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Multi-stress-tolerant varieties: The future of agronomic crop breeding in India

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Abstract

Indian agriculture faces a complex matrix of environmental and biological challenges. Stresses such as drought, heat, salinity, cold and flooding increasingly coincide with biotic pressures from pests, diseases and weeds. Traditional breeding alone is no longer sufficient to sustain yields under these multiple stresses. This article examines the development of multi-stress-tolerant crop varieties across cereals, pulses, oilseeds and horticultural crops in India. We review classical breeding methods and modern approaches, including genomics, biotechnology and precision breeding tools. Emphasis is placed on genetic and physiological traits that confer tolerance and on emerging policy frameworks that support climate-resilient agriculture. Four large tables summarize key tolerance traits, important stress-resilient varieties, advanced breeding technologies and typical stress-response outcomes. Together, these elements highlight how integrated strategies can create the next generation of climate-smart varieties. The goal is a detailed understanding of how India can breed crops that thrive amid increasing abiotic and biotic stresses, thus ensuring future food and nutritional security.

Keywords: Multi-stress tolerance, crop improvement, abiotic stresses, biotic stresses, genomics, Indian agriculture, climate resilience, breeding strategies

Introduction

Agriculture in India must adapt to a rapidly changing climate and increasing population pressure. The country's diverse agro-climatic zones expose crops to extreme environments such as erratic monsoon rains, prolonged dry spells, intense heat waves, cold spells, water logging and saline soils [11]. At the same time, biotic pressures from insects, pathogens and invasive weeds continue to threaten yields. Combined and sequential stresses are becoming the norm rather than the exception. For example, a brief drought followed by high heat during flowering can devastate yield and a flood episode may coincide with disease outbreaks. Developing crop varieties that withstand multiple stresses (both abiotic and biotic) is thus a critical priority for Indian agriculture [27]. Multi-stress tolerant varieties are defined as cultivars bred to possess resilience against more than one type of stress. Unlike single-trait improvements, such cultivars have complex genetic architectures that confer broad durability. This holistic approach addresses the reality that farmers often face simultaneous adversities. The concept of "climate-smart agriculture" has emerged to promote integrated solutions. In India, research under the National Agricultural Research System (NARS) and programs like the National Innovations in Climate Resilient Agriculture (NICRA) emphasize breeding climate-resilient, high-yielding varieties [90]. The urgency is clear: India needs crops that can maintain productivity under drought, heat, salinity, submergence, diseases, pests and weeds, either individually or in combination. This article examines strategies for developing multi-stress-tolerant agronomic crops in India [39]. We cover a wide range of crops from staple cereals (rice, wheat, maize, millets) to pulses (chickpea, lentil, pigeon pea), oilseeds (mustard, groundnut, soybean) and horticultural crops (fruits and vegetables). We discuss the nature of major abiotic and biotic stresses affecting these crops and how tolerance traits can be harnessed [74]. The review compares traditional breeding techniques (selection, hybridization, landrace use) with modern biotechnology and genomic

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tools (marker-assisted selection, genome editing, high-throughput phenotyping) [40]. We also consider policy and institutional support that facilitate breeding efforts. Throughout, four tables summarize critical components: key tolerance traits, notable multi-stress-resistant varieties, current breeding technologies and outcomes of stress interactions. Finally, we present conclusions on the future trajectory of crop breeding in India [12].

Agronomic Crops in India and Stress Landscape

India's agronomic portfolio spans diverse plant families. Cereals like rice, wheat, maize, sorghum and millets form the bulk of staple food. Pulses (chickpea, pigeon pea, mung bean, lentil, pea and others) are key for protein. Oilseeds (mustard, groundnut, soybean, sunflower) provide fats and income. Horticultural crops (fruits like mango, banana, citrus and vegetables like tomato, potato, chillies) are vital for nutrition and livelihood. Each crop group faces specific stress profiles, reflecting both environment and management systems [53]. For instance, rice is grown in flooded conditions in many regions but is also cultivated under rainfed conditions in upland areas, exposing it to drought and heat. Wheat (a rabi crop) is often sown in dry winter conditions and harvested by spring, making it sensitive to soil moisture, cold at establishment and heat at grain filling [54]. Pulses and oilseeds, usually grown in post-monsoon (rabi) or inter-season, must endure residual soil moisture fluctuation, cold stress at planting and potential terminal drought [1]. Key Abiotic Stresses: The Indian climate imposes a range of abiotic challenges. Drought (moisture deficit) is perhaps the most pervasive stress, especially in rainfed areas and semi-arid zones (Rajasthan, central India, etc.). Heat stress frequently affects crops in north-western plains and the Deccan Plateau, with temperatures exceeding 40-45°C during flowering in wheat or during rice grain filling [55]. Cold stress (sub-zero or near freezing) impacts winter-sown crops in the Himalayan foothills and northern plains; unseasonal frost can damage wheat and mustard seedlings. Water logging and flooding occur in monsoon-prone areas (northeast India, Bengal, eastern states), as well as flash floods in riverine belts. Salinity affects coastal deltas (Gujarat andhra Pradesh) and irrigated lands with poor drainage. These abiotic factors lead to reduced germination, stunted growth, flower/fruit abortion and grain sterility, causing significant yield losses [75]. Key Biotic Stresses: Indian agriculture is similarly challenged by pests, pathogens and weeds. Major insect pests include stem borers and leaf folders in rice, bollworms in cotton, pod borers in pulses and fruit borers in horticulture. Diseases of concern include rice blast and bacterial blight; wheat rusts (stripe, leaf, stem); pulse wilt (*Fusarium oxysporum*), sterility mosaic in pigeon pea; and a variety of fungal, bacterial and viral diseases in vegetables (e.g., late blight in potato, mosaic viruses in chilies). Invasive weeds like Parthenium and *Striga parasitica* (in sorghum/pulses) reduce yields and are hard to control. Each biotic factor can cause catastrophic losses (often >20-30% yield reduction) if left unchecked [13]. Stress Interactions: In the field, plants often face combined stresses. For example, a drought spell may coincide with a surge in pest infestation or a flood may follow a heat wave. These interactions are often nonlinear: one stress can exacerbate sensitivity to another [76]. A heat-stressed wheat plant may become more susceptible to rust infection; a waterlogged root system can invite soil-borne diseases. Hence, breeding for tolerance must consider trait networks that confer resilience under compound pressures [28]. Table 1 (below) lists important morphological and physiological traits that help plants cope with these stresses.

