | Variety | Year | Abiotic Stress | Area of Adoption | Other Features | References |
|---|---|---|---|---|---|---|
| | Co 0118 (Karan-2) | 2009 | DT and WL | PB, HR, RJ, UK, Western and Central UP | Early, non-flowering, Resistant to red rot | https://sugarcane.icar.gov.in |
| | Co 0232 | 2009 | WL and Early DT | AS | Early, Resistant to red rot and wilt. | |
| | Co 0233 | 2009 | WL and Early DT | AS | Midlate, non-flowering variety, Resistant to red rot and wilt | |
| | Co 0238 (Karan-4) | 2009 | LT, DT and WL | PB, HR, RJ, UK, | Early, sparse flowering, Resistant to red rot | |
| | Co 124 (Karan 5) | 2010 | DT and WL | Western and Central UP | Mid-late, Moderately resistant to red rot | https://iisr.icar.gov.in/ |
| | Co 0239 (Karan-6) | 2010 | DT and WT | PB, HR, RJ, UK, Western and Central UP | Early, non-flowering, moderately resistant to red rot | https://sugarcane.icar.gov.in |
| Sugarcane | CoOr 03151 (Sabita) | 2011 | DT and WL | Coastal TN, AP, OR | Early, Resistant to red rot & wilt, early shoot borers and scale insect | |
| | Co 0237 | 2012 | LT, DT and WL | PB, HR, RJ, UK, Western and central UP | Early, non-lodging and non-flowering, Resistant to red rot | |
| | Co 0403(Samriddhi) | 2012 | DT and SL | GJ, MH, KA, KL, TN, AP, MP | Early, Moderately Resistance to red rot, | https://iisr.icar.gov.in/ |

| Crop | Variety | Year | Abiotic Stress | Area of Adoption | Other Features | References |
|---|---|---|---|---|---|---|
| | | | | | R to smut, good ratoon, good jaggery quality | |
| Sugarcane | Co 06027 | 2013 | DT and SL | GJ, MH, KA, KL, TN, AP, MP | Mid-late, moderately resistant to red rot, | https://iisr.icar.gov.in/ |
| | CoPK 05191 (Pratap Ganna 1) | 2013 | DT and WL | PB, HR, RJ, Central & Western UP, UK | Early, moderately resistant to red rot, good ratooner | |
| | Co 09004 (Amritha) | 2017 | Tolerant to DT and SL | GJ, MH, KA, KL, TN, AP, MP | Early, MR to red rot, Resistance to smut & Yellow leaf Disease | |
| | CoPb 95 | 2021 | Frost and WL | PB | Resistance to red rot disease, moderately resistant to smut and | |

**HT=High temperature; DT= Drought tolerant; SL= Salinity tolerant; LT= Low temperature tolerant; WL= Water-logging tolerant**

### 2.1.3 Forage and fodder crops:

Fodder and forage crops play a crucial role in ensuring the sustainability of livestock farming by providing essential nutrition for animals. These crops not only support animal health and productivity but also contribute to soil conservation and improve the overall agricultural ecosystem. The ICAR-Indian Grassland and Fodder Research Institute (IGFRI) in Jansi is at the forefront of research and development in this field. IGFRI also focuses on developing and promoting varieties of forage and fodder crops that are resilient to various environmental stresses, such as drought, salinity, and temperature extremes. By addressing these challenges, ICAR-IGFRI helps to enhance the stability and productivity of livestock systems, ensuring food security and economic stability for farmers in India. Their innovative research supports the development of stress-resistant crops, which are essential for maintaining fodder availability in the face of changing climatic conditions. The multi-stress tolerant varieties of different fodder crops developed by ICAR-IGFRI are presented in Table 7.

**Table 7. Multiple stress tolerant varieties of forage and fodder crops**

| Crop | Variety | Year | Organization | Area of adoption/ state | Multiple stresses | Biotic stress | Other features |
|---|---|---|---|---|---|---|---|
| Anjan grass/ Buffalo grass | Bundel Anjan-1 | 1989 | ICAR-IGFRI, Jhansi | All India | DT+LT | - | Frost hardy |
| Dhaman grass/ Bird wood grass | Bundel Dinanath-2 | 1989 | IGFRI, Jhansi | All India | DT+LT | - | Lodging tolerant |
| Setaria grass | Setaria-92 | 2005 | ICAR-IGFRI, Jhansi | HP, UK | DT+WL+LT | - | - |
| | S-18 | 2012 | ICAR-IGFRI, Jhansi | HP, UK | DT+LT | - | - |

### 2.1.4 Horticultural crops:

Horticultural crops, including fruits, vegetables, medicinal plants, aromatic herbs, and ornamental species are vital for their nutritional, medicinal, and aesthetic contributions to human life. As the global population continues to expand, the demand for these crops is increasing, highlighting the importance of horticulture in meeting dietary needs and improving quality of life. However, these crops are increasingly challenged by a range of abiotic stresses such as extreme temperatures, drought, flooding, salinity, and pH imbalances (Maneesha *et al*., 2021). Climate change exacerbates these challenges by causing more frequent and severe

weather events, including prolonged droughts and intense rainfall, which disrupt crop growth and reduce yields.

Horticultural perennials, including many fruit trees and shrubs, have longer life cycles and are adapted to withstand and recover from stress impact. They often possess more robust mechanisms for coping with stresses, such as deeper root systems and better stress acclimation processes. However, extreme climatic events often lead to multiple simultaneous abiotic stresses in horticultural crops, prompting plants to employ various physiological and molecular strategies for survival. Understanding these complex responses, including antioxidant, hormonal, and genetic mechanisms, is crucial for developing stress-resistant varieties. The impact of combined abiotic stresses, exacerbated by global warming and environmental pollution, is intricate and not fully understood, often complicated by concurrent biotic stresses. To address these challenges, it is essential to conduct detailed studies on how horticultural crops respond to multiple stresses, starting with simpler crops like tomatoes and cucumbers and extending to more complex species. Utilizing advanced research technologies, such as remote sensing and high-throughput phenotyping, can accelerate the development of resilient varieties. Ultimately, advancing varietal development through these insights is vital for mitigating the effects of multiple abiotic stresses and ensuring the sustainability of horticultural production.

**A. Fruits crops:**

India cultivates over 7.02 million hectares (Mha) of fruits, producing 110.20 million tons (Mt) during 2022-23. Its diverse geography and climate support the growth of tropical, sub-tropical, temperate, and arid fruit crops. Leading states in fruit production include Andhra Pradesh, Maharashtra, Gujarat, and Uttar Pradesh. Despite efforts to promote fruit consumption, per capita intake in India remains below the World Health Organization's (WHO) recommended 400 grams per day, averaging less than 200 grams.

Rising global temperatures, predicted to exceed 1.5°C by the end of the 21$^{st}$ century, will increase the frequency of extreme weather events such as heatwaves, droughts, and erratic rainfall (Hoegh-Guldberg, 2018). Semi-arid and arid regions are particularly vulnerable to extended dry spells and reduced precipitation, exacerbating issues like soil salinity, alkalinity, and waterlogging. These climatic shifts will disrupt fruit crop management practices, including planting, pollination, and physiological functions such as photosynthesis and transpiration. Pests and diseases are expected to increase, leading to additional yield losses, particularly in problematic soils. While some fruit crops, with deep root systems, may exhibit higher tolerance

to stress, they remain vulnerable during various growth stages. The severity and duration of stress will directly impact their productivity.

To meet rising food and nutritional demands, the fruit industry must overcome abiotic stress challenges. Developing stress-resilient strategies, such as better understanding plant responses to adverse conditions, is crucial for sustainable yields. Fruit crops generally tolerate various abiotic stresses, yet weather variability during critical stages can reduce flowering, fruit set, and yield quality. Factors such as heat waves, fluctuating temperatures, floods, droughts, and unseasonal rains negatively affect growth, photosynthesis, and pollination, leading to lower fruit quality and increased pest outbreaks. Warmer temperatures may harm pollinators, further reducing fruit set. These stresses influence post-harvest quality and shelf life, necessitating an understanding of plant responses to develop strategies for mitigating their impact on yield and productivity.

Water is a crucial yet limited resource for plant growth, increasingly strained by climate change, urbanization, and population growth, especially in semi-arid and arid regions. Water stress, where plants receive insufficient water, affects photosynthesis, nutrient uptake, and overall plant morphology. It leads to reduced growth, fruit yield, and quality. However, plants respond through physiological, morphological, and molecular adaptations, such as reducing leaf area and altering gene expression. To achieve optimal production, bananas need at least 100 mm of evenly distributed rainfall each month. The crop is very sensitive to drought, experiencing yield reductions of up to 65% when annual rainfall falls below 1,100 mm. (Robinson and Sauco, 2010). Citrus trees exposed to drought stress exhibit significant reductions in growth and cellular metabolic processes, leading to lower crop yields and fruit quality. Drought stress decreases key physiological parameters, including stomatal conductance, net $CO_2$ assimilation, and leaf transpiration (Pérez-Pérez *et al.*, 2002). The ability of citrus trees to cope with water stress varies by genotype. The ranking of drought tolerance is as follows: high tolerance includes mandarins (*Citrus reticulata* spp.), rangpur lime, rough lemon, sour orange, and Citrus macrophylla; medium tolerance includes lemon, trifoliate orange, citrange hybrid, and Citrus chuana; while sweet orange, *Citrus verrucosa*, and grapefruit have poor tolerance (Zaher-Ara *et al*., 2016).

Waterlogging occurs when water enters the soil faster than it can drain, caused by heavy rainfall, over-irrigation, or a high-water table. Soil structure, drainage capacity, and compaction determine the severity and duration of waterlogging. Climate change has increased

unpredictable rainfall, exacerbating waterlogging incidents globally. Waterlogging deprives roots of oxygen, leading to hypoxia, root death, and reduced nutrient uptake. Prolonged waterlogging results in the accumulation of harmful gases like hydrogen sulphide, leading to nutrient imbalances, particularly nitrogen loss. Waterlogging stress in fruit crops leads to several detrimental effects, including reduced net photosynthetic rate, decreased stomatal conductance, stunted plant growth, wilting, reduced leaf size, leaf abscission, restricted vegetative and root growth, and root necrosis (Schaffer *et al*., 2006). In addition to vegetative growth, waterlogging also affects reproductive processes, resulting in reduced flowering, lower yields, and, in severe cases, plant death. Moreover, waterlogging creates conditions favourable for diseases such as Phytophthora root rot, which has been observed in fruit crops like citrus, papaya, and avocado, further impairing plant growth and productivity.

Greenhouse gas emissions are significantly raising global surface temperatures, with projections indicating an increase of over 1.5-2.0°C by the end of the 21st century. This temperature rise contributes to more frequent extreme weather events, such as heatwaves and changes in rainfall patterns. These climatic shifts pose a severe threat to fruit crop growth and development, as every plant requires an optimal temperature range for proper physiological functioning. Deviations from this range, whether in the form of heat or cold stress, affect processes like germination, flowering, fruit set, and maturation. Temperature significantly affects fruit development and quality. High temperatures can impair colour development in various fruit trees, such as grapes. Furthermore, fruit firmness is affected by temperature. For example, "Fuerte" avocados exposed to direct sunlight at 35°C were found to be 2.5 times firmer than those shaded at 20°C. This difference is linked to changes in cell wall composition, cell count, and turgor properties (Woolf *et al*., 2000). Temperature also impacts pollinator behaviour, altering visit frequency and interactions within flowers. Over an entire season, temperature changes can affect pollinator abundance and diversity, increase mortality rates, and influence pest populations, diseases, and natural enemies (Chakraborty and Newton, 2011). The effects of high temperatures are more pronounced in temperate fruit crops compared to tropical and subtropical ones. In regions like the Kashmir Valley, rising temperatures and decreased rainfall are causing apricots and cherries to vanish, while apple yields and quality are deteriorating in Jammu. Winter chilling is crucial for temperate fruit crops; inadequate winter chill due to climate change may lead to production failures and reduced yield potential, making orchard operations economically unfeasible (Erez, 2000).

Heat stress, typically occurring when temperatures rise 10-15°C above optimal, negatively impacts photosynthesis, nutrient uptake, and reproductive phases. Pollination processes, including pollen tube growth and stigma receptivity, are particularly sensitive to temperature increases, leading to reduced fruit set and impaired quality, such as poor colour development and smaller fruit size. High temperatures also affect fruit firmness and may reduce the efficacy of pollinators, while simultaneously increasing pest populations and disease risks. Conversely, cold stress, particularly below 15°C, causes tissue damage, inhibits growth, and disrupts membrane stability. Plants attempt to cope through morphological and biochemical changes, like increasing stress-related proteins and antioxidants. However, prolonged exposure to either extreme can result in reduced yield, poor fruit quality, and, in severe cases, plant death.

Among extreme weather events, hailstorms are particularly devastating, causing significant damage to standing fruit crops within a short duration. The extent of damage is determined by the size and number of hailstones per unit area, wind intensity, and the crop's growth stage at the time of the hailstorm. Even brief episodes of hail can severely injure fruit trees, reducing quality and causing further losses due to diseases such as blight, mold, canker, and fruit rots. Two primary types of hail damage are observed in fruit crops, with injuries predominantly occurring on the windward side of stems or branches, while the leeward side experiences minimal damage. Primary injuries result from the direct mechanical impact of hailstones, leading to defoliation, tearing of leaf blades, branch and stem breakage, plant lodging, bark peeling, stem lesions, fruit cracking, and premature fruit drop. Secondary injuries follow, including dieback of damaged parts, reduced plant height, staining, bruising, discolouration of leaves and fruits, and fruit rotting due to fungal and bacterial infections. These injuries significantly degrade fruit quality and can lead to further economic losses for growers. The varieties of fruit crops showing tolerance to different abiotic stresses are listed in Table 8.

**Table 8. Multiple stress tolerant varieties of fruit crops**

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Organization/ Source/ References | Abiotic stresses | Biotic stresses | Other features |
|---|---|---|---|---|---|
| **Aonla** | Goma Aishwariya | https://ciah.icar.gov.in/variety.php | DT | | Early |
| **Apple** | MM111 | Chandal and Chaouhan (1992) | DT | Wooly apple aphid, fire blight and crown and root rots | - |
| | MM106 | Chandal and Chaouhan (1992) | DT, WL | Wooly apple aphid | Semi-dwarf |
| | MM104 | Chandal and Chaouhan (1992) | DT | Wooly apple aphid | - |
| | Y-series | Yang *et al*. (2011) | DT, ST | | - |
| | Budagovski 9 | Handbook of Horticulture (2019) | Winter frost | Collar rot, powdery mildew and apple scab | - |
| | Pusa apple rootstock 101 | Handbook of Horticulture (2019) | Low chilling, Wider soils and agro-climatic conditions | Wooly apple aphid, powdery mildew and apple scab | - |
| | Merton 793 | Handbook of Horticulture (2019) | Wide soil conditions | Wooly apple aphid, Collar rot, replant problem | - |
| **Avocado** | West Indian race | Cooper (1951); Handbook of Horticulture (2019) | DT, ST | - | - |
| **Bael** | Goma Yashi | https://ciah.icar.gov.in/variety.php | DT, HT | - | Dryland/rainfed/semi-arid regions, spineless |
| | Thar Divya | https://ciah.icar.gov.in/variety.php | DT, HT | - | Dryland/rainfed/semi-arid regions |

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Organization/ Source/ References | Abiotic stresses | Biotic stresses | Other features |
|---|---|---|---|---|---|
| **Banana** | Kaveri Saba | Ravi and Vaganan (2016) | DT, ST | - | Suitable for marginal soils |
| | Monthan (ABB) | Ravi and Vaganan (2016) | DT, ST | - | - |
| | Karpuravalley (ABB) | Ravi and Vaganan (2016) Handbook of Horticulture (2019) | DT, ST | Leaf spot | - |
| | Poovan (AAB) | Ravi and Vaganan (2016) | DT | Nematodes | - |
| | Pisang Awak | De Langhe (2002) | DT | Nematodes | - |
| | Phule pride | MPKV, Rahuri | High winds and lodging | Sigatoka tolerant | - |
| | Udhayam (ABB) | Handbook of Horticulture (2019) | Long distance transportation | Sigatoka, nematode tolerant | - |
| **Ber** | Thar Malti | https://ciah.icar.gov.in/variety.php | DT, Frost and LT | - | frost-tolerant and has a semi-erect growth habit. |
| | Thar Bhubharaj | | - | - | - |
| | Goma Keerthi | | DT | Fruit borer, fruit fly | - |
| **Cherry** | Mazzard F12/1 | Ranney (1994); Handbook of Horticulture (2019) | DT, WL | Phytophthora and oak root fungus | Good anchoring |
| | Gisela 12 | Handbook of Horticulture (2019) | Wide soil adaptability and heavy soils | - | Precocious, semi dwarf |
| | Colt | Handbook of Horticulture (2019) | Good anchoring | Gummosis, crown rot, stem pitting virus and bacterial canker | - |
| **Citrus** | Rangpur Lime | Stuchi *et al*.(2000a); Pompeu Junior (2005); Cantuarias-Avilles *et al*. (2011); Patel *et al*. (2011) | DT, ST | Gummosis and root rot | - |

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Organization/ Source/ References | Abiotic stresses | Biotic stresses | Other features |
|---|---|---|---|---|---|
| | Cleopatra mandarin | Bhusal et al. (2002) | DT, ST, WL | Tristeza virus | - |
| | Sour orange | Patel *et al*. (2011); Levy *et al.* (1999), Storey (1995) | DT, ST | - | - |
| | Trifoliate orange | Bhusal *et al*. (2002); Sahin-Cevik and Moore (2006b); Lang *et al*. (2005) | DT, WL, LT | Foot rot and Tristeza virus | - |
| | Rough lemon | Patel *et al*. (2011); Levy *et al*. (1999), Storey (1995) | DT, ST, WL | Tristeza virus | - |
| **Grapes** | 110R (Richter 110) | Keller, 2015;Carbonneau, 1985) Cirami *et al*. (1994), Galet (1998); Whiting (2005); Flexas *et al*. (2009) | DT, ST, $Mg^{++}$ and $Fe^{++}$ deficiency | - | - |
| | 99R | Keller, (2015); Carbonneau (1985); Cirami *et al*. (1994); Galet (1998); Whiting (2005); Flexas *et al*. (2009) | DT, ST | - | - |
| | 1103P (1103 Paulsen) | Walker *et al*. (2002),; Cirami *et al*. (1994); Carbonneau (1985); Flexas *et al*. (2009) | DT, ST, $Mg^{++}$ and $Fe^{++}$ deficiency | - | - |
| | Ramsey | Walker *et al*. (2002); Cirami *et al*. (1994); Carbonneau, 1985; Flexas *et al*. (2009) | DT, ST | | Increase N and K uptake |
| | Homony | Cirami *et al*. (1994) | DT, ST | - | - |
| | Dog Ridge | Sauer (1968); Palaniappan (1986); Upreti and Murti (2010); Jogaiah *et al*. (2014); Walker *et al*. (2004) | DT, ST | Phylloxera | Increase N and K uptake |
| | 1616 | Southey and Jooste (1991); Strauss and Archer (1986); Walker *et al.* (2010). | ST, WL | - | - |
| | 101-14 MGt, | Southey and Jooste (1991); Strauss and Archer (1986); Walker *et al*. (2010). | ST, WL | - | - |
| | 140 Ruggeri | Bavaresco, Fraschini, and Perino (1993); Carbonneau (1985), Southey (1992), Cirami *et al*. (1994); Galet | DT, ST, $Fe^{++}$ deficiency | - | |

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Organization/ Source/ References | Abiotic stresses | Biotic stresses | Other features |
|---|---|---|---|---|---|
| | | (1998); Whiting (2005); Audeguin *et al*. (2007); Flexas *et al*. (2009) | | | |
| **Mango** | 13-1 | Galán Saúco (2019) Kadman *et al*. (1976); Gazit and Kadman (1980) | DT, ST. Tolerant to calcareous soils (>20%) | - | - |
| | Hilacha | Anon. (2013) | WL, High soil pH | - | - |
| | Gomera 3 | Duran Zauza *et al*. (2003) | ST, nutrient stress | - | - |
| **Mulberry** | Thar Lohit | https://ciah.icar.gov.in/variety.php | LT, HT | -- | Low (frost) and high temperature tolerant (-20C to $49^0$ C) |
| | Thar Neelkanth | | DT, LT, HT | - | - |
| | Thar Harit | | DT, LT, HT | - | - |
| **Peach** | Peach × *P. davidiana* hybrids | Beckman and Lang (2003) | DT, nutrient stress | Nematode | - |
| | Peach x almond hybrids | Wang *et al*. (1985) | DT, nutrient stress | - | |

**B. Vegetable crops:**

Vegetables are crucial in every household because they are rich in essential nutrients like vitamins, minerals, and dietary fibres. Among these, tomatoes, onions, and potatoes (TOP) are especially important because they are always in high demand, no matter the season, region, or religion. These vegetables play a vital role in ensuring nutritional security, creating jobs, and increasing farmers' incomes in India. However, extreme environmental conditions can impose stress to plants, which can hinder their growth and development. Vegetables are highly susceptible to drought, salinity, flooding, heat, frost, hailstorm, and heavy metal toxicity. When plants face abiotic stress, they often exhibit similar responses such as inhibited seed germination and seedling growth, disrupted nutrient balance and metabolism, reduced photosynthesis, osmotic and oxidative stress, cell dehydration, and protein damage. The severity of these impacts depends on the plant species, growth stage, and the intensity and duration of the stress. For example, in tomatoes, temperatures above 28°C combined with water deficit stress can lead to up to 40% flower drop, and drought conditions can cause up to 50% yield loss. Potatoes, now grown in non-traditional areas during winter, are also severely affected by abiotic stresses, especially during the sensitive seedling and reproductive stages. As climate change progresses, vegetable crops will likely to face increasing abiotic stresses, making it essential to understand these effects on tomato, onion, and potato production and quality.

