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Climate-resilient vegetable cultivars

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Abstract
Climate change amplifies the effects of abiotic stresses that negatively impact the productivity, quality and reliability of vegetable production. This review summarizes recent research (2020-2025) on the impact of heat, drought, salinity and waterlogging, along with associated disease pressure, on vegetable crops. It analyzes the role of various stress physiology and signal transduction pathways, available breeding resources, and genomic technologies. The review also examines phenotyping and the use of stress-tolerant rootstocks to enhance vegetable crop resilience. Improving vegetable crop resilience requires an understanding of multiple stress tolerance pathways, including tolerance to various stresses at different growth stages that may affect the viability of pollen, fruit set, and final marketable yield. There is a need to enhance integration of breeding and agronomy and the use of repeated multi-environment field trials to develop crop varieties to sustain vegetable production under the altering climate.

Keywords: Abiotic stresses, Vegetable crops, Climate resilience, Stress-tolerant rootstocks, Genomic technologies

1. Introduction

Vegetable crops support dietary diversity, farm income and intensive horticultural systems, but their short production cycles and sensitive reproductive stages make them vulnerable to changing temperature and water regimes. Heat at flowering can reduce pollen viability and fruit set, whereas drought restricts carbon assimilation and fruit growth; salinity adds osmotic and ionic constraints that may persist after irrigation (Saeed *et al.*, 2023; Graci *et al.*, 2024; Guo *et al.*, 2022; Roșca *et al.*, 2023; Khan *et al.*, 2024) [1, 2, 3, 4, 5]. Stress responses also vary across cultivars, growth stages and production environments, so a favorable laboratory indicator cannot be equated with stable marketable yield. Wild relatives and improved breeding populations offer valuable genetic variation, while molecular selection, genome editing, physiological phenotyping and grafting provide complementary approaches to adaptation (Graci *et al.*, 2024; Bashary *et al.*, 2024; Sanwal *et al.*, 2022) [2, 6, 7]. However, evidence generated under isolated stress treatments is often difficult to extrapolate to fields where heat, water scarcity and salinity interact. This review evaluates the mechanisms and breeding options for climate-resilient vegetables, identifies crop-specific priorities and research gaps, and emphasizes multi location assessment of yield, product quality and resource use.

2. Climate-related stresses and their impacts on vegetable crops

2.1. Heat stress and reproductive vulnerability

The productivity of vegetable crops is affected not only by increases in mean temperature but also by the frequency, duration and timing of extreme heat events. High temperatures alter photosynthetic carbon assimilation, membrane stability and assimilate distribution, while the reproductive phase is often particularly sensitive. In tomato, exposure during flowering can impair pollen development, pollen germination and fertilization, thereby reducing fruit set even when vegetative growth remains relatively vigorous. Reviews of heat-resilience pathways in vegetables identify the need to evaluate marketable yield and product quality rather than treating seedling survival as an adequate proxy for tolerance (Saeed *et al.*, 2023; Graci *et al.*, 2024; Khan *et al.*, 2024) [1, 2, 5].

Heat sensitivity is crop- and genotype-dependent. Tomato germplasm derived from the wild relative *Solanum pimpinellifolium* offers useful variation in reproductive traits; evaluation of backcross inbred lines has demonstrated the value of measuring flower abnormalities and fruit set under elevated temperature (Bashary *et al.*, 2024) [6]. In pepper, crop-simulation analyses also indicate that the timing of heat exposure can modify yield responses, reinforcing the importance of developmental-stage-specific assessment (Park *et al.*, 2025) [8]. For leafy vegetables, temperature-driven premature bolting and loss of leaf quality represent different breeding targets from the fruit-set traits relevant to tomato and pepper (Saeed *et al.*, 2023) [1].

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2.2. Drought, salinity and excess water

Drought limits water uptake and reduces cell expansion, leaf conductance and photosynthesis. Stomatal closure can conserve water but simultaneously restrict carbon dioxide entry, creating a trade-off between water saving and biomass accumulation. In pepper, experimental comparisons of soil-water availability and stress duration show that growth predictions depend on both the intensity and the length of water deficit (Zhu *et al.*, 2024) [9]. Consequently, trials should record soil-moisture dynamics, plant water status, fruit number and marketable yield instead of relying on a single end-point measure. Studies of water-stress-tolerant pepper rootstocks likewise show that root distribution and hydraulic traits can influence the response to deficit irrigation (Gisbert-Mullor *et al.*, 2023) [10].