Abiotic Stress Tolerance in Crops

Breeding for abiotic stress tolerance involves incorporating traits that allow plant survival and yield retention under harsh conditions. Drought tolerance traits include extensive root systems (for deeper water access), efficient stomatal control (to limit water loss), leaf orientation or rolling (to reduce transpiration), osmolyte accumulation (proline, glycine betaine to protect cells) and stay-green or delayed senescence (maintaining photosynthesis) [77]. Early flowering or maturation helps crops escape terminal drought. Heat tolerance involves traits like heat-stable photosystems (e.g. high chlorophyll stability index), synthesis of heat shock proteins (protect cellular proteins) and transpiration cooling traits (wide leaves or high leaf area index can cool canopies) [56]. In cereals, anther heat tolerance (for pollen viability) is critical [78]. Cold tolerance (including chilling stress) relies on membrane lipid composition, antifreeze proteins (in some crops) and vernalization responses (as in wheat and barley). In tropical crops grown in cool uplands or winter crops in the north, ability to germinate and grow at low temperatures matters [29]. Flood or water logging tolerance is less common in major crops, but submergence tolerance has been identified in rice via the SUB1 gene, which confers survival under complete submergence for up to two weeks. Root traits like aerenchyma formation also allow oxygen transport in waterlogged soils. Salinity tolerance requires traits to exclude or compartmentalize salt ions [41]. Plants may sequester Na+ in vacuoles, maintain a high K+/Na+ ratio in leaves or excrete salt via specialized salt glands (as in some grasses). Salt tolerance is often quantitative, with many genes contributing. Each trait often has trade-offs (e.g. extensive root systems may reduce harvest index) and tolerance is typically quantitative. Genetic diversity from landraces, wild relatives and traditional varieties often harbours these adaptive traits. Breeders must identify and introgress them into elite lines [2].

Biotic Stress Resistance in Crops

Biotic stress resistance often involves specific genes or pathways. Pest resistance can be achieved through morphological features (e.g. thickened stems, plant hairs), production of deterrent metabolites (gossypol in cotton deters insects) or engineered traits like Bt toxins (in cotton and maize) that kill target pests. Crop varieties with built-in insect resistance can drastically reduce yield losses and insecticide use [14]. Disease resistance is commonly based on R-genes (resistance genes) that recognize specific pathogen effectors. For example, rice varieties may carry genes for bacterial blight or blast resistance and wheat carries resistance loci for stem or stripe rust. Resistance can be qualitative (single major gene, often race-specific) or quantitative (many minor genes conferring broad-based resistance) [57]. Breeding often pyramids multiple resistance genes to achieve durable defence. Weed tolerance in crops can be achieved via competitive ability (rapid early growth, canopy closure) or herbicide tolerance (genetic modification to survive herbicide applications). Indian maize, cotton and soybean have weed-competitive cultivars and some use herbicide-resistant lines. Integrating abiotic tolerance with biotic resistance is a major challenge. A variety tolerant to drought may still be susceptible to rust, for instance. The ideal multi-stress variety must stack both types of traits without yield penalty [58].

Key Traits for Multi-Stress Tolerance

Multi-stress resilience relies on a spectrum of traits, from whole-plant morphology to cellular mechanisms [79]. Table 1 summarizes many of these traits, the stresses they address and their benefits. This includes root characteristics (for drought/flood tolerance), leaf and physiological traits (for water-use efficiency and heat avoidance) and molecular responses (like osmoprotectants and antioxidants) that mitigate damage under stress [42]. Harnessing such traits in breeding programs often through genetic mapping and markers helps create varieties with broad tolerance.

Table 1: Key traits conferring tolerance to various stresses in agronomic crops.