Abiotic stresses impact plant growth, physiological and biochemical processes, and damage cellular components. Even minimal exposure to stress can significantly reduce the yield of vegetable crops, as fruit-bearing vegetables undergo vegetative and reproductive growth simultaneously. Therefore, it is essential to understand the critical developmental stages of these crops to implement effective interventions and mitigate the effects of abiotic stresses.

In vegetables, mitigating the impact of abiotic stresses can be achieved by taking a whole-plant approach and identifying stress-tolerant genotypes. These genotypes should be screened from diverse germplasm for mechanisms that enable stress avoidance, escape, and tolerance. For instance, promoting deep rooting can help plants maintain leaf cooling and escape the effects of high temperatures (Wien, 2020). In tomatoes, significant genetic diversity in heat stress tolerance has been found, with lines 2195 and the variety Arka Vikas identified as tolerant cultivars (Laxman *et al*., 2013; Manish *et al*., 2017). In onions, the white variety 'Bhima Shubhra' and the local red variety exhibited the highest water productivity under

medium to severe water deficit conditions (Wakchaure *et al*., 2021). Local cultivars tend to be most tolerant to abiotic stresses as they have been cultivated by farmers for many years. The vegetable varieties developed for abiotic stress tolerance are listed in Table 9.

**Table 9. Multiple stress tolerant varieties of vegetable crops**

| Crop | Variety | Year | Organization | Area of adoption/ state | Multiple stresses | Other features |
|---|---|---|---|---|---|---|
| **Bottle Guard** | TharSamridhi | - | CIAH, Bikaner | RJ | DT+HT | |
| | PusaSantushti | 2005 | IARI, New Delhi | DL, PB, UK, BH, MP, MS | HT+LT | Fruits are attractive green, smooth, pear Shaped, |
| **Brinjal** | KashiSandesh | 2004 | IIVR, Varanasi | UP, MP and JH | DT+HT | - |
| | KashiTaru | 2005 | IIVR, Varanasi | UP | DT+HT | |
| **Carrot** | Ooty-1 | 1997 | TNAU, Coimbatore | Temperate regions | DT+LT | Resistant to powdery mildew, leaf spot |
| **Tomato** | ArkaMeghali | 2006 | IIHR, Bengaluru | - | DT+HT | |
| | ArkaVikas | | IIHR, Bengaluru | GJ, HP, KA, MP, MS, OR, UP, WB | DT+HT | Suitable for rainfed and irrigated |
| | Pusa Sadabahar | | IARI, New Delhi | | LT+HT | - |
| **Cluster bean** | RGC-936 | | RSSC, Rajasthan | RJ | DT+HT | - |

HT=High temperature; DT= Drought tolerant

### C. Medicinal, aromatic and plantation crops

The abiotic stress in horticulture crops is having a wide impact on productivity, quality and adoption to new environments. In particular, hardy crops such as plantations, spices, and medicinal and aromatic plants that are known for their abiotic stress tolerance are also not excluded from the impact of such stresses. Even though most plantation, spices and medicinal plants are abiotic stress tolerant, however, they were most sensitive to biotic stresses also. Having multiple stresses either biotic or abiotic stresses in one variety along with good yield characteristics is much required in a changing climate scenario. There are most successful and prominent examples of multiple stress-tolerant varieties exist in plantation, spices, medicinal and aromatic crops. For example, cashew was introduced to India in the 16$^{th}$ century AD in coastal areas for soil stabilisation, it is known for drought hardy and salinity tolerance, however, tea mosquito bugs and root and stem borers are serious threats to cashews. India is a major producer and exporter of mint and Mint products. Japanese mint (*Mentha arvensis*) variety "Kushal" withstands waterlogging, is suitable for late-season planting (April) and is tolerant to leaf spot, rust, and powdery mildew diseases. Cumin is one of the seed spices grown in the deserts of Rajasthan and Gujarat known for low moisture-requiring and salinity-tolerance crop. However, suffering from frost and wilt disease leads to huge crop losses. The selection from Gujarat cumin-3 is frost tolerant and also to *Fusarium* wilt disease. Yet another example of salinity, drought and die-back disease tolerance in periwinkle crops is Dhawal and Prabhal. Small cardamom is the most valued spice crop that is being affected by climate change and IISR, research centre Appangala has come out with a good selection i.e., IISR- Manushree which is tolerant to drought and moderately resistant to leaf blight disease. The important varieties of the plantation, spices, medicinal and aromatic plants are known to be tolerant to more than one stress with at least for one abiotic stress (Table 10).

**Table 10. Multiple stress tolerant varieties of medicinal, aromatic and plantation crops.**

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Year | Organization/Source/References | Abiotic stresses | Biotic stresses |
|---|---|---|---|---|---|
| **Black pepper** | Panniyur 9 | 2016-17 | Pepper research station, Panniyur, KAU, Kerala http://14.139.189.27/AICRPS/ Varieties.pdf | Drought and cold stress | Phytophthora foot rot, |
| | Panniyur 8 | 2013 | Pepper research station, Panniyur, KAU, Kerala http://14.139.189.29/Search Varieties?usrCrName=Black+Pepper | Drought | Phytophthora foot rot |
| | Panchami | 2001 | IISR, Calicut; http://14.139.189.29/Search Varieties?usrCrName=Black+Pepper | Drought | Nematodes |
| | Snigandhini | | Farmers variety, Sirsi, Karnataka http://14.139.189.29/Search Varieties?usrCrName=Black+Pepper | drought tolerant | Virus resistance |
| **Small cardamom** | PV3 (S 1) | 2014 | CRS, Pampadumpara, Idukki, Kerala http://14.139.189.27/AICRPS/ Varieties.pdf | moderately tolerant to drought | Thrips and capsule borer |
| | IISR Manushree | 2022 | IISR (RC), Appangala; http://14.139.189.29/Search Varieties?usrCrName=Cardamom | Drought | Leaf blight |
| | ICAR-5 | 2006 | ICRI, Myladumpara, Idukki, Kerala http://14.139.189.29/Search Varieties?usrCrName=Cardamom | Moderate drought | Moderately tolerant to virus and rhizome rot |
| | ICAR-6 | 2006 | | Moderate drought | Moderately tolerant to thrips |

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Year | Organization/Source/References | Abiotic stresses | Biotic stresses |
|---|---|---|---|---|---|
| **Fenugreek** | Narendra Methi 2 | 2015 | NDAUT, Kumaraganj, UP, http://14.139.189.29/Search Varieties?usrCrName=Fenugreek | Salinity tolerance | Moderate resistance to *Cercospora* leaf spot, downy mildew |
| | Narendra Richa | 2018 | NDAUT, Kumaraganj, UP http://14.139.189.29/Search Varieties?usrCrName=Fenugreek | Dual purpose, alkaline tolerant | Moderate resistance to powdery mildew |
| | Lam Methi-2 | 2020 | Dr.YSRHU, Lam Gunturhttp://14.139.189.29/Search Varieties?usrCrName=Fenugreek | Low moisture stress | - |
| **Turmeric** | Narendra Haldi 3 | 2014 | NDAUT, Kumaraganj, UP http://14.139.189.29/Search Varieties?usrCrName=Turmeric | Salinity | Root knot nematode, moderate resistance leaf spot and blotch |
| | NDH-98 | 2016 | NDAUT, Kumaraganj, UP | Tolerance to salinity | Leaf spot and leaf blotch |
| | IISR Pragati | 2016 | ICAR-IISR, Calicut | Low water requirement | moderately tolerant to root-knot nematodes |
| **Coriander** | RCr-480 | 2006 | SKNAU, Jobner, Rajasthan | Frost | Less susceptible to aphid and powdery mildew |

| **Crop** | **Variety/ Rootstocks/ Species/ Cultivars** | **Year** | **Organization/Source/References** | **Abiotic stresses** | **Biotic stresses** |
|---|---|---|---|---|---|
| | Sindhu | 1991 | HRS, YSRHU, Guntur | tolerant to drought | Wilt and powdery mildew |
| | RCr 446 | 1997 | SKNAU, Jobner, Rajasthan | Limited moisture stress | Moderately resistant to stem gall and wilt |
| | RCr 436 | 1995 | SKNAU, Jobner, Rajasthan | Limited moisture stress | Resistant to root rot & root knot nematodes |
| | RCr 20 | 1995 | SKNAU, Jobner, Rajasthan | Limited moisture stress | Stem gall |
| | Sadhana | 1989 | HRS, YSRHU, Guntur http://14.139.189.29/Search Varieties?usrCrName=Cumin | rainfed condition, and moisture stress | Field tolerance to white fly, mites and aphids. |
| **Cumin** | Gujarat Cumin-3 | 1999 | SKDAU, Jagudan, Gujarat | Frost | Fusarium wilt resistance |
| **Plantation Crops** | | | | | |
| Cocoa | VTLCH-5 (Nethra Centura) | 2016 | Nagaraja et al., 2022, Indian Horticulture, November–December 2022 | Low moisture stress | Moderately tolerant to Black pod, tea mosquito bug |
| | VTLCH-1 | 2006 | Nagaraja et al., 2022, Indian Horticulture, November–December 2022 | | Black pod rot and tea mosquito bug |
| | VTLCS-1 | 2006 | | | |
| Rubber | RRII208 | | Annual Report 2020-21, Rubber Borad, | Drought | Abnormal leaf fall |

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Year | Organization/Source/References | Abiotic stresses | Biotic stresses |
|---|---|---|---|---|---|
| | RRII 600 | - | - | Drought and cold | - |
| | RRII 430 | - | - | Drought | - |
| | Clone P021, P101, P107 | - | - | Drought and cold | - |
| Coconut | Chandra Kalpa | 1985 | Maheswarappa et al, 2016. Coconut varietal improvement efforts of AICRP on Palms, 2016. Technical bulletin No. 104. | Low moisture stress | - |
| | Kalpa Harita | 1985 | - | Drought | Eriophyid mite |
| | Kera keralam | 2007 | Maheswarappa et al, 2016. Coconut varietal improvement efforts of AICRP on Palms, 2016. Technical bulletin No. 104. | Low moisture stress and coarse textured sandy soils | - |
| | Kalpa mitra | 2007 | | Low moisture stress | |
| | Kalpa taru | 2015 | | Low moisture stress, | - |
| | Kalpa samrudhi | - | | Crown choking disorder | Moderately tolerant to stem bleeding disease, red palm weevil |
| | Kamarup (Assam green tall) | 2001 | AICRP on Pakms http://14.139.158.118/docs/AICRP.gov/cropimprovement.html | Cold tolerant (<8°C) and semi water logged condition | Tolerant of red palm weevil, rhinoceros beetle, stem bleeding disease |

| Crop | Variety/ Rootstocks/ Species/ Cultivars | Year | Organization/Source/References | Abiotic stresses | Biotic stresses |
|---|---|---|---|---|---|
| **Medicinal and aromatic crops** | | | | | |
| Japnese mint Mentha arvensis | Kushal | 2002 | Menthol mint variety 'Kushal' released for late transplanting. CIMAP Newsletter (2002) 1: 3. | Withstands waterlogging, late season planting (April) | Tolerant to leaf spot, rust and powdery mildew |
| Sweet basil | CIM-Sharada | 2015 | https://14.139.57.217/cimvariety /showvariety.aspx?vid=72 | Rainfed, short duration | Sucking Insects resistant |
| Lemon grass | Nima | 2003 | Citral rich and high yielding lemongrassvariety 'Nima' released fo r commercialization. CIMAP Newsletter (2003) 1:4. | Drought, marginal, high pH, alkaline soils | - |
| | Chirharit | 2001 | Chirharit —a high yielding lemongrass variety with frost resistance, stay-green habit and new chromosomal ploidy status. J. Med. Arom. Pl. Sci. (2001) 23: 137-140 | Frost resistant variety | - |
| Palmarosa Cymbopogo n martinii | CIM-Harsh | 2009 | https://14.139.57.217/cimvariety/showvariety.asp x?vid=27 | Drought and salinity resistant | - |
| Vettiver Periwinkle | Tripta, Trishna | 1987, 1986 | https://14.139.57.217/cimvariety/showvariety.asp x?vid=27 | Suitable for drought, marginal land and alkaline soils | - |

| **Crop** | **Variety/ Rootstocks/ Species/ Cultivars** | **Year** | **Organization/Source/References** | **Abiotic stresses** | **Biotic stresses** |
|---|---|---|---|---|---|
| Catharanthus roseus | CIMAP-Vridhi | 2007 | Registration of a yigh yielding variety "CIM-Vridhi" of Vetiver (Vetiveria zizaniodes L. Nash). J. Med. Arom. Pl. Sci. (2008) 30:105-108. | Drought marginal land | - |
| | Dhawal, prabhal | 1997 | https://14.139.57.217/cimvariety/showvariety.aspx?vid=11 | Salinity and drought | Resistant to die back |

SECTION 3

# A Way Forward: Upscaling the Development and Adoption of Multi-Stress Tolerant Crop Varieties

## 3.1 Strategies for the Development of Multi-Stress Tolerant Crop Varieties

As the impacts of climate change become increasingly severe, the development of multi-stress tolerant crop varieties has emerged as a crucial strategy for ensuring agricultural resilience. In India, the National Agricultural Research System (NARS) has made notable strides in creating and releasing varieties of crops that can withstand multiple environmental stresses. The information on such MSTCVs was compiled and presented in the previous section/ chapter. Most of the varieties were not developed through targeted breeding for multiple stress tolerance but rather developed during disease resistance breeding as evident from their response to disease (Table 5-10). Hence, such varieties may not be smart enough to persist or perform under the prevalence of complex nature stresses—such as repetitive or recurrent stresses, and combinable and multiple stresses. To effectively mitigate these challenges and enhance agricultural productivity, it is essential to employ well-planned and multifaceted strategies. This section explores advanced approaches in breeding and genetic selection, incorporating genetic diversity from wild relatives, and utilizing cutting-edge molecular techniques. These strategies are critical in accelerating the development of climate-smart varieties (CSV) that can withstand a range of complex stresses, thereby enhancing the resilience and sustainability of farming systems.

Strategies encompass breeding for stress-specific markers, incorporating genetic diversity from wild relatives, and employing advanced molecular techniques to accelerate the development of resilient crop varieties. Collaborative research efforts are pivotal in harnessing these strategies effectively. The Drought Tolerant Maize for Africa initiative, followed by the Stress Tolerant Maize for Africa initiative, has developed over 200 climate-smart maize varieties. These varieties have been created through genetic selection and testing of maize lines that thrive and produce grain under drought and nitrogen-poor conditions. Improved yields are linked to selecting plant types that quickly produce female flowers, or “silks,” following male flowers, allowing them to better survive drought. Released through a collaborative network including CGIAR, CIMMYT, IITA, national programs, NGOs, and over 100 private sector partners, these improved varieties offer 25-30% higher yields than conventional maize in drought-prone areas. This success underscores the critical role of extensive collaboration in developing climate-resilient crops that address multiple stress factors and minimize risks for farming communities (https://www.cgiar.org/innovations/climate-smart-maize).

Similarly, the International Rice Research Institute (IRRI) has developed climate-smart rice varieties with traits for multiple stresses under the GSR program. Using genomics-assisted breeding (GAB) and an enhanced green super rice (GSR) breeding strategy, IRRI, in collaboration with national programs, has created and distributed over 240 climate-smart rice varieties (both inbred and hybrid) that tolerate various abiotic and biotic stresses without sacrificing grain yield and quality. In just seven years, 26 IRRI-bred climate-smart rice varieties (CSRVs) were released, and 91 cultivars were nominated for national cooperative yield trials. These released CSRVs are now cultivated on more than 2.7 million hectares across Asia and Africa (Ali *et al*., 2020). This highlights the importance of multidisciplinary and collaborative research in developing climate-smart, multi-stress tolerant crop varieties.

The different strategies that need to be employed to accelerate the development of climate-smart varieties tolerant to multiple stresses are described briefly in the following section.

### 3.1.1 Understanding the response of crops to multiple stresses

Understanding the response and mechanism and traits associated with multiple stress tolerance is very important to devising strategies for the development of climate-smart varieties. Most of the studies focused on single stress rather than combined or multiple stresses. Hence, under such circumstances, it is difficult to deploy the traits and genes to develop crop varieties with multiple stress tolerance. Therefore, bridging the research gap by focusing more on understanding the crop response against multiple stresses is very crucial and a step forward for the development of climate-smart varieties. These assertions are proven true as maize and rice crops witnessed a greater number of CSV compared to other crops reflecting the basic and substantial research efforts dedicated to understanding the insights of crop response to multiple stresses, as given in Tables 11 and 12.

**Table 11. Multiple stresses in maize and their insights or salient findings**

| Stresses | Salient findings/ observations | Reference |
|---|---|---|
| Drought + Heat | Affects pollination and thus causes yield loss of up to 100 % | Heiniger (2001) |
| | Genotypes tolerant to heat are also likely to tolerate combined stresses | Tandzi *et al.* (2019) |
| | Developed low-cost tools to screen genotypes against multiple stresses | Kebede *et al.* (2012) |
| | Identified the tolerant maize germplasm for drought and heat. | Chen *et al.* (2012) |
| | Identified SNPs associate with combined stress tolerance | Yuan *et al.* (2019) |
| | Identified donors for combined drought and heat stress tolerance | Cairns *et al.* (2013) |
| | Separated heat effect from moisture stress | Carter *et al.* (2016) |
| | Photorespiration and raffinose-oligosaccharide metabolism are potential markers for combined stress tolerance | Obata *et al.* (2015) |
| | Hybrids with higher antioxidants, osmolytes and photosynthetic pigments tolerant to combined stress | Meseka *et al.* (2018), Hussain *et al.* (2019) |
| | Better root architecture traits confer the combined stress tolerance | Vescio *et al.* (2021) |
| Drought + chilling | Antioxidative defence system and root architecture play key role in combined stress tolerance | Hussain *et al.* (2020) |
| | Drought enhances chilling tolerance in cold-sensitive varieties | Irigoyen *et al.* (1996) |
| Drought + waterlogging | Combined stress tolerance depends on the interaction of stresses and is associated with leaf area, plant height stem diameter etc. | Rafique *et al.* (2020) |
| Drought + low N | Yield and its contributing traits are severely affected in drought + low-N and chlorophyll content significantly reduced in both the stress combinations and low-N has a synergistic effect on the maize growth. | |
| Waterlogging + low N | | |
| Drought + N stress | Under severe drought, the N level did not affect biomass and yield, but with high N, 10 days drought period causes biomass and yield loss. | George *et al.* (2013); Li *et al.* 2020 |
| | The impact was more pronounced in roots and stems compared to leaves, in terms of the number of genes and metabolic pathways influenced, showing tissue specificity. Traits and genes associated with drought | Humbert *et al.* 2013; Molla *et al.* (2014) |

| Stresses | Salient findings/ observations | Reference |
|---|---|---|
| | tolerance play a significant role in enhancing nitrogen use efficiency (NUE). | |
| | Overuse of nitrogen fertilizers without adequate water management can negatively impact grain filling and reduce drought tolerance. | Humbert et al. (2013); Su *et al*. (2020) |
| | Assessed the effects of water and nitrogen on maize yield, water productivity (WP), and NUE based on global level data. | Li *et al*. (2020) |
| Waterlogging + N stress | Salinity caused by waterlogging causes N stress | Mokhele *et al*. (2012) |
| | Reduction in chlorophyll and accelerate leaf senescence. Application of optimal N in splits compensates impacts by improving PS-II efficiency. | Wei *et al*. (2016); Wu *et al*. (2018) |
| | Application of high N fertilizers at vegetative stage mitigating the effect of water stresses at grain filling stage | Nasielski *et al*. (2019) |
| Heat + N stress | Modifies the rate of water and nitrogen absorption by influencing transpiration and soil moisture levels | Dong *et al*. (2001) |
| | Affects photosynthetic rate, grain development and yield | Tjoelker *et al*. (1999) |

**Source**: Modified from Boraiah *et al*. (2022)

Radha *et al*. (2022) reported the varying physio-molecular responses of rice to combined abiotic stresses, focusing on grain quality and yield traits, and proposed strategies for improving grain quality under multiple stress conditions. Schweiger *et al.* (2023) investigated the impacts of sequential stresses—drought, waterlogging, and re-drying—on wheat. They observed that these conditions significantly reduced both shoot and root biomass, increased transpiration rates per unit leaf area, and lowered instantaneous water use efficiency. Stressed plants showed decreased levels of many organic acids from the citrate cycle, while amino acids were more concentrated. Gene expression analysis revealed that some genes were specifically responsive to drought or waterlogging, while others were upregulated during both treatments and the subsequent re-drying phase. These findings enhance our understanding of wheat's adaptability to fluctuating water conditions, indicating potential physiological adjustments that may help the plants cope with stress.