Salinity imposes an initial osmotic limitation on water uptake and, with longer exposure, ionic toxicity caused by excessive sodium or chloride accumulation. In tomato, the resulting effects include impaired photosynthesis, nutritional imbalances and altered growth, with considerable variation among genotypes and developmental stages (Guo *et al.*, 2022; Roşca *et al.*, 2023) [3, 4]. Rootstock studies demonstrate that salt-tolerant eggplant genotypes can alter sodium partitioning in a tomato scion, but yield and fruit-quality responses must be assessed in addition to tissue ion concentrations (Sanwal *et al.*, 2022) [7]. Excess water creates a different constraint: saturated soils restrict oxygen supply to roots, impairing respiration and nutrient acquisition. Waterlogging therefore should not be interpreted as simply the opposite of drought; resilience may require distinct morphological and metabolic adjustments (Hanaka *et al.*, 2023) [11].

2.3. Concurrent stresses and trait prioritization

Under production conditions, climatic hazards rarely occur in isolation. Heat can coincide with soil drying; saline irrigation may accompany high evaporative demand; and heavy rainfall may be followed by disease-favorable humidity. Responses to two stresses cannot be reliably inferred by adding responses measured under separate single-stress treatments, because resource allocation and signaling pathways interact (Saeed *et al.*, 2023; Guo *et al.*, 2022; Khan *et al.*, 2024) [1, 3, 5]. For breeding, the relevant outcome is sustained marketable production in the target environment, with acceptable fruit appearance, nutritional properties, shelf life and input requirements. This calls for clearly defined stress treatments, stage-specific measurements, repeated harvest assessments where appropriate, and validation across representative cultivation systems (Saeed *et al.*, 2023; Zhu *et al.*, 2024; Park *et al.*, 2025) [1, 9, 8].

3. Physiological and molecular mechanisms underlying climate resilience

3.1. Water balance, photosynthesis and heat protection

Stress tolerance emerges from coordinated mechanisms of avoidance, acclimation, damage limitation and recovery. Maintenance of relative water content depends on root water acquisition, stomatal regulation and the capacity to restrict nonproductive water loss. Drought-resistant genotypes may accumulate compatible solutes, including proline and soluble carbohydrates, to help sustain cellular osmotic balance; nevertheless, osmolyte accumulation alone does not demonstrate superior field performance. Heat tolerance depends on maintaining photosystem function, protein folding and membrane integrity. Heat-shock proteins act as molecular chaperones, while heat-responsive transcription factors coordinate protective gene expression (Saeed *et al.*, 2023; Graci *et al.*, 2024; Khan *et al.*, 2024) [1, 2, 5].

Photosynthetic stability can be examined through chlorophyll fluorescence, gas exchange, chlorophyll retention and reproductive carbohydrate availability. These indicators should be interpreted alongside temperature, light and moisture measurements, because an apparently protective response such as rapid stomatal closure may ultimately depress growth when stress persists. In potato, experimental work on the StMAPKK5 signaling component links heat responses with changes in growth, photosynthesis and antioxidant defenses, illustrating the connections among signaling and whole-plant traits (Zhu *et al.*, 2024) [12].

3.2. Ion homeostasis, oxidative stress and hormonal coordination

Salinity tolerance involves limiting the entry of toxic ions, regulating their long-distance transport, compartmentalizing them in vacuoles and maintaining potassium-to-sodium balance. Tomato studies identify ion transport and tissue-specific salt distribution as important components, although the efficacy of individual mechanisms depends on genotype, growing medium and exposure level (Guo *et al.*, 2022; Roşca *et al.*, 2023) [3, 4]. Reactive oxygen species (ROS) are produced during normal metabolism but can accumulate excessively during heat, drought or salinity, causing lipid peroxidation and damage to membranes and proteins. Enzymatic antioxidants such as superoxide dismutase, catalase and ascorbate peroxidase, together with nonenzymatic antioxidants, contribute to oxidative-stress management (Saeed *et al.*, 2023; Khan *et al.*, 2024; Zhu *et al.*, 2024) [1, 5, 12].

Calcium signaling, mitogen-activated protein kinase cascades and phytohormone networks connect stress perception with downstream responses. Abscisic acid is particularly relevant to drought-induced stomatal regulation, while ethylene and other hormones participate in growth adjustment and recovery. Because the same signaling modules also regulate development, constitutively stronger defense responses may incur reproductive or growth penalties. Breeding should therefore favor adaptive regulation that protects reproductive development and yield, rather than maximizing one biochemical marker under all conditions (Saeed *et al.*, 2023; Guo *et al.*, 2022; Zhu *et al.*, 2024) [1, 3, 12].