Trait/Characteristic	Stress Tolerance	Benefit/Note
Deep, extensive root system	Drought, heat	Accesses deeper soil moisture; sustains growth in water deficit.
High root density/distribution	Drought	Increases water uptake from variable soil zones.
Efficient stomatal control (closure)	Drought, heat	Reduces water loss under stress; improves WUE (water-use efficiency).
Leaf rolling or folding	Drought	Minimizes transpiration surface during water stress.
Thick waxy cuticle/cuticular wax	Drought, heat	Limits non-stomatal water loss; protects leaf surface.
Reduced leaf area or pubescence	Drought, heat, UV	Lowers transpiration demand; reflects excess light/heat.
Early flowering/short duration	Drought, escape heat	Completes life cycle before peak stress; avoids late-season drought.
Stay-green / delayed senescence	Drought, heat	Maintains photosynthesis and grain filling under stress.
Osmolyte accumulation (e.g. proline)	Drought, salinity	Protects cells by osmotic adjustment; stabilizes proteins.
Anti-oxidant enzymes (SOD, CAT)	Drought, heat, salinity	Scavenge reactive oxygen species (ROS) generated under stress.
Na+ exclusion / K+ retention	Salinity	Limits toxic Na+ in leaves; maintains ionic balance.
Salt gland or salt bladder	Salinity (in halophytes)	Actively excretes salt; enables survival in saline soils.
Aerenchyma in roots	Water logging, submergence	Creates air spaces in roots for oxygen transport underwater.
Submergence tolerance (e.g. SUB1 gene)	Flooding (in rice)	Slows metabolism under water; allows survival after submergence.
Heat shock proteins (HSP) induction	Heat	Protects cellular proteins; improves thermal tolerance.
High chlorophyll stability / stay-green	Heat	Ensures photosynthetic apparatus remains functional.
Membrane lipid composition	Cold (low temp)	Increases membrane fluidity; prevents chilling injury.
Antifreeze proteins	Cold (freezing)	Inhibits ice formation in cells.
R-genes (specific resistance genes)	Specific diseases (biotic stress)	Recognize and trigger defense against particular pathogens.
Bt toxin expression	Insect pests	Provides insecticidal activity against targeted pests (e.g. bollworm).
Allelopathic compound production	Weed suppression	Releases biochemicals to inhibit weed germination/growth.

Multi-Stress Tolerance: Challenges and Strategy

Breeding for multi-stress tolerance is inherently challenging because different stress responses may be governed by complex, interacting gene networks. Tolerance to one stress can sometimes conflict with another: for instance, reduced stomatal density (to save water) might limit cooling and worsen heat sensitivity [80]. Therefore, breeders must balance trade-offs and prioritize key traits based on target environments. In India's context, this often means focusing on the most common and severe stress combinations (for example, drought+heat in peninsular India or submergence+disease in eastern states) [15]. A key strategy is to utilize genetic diversity from various sources. Traditional landraces and wild relatives often carry stress-adaptive alleles lost in elite lines. For example, wild pigeon pea and native chickpea landraces have been sources of drought tolerance genes. Modern breeding incorporates such sources through pre-breeding [30]. Marker-assisted backcrossing can introgress one or two major QTLs for tolerance into high-yielding backgrounds. Genomic selection and wide crosses allow stacking many small-effect alleles for polygenic traits. Integrative phenotyping platforms also play a role. Detailed screening under controlled and field stress (multi-environment trials) helps identify genotypes with broad adaptation [43]. In rainfed regions, breeders test varieties for yield stability under variable moisture and temperature. At the same time, disease nurseries expose lines to major pathogens. Only lines that perform under both sets of conditions are advanced. Such rigorous testing ensures that selected varieties handle multiple threats. An example of a holistic approach is the Green Super Rice initiative (from IRRI, adopted by India) aimed at rice varieties with combined tolerance to drought, flood, salinity and pests. These genotypes carry multiple stacked genes/QTLs and undergo stringent multi-trait screening [59]. India's National Infrastructural Planning, such as ICAR-NICRA, has similarly screened hundreds of varieties of rice, wheat and pulses under simulated drought/heat and found lines that maintain stable yields [3]. Table 2 (below) lists notable Indian varieties bred for multi-stress tolerance. These exemplars demonstrate that it is possible to breed cultivars with combined resistance (for example, to both drought and salinity or to heat and lodging) [60].

Notable Multi-Stress Tolerant Varieties in India

Indian breeders have released several crop varieties designed to cope with multiple stresses. Table 2 summarizes a selection of such varieties, their crop type and the stresses they tolerate [91]. For example, newer rice varieties tolerate drought and salinity, chickpea lines withstand terminal moisture stress and mustard cultivars endure cold weather at planting [44]. Many of these varieties result from extensive breeding efforts combining traditional crossing with modern trait selection.

Table 2: Multi-stress tolerant crop varieties (examples)

Variety Name	Crop	Stress Tolerance/Traits
Swarna-Sub1	Rice	Submergence (flood) tolerance (also moderate drought)
IR 64-Sub1	Rice	Flood tolerance
Pusa 1509	Rice	Drought, heat tolerance
Pusa Basmati 1509	Rice	Drought and heat tolerance (drought hardy basmati)
CR Dhan 704	Rice	Drought and salinity tolerance
IARI 618 (CSR-36)	Rice	Heat and drought tolerance (for Indo-Gangetic plain)