**Table 12. Multiple abiotic and biotic stresses affecting physio-biochemical traits in rice**

| Physio-biochemical traits affected by stress | Effect | Reference |
|---|---|---|
| ***Drought and temperature*** | | |
| Transpirational cooling | Reduction | Costa *et al*. (2021) |
| Protein catabolism | Increase | Jagadish *et al*. (2011) |
| Lipid peroxidation | Increase | |
| PSII function | Reduction | |
| Leaf gas exchange | Reduction | Perdomo *et al*. (2015; 2016) |
| Water use efficiency | Reduction | |
| Growth and biomass accumulation | Reduction | |
| Panicle number | Reduction | Mukamuhirwa *et al*. (2019) |
| Anther dehiscence and pollen germination | Reduction | Rang *et al*. (2010; 2011) |
| Peduncle length | Reduction | |
| Pollen number | Reduction | |
| Spikelet sterility | Increase | |
| Starch biosynthesis | Inhibition | Costa *et al*. (2021) |
| Protein biosynthesis | Reduction | |
| Amylose content | Reduction | |
| structure of amylopectin | Alteration | |
| Grain chalkiness | Increase | Lawas *et al*. (2018) |
| Grain protein and mineral content | Increase | Mariem *et al*. (2021) |
| LEAs and HSPs accumulation | Increase | Piveta *et al*. (2020) |
| Fatty acid desaturation | Reduction | |
| Sucrose accumulation | Increase | Li *et al*. (2015) |
| **Drought and elevated $CO_2$** | | |
| Calvin cycle of photosynthesis | Reduction | Shankar *et al*. (2022) |
| Canopy dark respiration | Reduction | |
| Stomatal aperture | Reduction | |
| Transpirational cooling | Reduction | |
| Canopy temperature | Increase | |
| RUBISCO large and small subunits | Reduction | |
| $CO_2$ exchange rate | Reduction | |
| Productivity | Reduction | Prabnakorn *et al*. (2017) |
| Protein and mineral content in grains | Reduction | Ouyang *et al*. (2017) |
| Canopy net photosynthesis | Improvement | |
| Maintenance of mid-day photosynthesis | Improvement | |
| Synthesis of ABA | Delayed | Li *et al*. (2020) |
| **High temperature and $eCO_2$** | | |
| Grain filling | Reduction | |
| Panicle number | Reduction | Wang *et al*. (2020) |
| Spikelet number per panicle | Reduction | |

| **Physio-biochemical traits affected by stress** | **Effect** | **Reference** |
|---|---|---|
| Thousand-grain weight | Reduction | Chaturvedi *et al*. (2017) |
| Grain appearance | Improvement | Liu *et al*. (2017) |
| C, N, and P ratios in grain | Alteration | Wang *et al*. (2019) |
| Whole plant C/N ratio | No change | Cheng *et al*. (2010) |
| **Salinity and drought** | | |
| ROS production | Increase | Landi *et al*. (2017) |
| Damage to proteins, DNA and membranes | Increase | |
| Osmo protectants | Enhanced | Kumar and Kumar (2018) |
| Antioxidant activity | Increase | |
| Programmed cell death | Increase | Bhar *et al*. (2020) |
| Photosynthetic rate and efficiency | Reduction | Wu *et al.* (2019) |
| Grain filling | Reduction | |
| Grain yield | Reduction | |
| **Salinity and submergence** | | |
| Aerenchyma formation | Increase | Ray *et al*. (2021) |
| Respiratory burst oxidase homolog (RBOH) signalling | Increase | |
| Ethylene production | Increase | |
| **Salinity and high temperature** | | |
| $K^+$ transporter *OsHKT1;5* | Downregulation | Nahar *et al*. (2022) |
| Upregulated *OsHSP18*, *OsP5CS* | Upregulation | |
| $Na^+/H^+$ antiporter *OsNHX* | Upregulation | |
| **Heat and Blast Disease** | | |
| Membrane stability | Improved | Zhao and Cui (2020) |
| Heat shock proteins (HSPs) | Increase | |
| Pathogenesis-related proteins (PRPs) | Increase | |
| Stress-responsive pathways | Upregulation | |
| **Flooding and Sheath Blight** | | |
| Aerenchyma cells | Increase | Ismail Eizenga (2014) |
| ethylene-responsive genes | Upregulation | |
| defense mechanisms | Enhanced | |
| **Salinity and Bacterial Blight** | | |
| Ion homeostasis and production of, including, to counteract both salinity and bacterial infection. | Regulation | Reddy and Choi (2017) |
| defence-related compounds including antimicrobial peptides | Increase | |
| **Heat and Root-Knot Nematodes** | | |
| Heat shock proteins | Increase | Sinha and Kumar (2019) |
| nematode-specific defence proteins | Increase | |
| Root architecture | Improved | |

### A. Stress responses under elevated $CO_2$ and combined stress condition

Research on the impact of global warming on crop plants indicates that elevated $CO_2$ ($eCO_2$) concentrations can boost productivity by up to 40% for $C_3$ crops and 10% for $C_4$ crops (Lotze-Campen *et al*., 2009). For example, $eCO_2$ can enhance crop biomass by as much as 50% (Rogers *et al*., 1993). However, understanding how plants respond to combined stresses—particularly drought and heat—under $eCO_2$ is essential, especially in the context of global warming. Abdelhakim *et al*. (2022) emphasized the adaptive physiological and biochemical responses of crops to these stresses and discussed the mitigating effects of $eCO_2$. Similarly, Vijayalakshmi *et al*. (2023) found that $CO_2$ enrichment reduced stomatal frequency while increasing photosynthesis rates in green gram and rice, alongside improved pollen viability and germination under drought and heat stress. Notably, rice and green gram showed greater yield increases (15.34% and 16.58%, respectively) compared to maize and ragi.

Moreover, Li *et al*. (2019) reported a 20.8% yield loss due to the combined effects of heat and drought at 800 ppm $eCO_2$, while Vanaja *et al*. (2024) observed negative impacts of elevated temperatures interacting with $eCO_2$ on maize hybrids' phenology, physiology, biomass, and grain yield. Among the hybrids, 900M GOLD performed well at temperatures above 35°C, whereas DHM117 thrived under both elevated temperature and $eCO_2$, showcasing improved physiological responses. A meta-analysis revealed that while $eCO_2$ can increase grain yield and starch content in rice, wheat, and maize, it may decrease protein and mineral content. The impact of stomatal conductance for $CO_2$ can lead to water loss, affecting transpiration efficiency. Most studies indicate that $eCO_2$ can mitigate combined stresses, highlighting opportunities to leverage these conditions through a deeper understanding of its mechanisms, as summarized in Table 13.

**Table 13. Mitigation effect/mechanisms of $eCO_2$ under combined heat and drought in different crops**

| Crops | Possible mitigation effect/mechanisms of $eCO_2$ under combined heat and drought | References |
|---|---|---|
| Wheat | Elevated $CO_2$ levels resulted in a 20.8% increase in wheat grain yield | Li *et al*. (2019) |
| | The mitigation efforts were evident in the enhanced final yield | Fitzgerald *et al*. (2016) |
| | Elevated $CO_2$ enhanced photosynthesis and sustained higher Fv/Fm in certain genotypes under combined stress, compared to ambient $CO_2$ | Abdelhakim *et al*. (2021) |

| | | |
|---|---|---|
| | Water use efficiency was enhanced but no impact of $eCO_2$ on yield enhancement | Abdelhakim *et al*. (2022) |
| Tomato | No $eCO_2$ mitigation due to increased severity of water deficit. | Zhou *et al*. (2020) |
| *Arabidopsis* | Mitigation is associated with reduced photorespiration and increased content of different antioxidant mechanisms. | Zinta *et al*. (2014) |
| | $eCO_2$ increased stress tolerance under combined drought and heat by mitigating oxidative stress and improving the water status of plants. | Abo Gamar *et al*. (2019) |
| | $eCO_2$ partially mitigated the adverse effect of stresses on some traits in the selected genotypes. | Abo Gamar *et al*. (2021) |
| *Brassica napus* | Improved plant water relations | Diksaityt *et al*. (2019) |
| Cotton | Elevated $CO_2$ improved biomass and water use efficiency (WUE), but this effect was not observed under high temperatures and rapid water deficit due to stomatal limitations | Broughton *et al*. (2017) |

**Source**: Modified from Abdelhakim *et al*. (2022)

Plants develop various adaptive mechanisms to cope with the interplay of multiple environmental stresses, such as heat and drought. The interaction of these stresses under elevated $CO_2$ ($eCO_2$) conditions is particularly important to understand due to their opposing effects. For example, while a higher transpiration rate is crucial for cooling leaves under heat stress, improved water use efficiency (WUE) is essential under drought stress to minimize water loss and maintain photosynthesis (**Table 13**). The severity of combined stress often depends on which stress predominates, with drought generally being more dominant depending on its intensity and duration.

Although $eCO_2$ can mitigate plant responses to individual stresses by enhancing photosynthesis and improving plant-water relations, this benefit may be reduced when stresses occur frequently. The lack of improvement in final yield despite enhanced photosynthesis under $eCO_2$ could be due to limitations such as source-sink imbalances, nutrient deficiencies, or differences among cultivars as reported by Vanaja *et al*. (2024).

The adverse effects of combined heat and drought stress during critical stages such as flowering and grain-filling highlight the need to explore whether heat-tolerant or drought-tolerant cultivars might better exploit $eCO_2$ to mitigate these stresses. Understanding how different genotypes, growth environments, and agronomic practices interact (G × E × M) is

crucial for improving combined stress tolerance and developing climate-resilient crops. Further research and the application of advanced phenomics approaches will be essential to better understand these interactions and enhance stress resilience in target environments.

**B. Factors influencing crop responses against multiples stresses**

To develop climate-smart crop varieties capable of enduring multiple stresses, it is crucial to understand several interrelated factors determining crop responses against multiples stresses. These include genetic traits, environmental conditions, and physiological mechanisms, all of which play vital roles in determining a plant's response in terms sensitive and resilience to stresses.

**Genetic Factors** are reflecting intrinsic inherent system of crops evolved through reorganizing genome aligning with natural genetic variation as well as selection pressure exerted during their domestication. During the course of dynamic variation crops being developed different responsive mechanisms to encounter a variety of stress conditions. Thus, the varieties with specific genetic traits exhibit varying levels of resistance or tolerance to both biotic stresses, such as pests and diseases, and abiotic stresses. For instance, plants with particular stress-responsive genes can produce proteins that help fend off pathogens or enhance their ability to cope with water scarcity. By identifying and introgression of these beneficial genetic factors/traits, breeders can develop varieties that are better suited to challenge the diverse multiple stresses posed by changing climates.

**Environmental factors** further influence a crop's stress response and are essential considerations in breeding climate-smart varieties. Factors such as soil quality, including pH and nutrient levels, and climate variables like temperature and rainfall patterns, all affect plant health. For example, a variety that performs well under optimal conditions might struggle under extreme temperatures or variable rainfall. By understanding how environmental factors interact with genetic traits, breeders can develop varieties that are robust across a range of conditions, ensuring consistent performance even in unpredictable climates.

**Stress interactions** introduce additional complexity in the prevalence of multiple or combined stresses. The effects of multiple stresses can be more severe than the sum of their individual impacts. For instance, the combined impact of drought and high temperatures can exacerbate stress beyond what either condition would cause on its own. Plants need to deploy a range of

physiological responses to manage these combined stresses effectively. Recognizing and addressing these interactions is crucial for tailoring the breeding strategies for developing varieties that can thrive under multiple stress conditions.

A critical aspect of developing these climate-smart varieties is comprehending the interactions between host and stress factors. For instance, in host-pathogen interactions, a plant's ability to resist a pathogen can be influenced by its response to environmental stressors. A plant that is under drought stress may become more susceptible to certain diseases because its defense mechanisms are compromised. Thus, understanding how environmental stresses affect pathogen resistance is essential for breeding varieties that are not only resistant to diseases but also resilient under diverse environmental conditions.

Overall, developing climate-smart and multiple-stress-tolerant crop varieties will require a comprehensive understanding of the interplay between genetic, environmental, and physiological factors. By focusing on these elements and their interactions, breeders can design strategies to enhance crop's intrinsic inherent ability to tolerate and perform better under multiple stress conditions. This holistic approach ensures that new varieties will be robust, climate resilient, and capable of sustaining agricultural productivity in evolving stress conditions being accelerated due to climate change.

### C. Crop-stress factor interaction at molecular level

Plants perceive and respond to both abiotic and biotic stresses through complex signalling mechanisms, though the nature and outcomes of these responses vary. Abiotic stresses, such as heat and drought, trigger cellular responses via receptors on the plasma membrane, which detect stress signals and activate intracellular second messengers like calcium ions ($Ca^{2+}$), reactive oxygen species (ROS), and inositol phosphates. These signals initiate cascades leading to changes in gene expression and hormone production, such as abscisic acid (ABA), which help the plant adapt to adverse conditions (Hasegawa *et al*., 2000). In contrast, biotic stresses from pathogens like fungi and bacteria are detected by pattern recognition receptors (PRRs) and nucleotide-binding leucine-rich repeat receptors (NLRs) that recognize pathogen-associated molecular patterns (PAMPs) or specific effector molecules. This recognition triggers innate immune responses, including the production of antimicrobial compounds, reinforcement of cell walls, and activation of systemic defences like systemic acquired resistance (SAR) (Jones and Dangl, 2006; Glazebrook, 2005). Hormones such as salicylic acid

and jasmonic acid play critical roles in orchestrating these defense mechanisms, targeting both pathogen-specific and broad-spectrum defences (Howe and Schilmiller, 2002). While both types of stresses involve ROS and $Ca^{2+}$ signalling, their specific pathways and outcomes reflect the distinct nature of abiotic and biotic challenges (Nürnberger and Lipka, 2005; Zhu, 2016).

**i. Crops perception to abiotic stress**

Abiotic stresses such as heat and drought are primarily detected through physical and chemical changes in the environment that directly affect cellular processes. For example, heat stress causes a rise in temperature that leads to protein denaturation and membrane instability. Plants sense this change through temperature-sensitive receptors and heat shock proteins (HSPs) that stabilize proteins and enhance stress tolerance (Wang *et al*., 2004). Similarly, drought stress is perceived through reduced water availability, which triggers changes in turgor pressure and osmotic balance. The plant responds by activating osmoprotectants and adjusting stomatal behaviour to minimize water loss through transpiration (Chaves *et al*., 2003).

The perception of abiotic stress is often linked to changes in physical parameters that plants can measure directly. For instance, drought-induced changes in soil moisture levels are easily detected by roots, which then signal the plant to activate drought response pathways involving abscisic acid (ABA) and other stress hormones (Kramer and Boyer, 1995). The direct and measurable nature of these signals often makes abiotic stress perception relatively straightforward for plants.

**ii. Crops perception to biotic stress**

In contrast, biotic stresses involve the recognition of pathogen-specific molecules, which requires a more intricate detection system. Pathogens such as fungi and bacteria introduce various molecular patterns into the plant tissue, known as pathogen-associated molecular patterns (PAMPs) or effectors. Plants use pattern recognition receptors (PRRs) and nucleotide-binding leucine-rich repeat (NLR) receptors to detect these molecules (Jones and Dangl, 2006). This detection initiates a complex immune response that includes local and systemic defence mechanisms.

For instance, when a fungal pathogen infects a plant, it secretes effector proteins that interfere with the plant's normal cellular functions. The plant must recognize these effectors

through specific receptors and activate defence pathways, such as the production of antimicrobial compounds and the strengthening of cell walls (Kaur *et al*., 2022). This process involves intricate signalling networks and often requires a pre-existing immune memory or heightened the state of alertness.

The complexity in detecting biotic stress arises from the need to differentiate between numerous pathogen types and their strategies for evasion. Unlike abiotic stresses, which involve more uniform environmental changes, biotic stresses are highly specific and can vary greatly between different pathogens and even strains within the same species.

A notable example of abiotic stress perception is drought stress in crops such as wheat, where drought conditions lead to a measurable decrease in soil moisture and plant water status, which can be directly correlated with physiological responses like stomatal closure and osmotic adjustments (Boyer, 1982). In contrast, biotic stress response/preception includes sequential events viz., infection of pathogen on host, recognition of pathogen but host and interaction between pathogen and host. Here, the recognition of bacterial effectors requires a complex network of immune receptors and signalling pathways, which must be finely tuned to detect and respond to specific pathogen molecules (Zipfel *et al*., 2004).

In summary, while plants have evolved mechanisms to perceive both abiotic and biotic stresses, abiotic stress perception tends to be more direct due to clear physical changes in the environment. Biotic stress, on the other hand, involves recognizing specific pathogen molecules through intricate and specialized detection systems. This complexity often makes biotic stress perception more challenging for plants compared to abiotic stress. But when comparing the ease of tracing and detecting specific gene or molecular interactions at the cellular level between different stress types in plants, biotic stresses, such as pathogen infections, often offer more straightforward targets for identification and manipulation than abiotic stresses. This relative ease is attributed to several key factors.

Model Systems and Clear Signalling Pathways further simplify the study of biotic stress responses. Extensive research has established well-characterized signalling pathways and defense mechanisms in pathogen-plant interactions. A notable example is the interaction between specific pathogen effectors and plant resistance (R) genes. For instance, the recognition of the fungal effector AvrPm3 by the wheat gene Pm3 initiates a robust immune

response, providing a clear framework for identifying and manipulating genes associated with disease resistance (Srichumpa et al., 2005).

Genomic Tools and High-Throughput Technologies have greatly enhanced the identification of genes involved in biotic stress responses. Advances in genomics, transcriptomics, and proteomics, such as genome-wide association studies (GWAS) and quantitative trait locus (QTL) mapping, are particularly effective in pinpointing genes linked to disease resistance (Mackay and Powell, 2007). These technologies allow for detailed exploration of pathogen interactions at the molecular level, accelerating the development of resistant crop varieties.

There are several examples available to illustrate the successful exploitation basic understanding of host-pathogen interaction in crop improvement particularly development of disease resistance varieties. In wheat, resistance to *Fusarium* head blight (FHB) has been associated with specific genes such as *Fhb1* and *Fhb2*. Research into the molecular interactions between wheat and the *Fusarium* pathogen has enabled the development of resistant varieties through genetic mapping and functional validation (Yu *et al*., 2008). Similarly, in tomatoes, the *Rpi-blb2* gene provides resistance to late blight caused by *Phytophthora infestans*. The identification and characterization of this gene have led to the development of late blight-resistant tomato varieties (Halterman *et al*., 2016). In rice, the *Xa21* gene, which encodes a receptor-like kinase, plays a crucial role in recognizing bacterial signals and initiating a defense response against *Xanthomonas oryzae* pv. *oryzae*. The cloning and functional analysis of *Xa21* have facilitated the development of rice varieties with enhanced resistance to bacterial blight (Song *et al*., 1995).

The specificity of pathogen-plant interactions and the clarity of the associated signalling pathways make it relatively easier to trace and detect genes and molecular mechanisms involved in biotic stress responses. This specificity has led to successful development of resistant varieties in several agricultural crops including wheat, rice, groundnut, pigeon pea, tomato, etc. The conceptualization of Zig-Zag Model to explain the interaction of host-pathogen (stress factor) to be considered as an important disease resistance breeding, which aids in identification of genes involved in disease resistance mechanism.

### iii. Zig-Zag Model: A versatile tool for explaining host–pathogen interactions

The zig-zag model, proposed by Jones and Dangl (2006), describes the dynamic interaction between host plants and pathogens in two main phases viz., Pattern-Triggered Immunity (PTI) and Effector-Triggered Immunity (ETI). The first line of defense (PTI) is triggered when the plant detects conserved pathogen-associated molecular patterns (PAMPs) using pattern recognition receptors (PRRs). This recognition initiates a broad, non-specific immune response. For example, the detection of flagellin, a PAMP from bacterial flagella, activates PTI in plants, leading to basal resistance. Pathogens can overcome PTI by secreting specific effectors that manipulate host cellular processes (Fig. 5). Plants respond to these effectors with ETI, mediated by resistance (R) genes. These R genes encode receptors that specifically recognize the pathogen's effectors, leading to a more robust and specific defence response. This interaction often results in localized cell death to restrict pathogen growth.

The zig-zag model illustrates how plants first engage in a broad defence strategy (PTI) and then, if necessary, mount a more targeted response (ETI) against specific pathogens. This model is foundational for understanding the genetic and molecular basis of disease resistance and provides insights into the development of resistant crop varieties. The zig-zag model effectively captures the sequential and dynamic nature of plant-pathogen interactions, highlighting the role of both broad and specific immune responses. This model helps explain why biotic stress responses are more straightforward to trace and manipulate at the molecular level compared to abiotic stress responses. By understanding these interactions, researchers can identify specific genes involved in resistance and develop crops with enhanced disease resistance. For example, RPS2 detects the AvrRpt2 effector from *Pseudomonas syringae*, leading to a targeted immune response (Bent *et al*., 1994). Similarly, *Xa21* in rice confers resistance by recognizing the AvrXa21 effector from *Xanthomonas oryzae* (Song *et al*., 1995). The zig-zag model highlights how PRRs and R genes work in tandem, with PRRs mediating the initial defence and R genes triggering a more specific and robust response upon effector recognition.

### iv. Stress signalling network model: A generalized model to explain crop perception and response to abiotic stresses

The models explaining abiotic stress responses in plants are not as well-defined as the zig-zag model for biotic stress, they provide crucial insights into how plants manage these challenges. One prominent model is the “stress signalling network” model, which details how plants

perceive and respond to various abiotic stresses like drought, heat, and salinity through intricate networks of signalling pathways and molecular interactions.

In the stress signalling network model, the process begins with perception and initial response. Plants detect abiotic stresses through specialized receptors and sensors. For example, in the case of drought stress, changes in water potential and osmotic pressure are sensed, triggering receptors such as abscisic acid (ABA) receptors to initiate a response (Ma *et al.*, 2009). Similarly, heat stress is perceived through heat shock proteins (HSPs) and various transcription factors (Gomez-Pastor *et al.*, 2018).

Following perception, signal transduction pathways come into play. The initial stress signals activate second messengers like calcium ions ($Ca^{2+}$), reactive oxygen species (ROS), and inositol phosphates. These messengers propagate the stress signal within the cell and activate various protein kinases and transcription factors. For instance, during heat stress, the HsfA1 transcription factor is activated, which in turn promotes the expression of heat shock proteins (HSPs) crucial for stress mitigation (Nakashima *et al.*, 2009).

The gene regulation and response phase involve the activation of transcription factors that regulate stress-responsive genes, including late embryogenesis abundant (LEA) proteins and HSPs. These proteins play a critical role in alleviating stress by stabilizing cellular proteins, protecting cellular structures, and enhancing overall stress tolerance. For example, DREB1/CBF transcription factors are known to activate genes that bolster drought resistance (Yamaguchi-Shinozaki and Shinozaki, 2006).

Finally, the model encompasses adaptive responses where feedback mechanisms enable plants to adjust their growth, metabolism, and development to better cope with stress conditions. This includes processes like osmotic adjustment, increased synthesis of protective proteins, and modifications in growth patterns to optimize survival under adverse conditions.

In rice, *OsDREB1* (a transcription factor) and *OsHSP* (heat shock proteins) are key components of the stress signalling network. *OsDREB1* enhances drought tolerance by regulating genes involved in osmotic stress response, while *OsHSP* helps in protein stabilization under heat stress (Dubouzet *et al*., 2003; Xiang *et al.*, 2018).

The stress signalling network model helps to understand the complex interactions between stress perception, signal transduction, gene regulation, and adaptive responses, providing a framework for developing stress-resistant crops by manipulating these pathways. This generalized model helps in elucidating how plants manage and adapt to abiotic stresses, although it is continuously refined with ongoing research.

**v. Cross-talk between abiotic and biotic stress signalling in plants**

The interplay between abiotic and biotic stress signaling in plants is complex and involves a coordinated response mediated by various signaling pathways (Fig. 5). Under abiotic stresses such as drought, heat, or salinity, plants activate signaling cascades primarily driven by the production and accumulation of abscisic acid (ABA). This ABA-mediated signaling influences downstream pathways, modulating cellular calcium levels and reactive oxygen species (ROS) production. Conversely, during biotic stress, signaling pathways are regulated by phytohormones like salicylic acid (SA) and jasmonic acid (JA). Recent research indicates that ABA also plays a critical role at the early stages of pathogen infection by modulating the production of SA and JA, thereby influencing the plant's response to pathogens Dixit *et al*., (2024).

In-depth basic study is essential to understand and exploit signaling involves cross-talk that activates transcription factors (TFs) such as WRKY, MYB, and COI. This complex dynamic signal-response process may enable to unravel the key genes responsible for multiple stress tolerance which plays a crucial role in development of climate smart varieties with enhanced multiple stress tolerance.

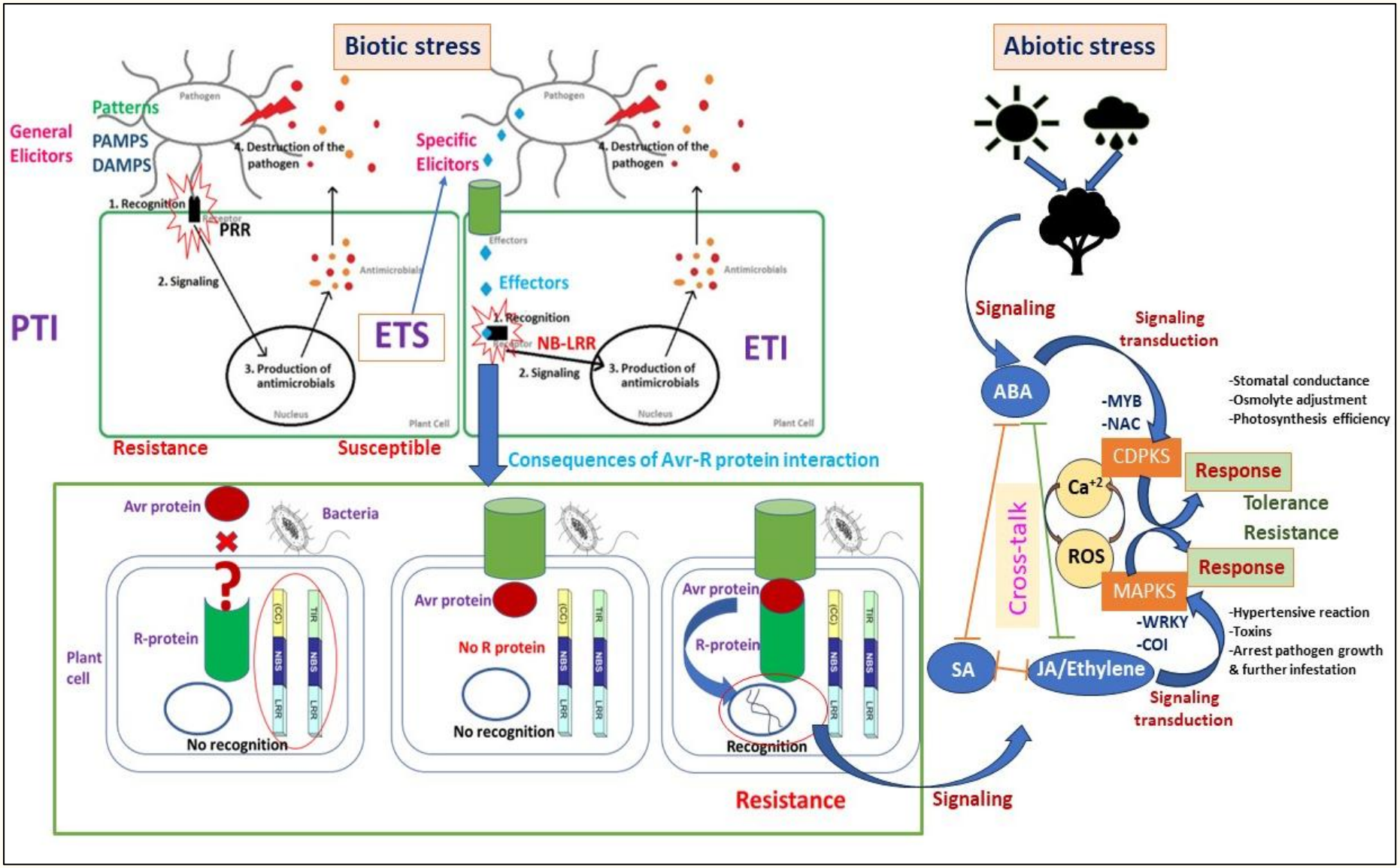



**Figure 5. Schematic model illustrating the plant-stress (biotic and abiotic) interactions at the molecular level**

Developing crop varieties that are tolerant to abiotic stresses such as drought, salinity, and extreme temperatures presents several significant challenges. Unlike biotic stresses, which involve specific pathogen-host interactions, abiotic stresses affect multiple physiological and biochemical processes, making it difficult to identify precise genetic targets for improvement. These stresses often interact in complex ways, further complicating breeding efforts. Tolerance to abiotic stresses is generally controlled by multiple genes with small effects, adding to the complexity compared to single-gene resistances seen in biotic stresses. Additionally, abiotic stress responses can vary significantly based on environmental conditions, leading to site-specific effectiveness of tolerance traits. The unpredictable nature of these stresses further complicates evaluation and selection processes. Integrating multiple stress tolerance traits requires advanced breeding techniques and careful balancing of trade-offs, such as maintaining yield while improving stress resilience. Moreover, the incomplete understanding of the underlying molecular mechanisms and the high costs associated with advanced genomic and breeding technologies present additional barriers. Addressing these challenges requires ongoing research, innovative breeding strategies, and robust agricultural infrastructure to enhance crop resilience and ensure agricultural productivity in the face of a changing climate.

### 3.1.2 Designing Climate-Smart Breeding Programs for Development of Multi-Stress Tolerant Crop Varieties

Better understanding of how crops respond to multiple stresses including molecular interactions of crop-stress factors at cellular level is crucial for designing effective breeding programs. Integrating conventional and molecular breeding approaches for developing climate-smart varieties with multiple stress tolerance represents a forward-thinking strategy to address the challenges posed by climate change and environmental stresses. Conventional breeding methods, including identification of potential donors and hybridization, provide a foundational approach for creating genetic variability, while molecular breeding techniques—such as genetic engineering, marker-assisted selection (MAS), and genomic selection—offer precision and efficiency in identifying and incorporating stress-tolerant traits/genes/QTLs. By combining these approaches, breeders can leverage the strengths of both strategies: the broad adaptability and proven effectiveness of conventional methods with the targeted, gene-specific advancements offered by molecular tools. This integrated breeding design (Fig. 6) enables the development of crop varieties that are not only more resilient to multiple stresses but also more

adaptable to varying climate conditions, ensuring improved food security and agricultural sustainability in the face of a changing climate.

**A. Pre-breeding: Exploiting and enriching the PGRs**

Pre-breeding plays a crucial role in identifying donor plants for the development of multi-stress tolerant crop varieties by systematically evaluating genetic resources for desirable traits. This process involves collecting and characterizing diverse germplasm from various environments, including wild relatives and landraces, to identify sources of genetic variation that confer tolerance to multiple stresses such as drought, salinity, and heat. By subjecting these materials to controlled stress conditions and performing molecular analyses, researchers can pinpoint specific genes or traits associated with stress resilience. For instance, advanced techniques like quantitative trait locus (QTL) mapping and genome-wide association studies (GWAS) help to identify key genetic markers linked to stress tolerance. These identified donors, which exhibit robust stress-resistant characteristics, are then utilized in breeding programs to introduce and combine these beneficial traits into elite crop varieties. Thus, pre-breeding effectively narrows down the potential donor lines, ensuring that the resulting varieties have a genetic foundation for enduring various environmental challenges.

A broad genetic base is crucial for stress breeding, as it ensures the development of crop varieties capable of withstanding a variety of environmental stresses. By incorporating a wide range of genetic resources, breeders can integrate multiple stress tolerance traits into crops, enabling them to manage diverse stress conditions simultaneously. Among diverse genetic resources, wild species are crucial for developing multiple stress-tolerant crops due to their unique broad genetic base with sources traits/genes that confer resilience to multiple stresses. These species provide a diverse pool of genes that help crops withstand challenges such as drought, heat, salinity, and pest infestations.

For example, maize varieties have been enhanced by including genes from wild relatives, which improved their resilience to both drought and heat stress (Tripathi *et al*., 2020). In wheat, the integration of diverse genetic materials has led to varieties that adapt well to different soil types, temperatures, and water availability. Similarly, in rice, using a broad genetic base has facilitated the development of varieties resistant to multiple diseases, such as rice blast and bacterial blight, thus preventing large-scale epidemics (Zhou *et al.,* 2022). Moreover, crops with a broad genetic base tend to exhibit greater yield stability across various

environments because they are less susceptible to specific stress conditions. Soybean varieties developed from diverse genetic resources have demonstrated stable yields under drought, salinity, and varying soil conditions. Additionally, a broad genetic base provides a wealth of traits and genetic variations, allowing breeders to incorporate new beneficial traits. For instance, integrating wild relatives into tomato breeding has introduced traits for improved drought tolerance and disease resistance, enriching the genetic pool for further improvements (Ebert *et al*., 2015). The wild relative of different crops which are reported to be tolerant to different stresses have been presented in Table 14.

**Table 14. Wild species of crops known for different abiotic stress tolerance**

| Crop | Abiotic Stresses | Wild Species | References |
|---|---|---|---|
| **Field crops** | | | |
| Rice | DT | *O. barthii* (AA) | Kapazoglou *et al*. (2023) |
| | | *O. australiensis* (EE) | |
| | | *O. glaberrima* (AA) | |
| | | *O. longistaminata* (AA) | |
| | | *O. punctata* (BB, BBCC) | |
| | FL | *O. schlechteri* (HHKK) | Kapazoglou *et al*. (2023) |
| | | *O. latifolia* (CCDD) | |
| | | *O. grandiglumis* (CCDD) | |
| | | *O. ridleyi* (HHJJ) | |
| | HT | *O. barthii* (AA) | Kapazoglou *et al*. (2023) |
| | | *O. australiensis* (EE) | |
| | | *O. meridionalis* (AA) | |
| | | *O. glaberrima* (AA) | |
| | | *O. longistaminata* (AA) | |
| | CL | *O. granulata* (GG) | Kapazoglou *et al*. (2023) |
| Cowpea | DT | *Vigna exilis* | Kapazoglou *et al*. (2023) |
| | | *Vigna heterophylla* | |
| | | *Vigna kirkii* | |
| | | *Vigna trilobata* | |
| | | *Vigna riukiensis* | |
| | HT | *Vigna hainiana* | Kapazoglou *et al*. (2023) |
| | | *Vigna stipulacea* | |
| | SL | *Vigna luteola* | Kapazoglou *et al*. (2023) |
| | | *Vigna marina* | |
| | | *Vigna nakashimae* | |
| | | *Vigna riukiuensis* | |
| | | *Vigna vexillata* | |

| Crop | Abiotic Stresses | Wild Species | References |
|---|---|---|---|
| | | *Vigna trilobata* | |
| | Extreme soils | *Vigna minima* | Kapazoglou *et al*. (2023) |
| | | *Vigna indica* | |
| | WL | *Vigna vexillata* | Kapazoglou *et al*. (2023) |
| Groundnut | DT | *Arachis dardani* | Kapazoglou et al. (2023) |
| | | *Arachis diogoi* | |
| | | *Arachis duranensis* | |
| | | *Arachis glabrata* | |
| | | *Arachis magna* | |
| | HT | *Arachis diogoi* | Kapazoglou et al. (2023) |
| | | *Arachis duranensis* | |
| | | *Arachis glabrata* | |
| | | *Arachis ipaensis* | |
| | CL | *Arachis duranensis* | Kapazoglou et al. (2023) |
| | | *Arachis glabrata* | |
| | | *Arachis paraguariensis* | |
| | SL | *Arachis diogoi* | Kapazoglou *et al*. (2023) |
| | | *Arachis duranensis* | |
| | | *Arachis glabrata* | |
| | UV-Exposure Tolerance | *Arachis stenosperma* | Kapazoglou *et al*. (2023) |
| Alfalfa | DT, SL and CL | *Medicago truncatula* | Kapazoglou *et al*. (2023) |
| | | *Medicago ruthenica* | |
| | | *Medicago polymorpha* | |
| | | *Medicago falcata* | |
| **Vegetables** | | | |
| Tomato | DT | *Solanum habrochaites (syn. Solanum hirsutum)* | Kapazoglou *et al*. (2023) |
| | | *S. pennellii* | |
| | | *S. pimpinellifolium* | |
| | | *S. cheesmanii* | |
| | | *S. chilense* | |
| | | *Solanum sitiens* | |
| | SL | *S. pennellii* | Kapazoglou *et al*. (2023) |
| | | *S. pimpinellifolium* | |
| | | *S. hirsutum (syn. S. habrochaites)* | |
| | | *Solanum parviflorum* | |
| | HT | *S. habrochaites (syn. S. hirsutum)* | Kapazoglou *et al*. (2023) |

| Crop | Abiotic Stresses | Wild Species | References |
|---|---|---|---|
| | | *S. pennellii* | |
| | | *S. pimpinellifolium* | |
| | | *S. cheesmanii* | |
| | | *Solanum chmielewskii* | |
| **Fruit crops** | | | |
| Annona | DT unfavourable soil conditions | *A. reticulata* | Handbook of Horticulture, 2019 |
| Apple | DT | *Malus prunifolia* | Kapazoglou *et al*. (2023) |
| | | *Malus sieversii* | |
| | HT | *Malus prunifolia* | Kapazoglou *et al*. (2023) |
| | | *Malus sieversii* | |
| | CL | *Malus prunifolia* | Kapazoglou *et al*. (2023) |
| | | *Malus baccata* | |
| | | *Malus sieversii* | |
| Avocado | DT, ST | *P. americana*, var. *americana* | Cooper (1951) Handbook of Horticulture, 2019 |
| Banana | DT | *Musa balbisiana* | Ravi and Vaganan (2016) |
| Blueberry | DT, HT | *V. darrowi* | Camp (1945); Ballington (1990); Chandler *et al*. (1985); Hancock *et al*.(1995); Luby *et al*. (1991); Lyrene (1993) |
| | DT, HT | *V. amoneum* | |
| | DT, HT | *V. myrsinites* | |
| | DT, HT | *V. arboreum* | |
| | DT, HT | *V. pallidum* | |
| | DT, HT | *V.tenellum* | |
| Ber | DT, ST | *Z. rotundifolia* | Gupta *et al*. (2002) |
| | DT, ST | *Z. nummularia* | Meena *et al*. (2003) |
| | DT, ST | *Z. spina-christi* | Sohail *et al*. (2009) |
| Citrus | DT, ST + Gummosis and root rot | *C. limonia* | Stuchi *et al*. (2000); Pompeu Junior 2005, Cantuarias-Avilles *et al*. (2011); Patel *et al*. (2011) |
| | DT, ST, WL +Tristeza virus | *C. reshni* | Bhusal *et al.* (2002) |
| | DT, ST | *C. aurantium* | Patel *et al*. (2011); Levy *et al*. (1999); Storey (1995); |
| | DT, WL, LT + Foot rot and Tristeza virus | *Poncirus trifoliate* | Bhusal *et al*. (2002); Sahin-Cevik and Moore (2006b); Lang *et al*. (2005) |
| | DT, ST, WL + Tristeza virus | *C. jambhiri* | Patel *et al*. (2011); Levy *et al*. (1999); Storey (1995) |

| **Crop** | **Abiotic Stresses** | **Wild Species** | **References** |
|---|---|---|---|
| Cranberry | Cold Tolerance | *Vaccinium oxycoccos* | Kapazoglou *et al*. (2023);Kapazoglou *et al*. (2023) |
| Guava | Wilt and nematode | *P. friedrichsthalianum* | Handbook of Horticulture, (2019) |
| Grapevine | Drought Tolerance | *Vitis yeshanensis* | Xiaoyue *et al*. (2020) |
| | Salt Tolerance | *Vitis sylvestris* | Kapazoglou *et al*. (2023) |
| Kiwi | DT, ST, WL | *A. valvata* | Zong *et al*. (2019); Li *et al*. (2020); Bai *et al*. (2019) |
| Mango | WL | *M. andamanica* | Handbook of Horticulture (2019) |

DT=Drought tolerance; ST= Salinity tolerance; WL= Waterlogging tolerance; CL= Cold tolerance

In addition to wild species, several other genetic resources can be utilized in stress breeding to enhance crop resilience and adaptability.