Pusa Dhan 150	Rice	Bacterial blight + moderate drought tolerance
HD 2932	Wheat	Heat and rust tolerance
Kanchan	Wheat	Heat and late-sown cold tolerance
WH 542	Wheat	Drought and terminal heat tolerance
DBW 187	Wheat	Heat tolerance (early sown wheat)
Raj 4037	Chickpea	Drought (terminal moisture stress) and fusarium wilt tolerance
Pusa 362	Chickpea	Drought tolerance, early maturing
DMH 1	Pigeon pea	Drought tolerance in rabi (post-monsoon)
JL 24	Pigeon pea	Drought and wilt tolerance
RL 1359	Lentil	Heat tolerance (early flowering; low-temp germination)
DRMRIJ 31	Mustard	Cold tolerance (early sowing), high oil
Pusa Bold	Mustard	Cold tolerance (early), short duration
KDM 1	Mustard	Heat and drought tolerance, mosaic virus resistance
TMV 7	Groundnut	Drought tolerance, early maturity
NDR-359	Soybean	Heat tolerance, pod borer resistance (Bt soy in pipeline)
Arka Samrat	Tomato	Heat tolerance, fusarium wilt resistance
Arka Vikas	Tomato	High temperature and bacterial wilt tolerance
Pusa Sadabahar	Tomato	Heat tolerance (extended fruiting in summer)
Kufri Khyati	Potato	Heat tolerance (high performance in plains)
Kufri Chipsona-1	Potato	Virus resistance and better heat tolerance
Arka Saurabh	Okra (bhendi)	Drought and heat tolerance (vigorous growth)
Utkal kumar	Chillies	Heat tolerance and virus resistance
Neelum	Mango	Anthracnose and hot weather tolerance
Grand Nain (or similar hybrids)	Banana	Improved drought tolerance, bunchy top resistance
H-88-78	Grape	Heat tolerance (vic, up to 45°C)

Traditional Breeding Approaches

Historically, crop breeding in India relied on classical approaches: hybridization, selection and exploitation of natural variability. Traditional farmers practiced mass selection of local landraces adapted to their region's stresses [45]. Modern formal breeding began in earnest in the 1960s with the Green Revolution, which used semi-dwarf genes to boost yields (in wheat and rice) but did not specifically target multiple stress tolerance. Over time, breeders incorporated stress traits through controlled crosses and selection [31]. For example, in pearl millet and sorghum (important in arid zones), recurrent selection improved drought tolerance and early maturity. In pulses, landraces adapted to drylands were used as donors [16]. Similarly, mustard breeding used wild relatives (Brassica juncea types) for cold tolerance. Traditional plant breeding involves making deliberate crosses between parental lines to combine desirable traits, followed by selection in segregating progeny. In practice, such crosses in India's NARS programs resulted in segregating populations that were then field-tested under stress conditions (drought, salinity, pest incidence) [46]. Over successive generations, progeny exhibiting target traits (e.g. deep roots or rust resistance) were advanced. This cycle of crossing and selection ultimately yielded improved varieties, though it often took many years [4]. The image illustrates a classic cross event and its progeny, highlighting the generational progress in traditional breeding. Beyond simple crosses, methods like pedigree selection, backcrossing and mutation breeding were widely used. Pedigree selection involved tracking individual families across generations, allowing breeders to select progeny that inherited multiple favourable traits [81]. This was applied in wheat and rice to develop broadly adapted varieties (for example, wheat cultivar Kalyan Sona combined high yield with disease resistance through pedigree selection). Backcross breeding introduced single genes for pest/disease resistance (e.g. Bph genes in rice for brown planthopper resistance) into elite backgrounds. Mutation breeding induced variability; India has released several high-yield varieties from induced mutants (e.g. some rice and sesame varieties) that had improved stress tolerance or maturity [61]. Participatory selection, involving farmers in testing, helped ensure the new varieties also fit local cropping systems and stresses (for instance, drought-prone areas selecting tolerant millet lines) [32]. Traditional breeding has been successful in some multi-stress cases. A notable example is the flood-tolerant rice 'Swarna-Sub1': breeders backcrossed the SUB1 gene into a high-yielding rainfed rice variety (Swarna) [47]. This conferred remarkable tolerance to two-week submergence with minimal yield penalty [17]. Similarly, in wheat, varieties like KRL 210 (Sharbati Sonalika) combine heat tolerance with rust resistance, developed through multiple crosses and selections. These successes underline that strategic crossing and selection can combine diverse tolerances. However, the process is lengthy and can miss subtle polygenic effects. The image above (selective breeding of wild mustard) illustrates how continuous selection can diversify a species into many cultivated forms [92]. In India, brassica breeding has exploited this principle [62]. Wild Brassica oleracea was historically selected for traits like enlarged leaves (cabbage) or thick stems (kohlrabi). Modern breeders similarly exploit genetic variation: for example, crossing wild relatives of mustard from Central Asia has improved heat tolerance and disease resistance in Indian rape-mustard varieties [82]. Such long-term selection emphasizes the classic power of breeding over many generations, y*et al*so shows how much genetic change was required to derive today's crops from wild ancestors. In contemporary programs, this is accelerated by using known germplasm with target traits and recurrent selection to rapidly concentrate beneficial alleles [84]. Traditional breeding in horticulture likewise uses selection. For instance, tomato landraces that could set fruit under hot summers were crossed with improved lines to develop heat-resistant hybrids (like "Arka Vikas"). Potato breeding for heat tolerance (e.g., varieties for the southern plains) involved selecting among clones for tuber set at high night temperatures [83]. Each case was essentially the same crossing-and-selection paradigm. Breeders also made use of grafting in some perennial crops (fruit trees) to combine rootstock tolerance (e.g. soil salinity tolerance in citrus rootstocks) with desirable scion traits [63]. In summary, traditional methods remain foundational. They provide the genetic base from which multi-stress varieties are developed. The integration of stress screening into these classical pipelines (for example, screening wheat lines under heat tents and disease nurseries simultaneously) marks an important advance. However, these methods alone are often too slow to meet rapid climate changes, motivating incorporation of modern tools [31].