**Landraces**, which are traditional varieties adapted to local conditions, offer sources of valuable traits for stress tolerance, such as drought resistance seen in some rice and wheat landraces. India boasts a rich array of landraces due to its diverse agro-climatic zones and traditional farming practices. The country's varied agro-climatic conditions and soil types create numerous ecological niches, leading to the development of landraces uniquely adapted to local conditions such as drought, flood, and soil salinity. Traditional farming practices, including selective breeding and seed saving, have preserved these unique varieties over generations, ensuring their continued relevance. Additionally, the geographical isolation of many regions, coupled with the cultural significance of agriculture, has led to the cultivation of landraces with specific traits desired by local communities. This combination of environmental diversity and traditional agricultural methods has resulted in India having a remarkably extensive and varied collection of landraces in few crops like rice, millets, pulses, brinjal, etc. Use of such landraces is very crucial in development of climate smart or multi-stress tolerant crop varieties as witnessed in rice for developing salinity and submergence tolerant varieties through introgression of QTLs/genes/traits from Pokkali (Chen *et al*., 2020) and FR13A landrace (Bailey-Serres *et al*., 2010), respectively.

The pre-breeding not only the gateway for utilizing the broader genetic material, it also provides a platform to enrich PGRs for multiple stress tolerance via adding genetic and genomic resources to existed gene pool. For instance, interspecific hybrids, created by crossing species within the same genus, bring together traits/ genes for multiple stress tolerance from both parents, as demonstrated in hybrids between *Glycine max* and *Glycine soja* (Zhuang *et al*., 2022). **Mutants** created through mutation breeding can reveal novel stress-tolerant traits, as seen in *Arabidopsis* and maize mutants. **Genetically modified organisms (GMOs)** use targeted gene insertion to confer stress resistance, such as *Bt* genes for pest resistance or drought-resistant modifications. Ning *et al*. (2017) found that transgenic *G. max* lines expressing GsWRKY20 from *G. soja* experienced less yield loss under drought stress compared to their non-transgenic control counterparts. Traits specific **germplasm collections** registered for different stress tolerance in gene banks preserve a broad array of genetic material comprising landraces, wild relatives, mutants, and improved varieties, providing a rich resource for stress resistance breeding programs. Some of the abiotic stress tolerant germplasm registered in NBPGR are presented in Table 15.

**Table 15. Germplasm of different crops registered for traits associated with different abiotic stress tolerance**

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| **Cereals** | | | | |
| **Rice** | IC296798 | 2001 | Aluminium toxicity and moderately tolerant to salinity | ICAR-Central Island Agricultural Research Institute (CARI), Port Blair, Andaman and Nicobar Islands |
| | IC296799 | 2001 | Tolerant to salinity and iron toxicity | |
| | IC283020 | 2004 | Tolerant to complete submergence | ICAR-National Rice Research Institute Cuttack, Cuttack, Odisha |
| | IC471839 | 2005 | Anaerobic respiration tolerant seedling | |
| | IC567648 | 2008 | Salinity tolerance | Govind Ballabh Pant University of Agriculture and Technology (GBPUA& T) Pant Nagar, Uttarakhand |
| | IC283026 | 2008 | Tolerant to complete submergence | ICAR-National Rice Research Institute Cuttack, Cuttack, Odisha |
| | IC258997 | 2008 | Tolerant to complete submergence | |
| | IC39575 | 2008 | Tolerant to complete submergence | |
| | IC256777 | 2008 | Tolerant to complete submergence | |
| | IC256806 | 2008 | Tolerant to complete submergence | |
| | IC283068 | 2008 | Tolerant to complete submergence | |

| **Crops** | **Registered germplasm** | **Year** | **Abiotic stresses** | **Developed institute** |
|---|---|---|---|---|
| | IC569481 | 2009 | Tolerance to phosphorous deficient soils | ICAR-Indian Institute of Rice Research (IIRR), Rajendranagar, Hyderabad, Telangana |
| | IC0258990 | 2010 | Tolerant to complete submergence up to 10 days only | ICAR-National Rice Research Institute Cuttack, Cuttack, Odisha |
| | IC0256801 | 2010 | Tolerant to complete submergence | |
| | IC0258830 | 2010 | Tolerant to complete submergence | |
| | IC0380753 | 2010 | Vegetative stage drought tolerance | |
| | IC0256590 | 2010 | Vegetative stage drought tolerance | |
| | IC0575277 | 2014 | Elongation ability of shoot under submergence | |
| | IC0575273 | 2014 | Submergence tolerance (20 days). | |
| | IC0599689 | 2014 | Tolerant (SES score 3) to salinity stress (EC=12 dsm-1) at seedling stage. | ICAR - Central Coastal Agricultural Research Institute), ELA, Old Goa, Goa |
| | IC0513420 | 2017 | Tolerant to drought stress | ICAR-National Rice Research Institute Cuttack, Cuttack, Odisha |
| | IC619320 | 2017 | Tolerant to salinity stresses up to EC 10.0 dS/m. | ICAR-Central Soil Salinity Research Institute Karnal, Haryana |
| | IC619227 | 2017 | Tolerant to coastal salinity. | ICAR-Indian Institute of Rice Research (IIRR), Hyderabad, Telangana |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| | IC639318 | 2017 | Tolerant to alkalinity stresses up to pH 9.9. | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |
| | IC0619319 | 2019 | Tolerant to alkalinity stresses up to pH 9.9 and salinity stresses up to ECe 10.0 dS/m | |
| | IC413644 | 2019 | Tolerant to the combined stress of drought and salinity. Tolerant to vegetative stage stagnant flooding. | ICAR-National Rice Research Institute, Cuttack, Odisha |
| | IC574806 | 2019 | Tolerant to anaerobic germination | |
| | IC0599610 | 2019 | Tolerant to salinity stress. | |
| | IC596460 | 2019 | Tolerant to salinity stress at vegetative stage. | |
| | IC413613 | 2019 | Tolerant to salinity stress both at seedling and reproductive stage. | |
| | IC632071 | 2019 | Tolerant to low soil phosphorous condition. | ICAR-Indian Institute of Rice Research, , Hyderabad, Telangana |
| | IC632074 | 2019 | Drought and Heat stress tolerant | |
| | IC0599273 | 2020 | High temperature tolerance | |
| | IC627947 | 2020 | Tolerant to salinity stresses up to ECe 10.0 dS/m | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |

| **Crops** | **Registered germplasm** | **Year** | **Abiotic stresses** | **Developed institute** |
|---|---|---|---|---|
| | IC576152 | 2021 | Vegetative stage drought tolerance. | ICAR-National Rice Research Institute, Cuttack, Odisha |
| | IC330611 | 2021 | Vegetative stage drought tolerance. | |
| | IC330470 | 2021 | Vegetative stage drought tolerance. | |
| | EC670488 | 2021 | Tolerant to high temperature stress | ICAR-Indian Agricultural Research Institute, Pusa campus, New Delhi |
| | IC638602 | 2021 | Salinity Tolerant | Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu |
| | IC0298323 | 2021 | Salinity tolerant | ICAR-National Institute for Plant Biotechnology, New Delhi |
| | IC394535 | 2021 | Anaerobic germination tolerant | |
| | IC591486 | 2021 | Anaerobic germination tolerant | |
| | IC639795 | 2021 | Tolerance to sheath blight and low soil P tolerance. | ICAR-Indian Institute of Rice Research, Hyderabad, Telangana |
| | IC640651 | 2021 | Highly drought tolerant and resistant to blast disease. | Central Rainfed Upland Rice Research Station, ICAR-NRRI, Hazaribagh, Jharkhand |
| | IC575321 | 2021 | Tolerant to salinity stress and stagnant flooding (both fresh and saline water). | ICAR-National Rice Research Institute, Cuttack, Odisha |
| | IC640648 | 2021 | Tolerant to salinity at vegetative stage (12 dS $m^{-1}$). Tolerant to salinity at | |

| **Crops** | **Registered germplasm** | **Year** | **Abiotic stresses** | **Developed institute** |
|---|---|---|---|---|
| | | | reproductive stage (8 dS $m^{-1}$). | |
| | IC560851 | 2021 | Drought tolerant | ICAR NRRI, Central Rainfed Upland Rice Research Station, Hazaribagh, Jharkhand |
| | IC0640883 | 2021 | Drought and Phosphorus starvation tolerant and Weed competitiveness. | |
| | IC643971 | 2022 | Heat-tolerant | ICAR-Indian Institute of Rice Research, Hyderabad, Telangana |
| | IC645776 | 2022 | Tolerant to low soil Nitrogen content | |
| | IC645772 | 2022 | Tolerance to acidic soils (pH 4.3 – 5.2) | |
| | IC646829 | 2022 | Highly tolerant to submergence and high anaerobic germination potential. | ICAR-NRRI, Central Rainfed Upland Rice Research Station, Hazaribagh, Jharkhand |
| | IC0645856 | 2022 | Tolerant to vegetative stage drought stress. | ICAR-National Rice Research Institute, Cuttack, Odisha |
| | IC0645857 | 2022 | Tolerant to vegetative stage drought stress | |
| | IC0645858 | 2022 | Tolerant to drought. Moderately tolerant to submergence and anaerobic germination. | |
| | IC0640862 | 2023 | Tolerant to submergence with high anaerobic germination potential. | ICAR NRRI, Central Rainfed Upland Rice Research Station, Hazaribagh, Jharkhand |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| | IC648601 | 2023 | Submergence tolerance. | Acharya NG Ranga Agricultural University, Andhra Pradesh |
| | IC648979 | 2023 | Tolerance against soil sodicity | Chandra Shekhar Azad University of Agriculture & Technology, Kanpur, Uttar Pradesh |
| | IC650728 | 2023 | Multiple tolerance to sheath blight, sheath rot, RTD, leaf blast and neck blast diseases. Drought tolerance | ICAR-Indian Institute of Rice Research, Hyderabad, Telangana |
| | IC650767 | 2023 | Reproductive stage drought tolerant and resistance to blast and bacterial blight. | ICAR-Indian Institute of Rice Research, Hyderabad, |
| | IC635486 | 2023 | Salt tolerance (EC-5 to 11.95ds/m) | Acharya NG Ranga Agricultural University, Sugarcane Andhra Pradesh |
| | IC650731 | 2023 | Tolerance to reproductive stage drought stress. Tolerance to Submergence. Resistance to blast | ICAR-NRRI, Central Rainfed Upland Rice Research Station, Hazaribagh, Jharkhand |
| | IC650733 | 2023 | Tolerant to low soil N | ICAR-Indian Institute of Rice Research, Hyderabad, Telangana |
| | IC650735 | 2023 | Tolerant to low soil N | |
| **Wheat** | IC296681 | 1997 | Heat and drought tolerant | ICAR-Indian Institute of Wheat & Barley Research, Karnal, Haryana |
| | IC296742 | 1999 | Salinity/ alkalinity tolerant | |
| | IC296743 | 1999 | Heat tolerant | |
| | IC296767 | 2004 | Heat tolerant | Dr. Panjabrao Deshmukh Krishi Vidyapeeth Akola, Maharashtra |
| | IC443619 | 2005 | Heat tolerance | ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi |
| | IC443622 | 2005 | Drought & lodging resistance | |

| **Crops** | **Registered germplasm** | **Year** | **Abiotic stresses** | **Developed institute** |
|---|---|---|---|---|
| | IC546937 | 2006 | Heat tolerance | CCS Haryana Agricultural University, Hisar, Haryana |
| | IC546939 | 2006 | Lodging resistance | |
| | IC546936 | 2007 | Tolerant to salinity, sodicity and water logging | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |
| | IC029007A | 2011 | Terminal heat tolerance; | CCS Haryana Agricultural University, Hisar, Haryana |
| | IC035117 | 2011 | Terminal heat tolerance | |
| | IC0594376 | 2011 | Drought tolerant | ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi |
| | IC0594377 | 2011 | Drought tolerant | |
| | IC0594378 | 2011 | Drought tolerant | |
| | IC0594379 | 2011 | Drought tolerant | |
| | IC0590878 | 2012 | Lodging resistance | ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana |
| | IC408331 | 2009 | Salt tolerance, | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |
| | IC0582907 | 2010 | Early heat and drought tolerance | Dr. Panjabrao Deshmukh Krishi Vidyapeeth Akola, Maharashtra |
| | IC036761A | 2015 | Heat tolerant | ICAR-Indian Institute of Wheat & Barley Research, Karnal, Haryana |
| | IC0621693 | 2017 | Heat tolerant | |
| | IC625994 | 2018 | Heat tolerant | |
| | EC531185 | 2018 | Drought tolerant | ICAR-National Bureau of Plant Genetic Resources, New Delhi |
| | IC36761 | 2019 | Drought tolerant | ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana |
| | IC635017 | 2020 | Drought and Heat Tolerant | |
| | IC635018 | 2020 | Heat tolerant | |
| | IC635019 | 2020 | Drought and Heat tolerant | |
| | IC635697 | 2020 | Drought Tolerant | |
| | IC638605 | 2020 | Heat and drought tolerance | |
| | IC637557 | 2020 | Heat tolerant | |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| | IC638868 | 2021 | Drought tolerant | |
| | INGR21192 | 2021 | Heat stress tolerant | |
| | IC640668 | 2022 | Water stress tolerant | |
| | IC336816 | 2022 | Heat tolerant | Plant Biotechnology Centre, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan |
| | IC335971 | 2022 | Heat tolerant | |
| | IC645762 | 2022 | Heat tolerant | ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana |
| | IC128335 | 2022 | Drought tolerant | ICAR-National Bureau of Plant Genetic Resources, Pusa Campus, New Delhi |
| | IC416188 | 2022 | Terminal heat tolerance | |
| | IC533742 | 2022 | Salt tolerance | |
| | EC178071 | 2022 | Salt tolerance | |
| | IC112049 | 2023 | Terminal heat tolerant | |
| | IC0648495 | 2023 | Terminal heat tolerance and resistant to spot blotch | Nuclear Agriculture & Biotechnology Division, Bhabha Atomic Research Centre, Trombay, Mumbai, Maharashtra |
| | IC651969 | 2024 | Drought and Heat Tolerant | ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana |
| | IC651970 | 2024 | Drought tolerant | |
| | IC651971 | 2024 | Drought stress tolerant | |
| | IC651972 | 2024 | Drought and heat stress tolerance. Resistant to yellow rust of wheat | |
| | IC651973 | 2024 | Heat stress tolerance (HSI: 0.76) | |
| **Maize** | IC411287 | 2004 | Waterlogging tolerant | Acharya N G Ranga Agricultural University, (ANGRAU), Andhra Pradesh |
| | IC411288 | 2004 | Tolerant to lodging | |
| | IC0594467 | 2013 | Drought tolerant | |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| | IC0589129 | 2011 | Drought and waterlogging tolerant | |
| | IC0589130 | 2011 | Drought tolerant | |
| | IC0589131 | 2011 | Drought tolerant | |
| | IC0589132 | 2011 | Drought tolerant | |
| **Sorghum** | IC549901 | 2007 | Drought tolerant | Centre on Rabi Sorghum, ICAR-Indian Institute of Millets Research, Hyderabad |
| | IC343586 | 2020 | Drought tolerant | ICAR-Indian Institute of Millets Research, Hyderabad, Telangana |
| **Pearl Millet** | IC296716 | 1998 | Tolerant to drought and Heat | Bajra Section, Dept of Plant Breeding, CCS Haryana Agricultural University, Hisar, Haryana |
| | IC296734 | 1999 | Drought tolerant | ICAR-Central Arid Zone Research Institute (CAZRI), Jodhpur, Rajasthan |
| **Barley** | IC650742 | 2023 | Drought tolerance | ICAR-National Bureau of Plant Genetic Resources, Pusa Campus, New Delhi |
| | IC651979 | 2024 | Salinity | |
| **Finger Millet** | IC595249 | 2023 | Non-lodging | Agricultural Research Station, Perumallapalle, Andhra Pradesh |
| **Pulses** | | | | |
| **Chickpea** | IC0589349 | 2011 | Drought tolerant | Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri |
| | IC272450 | 2021 | Heat tolerant. | ICAR-Indian Institute of Pulses Research, Kanpur, Uttar Pradesh |
| | INGR20023 | 2020 | Tolerant to waterlogging, Resistant to Phytophthora stem blight disease | |
| **Soybean** | EC34101 | 2019 | Photo insensitive | |
| | IC646860 | 2022 | Waterlogging | |
| **Lentil** | IC0621470 | 2017 | Drought tolerance | ICAR-Indian Agricultural Research Institute, New Delhi |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| | IC643972 | 2023 | High salt tolerance (ECe5.8-6.7dS/m) | |
| | IC643973 | 2024 | Heat tolerance | |
| | IC530491 | 2022 | Waterlogging tolerant | Division of Plant Physiology, ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi |
| | IC519933 | 2022 | Waterlogging tolerant | |
| **Cowpea** | IC0625644 | 2024 | Photo-thermo insensitive | ICAR-Central Institute for Arid Horticulture, Bikaner, Rajasthan |
| | IC0628910 | 2024 | Photo-thermo insensitive | |
| **Oilseeds** | | | | |
| **Groundnut** | IC637587 | 2021 | Drought tolerant. CAM (Crassulacean Acid Metabolism) variant | ICAR-Directorate of Groundnut Research Junagadh, Gujarat |
| | IC637588 | 2021 | Salinity tolerant | |
| **Castor** | IC296674 | 2004 | drought tolerant | Dryland Agriculture Unit, CCS Haryana Agricultural University Hisar, Haryana |
| | IC274758 | 2008 | Early maturity & drought tolerance | ICAR-Indian Institute of Oilseeds Research Hyderabad, |
| **Indian Mustard** | IC0593927 | 2013 | Salinity tolerance | ICAR-Directorate of Rapeseed Mustard Research Bharatpur, Rajasthan |
| | IC553910 | 2008 | Salinity tolerance | Govind Ballabh Pant University of Agriculture and Technology Pantnagar, Uttarakhand |
| | IC0583386 | 2010 | High water use efficiency, thermo tolerance at terminal stage, salinity tolerance at juvenile stage | ICAR-Directorate of Rapeseed Mustard Research, Bharatpur, Rajasthan |
| | IC0584669 | 2011 | Tolerance to salinity at 10 ds/m at seedling stage | CCS Haryana Agricultural University, Hisar, Haryana |