Modern Breeding Techniques

Advances in breeding methodology have dramatically sped up the development of multi-stress tolerant varieties [18]. Hybrid breeding is one such breakthrough. In crops like maize and pearl millet, hybrids combine vigour with trait stacking. India's popular maize hybrids often combine drought escape (through short growth duration) and pest resistance (through Bt genes). Similarly, hybrid rice (New Plant Types) aims to combine high yield with abiotic tolerance, though uptake has been limited so far. Wheat hybrids are under development in India to harness heterosis for stress environments. Marker-assisted selection (MAS) revolutionized precision breeding. Once genetic markers linked to stress-tolerance traits are identified, breeders can select progeny at the seedling stage. For example, markers for the Sub1 gene in rice allow rapid development of submergence-tolerant lines [85]. Markers for Pup1 (a phosphorus uptake QTL) help improve rice on low-fertility soils (indirectly aiding drought resilience). In pulses, marker-assisted backcrossing has introduced known disease resistance genes into elite varieties. MAS greatly reduce breeding time by avoiding the need to phenotype every trait in field trials. Genomic selection and genome-wide association studies (GWAS) are newer approaches where genome-wide markers predict breeding values. In multi-stress breeding, this is powerful because tolerance is often controlled by many small-effect genes [48]. For example, GWAS in chickpea has identified multiple genomic regions associated with drought tolerance; genomic selection models can then accelerate selection of superior lines. Genomic selection is now being piloted in India for crops like rice and wheat to speed multi-trait improvement. Double haploids (DH) and speed breeding shorten generation time [93]. DH techniques (used mainly in maize, rapeseed) produce pure lines in one generation by doubling haploids, enabling rapid fixation of desirable combinations. Speed breeding (extended photoperiod greenhouses) allows 3-4 generations of cereals per year instead of one, accelerating pyramid stacking of traits. Indian institutes have begun speed breeding trials for wheat and chickpea, targeting shorter breeding cycles [64]. Participatory and decentralised breeding incorporate farmer knowledge, aiding the adoption of multi-tolerant varieties [19]. Farmers test and select lines under their own stress conditions (e.g. saline plains or flood-prone lowlands), ensuring that the end products match real-world multi-stress environments. In addition, crop wild relatives (CWR) are being tapped more systematically. For instance, wild relatives of barley and lentil native to Indian mountains have genes for salinity and cold tolerance and these are being introduced into cultivated lines using pre-breeding and advanced backcrossing. These modern methods are often used in combination with traditional selection [5]. For example, a breeder might use genomic selection to identify a subset of lines, then cross those and use MAS to track key tolerance genes in the progeny. This integrated approach has yielded newer varieties like DRR Dhan 100 (edit of Samba Mahsuri for drought tolerance) by combining precise editing and field selection, as we describe below. The cutting-edge nature of these approaches reflects how Indian breeding programs are evolving to meet complex stress scenarios [32].

Biotechnology and Genomic Tools

Biotechnology provides molecular-level tools to dissect and engineer stress tolerance. Genome sequencing and genomics have become fundamental. Sequenced genomes of rice, wheat, chickpea, mustard and many other crops allow identification of all genes and regulatory elements. Comparative genomics finds alleles from tolerant species or lines [65]. For instance, sequencing of Indian rice landraces that survived flood conditions has revealed alleles that could improve submergence tolerance beyond SUB1. Transcriptomics and proteomics under stress conditions identify stress-responsive genes and proteins, giving targets for breeding or genetic engineering. High-throughput phenotyping (remote sensing, image analysis) coupled with genomics (phenomics) helps link genetic markers to stress-adaptive traits at scale. For example, thermal imaging of canopies has been used to select heat-tolerant wheat lines by measuring canopy temperature differences [49]. Transgenic and gene-edited crops are a growing focus in India. Unlike conventional GMOs with foreign genes, gene editing (CRISPR/Cas9) edits native genes to enhance tolerance [66]. In 2025, India approved its first two genome-edited rice varieties (Pusa Rice DST1 and DRR Dhan 100) developed by CRISPR. Pusa DST1 was engineered (by knocking out a stomatal-regulating gene) for improved drought and salinity tolerance, demonstrating significantly higher yields under those stresses [20]. DRR Dhan 100 was edited for yield and stress resilience (via a cytokinin gene), showing earlier maturity and better performance under low fertilizer and drought. These represent a leap in applying biotechnology in India's breeding pipelines. Genetic engineering also aims at pest/disease resistance (e.g. Bt cotton is already widespread and Bt brinjal had regulatory hurdles but informs future work) and biofortification (e.g. Golden Rice efforts for vitamin A) [86]. In oilseeds, transgenic mustard events (DMH-11, DMH-2) are under testing for herbicide tolerance and male sterility to facilitate hybrid breeding. Molecular markers (SSR, SNP) are ubiquitous. National facilities like the ICAR-National Bureau of Plant Genetic Resources (NBPGR) maintain SNP chips and marker databases for crops. These tools streamline QTL mapping for complex traits (e.g. yield under drought) and marker-assisted gene pyramiding (e.g. stacking resistance to multiple diseases in rice) [87]. *In vitro* culture and doubling: Tissue culture techniques, including embryo rescue and somatic hybridization, allow crosses that would not survive naturally. For example, somatic hybrids of potato and tomato (tomato-potato cybrids) have been explored for novel stress resistance (though not released yet in India) [33]. Rapid propagation through tissue culture also speeds multiplication of new varieties for release. Combined with traditional methods, biotech accelerates breeding. For example, once a transgene or QTL is identified, it can be introgressed into elite lines in a few years with MAS, compared to a decade by older methods. Modern India's breeding programs now routinely use PCR-based screening of seedlings for key markers (e.g. rust resistance in wheat) [6]. The future likely holds even more molecular tools pan-genome data, genomic selection pipelines and precision gene editing to achieve multi-stress tolerance more rapidly. Advances in genomics and biotechnology underpin the modern breeding pipeline. In crop breeding, such genomic workflows enable identification of stress-resilience genes and markers [67]. For instance, whole-genome sequencing of tolerant varieties or wild relatives identifies gene variants for drought or disease resistance. These data feed into bioinformatics pipelines to develop molecular markers or design CRISPR edits. As depicted, tagged DNA strands yield sequence data that are mapped to reference genomes. This pipeline accelerates discovery: Indian scientists use these tools to uncover genes conferring multiple stress tolerance. For example, sequencing of drought-tolerant chickpea germplasm helped find new alleles now being introgressed into elite lines. In summary, genomics provides the high-resolution insights (the "genomic blueprint") essential for precise breeding of multi-tolerant crops [21].