| **Crops** | **Registered germplasm** | **Year** | **Abiotic stresses** | **Developed institute** |
|---|---|---|---|---|
| | IC0511389 | 2015 | Salinity tolerant | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |
| | IC0598624 | 2015 | Drought tolerant | ICAR-Directorate of Rapeseed Mustard Research, Bharatpur, Rajasthan |
| | IC624502 | 2017 | High tolerance to salinity (ECe 12 dS/m) and alkalinity (pH9.4). | ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana |
| | IC626000 | 2018 | Heat tolerant. Resistant to *Alternaria brassiceae.* | National Institute of Plant Biotechnology New Delhi |
| | IC630607 | 2019 | Tolerant to Salinity (ECe 14-15 dS/m) and Alkalinity (pH 9.4-9.5). | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |
| | IC632085 | 2019 | Drought tolerant | ICAR-Directorate of Rapeseed Mustard Research, Bharatpur, Rajasthan |
| | IC520764 | 2019 | High temperature stress tolerant | |
| | IC632086 | 2019 | Drought tolerance | |
| | IC632087 | 2019 | Thermo tolerance at juvenile stage | |
| | IC609646 | 2020 | High temperature tolerance at seedling stage. | ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi |
| | IC640708 | 2021 | Heat tolerant | ICAR-Directorate of Rapeseed Mustard Research, Bharatpur, Rajasthan |
| | IC645773 | 2022 | High temperature tolerance at seedling stage | |
| | IC645774 | 2022 | High temperature tolerance at seedling stage. Moisture stress tolerance. | |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| | IC640189 | 2022 | High tolerance to soil Sodicity stress (up to pH 9.4) | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |
| **Safflower** | IC0588696 | 2011 | Drought tolerance and resistance to *Fusarium* wilt. | ICAR-Indian Institute of Oilseeds Research (IIOR), Hyderabad, Telangana |
| **Fibre Crops** | | | | |
| **Cotton** | IC296863 | 2003 | Photo- thermo insensitivity | ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi |
| | IC408326 | 2003 | High temperature tolerant | |
| | IC0587405 | 2011 | Drought tolerant | ICAR-Central Institute for Cotton Research Nagpur, Maharashtra |
| | IC648615 | 2024 | Salinity tolerant | ICAR-Central Soil Salinity Research Institute, |
| | IC648616 | 2024 | Salinity tolerant | |
| **Sugar Crops** | | | | |
| **Sugarcane** | IC296848 | 2003 | Tolerant to salinity and resistant to red rot and smut | Acharya N G Ranga Agricultural University, (ANGRAU), Andra Pradesh |
| | IC0594465 | 2012 | Waterlogging tolerant | ICAR-Sugarcane Breeding Institute (SBI), Coimbatore, Tamil Nadu |
| | IC565018 | 2009 | Tolerant to waterlogging, salinity and drought | Sugarcane Breeding Institute Regional Centre, Karnal, Haryana |
| | IC0612061 | 2015 | High juice quality under waterlogged condition | ICAR-Sugarcane Breeding Institute, Coimbatore, Tamil Nadu |
| | IC635053 | 2020 | Drought tolerant | |
| | IC636675 | 2020 | Drought tolerant | |
| | IC636674 | 2020 | Drought tolerant | |
| | IC636676 | 2021 | Drought tolerant | |
| | IC646869 | 2022 | Drought tolerant | |
| | IC646870 | 2022 | Drought tolerant | |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| **Potato** | EC460686 | 2009 | Frost tolerant | ICAR-Central Potato Research Institute, Shimla |
| | EC412923 | 2009 | Frost tolerant | |
| | IC0616580 | 2016 | Photo-insensitive and high resistance to late blight | |
| | IC623447 | 2017 | Drought tolerant | |
| **Fruit and plantation crops** | | | | |
| **Mango** | IC0594046 | 2023 | Salt tolerant | ICAR-CSSRI Regional Research Station, Lucknow, Uttar Pradesh |
| **Tea** | IC522955 | 2006 | Drought tolerant | UPASI Tea Research Foundation Tea Research Institute, Nirar Dam, Valparai, Coimbatore, Tamil Nadu |
| | IC522963 | 2006 | Drought tolerant | |
| | IC0587386 | 2011 | Temperature tolerant, Resistance to tea thrips. | Tocklai Tea Research Institute (TTRI), Tea Research Association (TRA), Tocklai Experimental Station, Jorhat, Assam |
| | IC0587391 | 2011 | Tolerant to water logging | |
| | IC0587396 | 2011 | High leaf water potential, Bright infusion, Leaf apex bluntly acuminate, pubescence sparse, serration very low | |
| | IC0587398 | 2011 | Radiation tolerant | |
| | IC0587401 | 2011 | Drought Tolerant | |
| | IC0587402 | 2011 | Drought tolerant | |
| | IC0587403 | 2011 | Cold tolerant | |
| | IC0587404 | 2011 | Drought tolerant | |
| | IC0587772 | 2011 | Drought tolerant | |
| | IC0587774 | 2011 | Drought tolerant | |
| | IC0636680 | 2021 | Drought tolerant | UPASI Tea Research Foundation, Valparai, Coimbatore, Tamil Nadu |

| Crops | Registered germplasm | Year | Abiotic stresses | Developed institute |
|---|---|---|---|---|
| | IC0636684 | 2021 | Drought tolerant | |
| | IC0636685 | 2021 | Drought tolerant | |
| **Coffee** | IC296822 | 2001 | Drought tolerant | Central Coffee Research Institute Coffee Research Station, Chikmagalur, Karnataka |
| | IC296823 | 2001 | Drought tolerant | |
| **Ber** | IC0598427 | 2015 | Drought tolerant | ICAR-Central Institute for Arid Horticulture Bikaner, Rajasthan |
| **Vegetables** | | | | |
| **Tomato** | IC644011 | 2022 | Root Knot Nematode resistance. *Alternaria solani* resistance. ToLCV resistance and Heat tolerance | ICAR-Indian Institute of Vegetable Research, Varanasi, Uttar Pradesh |
| **Onion** | IC645764 | 2022 | Waterlogging tolerance | ICAR-Directorate of Onion and Garlic Research, Pune, Maharashtra |
| | IC645763 | 2022 | Drought tolerance | |
| | IC650752 | 2023 | High salinity tolerance (ECiw 7dS/m). | ICAR-Indian Agriculrural Research Institute, Pusa Campus, New Delhi |
| **Radish** | IC643967 | 2022 | High tolerance to irrigation water salinity (ECiw 8-10 dS/m) and soil sodicity (pHs 8.5) | ICAR-Central Soil Salinity Research Institute, Karnal, Haryana |
| **Sweet Potato** | IC0593650 | 2013 | Salinity tolerant | ICAR-Central Tuber Crops Research Institute Sreekariyam, Thiruvananthapuram, Kerala |
| | IC0593651 | 2013 | Salinity tolerant | |
| **Chilli** | IC646850 | 2022 | Heat stress tolerant | ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi |
| | IC646850 | 2022 | Heat stress tolerant | |

**Source:** NCBPGR, New Delhi. http://www.nbpgr.ernet.in:8080/registration/

Utilizing such diverse genetic resources allows breeders to develop crops with improved stress tolerance, contributing to agricultural sustainability in changing climate scenarios. For instance, the advancement of rice breeding for abiotic stress tolerance has been greatly bolstered by integrating genetic resources from wild rice species and landraces within the *Oryza* genus. Wild species, such as *Oryza rufipogon*, the progenitor of *O. sativa*, and *Oryza glaberrima*, known for nematode resistance, have been hybridized with domesticated rice to introduce valuable stress tolerance traits. Additionally, more distantly related species like *Oryza australiensis* have contributed resistance to pests such as the brown plant hopper (BPH). Future improvements are expected to involve targeted gene transfer from these wild relatives and related genera in the Erhartoideae sub-family, like *Leersia oryzoides* and *Potomophila parviflora*, to infuse novel stress tolerance traits. The discovery of specific alleles, such as *SUB1A-1* for submergence tolerance, underscores the potential of rare genes to confer multiple abiotic stress resistances. Utilizing the extensive and well-curated *O. sativa* germplasm, including valuable landraces like Khaiyan, will be crucial for identifying and incorporating critical genes for flood and other stress tolerances into modern rice varieties.

Effective strategies to exploit wild species include identifying and mapping stress-tolerant genes through genome sequencing, and using introgression breeding to incorporate these traits while maintaining crop performance. Genomic selection and marker-assisted breeding enhance efficiency by selecting beneficial genes from wild relatives, while genetic engineering allows for direct transfer of stress-resistance traits into crops. Additionally, conserving wild species in gene banks ensures a continual source of genetic diversity for future breeding. Hence, the integrated pre-breeding strategy with exploiting a versatile molecular and biotechnological technique and tools together, enable breeders to develop crops with improved adaptability and stability across diverse environmental conditions.

## B. Exploitation of identified genes/QTLs for improving abiotic stress tolerance

### i. Tolerance to saline and saline-alkaline stress in plants

Soil reclamation is one of the strategies to bring salinity affected lands to cultivation. A variety of methods, including mechanical (e.g. leaching, irrigation and drainage), chemical (e.g. application of gypsum) and biological (e.g. phytoremediation, cropping cycle, crop selection, crop rotation, intercropping, and green manuring) methods have been developed to reduce effects of salinity. However, breeding of salt tolerant crop varieties remains a relatively

inexpensive and long-term solution to sustainable production of crops under such conditions. Identification of genes and molecular mechanisms involved in salinity and saline-alkaline stress would be pivotal for modern breeding programs. Several QTLs have been identified in many crops responsible for salinity and saline-alkaline stress tolerance, which can be further exploited in marker assisted back-crossing (MABC) for introgressing such traits into high yielding but susceptible genotypes. For example, "SalTol" is a QTL in rice that maintains the Na:K ratio in shoots at the seedling stage (Thomson *et al*., 2010), imparting tolerance to salinity stress at early stage of plant growth. Similarly, Kna1 QTL is responsible for Na+ elimination, and maintenance of the $K^+/Na^+$ ratio in bread wheat (*T. aestivum* L.). Some other QTLs linked to tolerance to salinity/alkalinity stresses are listed in Table 16.

**Table 16. List of genes/QTLs identified to be involved in saline/alkali stress tolerance in plants**

| Crop | Stress | Genes | Reference |
|---|---|---|---|
| Rice | Salinity | *RAV2* | Takagi *et al*. (2015) |
| | Salinity | *SAPK2* | Zhang *et al*. (2019a) |
| | Salinity | *OsRR22* | Kumar *et al*. (2013 |
| | Salinity | *miR535* | Santosh Kumar *et al*. (2020) |
| Maize | $Na^+$ toxicity | *ZmNSA1* | Cao *et al*. (2020) |
| *Leymus chinensis* | $Na^+$ toxicity | *LcCHI2* | Liu *et al*. (2020) |
| *Soybean* | Osmotic | *GmMYB3a* | He *et al*. (2018) |
| | | *GsSKP21* | Liu *et al*. (2015) |
| *Soybean (G.soja_)* | high pH | *GsPPCK3* | Sun *et al*. (2014) |
| *Arabidopsis* | high pH | *PKS5* | Fuglsang *et al*. (2007) |
| | high pH | *J3* | Yang *et al*. (2010) |
| Soybean | oxidative damage | *GmPKS4* | Ketehouli *et al*. (2021) |
| Soybean | oxidative damage | *GsNAC019* | Cao *et al*. (2017) |
| *Suaeda salsa* | oxidative damage | *SsMT2* | Jin *et al*. (2017) |
| Tomato | Salinity | *HyPRP1* | Lou *et al*. (2017) |
| Adzuki bean | Osmotic<br>oxidative damage | *VaERF3* | Li *et al*. (2020a) |
| Chickpea | Osmoregulation under salt stress | *CaLG05; CaLG07* | Ahmed *et al*. (2021) |
| Potato | Salinity | *P5CS* | Kikuchi *et al*. (2015) |

**ii. Tolerance to heavy and other toxic metals**

Heavy metals and metalloids sometimes play fundamental roles in plant biology either as participants in metabolic reactions or as micronutrients (e.g. Co, Mn, Zn, Cu, and Mo) (Rahman *et al*., 2019). Such elements are known as essential heavy metals (Asati *et al*., 2016; Anum *et al*., 2019). However, if they exceed their threshold concentrations in soil, their actions harm plant development either directly or indirectly (Blaylock, 2000; Asati *et al*., 2016).

Plants employ several physiological, biochemical or molecular approaches for protection against heavy metal accumulation. ATPase are Heavy metal associated (HMA) genes that are linked to accumulation, transportation and eventual resistance to heavy metal stresses in plants. Based on their preference for specific metal substrates, two main subgroups of HMAs occur; Ag/Cu P1B-ATPase and the Pb/Zn/Cd Co P1B-ATPase (Axelsen and Palmgren, 2001). HMA genes can have tissue specific expression in plants. For example, in *Populus trichocarpa*, when exposed to Ag, Cd, Cu, Zn, Pb, Mn, and Co stress condition, HMA1 and HMA4 genes are expressed in leaves; whereas, HMA 5.1 in roots. In rice, high accumulation of copper in soil has been observed to elevate HMA5 expression (Deng *et al*., 2013). The H+-ATPase gene helps *Aeluropus littoralis* in remediation of Pb and Hg toxicity (Jam *et al*., 2014).

Plant-specific peroxidases (Class III) are known to play a role in enhancing tolerance to abiotic stresses and heavy metals such as aluminium, zinc, cadmium, and copper by detoxifying reactive oxygen species (ROS) and reactive nitrogen species (RNS) (Wu *et al*., 2017). Overexpressing OsPRX38 in transgenic rice has been shown to improve arsenic (As) tolerance by regulating lignin biosynthesis in roots, which reduces. As absorption. Similarly, the overexpression of metal resistance protein 1 (LmMTP1), derived from ryegrass, has increased resistance to zinc, cobalt, and cadmium in transgenic rice lines (Tong *et al*., 2023). Table 17 lists some of the genes and QTLs associated with tolerance to metal toxicity.

**Table 17. List of some Genes/QTLs involved in metal toxicity tolerance in plants**

| Plant | Toxicity | QTLs/gene | References |
|---|---|---|---|
| *Oryza sativa* | Cadmium (Cd) | *qRRDW3*, *qCCBR1-9*, *CAL 1* | Shilin *et al*. (2021)<br>Hu *et al*. (2018)<br>Luo *et al*. (2018) |
| | Iron (Fe) and Zinc (Zn) | *Fe- qFRSDW11*, *Zn-qZRRDW11* | Liu *et al*. (2016a) |
| | | *Fe-qFe1.1. qFe1.2*, | Anuradha *et al*. (2012) |

| Plant | Toxicity | QTLs/gene | References |
|---|---|---|---|
| | | *Zn- qZn3.1, qZn7.1* | |
| | Arsenic (As) | *miR156j* | Pandey *et al*. (2020) |
| *Wheat* | Cadmium (Cd) | *Cdu1* | Knox *et al*. (2009) |
| *barley* | Manganese (Mn) | *QSur.yf.3H, QLC.yf.3H* | Huang *et al*. (2018) |
| *Arabidopsis halleri* | Zinc (Zn) | *Zntol-1* | Willems *et al*. (2007) |
| *Maize* | Cadmium (Cd), Copper (Cu), and Lead (Pb) | *ZmMT* | Gao *et al*. (2022) |
| *Capsicum frutescens* | Cadmium (Cd), Copper (Cu), Lead (Pb), Zinc (Zn), and Iron (Fe) | *CaMYB family genes* | Xie *et al*. (2022) |
| *Rice and Arabidopsis* | Cadmium (Cd), Copper (Cu), Lead (Pb), and Zinc (Zn) | *OsHMP (46 genes) and AtHMP(55 genes)* | Li *et al*. (2020b) |
| *Solanum tuberosum* | Cadmium (Cd) | *Mn-MTP, Zn-MTP, and Zn/Fe-MTP* | Li *et al*. (2021) |
| *Cotton* | Mercury (Hg) | *miR164, miR171, miR390 and miR393* | Noman *et al*. (2019) |

**iii. Addressing nutrient deficiency stress**

Nitrogen is a crucial macronutrient for crop production, influencing grain yield, quality, flowering time, and root development for water and nutrient absorption (Place *et al*., 1970). Improving nitrogen use efficiency (NUE) is vital for enhancing its availability and crop yields. However, inconsistent global application rates can hinder NUE. Recent advances in genomics and proteomics are helping to identify candidate genes that regulate NUE in crops (Liu *et al*., 2016b; Rose *et al*., 2017). For instance, Saal *et al*. (2011) identified 82 QTLs for agronomic traits in barley using a doubled haploid population under two nitrogen fertilization conditions across six environments. In rice, QTLs linked to traits such as plant height, tiller number, grain yield, and chlorophyll content have also been identified (Ali *et al*., 2018). Additional QTLs related to nitrogen, phosphorus, and potassium use efficiency are listed in Table 18.

**Table 18. List of genes/QTL involved in nutrient use efficiency of major nutrients in plants**

| Gene/QTL | Nutrient | Crop | References |
|---|---|---|---|
| *qNGR9/DEP1* | Nitrogen | Rice | Sun *et al*. (2014) |
| *TOND1* | | Rice | Zhang *et al*. (2015) |
| *NRT1.1B* | | Rice | Hu *et al*. (2015) |
| *qNGR2/GRF4* | | Rice | Li *et al*. (2018) |

| Gene/QTL | Nutrient | Crop | References |
|---|---|---|---|
| *OsNRT2.1, sNRT2.2, OsNRT2.3a, OsAMT1.1, OsAMT1.2* | | Rice | Han *et al*. (2016) |
| *OsNPF2.4* | | Rice | Xia *et al*. (2015) |
| *OsNPF7.2* | | Rice | Hu *et al*. (2016) |
| *TGA1/TGA4 and NTR1.1* | | *Arabidopsis thaliana* | Canales *et al*. (2017) |
| *NRT2* | | *Brassica napus* | Tong *et al*. (2020) |
| *TaNPF1.1, TaNPF2.1, TaNPF6.1* | | Wheat | Buchner and Hawkesford (2014) |
| *OsPHT1;8* | Phosphorus | Rice | Jia *et al*. (2011) |
| *Pup1/OsPupK46-2/PSTOL1* | | Rice | Gamuyao *et al*. (2012); Heuer *et al*. (2009) |
| *OsPHT1;2* | | Rice | Liu *et al*. (2010) |
| *AtPHT1;5* | | *Arabidopsis thaliana* | Nagarajan *et al*. (2011) |
| *PHO2* | | Rice | Hu *et al*. (2011) |
| *AtAKT1, AtHAK5, AtKUP9, AtTPK1, AtCNGC1, AtSKOR* | Potassium | *Arabidopsis thaliana* | Harada and Leigh 2006; Kanter *et al*. (2010) |
| *OsHKT1;5, OsHKT8* | | Rice | Ren *et al*. (2005) |
| *HvHKT1;5, TmHKT1;5-A, TaHKT1:5-D* | | Barley and wheat | Munns *et al*. (2012); Nguyen *et al*. (2013) |
| *SlHKT1;1, SlHKT1;2* | | Tomato | Asins *et al*. (2013) |

## C. Integrating Functional Markers or Candidate Genes through Advanced Breeding Techniques for Enhancing Multi-Stress Tolerance in Crops: Beyond QTL introgression

Breeding programs focused on developing climate-smart, multi-stress-tolerant crop varieties utilize a range of breeding methods or strategies tailored to address environmental challenges. For instance, traditional plant breeding methods, rooted in Mendelian genetics, involve techniques like mass selection and pedigree selection, which are adapted based on the crop's mating system. These methods are fundamental for creating resilient varieties by selecting for desirable traits within natural genetic boundaries. For example, mass selection has been effectively used to improve drought tolerance in maize and other crops. Similarly, pedigree selection has been instrumental in developing rice varieties with enhanced resistance to both drought and flooding. Hybrid breeding capitalizes on the phenomenon of heterosis to enhance stress tolerance. This method has been notably successful in maize, where hybrids have shown

significant improvements in yield under drought conditions compared to non-hybrids (Boraiah *et al*., 2022). In the case of wheat, different conventional breeding approaches such as pure line, pedigree method, bulk scheme, and backcrossing has led to varieties with increased tolerance to both biotic and abiotic stresses (Tanjina *et al*., 2023; Singh *et al*., 2022; Langridge and Reynolds, 2021).