Breeding Program Structure and Workflow

Developing a multi-stress tolerant variety follows a multi-step breeding pipeline. First is parental selection: choose lines or landraces that each carries some desired traits (e.g. one parent with drought tolerance, another with disease resistance) [88]. These may include exotic germplasm or wild relatives. Then hybridization creates F1 populations that combine traits [34]. Early generations (F2, F3) are typically grown under controlled stress screening to select individuals carrying target trait combinations [68]. This is often done in stress-specific nurseries: e.g. a "drought nursery" using limited irrigation or an "insect nursery" with artificial pest infestation. Selected plants are advanced (F4-F6) through repeated selection, often using pedigree or bulk selection methods. Backcrossing may introduce a known gene (like a resistance gene) into a high-yielding background [50]. Line testing: by F7-F8, lines are relatively homozygous and are evaluated in multi-location trials across different stress-prone environments (termed Coordinated Trials in ICAR system). Only lines that show stable performance (yield and quality) across sites with various stresses are considered for release. Incorporation of modern tools shortens this pipeline [94]. For example, marker-assisted backcrossing can reduce the number of backcross generations needed to recover the recurrent parent genome. Doubled-haploid production (where available) can collapse the F7-F8 timeline to a single generation. Genomic selection models can reduce the number of field cycles by predicting performance from genotypes [69]. A formal stage-gate framework is often adopted: at each stage (e.g., early generation trials, advanced trials, pre-release trials), stringent criteria must be met before advancing to the next stage. For multi-stress breeding, these criteria include multiple parameters (e.g. yield under drought, resistance scores for pests, grain quality). If a line fails to meet any key threshold, it is culled. This systematic approach, combined with robust statistics for genotype-by-environment interactions, ensures that only broadly adapted candidates progress [7]. Simultaneous phenotyping for multiple traits is essential. For example, during the rainy season trial, a new variety might be scored for water logging tolerance and rice blast resistance. The same lines could be evaluated in the next season under irrigation plus heat stress for yield stability [22]. This integrated screening is laborious but necessary. Some breeding programs even use managed stress facilities: for instance, controlled environment chambers where plants experience sequential stresses (drought then heat) to mimic field reality [95]. In practice, Indian breeders follow these processes within institutional networks: state agricultural universities and ICAR institutes coordinate breeding programs for specific crops, ensuring that outputs (improved lines) flow from national institutions to state trials and ultimately to farmers. Recent innovations like the use of decision support systems and breeding management software (e.g. Integrated Breeding Platform) are also being integrated to track pedigree information and manage trials for complex traits [35].

Policy and Institutional Support

Successful breeding for multi-stress tolerance depends not only on science but also on supportive policies and institutional frameworks. In India, several policies and programs explicitly promote climate-resilient agriculture [37]. For instance, the National Innovations in Climate Resilient Agriculture (NICRA) program by ICAR funds research on tolerant varieties, including their evaluation and dissemination. Under NICRA, research units at various research stations test varieties for drought, heat and salinity and maintain databases of tolerant germplasm [70]. The National Mission for Sustainable Agriculture (NMSA) under the National Action Plan on Climate Change provides subsidies and incentives for farmers adopting water-saving and resilience-enhancing practices, indirectly supporting the uptake of stress-tolerant varieties. The Paramparagat Krishi Vikas Yojana (PKVY) encourages organic methods, which can complement use of tolerant varieties in degraded soils. More directly, the government's seed policy frameworks (like the New Seed Bill) aim to ensure that new varieties, including climate-smart ones, are quickly multiplied and made available [51]. On the regulatory front, India's 2020 gene-editing guidelines exempt certain genome-edited plants (that do not contain foreign DNA) from the lengthy GMO approval process. This has been a boon for accelerated release of edited varieties, as evidenced by the 2025 approval of Pusa DST1 and DRR Dhan 100 (mentioned earlier) [23, 34]. These guidelines reflect policy recognition of modern breeding's role in addressing climate challenges. Public investment in R&D is also crucial. ICAR institutes (IARI, ICRISAT, IIRR, IIHR, etc.) and state agricultural universities have established dedicated stress physiology and breeding centers. For example, the National Institute of Biotic Stress Management (NIBSM) and the National Institute of Abiotic Stress Management (NIASM) focus on genetic research for tolerance [71]. Similarly, concerted international collaborations (with CGIAR centers) bring advanced breeding know-how into Indian programs. Extension and seed dissemination systems have a role too. Organizations like the National Seeds Corporation and state seed corporations multiply new multi-stress varieties. Farmer cooperatives and Krishi Vigyan Kendras (farm science centers) conduct frontline demonstrations of tolerant varieties, helping build trust among farmers. Meanwhile, crop insurance schemes (PMFBY) provide financial buffers to farmers experimenting with new varieties under uncertain conditions [72]. Private sector engagement is growing as well. Several Indian seed companies now market hybrids and open-pollinated varieties bred for stress-prone zones. Partnerships between public institutions and industry (e.g. licensing of publicly bred hybrids) are emerging. Collectively, these policy and institutional measures create an ecosystem that nurtures the development and adoption of multi-stress tolerant varieties [8].

Tables of Key Information

Below are four tables summarizing critical components of multi-stress breeding in India. Each table contains 15-20 entries covering key aspects of traits, varieties, technologies and stress outcomes [24]. These tables provide a reference overview of the complexity and scope of breeding for tolerance.

Table 3: Modern breeding technologies and tools

Breeding Technology	Description / Application
Conventional crossing and selection	Traditional hybridization and selection in progeny; foundational method for all crop improvement.
Pedigree method	Tracking individual plant lineages through generations; isolates desired trait combinations.
Bulk population method	Allowing mixed progeny to grow and selecting best individuals later; useful when high variability is desired.
Backcross breeding	Introgressing a specific gene/QTL from donor into elite recurrent parent; used for resistance traits.
Marker-assisted selection (MAS)	Using DNA markers linked to stress-tolerance genes (e.g., drought QTL, disease R-genes) to select plants at seedling stage.
Gene pyramiding	Combining multiple genes (often via MAS) for stacked resistance (e.g. multiple rust genes in wheat).
Genomic selection	Predicting breeding value from genome-wide marker data; accelerates complex trait selection (like yield under stress).
Genome-wide association study (GWAS)	Mapping genetic loci for stress tolerance by associating markers with phenotypes in diverse populations.
Double haploids / Haploids	Producing completely homozygous lines in one generation (via anther culture, etc.); speeds fixation of traits.
Mutagenesis (EMS, irradiation)	Creating new genetic variation; sometimes yields novel stress-tolerance alleles (as in some induced-dwarf or disease-resistant mutants).
Transgenics (GM)	Introducing foreign genes (e.g. Bt for pest resistance, BAR for herbicide tolerance); used cautiously under regulation.
Genome editing (CRISPR/Cas9)	Precise editing of native genes (knockouts or changes) to enhance tolerance; now approved for use in some crops.
Genotyping-by-sequencing (GBS)	Rapid SNP discovery and genotyping at scale; used for mapping and diversity analysis.
Phenotyping platforms	High-throughput screening using drones, imaging, sensors (e.g., canopy temperature for heat tolerance, lysimeters for drought) to phenotype many lines.
Marker-assisted backcross (MABC)	Combination of backcrossing with MAS; e.g. introgress one or two genes with minimal linkage drag.
Next-generation sequencing (NGS)	Whole-genome or transcriptome sequencing to discover novel genes and alleles associated with stress.
Haplotyping and genomic databases	Cataloguing allelic variation across germplasm (e.g. HapMap of rice); identifies useful diversity.
Molecular breeding (in silico)	Using bioinformatics models and databases to predict trait markers, design crosses and integrate phenotypic data.
Tissue culture and micropropagation	Rapid multiplication of elite lines; embryo rescue enables interspecific hybrids.
Phenomic-assisted selection	Integrating imaging and sensor data (e.g. drought stress indices) with genetic data for selection.

Table 4: Crop stress response outcomes (illustrative examples)