The wide hybridization followed by selection and other breeding strategies including backcrossing may be employed to introduce stress-tolerant traits from wild relatives into cultivated varieties. The interspecific hybrids developed cross between durum and bread wheat proven to be tolerant to both heat and drought (Hassan *et al*., 2016). Additionally, recurrent selection, often used for cross-pollinated crops, has been successful in improving multi-stress tolerance in maize, sorghum, and pearl millet by selecting for traits that confer resistance to both biotic and abiotic stresses.

Hence, hybridization-based pre-breeding approaches enable the breeders to introgress the traits/genes from wild relatives into crops, and while mutation breeding has been proven to induce new genetic variations for enhanced biotic and abiotic resistance in crops. An introgression of genes from wild tomato relatives may improve the tolerance of cultivated tomato to heat and salinity (Ercolano *et al*., 2021). Similarly, mutation breeding led to the development of various biotic and abiotic stress resistant cultivars in India (Hazarika *et al*., 2023).

However, the breeding programmes designed mainly through conventional selection, hybridization and mutation approaches not sufficient to meet the targeted food production under changing climate scenario. Despite notable success in development of crop varieties with biotic and abiotic stress tolerance through conventional plant breeding, it is very crucial to include modern strategies or techniques or tools to speed up the stress resistance breeding. Introgression of traits or genes for multi-stresses is not so easy, particularly for abiotic stresses. Because most of the abiotic stress tolerance is controlled by polygenes with minor effect compared to disease resistance. Integrated breeding approaches such as marker assisted selection/ breeding, haplotype-based breeding, precision breeding which are backed up with QTLs/functional markers (FMs), genome editing and genetic engineering are most powerful and effective tools for development of climate smart varieties. Rosero *et al*. (2020) opined that the exploitation and introgression of natural genes from crop's wild relatives and landraces into

cultivated background using conventional and molecular methods is one of the best strategies for enhancing drought tolerance.

In the pursuit of developing multi-stress tolerant crop varieties, the integration of functional markers (FMs) into breeding strategies represents a significant advancement. By leveraging the latest methods in functional genomics, such as transcriptomics, TILLING, and association mapping, researchers can pinpoint genes that confer resistance to multiple biotic and abiotic stresses. FMs, due to their close genomic association with specific phenotypic traits, offer a precise tool for selecting plants that possess enhanced tolerance to various stress conditions simultaneously. This precision allows for the direct selection of stress-resistant traits, which is crucial in developing cultivars that can thrive under diverse and challenging environmental conditions. Consequently, the application of FMs in marker-assisted selection (MAS) not only accelerates the breeding process but also bring much desired efficiency and precision in developing multiple-stress tolerant varieties ultimately contributing to the enhancement of global food security by ensuring crop resilience across varying climates and pathogen pressures.

The most successful breeding approach for improving stress tolerance in reported to be marker assisted breeding through which several drought, flood and heat tolerant crop varieties have been developed and released (Rai *et al*., 2017 and Sandhu *et al*., 2019). Haplotype-based breeding have been employed for improving drought tolerance in pigeonpea (Sinha *et al*., 2020) also. Identification and unravelling markers/ QTLs (Asati *et al*., 2022 and Barmukh *et al*., 2022) and Cicer super-pangenome provides insights into genomic regions associated with muli-stress tolerance in chickpea (Khan *et al*., 2024).

Marker Assisted Forward Breeding has facilitated the introgression of resistance to biotic and abiotic stresses in rice. Dixit *et al*. (2023) created introgressed lines by pyramiding seven to ten genes into the recurrent parent Swarna, aiming to enhance resistance to multiple biotic stresses (including blast, BLB, BPH, and GM) while achieving a yield increase of 1.0 t $ha^{-1}$ under drought conditions, all without negatively impacting grain quality traits in non-stress situations.

Gene stacking or pyramiding in crops to enhance tolerance to multiple abiotic stresses is more challenging than developing resistance to multiple diseases. While many abiotic stress-responsive genes have been identified in crop plants, only a few have been effectively

combined for gene pyramiding to address multiple stresses. Although there has been notable success in improving crop resilience against various biotic and abiotic challenges, now is the time to prioritize multi-stress breeding as a key objective in breeding programs to overcome the stagnation in genetic gains caused by climate change. In addition to ongoing integrated breeding strategies, it is essential to revisit the fundamental mechanisms and traits linked to abiotic tolerance and biotic resistance.

**D. Potential traits to be considered in multiple stress breeding**

Breeding for multiple stress tolerance necessitates identification of morpho-physiological traits associated with tolerance to both abiotic and biotic stresses. The potential traits are known to play an important role in imparting tolerance and resistance in different abiotic and biotic stresses were discussed in this section.

Root system architecture (RSA) is particularly crucial for plants facing multiple environmental stresses, as it enables them to effectively navigate and adapt to complex conditions. In scenarios where plants encounter combined abiotic stresses—such as drought, salinity, and nutrient deficiency—RSA plays a vital role in ensuring survival and maintaining growth. For instance, in drought conditions, RSA can be modified to develop deeper roots to access moisture from lower soil layers, while in saline environments, roots may adapt by altering their growth pattern to avoid high-salinity zones. Additionally, under nutrient limitations, RSA can enhance the exploration of the soil for scarce resources by increasing root surface area or forming specialized root structures. This adaptability not only helps plants mitigate the impacts of individual stresses but also allows them to manage multiple stressors simultaneously. By optimizing root growth and function in response to diverse environmental challenges, RSA supports plants in maintaining their health, stability, and productivity despite adverse conditions.

Although recent studies have explored the impacts of combined abiotic stresses, understanding their effects on root systems architecture (RSA) remains limited. Roots, being the first to encounter edaphic based multi-stresses, play a crucial role in crop resilience. Investigating how roots respond to multiple stressors is vital for developing breeding tools to create more resilient varieties enhanced tolerance to multiple or combined stresses. In this context identifying the crops germplasm with better RSA is inevitable. Basavaraj *et al*. (2024) identified cowpea varieties viz., PL4 and DC15 which exhibits adventitious roots during

waterlogging condition and utilization of such genotype could aid in developing multi-stress tolerant cowpea varieties.

Similarly, role of nodulation in multiple stress tolerance cannot be under estimated as several studies shown that nodulation or sustained N fixation in legumes benefits under water stress and edaphic stresses including salt-stress (Valliyodan *et al*., 2017; Singh and Valdés-López, 2023).

Sánchez-Bermúdez *et al*. (2022) summarized current understanding on root responses to individual and combined stresses, highlighting changes in RSA and physiology that affect crop productivity. Hence, it is crucial to consider RSA as an important component trait in multi stress tolerance breeding. Understanding the morpho-physiological changes in root system architecture (RSA) is essential, as these modifications affect the plant's aerial parts. Changes in roots can influence vital physiological processes like stomatal conductance, photosynthesis, and carbon allocation, playing a significant role in adaptation to various stress conditions. Thus, interconnected root and shoot responses, further adds another complexity in designing the breeding strategies to enhance multi stress tolerance.

Leaf pubescence with various forms of trichomes, or leaf hairs, are diverse epidermal cells found on plant surfaces. These miniature structure present on different parts of plant play a crucial role in helping plants manage multiple stresses by trapping and absorbing dew to maintain water levels, enhancing photosynthetic efficiency under drought conditions, and providing a physical barrier against herbivores and pathogens. Theres number studies reported the role of these leaf pubescence in biotic and abiotic stress tolerance (Pandey *et al*., 2017).

Cuticular wax is another protective layer on plant surfaces, plays a crucial role in shielding plants from pathogen and insect invasion as well as other biotic stresses like drought and extreme temperatures. The increase in the cuticle's thickness and wax composition help plants in conserving water and reduce water loss through regulation of opening and closing of stomata. For instance, drought-tolerant varieties of wheat exhibited thicker cuticular layers, while absence of wax layer in drought-sensitive varieties did not (Hameed *et al*., 2002). Additionally, cuticular waxes act as barriers to pathogens and plants with altered or deficient wax layers, such as certain deficient mutants of *Zea mays* (Li *et al*., 2019 and Marcell *et al*., 2002) and *Sorghum bicolor* (Elango *et al*., 2020) exhibited increased susceptibility to diseases and moisture stress. Despite the lack of direct studies on cuticular wax under combined drought

and pathogen stress, evidence suggests that a thicker and more complex wax layer can confer resistance to both the stresses.

Canopy temperature is a valuable trait for assessing plant water status, reflecting the balance between root water uptake and shoot transpiration. Under conditions of high solar radiation and drought, reduced stomatal conductance and soil moisture deficit lead to decreased transpiration rates, which in turn raise canopy temperature (Rebetzke *et al*., 2013). Consequently, canopy temperature can serve as an indicator different stress tolerance in crop plants including drought and heat. Researchers often use canopy temperature depression (CTD)- the difference between air temperature and canopy temperature—as a more precise metric (Jackson *et al*., 1981). A positive CTD value indicates that canopy temperature is lower than the air temperature due to effective transpiration, while a negative value suggests the opposite. Genotypes with higher CTD values and cooler canopy temperatures under drought stress are more effective at utilizing available soil moisture to maintain lower canopy temperatures through transpiration. Thus, CTD can be a useful surrogate trait for breeding plants with enhanced tolerance to multiple stresses.

Leaf water potential is a crucial physiological trait affected by both abiotic and biotic stress, reflecting the plant's ability to maintain water balance. Changes in water potential are influenced by soil moisture levels and disruptions caused by pathogens and deficit moisture in the root zone due to diverse edaphic-water deficit stresses, which can compromise the plant's vascular or transpiration system. For instance, under drought conditions, plants close their stomata to minimize water loss, but pathogens like Uromyces phaseoli can inhibit this closure, leading to increased water loss and reduced drought tolerance. Similarly, some pathogens can lower leaf water potential even when soil moisture is adequate by damaging the xylem, as seen with *U. phaseoli* in *Phaseolus vulgaris* and *Xylella fastidiosa* in *Vitis vinifera*. Concurrent drought and pathogen infections exacerbate water stress, leading to decreased leaf water potential, reduced stomatal conductance, and impaired plant growth. Number of studies have shown that plants resistant to both drought and pathogens tend to maintain higher leaf water potential, which correlates with better resilience (Pandey *et al*., 2017). Factors such as xylem vessel diameter play a role in this resistance, with smaller xylem diameters often linked to lower susceptibility to vascular pathogens. Thus, leaf water potential, alongside xylem traits, serves as an important morpho-physiological marker for screening and breeding plants resilient to combined and multiple stresses.

Slow canopy wilting and stay green trait are important traits to be considered in multiple stress breeding. Slow wilting is a secondary or surrogative physiological trait in plants characterized by a gradual wilting under any stress conditions particularly drought and heat rather faster wilting, indicating enhanced resilience. Plants exhibiting slow wilting maintain higher leaf water potential and turgor pressure for extended periods compared to drought-sensitive varieties. This trait is often associated with a more efficient and extensive root system, improved water uptake, and stable transpiration rates, allowing these plants to better withstand periods of water scarcity. Slow wilting enhances overall plant resilience, leading to better growth and yield potential in stress-prone environments. Ye *et al*. (2020) identified QTLs associated with slow canopy wilting

Stay green (SG) is a crucial agronomic trait that enables plants to maintain photosynthetic activity and improve grain-filling even under stress. SG genotypes can be categorized into functional and non-functional types. Functional SG genotypes are particularly valuable as they either delay senescence (type-A) or progress more slowly through it (type-B), extending the active growth period. In contrast, non-functional SG genotypes may retain leaf greenness but have reduced photosynthetic capacity due to impaired chlorophyll degradation or external factors. The SG trait not only helps maintain leaf color but also enhances yield by increasing grains per ear, improving resistance to stem lodging, and boosting tolerance to biotic stresses. It has become a key trait in breeding programs for drought and heat stress tolerance in cereals (Kamal *et al*., 2019), especially in developing stress-tolerant wheat varieties (Cook *et al*., 2021; Latif *et al*., 2020).

The breeding strategy for multiple stress tolerance can be designed based on the targeted morpho-physiological traits associated with diverse biotic and abiotic stresses. Further, depending on the donors with combination of traits breeding method can be employed. The information on donors or germplasm tolerant to different stresses (individual or combination/multiple) is plays a very crucial in deciding breeding strategy. Hence, the information on germplasm lines registered for traits related to different abiotic stresses may helpful for breeder for donors and designing the breeding strategy thereof. However, prior to proceeding for designing the breeding programme, confirmation of traits along with its genetic control or inheritance of the targeted traits is crucial. In general, traits with abiotic or multiple stress tolerance are quantitative and polygenic, and may have a negative association with grain

yield components and might also interact with genetic and physiological mechanisms of similar traits.

## E. Integrating omics and modern tools into combined conventional-molecular breeding approaches to leverage multiple stress tolerance breeding

### i. Unravelling complex mechanism of multiple stress tolerance through genomics

The identification and introgression of multi-role pleiotropic genes/QTLs that enable plants to adapt to numerous abiotic stresses simultaneously without affecting yield and quality. Often genes or traits are exhibiting pleiotropic effect where the multi-stress tolerance is common. However, identifying such genes/traits plays a very crucial role in developing durable multi-stress tolerance mimicking horizontal disease resistance. Several studies reported that in most of the cases, the varieties with disease resistance exhibiting tolerance to different abiotic stresses as well. However, it should be validated through screening in the sick plots with a particular abiotic stress condition and further need to unravel the cross-talk signalling pathways and adaptive mechanisms at molecular level. Kayum *et al*. (2016) studied differentially expressed genes under biotic and abiotic stresses in *Brassica oleracea* and *B. napus*, which gave insights into the mechanisms for development of multi- stress tolerance lines.

Identifying genes and pathways involved in stress perception, cross-talk signalling, and defence responses is a crucial first step, but translating this basic knowledge into practical applications requires further efforts. A number of studies have demonstrated the potential of overexpressing genes that encode enzymatic antioxidants to enhance stress adaptation in plants. Additionally, significant progress has been made in identifying transcription factors (TFs) that confer tolerance to multiple stresses. For instance, TF families such as WRKY, NF-Y, and Zn-finger play vital roles in regulating gene expression and initiating cascades of stress-responsive genes (Husaini *et al*., 2022). These TFs, influenced by phytohormones like ethylene, jasmonic acid, and salicylic acid, are critical for orchestrating abiotic stress responses. Despite the extensive knowledge gained about TFs and their roles in managing various abiotic stresses, effectively selecting and utilizing key TFs for developing stress-tolerant crops through transgenic approaches remains a significant challenge (Wang *et al*., 2016). It is noteworthy that some genes involved in ROS scavenging were validated nearly 15 years ago, yet their commercial exploitation remains limited. Husaini *et al*. (2022) highlight that better exploitation

of specific TFs could enable simultaneous tolerance to multiple stresses, advancing our capacity to develop resilient crop varieties.

The gene encoding kinases, including Mitogen-Activated Protein Kinases (MAPKs), plays a crucial role in enhancing multiple stress tolerance in plants. These serine/threonine protein kinases phosphorylate various substrates involved in numerous cellular responses and are vital in signal transduction pathways. Different stresses, such as low temperature, wounding, high osmolarity, high salinity, and reactive oxygen species (ROS), activate the MAPK cascade, which serves as a key convergence point for cross-talk between different abiotic stress responses. Additionally, osmotin, a cysteine-rich PR-5c protein identified as a thaumatin-like stress-responsive protein, is synthesized, and accumulated by tobacco cells under salt and desiccation stress (Singh *et al*., 1985). This suggests that osmotin may also be a valuable gene or molecule for exploring pleiotropic roles in multiple stress tolerance.

Further emphasis on deciphering the molecular mechanisms underlying multi-stress adaptation is crucial for advancing the development of molecular tools aimed at enhancing plant resilience to complex stress scenarios. With the increasing frequency and severity of multi-stress conditions due to climate change, research is intensifying to understand plant responses to combined stresses (Jing *et al*., 2024). For instance, Renziehausen *et al*. (2024) have recently elucidated a molecular mechanism for combinatorial flooding (hypoxia) stress adaptation, highlighting the dual roles of certain stress-responsive pathways. These molecular insights are essential for leveraging advanced molecular tools and techniques to accelerate the development of climate-smart varieties with robust multi-stress tolerance.

In parallel, the development in genomic information has significantly enhanced our ability to conduct comparative genome analyses. Such analyses reveal important facts about genomic structural changes, synteny, and gene functions across related species. For example, comparative studies have shown that pigeon pea and soybean possess a similar repertoire of drought-responsive genes (Varshney *et al*., 2012). The genomic resources derived from these studies not only offer a deeper understanding of genetic diversity but also provide a solid foundation for trait discovery and the development of next-generation breeding tools. These advancements are pivotal in complementing molecular insights and accelerating breeding programs aimed at creating elite cultivars that are resilient to multiple stressors.

**ii. Exploiting QTL and Marker-Assisted Back-crossing**

Marker-assisted backcrossing (MABC) is an essential component of conventional breeding, offering a more effective method for transferring desired alleles at target loci from donor to recipient plants (Hasan *et al*., 2022). This approach introduces precision by enabling the integration of specific QTLs into genotypes using markers at defined loci, along with background markers throughout the genome (Frisch *et al*., 1999). Despite its potential, MABC has been underutilized for introgressing abiotic stress tolerance. However, there are successful examples, such as the development of submergence-tolerant rice varieties through the transfer of the major QTL Sub1, which was subsequently introduced into other cultivars (Singh *et al*., 2013). Additionally, the '*SalTol'* QTL was successfully transferred into the rice cultivar BR11 using MABC techniques (Gregorio *et al*., 2013). Given these successes, adopting MABC methods could play a crucial role in developing multiple abiotic stress-tolerant crop varieties in the future.

**iii. Exploiting genome-wide association studies (GWAS) to identify polymorphisms and SNPs for further utilization**

Genome-wide association studies (GWAS) are research methods used to identify genomic variants that are statistically linked to the risk of a disease or specific traits. This approach leverages linkage disequilibrium (LD) to explore relationships between genetic variations and phenotypes across numerous genotypes from natural populations. In GWAS, a large number of germplasm accessions, advanced breeding lines, and mutants can be genotyped, covering thousands of gene loci. High-throughput markers enhance the efficiency of selecting desirable traits expressed within the population (Russell *et al*., 2011). By employing GWAS, researchers can accurately pinpoint the necessary polymorphisms and genetic loci responsible for phenotypic variations under various abiotic and biotic stress conditions (Yu *et al*., 2018).

**iv. Exploiting the state- of- the- art genome editing tools for improving climate resilience**

The advent of modern tools like genome editing (GE) has significantly simplified the development of crops tolerant to abiotic and edaphic stresses. Techniques such as CRISPR/Cas9 and Cas12, specifically targeting SDN1 and SDN2 types of editing, are being utilized to enhance tolerance to multiple stresses in crop varieties. These second-generation editing tools are more efficient, less time-consuming, and cost-effective compared to first-generation methods like ZFNs and TALENs. With these advanced genome editing techniques,

breeders can now target multiple sites within the genome to develop crop varieties with desirable traits.

CRISPR technology has been widely applied across nearly all agricultural crops with available genome sequences, resulting in the release of over 20 genome-edited crop species (Ricroch *et al*., 2017), each expressing various agronomic traits, including those for abiotic stress tolerance. For instance, Zhang *et al*. (2019b) engineered a Cas9-OsRR22-gRNA expressing vector to modify the rice OsR22 gene, resulting in salinity-tolerant rice. These innovative CRISPR/Cas9 and Cas12 genome editing tools hold the potential to drastically reduce the time and costs associated with breeding. Moreover, when combined with speed breeding techniques, the timeline and expenses involved in developing new varieties can be further minimized.