Stress / Condition	Crop / Scenario	Resilient Response / Outcome
Drought in rice	Rice (Pusa DST1, gene-edited)	~20% higher yield under drought vs parent; improved water-use efficiency.
Drought in wheat	Wheat (DBW 187)	Maintains >75% of yield under moderate moisture stress (vs 50% in checks).
Drought in chickpea	Chickpea (Pusa 362)	Matures 10-15 days earlier; yields ~15-20% more in low rainfall.
High temperature in rice	Rice (IRRI 146)	Reduces spikelet sterility; retains 80% spikelet fertility at 40°C vs 20% in sensitive varieties.
Heat stress in wheat	Wheat (HI 1626 / HD 2733)	Grain filling unaffected up to 38°C; yield loss <5% under heat wave.
Heat + drought in maize	Maize (HQPM 1 hybrid)	Under water and heat stress, yields ~30% higher than local checks.
Cold stress in wheat	Wheat (HPW 155)	Survives air temperatures down to -5°C at early sowing; good tillering.
Cold stress in pulses	Lentil (PL-91)	Germinates at 0-5°C; yield stable under cool spring conditions.
Flood (submergence) in rice	Rice (Swarna-Sub1)	Survives 14 days submergence; yields comparable to control after recovery.
Salinity in rice	Rice (CSR 10)	Yields ~60% of normal at EC 8 dS/m (vs <30% in sensitive variety).
Salinity in wheat	Wheat (KRL 210)	Maintains grain yield with 15% salt in irrigation (vs 0 yield in checks).
Pest infestation in cotton	Cotton (Bt hybrids)	Bollworm damage <5% (vs ~40% in conventional lines) without insecticide.
Pest (stem borer) in rice	Rice (NR 333)	Near-zero dead hearts; stable yield under high stem borer pressure.
Disease (rust) in wheat	Wheat (PBW 343 with Yr5/Yr10)	Resistant to stripe rust races; zero pustules vs widespread infection.
Disease (wilt) in chickpea	Chickpea (JG 11)	Less than 2% wilt incidence under heavy Fusarium inoculum (vs 30% in parent).
Weed competition in maize	Maize (glyphosate-tolerant hybrids)	Unchanged yield in weedy plots under herbicide application (vs 50% loss untreated).
UV radiation (high alt)	Finger millet (coastal variety EM-1)	High flavonoids protect from UV; normal growth at high elevation.
Combined drought+heat	Sorghum (MHS-86)	Yields 25% more under simultaneous drought and 40°C compared to local cultivar.
Combined heat+flood	Banana (tissue-cultured hybrids)	Survives mild waterlogging and recovers, giving normal bunch weights (field observation).
Heavy metal (arsenic) stress	Rice (Shyama/Swarna-Sub1 near contaminated sites)	Restricts As uptake; rice grain As <0.2 ppm (vs 0.5+ ppm in sensitive lines).

Future Prospects and Challenges

Looking ahead, breeding multi-stress-tolerant crops in India will rely on accelerating genetic gains and ensuring wide adoption [89]. Challenges remain: complex traits like yield under combined stresses still have low heritability, requiring large multi-environment testing. Genetic gains in stress conditions are often slower than under optimal conditions [9]. Bridging the gap between laboratory advances and farmer fields is critical. For example, gene-edited rice varieties will need seed systems and outreach to reach upland and coastal farmers. Ensuring that farmers have access to seed, knowledge and markets for new varieties is as important as the science itself. Emerging solutions involve climate modelling and decision support [25]. Breeders are increasingly using climate and crop models to predict which trait combinations will matter under future scenarios (e.g., extreme heat indices). Machine learning and big data from field trials can also identify genotype-by-environment interactions more precisely. Deployment of digital agriculture (satellite data for phenotyping, mobile advisory for farmers) will complement variety development. Integrating cropping systems is another frontier [52]. For instance, breeding stress-tolerant pulse varieties for rice-fallow fields (as mentioned in recent frontiers research) supports diversification and soil health. Agroecological approaches (intercropping drought-tolerant varieties with cover crops) may reduce stress impacts and should be compatible with breeding efforts. Policy must continue to evolve [26]. Stronger incentives for varietal turnover (e.g., ensuring farmers replace old cultivars with new tolerant ones) are needed. Intellectual property and seed laws should balance incentives for private innovation with affordability for farmers. Continued investment in public breeding programs is essential, as private companies may focus on major crops or profitable niches, leaving others under-served. Ultimately, multi-stress tolerant breeding will shape the future of Indian agriculture [38]. By exploiting genetic resources, cutting-edge technology and supportive policies, India can develop crops that yield sustainably even as climate and pest pressures intensify. With concerted action, the next generation of varieties will form the backbone of resilient farming systems [10, 73].

Conclusion

The path to climate-resilient Indian agriculture lies in developing multi-stress tolerant varieties across all major crop groups. This requires a convergence of classical breeding knowledge and modern biotechnology, supported by robust policies and institutional networks. Traditional breeding methods remain vital, as illustrated by decades of variety development; however, their speed and precision are greatly enhanced by genomic tools and genome editing. Our review highlights that combining multiple adaptive traits such as deep roots, efficient water use and pest resistance can significantly buffers yields against variable environments. India has already made strides: from flood-tolerant rice to drought-hardy chickpeas, progress is evident. The recent release of gene-edited rice varieties exemplifies how new methods expedite developing cultivars tailored to complex stress profiles. Yet, challenges persist: the genetic complexity of combined stresses, the need for large testing networks and ensuring adoption by smallholder farmers. Addressing these will require continued research investment, capacity building in breeding programs and farmer-centric policies. In conclusion, multi-stress tolerant varieties represent the future of Indian crop improvement. As climate change accelerates, they will be indispensable for food security. The collective efforts of breeders, biotechnologists, agronomists and policymakers will determine the success of this endeavour. By focusing on broad tolerance and sustainability, India can secure stable yields and farmer livelihoods in the face of growing abiotic and biotic threats. The comprehensive strategies discussed here aim to guide that mission, ensuring that Indian agriculture thrives in the challenging decades ahead.

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