**v. Phenomics for accelerating the screening for multi-stress environment**

Phenomics, the digital measurement of plant phenotypes with managing big data, highlights significant challenges in conventional trait measurement methods, particularly in accurately capturing complex physiological traits. Traditional methods often rely on manual, time-consuming measurements that may lack precision and repeatability. For example, measuring traits associated with drought or heat tolerance typically involves labor-intensive processes like manual assessment of plant responses or visual scoring of symptoms, which can introduce subjective biases and inconsistencies. Additionally, conventional methods may fail to capture the dynamic nature of plant responses to environmental stressors, leading to incomplete or inaccurate data. This limitation is particularly pronounced when assessing traits influenced by multiple interacting factors, where high-throughput, consistent, and precise measurements are crucial for understanding the plant's performance under stress.

In contrast, phenomics offers a transformative approach by integrating advanced technologies to measure physiological and surrogate traits with greater accuracy and efficiency. Using high-throughput imaging systems, sensors, and automated data collection tools, phenomics enables the precise monitoring of plant responses in real-time, capturing detailed information on traits such as growth rates, biomass, leaf temperature, and water usage. These technologies provide a more comprehensive view of how plants cope with multiple stresses, allowing for the accurate estimation of traits that are difficult to measure through conventional methods. By leveraging phenomic data, breeders can better understand the underlying mechanisms of stress tolerance and make informed decisions in developing crop varieties with

enhanced resilience to multiple stresses. Along with bio-informatics, phenomics instrumental in enabling usage of big data collection aids accelerating the development of multi-stress tolerant crop varieties.

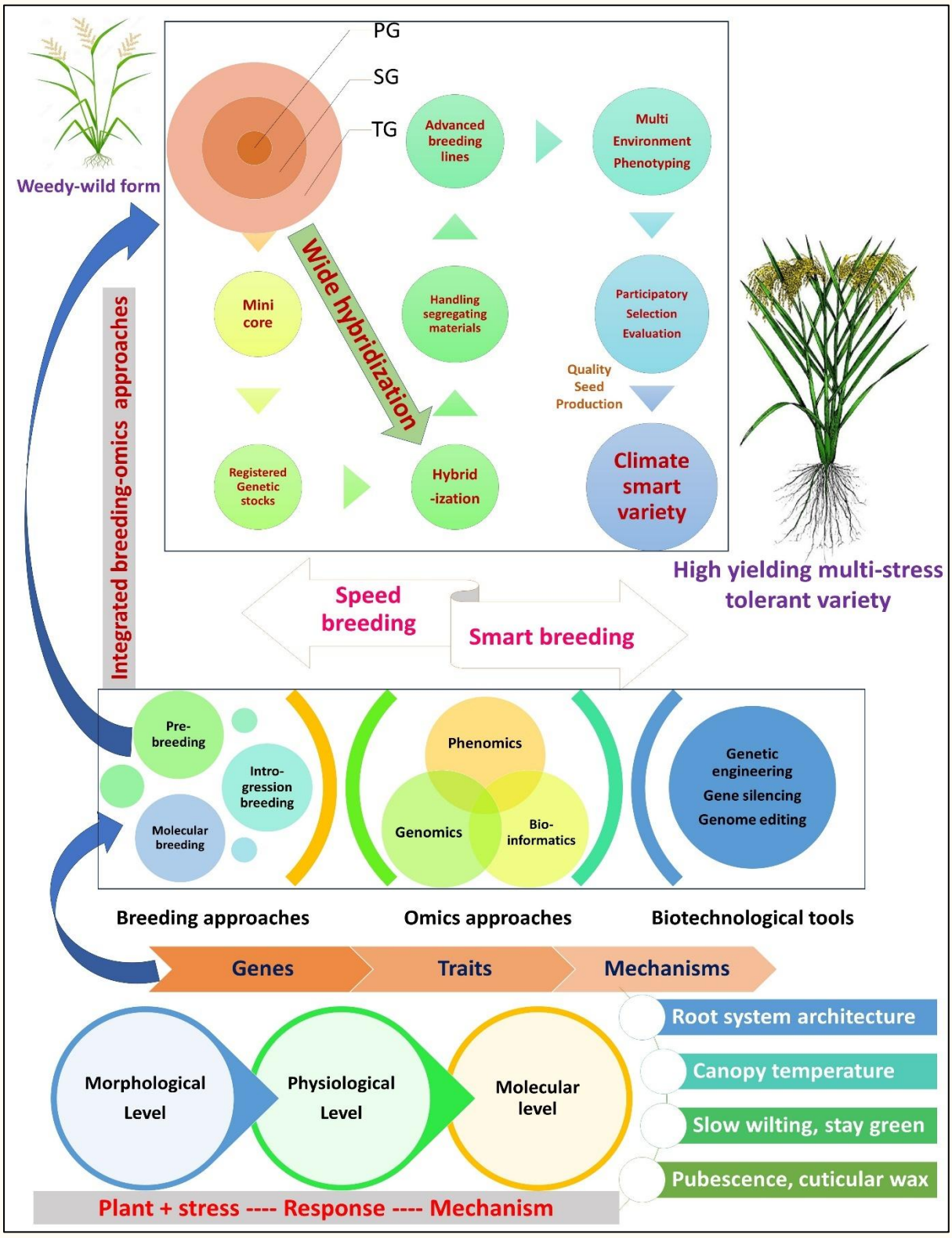



**Figure 6. Schematic illustration of breeding design for development of multi-stress tolerant crop variety. It can a top to bottom (forward genetics) or bottom to top (reverse genetics) approach depending on the resources, genetic material and strategies to be employed during breeding**

**programme. For understanding here indicated only reverse genetics with blue arrows. PG, SG and TG indicates genetic pool classes viz. primary, secondary and tertiary gene pools respectively.**

### 3.1.3 Green Super Rice (GSR) varieties: An example for successful breeding strategy for developing multiple stress tolerant varieties

The Green Super Rice (GSR) breeding program exemplifies a successful strategy for developing rice varieties that can withstand multiple abiotic and biotic stresses. Leveraging advancements in genotyping technologies like SNP chips, genotyping by sequencing (GBS), and whole-genome sequencing (WGS), researchers have effectively identified major quantitative trait loci (QTLs) associated with stresses such as drought, salinity, and flooding. This has facilitated the integration of molecular markers closely linked to stress tolerance traits, enhancing marker-assisted selection. Notable QTLs identified include Sub1 from the Indian landrace FR13A and Saltol from Pokkali, which have been successfully incorporated into various rice varieties such as Swarna-Sub1 and Samba Mahsuri-Sub1 (Ali *et al*., 2021).

The GSR strategy utilized 500 elite rice varieties from the 3000 Rice Genomes Project, focusing on primary recipient parents such as Huanghuazhan (HHZ) and Weed Tolerant Rice-1 (WTR-1). Through the Enhanced Backcross Breeding Program (EBBP) and designed QTL pyramiding (DQP), researchers rigorously screened BC1F2 populations under conditions of drought, salinity, and low nutrient inputs, identifying 845 promising selective introgression lines (SILs). This extensive evaluation resulted in the registration of 66 GSR breeding materials in China and the release of 59 varieties across Asia and Africa, demonstrating significant yield advantages. For instance, in Mozambique, GSR varieties provided up to ten times higher yields for smallholder farmers compared to conventional varieties.

Furthermore, the development of climate-smart rice hybrids at IRRI has advanced using EB-SILs and the DQP approach, focusing on restorer and maintainer backgrounds. This strategy prioritizes high-yielding, multi-stress tolerant varieties, informed by key fertility restoration loci. With over 100 restorer lines developed, the GSR program not only aims to enhance rice yield and quality but also contributes to sustainable agricultural practices in regions frequently affected by abiotic stresses. By utilizing cutting-edge genomic tools and collaborative research efforts, GSR is paving the way for resilient rice varieties that thrive in challenging environmental conditions.

### 3.2 Strategies for Scaling up Adoption and Cultivation of Climate-Smart Varieties in Stress-Prone Regions: Building resilience at farm level

The importance of climate-smart varieties cannot be underestimated, especially in the changing climate scenarios. These tolerant varieties offer a crucial solution for farmers having small holdings particularly in arid and semi-arid regions to sustain agricultural productivity amid increasing resilience to multi-stresses under changing climate scenario. Under increasing frequency and intensity of multi stresses, an effective adoption of these varieties can significantly enhance food security, stabilize livelihoods, and foster agricultural resilience. However, several critical factors influencing the adoption of climate smart varieties perform well under stress and non-stress condition (Boraiah *et al*., 2021). They emphasize that access to and availability of high-quality seeds is of paramount importance, as farmers need reliable cost-effective and quality seed sources to adopt new and climate-smart varieties successfully. Additionally, extension services and training are essential for educating stakeholders (farmers, seed producer and seller) about the mutual benefits of seed production of climate-smart varieties which significantly impacts adoption rates. Socio-economic factors, such as income levels and land ownership, also play a crucial role, as these determine a farmer's capacity to buy quality seeds of new varieties or hybrid along with other inputs recommended to cultivate the varieties. Finally, local adaptation and farmer involvement during the selection of final entries and their evaluation at field conditions mimicking prevalence of multi stress natural or artificial environmental conditions. Such participatory approach ensure that the varieties meet specific local needs and conditions, enhancing their relevance and acceptance among small-scale producer besides better performance irrespective of stress conditions. Considering the importance, we discussed these factors along with the strategies to enhance the adoption and cultivation of multi stress tolerant cop varieties.

#### 3.2.1 Factors Affecting the Adoption of Climate-smart Crop Varieties

The adoption of climate-resilient crop varieties among smallholder farmers, particularly in lower- and middle-income countries (LMICs), is influenced by a range of factors. These factors determine whether farmers will incorporate these varieties into their production systems to mitigate the impacts of climate change. Based on a scoping review of 202 papers conducted using the PRISMA-P framework, several key determinants of adoption of climate-smart varieties have been identified (Acevedo *et al*., 2020). The analysis highlights both enabling and hindering factors that affect the adoption of such varieties.

**A. Availability and effectiveness of extension services**

Extension services play a critical role in facilitating the adoption of climate-smart varieties. Effective extension programs provide farmers with essential information about the benefits and management of new crop varieties, including technical guidance on best management practices to realize their potential yield. The quality of extension services, including the frequency of interactions, the expertise of extension agents, and the appropriateness of the information provided, significantly impacts adoption rates. Studies have shown that areas with robust extension services experience higher adoption rates of climate-resilient varieties due to better farmer knowledge and support.

**Education levels of heads of households**

The educational background of farmers, particularly the heads of households, is another significant factor influencing adoption. Higher education levels are often associated with increased awareness of climate risks and the benefits of climate-smart varieties. Educated farmers are generally better equipped to understand and implement new agricultural technologies and are more likely adopt and utilize information about these promising varieties.

**B. Access to inputs including quality seed**

Access to necessary agricultural inputs such as seeds, fertilizers, and irrigation is crucial for the adoption of climate-smart varieties. The availability and affordability of these inputs can either facilitate or constrain the adoption process. For instance, if quality seeds of climate-resilient varieties are not accessible or affordable, farmers are less likely to adopt these crops. Effective supply chains and subsidy programs can enhance access to seed and other inputs and thereby increase adoption rates. It has been proven that local seed bank plays an important role in multiplication and distribution of climate resilient local varieties.

**C. Socio-Economic Status**

The socio-economic status of farming families affects their ability to invest and adopt new technologies including stress tolerant varieties. Wealthier households typically have more resources to invest in climate-resilient crops and the associated inputs, whereas poorer households may lack the financial capacity to make such investments. Socio-economic factors also influence risk tolerance and the perceived benefits of adopting new technologies.

**D. Social differences**

Social factors such as sex, age, marital status, and ethnicity have been found to influence the adoption of climate-resilient varieties. Gender, for example, can affect access to resources, information, and decision-making power, all of which impact the adoption process. Age and marital status may influence openness to new technologies and the availability of labor for implementing new practices. Fisher and Carr (2015) reported men plays an predominate role in adoption of drought-tolerant maize hybrid / new varietals seed in eastern Uganda. This indicates that often resource constraints prevent many women farmers from adopting drought-tolerant maize.

### 3.2.2 Strategies for enhancing the adoption of multi-stress-tolerant crop varieties

To enhance the adoption of multi-stress-tolerant crop varieties, a comprehensive approach is essential. Integrating participatory varietal development ensures that crop varieties meet local needs, while strengthening extension services provides farmers with vital information and support. Improving access to quality seeds through partnerships with private seed companies and seed banks is crucial, as is investing in transgenic seeds to boost stress tolerance. Addressing socio-economic barriers with financial support and inclusive policies that consider social factors ensures that all farmers can benefit. These combined strategies can significantly increase the adoption rates of resilient crop varieties, enhancing agricultural sustainability.

**A. Participatory Multi-Stress-Tolerant Crop Varietal Selection and Evaluation**

The adoption of multi-stress-tolerant crop varieties is crucial for improving agricultural resilience, particularly in arid and semi-arid regions where environmental stresses such as drought, salinity, and heat are prevalent. Participatory varietal selection (PVS) and evaluation are critical strategies in this regard. PVS involves engaging farmers and other stakeholders in the selection and testing of crop varieties, ensuring that the varieties developed are well-suited to local conditions and preferences.

Involving farmers in the selection and evaluation of crop varieties offers several important benefits, particularly in arid and semi-arid regions. Local relevance is a key advantage; farmers who experience stress factors firsthand are best positioned to identify the traits needed in new varieties. By incorporating their insights, the resulting varieties are tailored

to meet specific local needs, effectively bridging the gap between scientific research and practical application. This participatory approach ensures that crop varieties are not only technically advanced but also practically viable under local conditions.

Participatory methods offer significant advantages, particularly in enhancing acceptance and evaluation of crop varieties. Involving farmers in the selection process ensures that the chosen varieties meet the preferences and needs of end users, which is especially important in regions with established traditional practices. For example, in Ethiopia, participatory selection led to the development of drought-tolerant maize varieties that outperformed others (Girma, 2005). Similarly, in India, participatory variety selection has helped identify local rice varieties with improved heat tolerance, leading to higher adoption rates in stress-prone areas (Joshi and Witcombe, 1996). The success of these initiatives has encouraged broader adoption of participatory approaches for developing new rice varieties, particularly in salt-affected regions, as demonstrated by ICAR's efforts to select salt-tolerant rice genotypes (Singh *et al*., 2014). These examples underscore the effectiveness of participatory approaches in enhancing the relevance and impact of climate-smart crop varieties.

**B. Enhancing accessibility of quality seeds of multi-stress-tolerant crop varieties**

Ensuring access to high-quality seeds of multi-stress-tolerant crop varieties is crucial for their widespread adoption, especially in arid and semi-arid regions where agricultural productivity is severely affected by environmental stresses. The availability of these seeds can significantly impact livelihoods, food security, and nutritional security in such areas. A robust contingency plan for supplying quality seeds of climate-smart varieties tailored to diverse cropping systems is essential for maintaining crop production despite unpredictable weather conditions. This strategy not only emphasizes the conservation and inclusion of local varieties within the public-private seed chain but also balances preserving genetic diversity with enhancing farmers' access to high-yielding, modern multi-stress-tolerant varieties. This balance is particularly important given that many local cultivars adapted to climate stresses have become scarce among farmers (source: https://alliancebioversityciat.org/).

Community seed banks play a pivotal role in boosting farmers' resilience, especially for communities and households most affected by climate change. These seed banks improve access to and availability of diverse, locally adapted crops and varieties while also preserving valuable indigenous knowledge and skills related to seed management such as selection,

treatment, storage, multiplication, and distribution (Vernooy *et al*., 2017). In India, numerous local and community seed banks are actively maintaining a rich variety of local cultivars in collaboration with public institutions and NGOs. For instance, Nagubandi *et al*. (2021) reported that 97 community seed banks across fifteen Indian states manage approximately 779 crop varieties, including 538 indigenous landraces (69%) and 241 improved varieties (31%). Notably, the Navdanya Community Seed Banks network, spanning 22 states in India and Bhutan, has established over 124 decentralized, indigenous seed banks (source: https://navdanyainternational.org). This initiative supports farmers by reducing their dependence on costly commercial seeds and empowering them to transition from vulnerability to resilience in the face of climate change.

High-quality seeds are crucial for maximizing the performance of multi-stress-tolerant crop varieties. These seeds ensure uniform growth, higher germination rates, and enhanced resilience to environmental stresses. When seed quality is compromised, the benefits of stress-tolerant traits can be undermined, leading to suboptimal crop yields. Thus, the integrity of seed quality directly impacts agricultural productivity and the effectiveness of stress-tolerant varieties.

Market accessibility also plays a significant role in the distribution of quality seeds. In remote or underserved regions, logistical challenges can limit access to high-quality seeds. To address this, establishing efficient local seed production and distribution networks is essential. Such networks help overcome these challenges, making seeds more readily available and affordable for farmers. Improving market accessibility ensures that quality seeds reach those who need them most, thereby supporting better agricultural outcomes.

Training and support for farmers are equally important for optimizing seed use. Providing education on seed selection, management, and the advantages of multi-stress-tolerant varieties can significantly enhance seed utilization. Proper training equips farmers with the knowledge to handle seeds effectively, which can lead to improved crop performance and yields. By fostering a better understanding of seed management, training programs help farmers make the most of high-quality seeds.

In Kenya, the establishment of local seed banks and farmer cooperatives has significantly improved access to drought-tolerant seeds, resulting in higher adoption rates and enhanced crop yields in arid areas. These community-based initiatives underscore the

importance of local solutions for improving seed accessibility and agricultural resilience. Local seed banks have also integrated into seed sector enterprise networks, which is essential for generating demand, gaining recognition, and ensuring sustainability. Additionally, incorporating stress-tolerant traits into both legacy and new maize varieties can bolster the resilience of maize systems to changing growing conditions. These traits provide a strong business case for replacing outdated varieties with new, stress-adapted ones (Marenya *et al*., 2022). To further boost agricultural productivity in climate-vulnerable arid and semi-arid regions, various international organizations are working to strengthen production capacities, improve seed systems, and disseminate climate-resilient varieties of rainfed crops.

In conclusion, to enhance the adoption of stress-tolerant varieties, a multifaceted approach is crucial. The case study of DroughtTEGO® maize hybrids in Kenya highlights the need for improved information dissemination, adjusted seed pricing, and timely seed availability to overcome barriers to adoption (Muinga *et al*., 2019). Strengthening extension services, supporting women's control over resources, and facilitating access to credit can further support adoption efforts. Additionally, targeted promotional strategies tailored to different demographics can effectively raise awareness and interest. Implementing these strategies can significantly boost the adoption of stress-tolerant varieties, enhancing agricultural resilience and productivity amidst climate challenges.

## 4. Conclusion

The increase in frequency and intensity of multiple stresses underscore the urgent need for development of climate-smart crop varieties with enhanced tolerance to diverse stressors to stabilize productivity to ensure food security in a changing climate scenario. Unlike breeding for single abiotic stresses or disease resistance, developing crops that can withstand multiple stresses is the need of the hour but far more complex and difficult to address. Therefore, to cope with the situations, genetic augmentation for developing multiple stress tolerant crop varieties will be the key to manage the abiotic stresses, coupled with matching agronomic package of practices to minimize the impact and sustain the productivity. The situation is compounded further because of the fact that we would be required to produce more from less area. Therefore, land affected by drought, salinity, sodicity, alkalinity, acidity, contaminated by heavy metal, barren lands, degraded land, etc. need to be brought under cultivation.

The ambitious and daunting mission will only be successful if and only if climate smart varieties truly equipped with multiple abiotic stress tolerance are developed and quality seeds are made available to the farmers in time. However, to do so multi-pronged strategies involving conventional and molecular tools need to be employed in tandem in most of the crop species. The already identified QTLs/genes responsible for imparting drought, high and low temperature, waterlogging, salinity, alkalinity, sodicity, metal toxicity, nutrient use efficiency, etc. tolerance need to be incorporated in agronomic background and validated. Identification and mining of relevant genes involved in imparting multiple stress tolerance in wild species and land races should be put on a fast-track mode to hasten the incorporation of the identified genes/QTLs in minimum possible time. Additionally, fostering collaborative research networks and public-private partnerships is crucial for harnessing resources, knowledge, and expertise to advance multi-stress breeding.

In conclusion, the development of multi-stress tolerant varieties is pivotal for sustaining food and nutritional security amidst evolving climate challenges. By integrating advanced technologies, promoting collaboration, and engaging farmers, we can develop climate resilient crops capable of thriving under multiple environmental stresses, paving the way for ensuring food and nutritional security for future generations.

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**Notes**

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