3.3. Genetic control, molecular tools and phenotyping

Tolerance is generally a quantitative, environment-sensitive character governed by interacting loci and regulatory networks. Candidate genes and quantitative trait loci can identify useful mechanisms, but correlation between gene expression and stress exposure does not, by itself, establish a causal contribution to field resilience. Tomato research has connected heat-related reproductive traits with candidate genetic regulators, and newly characterized S. pimpinellifolium-derived lines provide material for further genetic dissection (Graci *et al.*, 2024; Bashary *et al.*, 2024) [2, 6]. Functional analysis with genome editing can provide stronger tests: targeted modification of *SlHyPRP*$_1$ and *SlDEA*$_1$ in tomato has been investigated for responses to drought, salinity and selected diseases (Saikia *et al.*, 2024) [13]. Such experiments are valuable mechanistic evidence but require further validation for agronomic stability and genotype-dependent effects.

Mechanism-guided phenotyping should integrate physiological measurements with direct yield and quality outcomes. Suitable indicators include canopy temperature, stomatal conductance, pollen viability, fruit set, relative water content, chlorophyll fluorescence, leaf ion concentrations, and post-stress recovery. Measurements at more than one growth stage distinguish early injury from persistent yield loss, while experiments across soil types, irrigation regimes and seasons test the transferability of observed tolerance. Physiological measurements can guide marker-assisted breeding and genomic selection, but no single stress-response marker substitutes for replicated performance testing (Saeed *et al.*, 2023; Bashary *et al.*, 2024; Zhu *et al.*, 2024; Park *et al.*, 2025; Gisbert-Mullor *et al.*, 2023) [1, 6, 9, 8, 10]. The interacting protection mechanisms are summarized in Figure 1.

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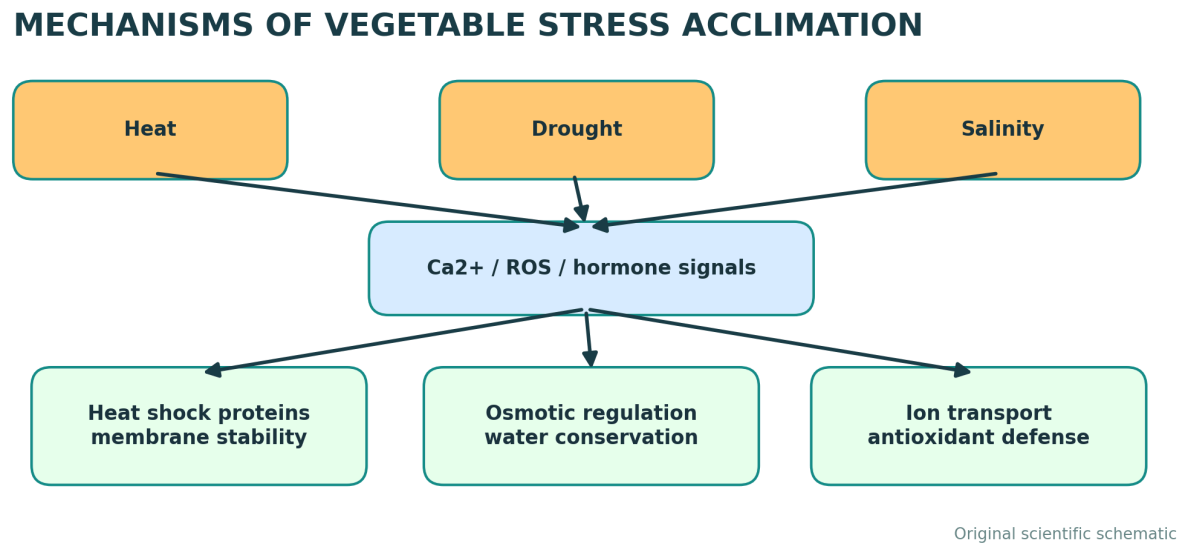


Figure 1. Selected physiological response networks linking thermal, water, and salinity stress to signaling, osmotic regulation, antioxidant protection, and ion homeostasis.

4. Breeding strategies for climate-resilient vegetable cultivars

Conventional breeding can combine small effect adaptation traits to meet complex market requirements. It can also integrate genetic diversity found in wild relatives, as illustrated with certain tomato plants and *Solanum pimpinellifolium*. However, we have to be careful when using wild relatives as they may introduce undesired traits, and we may need to increase the population size to improve the chances of recombination and rely on phenotypic selection. Among other breeding tools, marker-assisted selection (MAS) can be efficiently used for stable large-effect traits. For polygenic responses, training populations will need to represent the target environments, and genomic selection will be more appropriate. Molecular tools can facilitate but not replace multi-season selection. Stress tolerance confirmed under a controlled environment may not ensure stable productivity under farmers' management.

There are recent findings on rootstock-mediated resilience. Grafting improves the performance of a plant by using roots of better quality. Unlike a new cultivar, improving a plant with grafting keeps the genotype of the fleshy part of the plant the same and does not require the modification of the fruit genotype. This may improve accepted varieties in the market.

However, there are several factors that limit the widespread use of improved plants through grafting, such as restrictions on fruit quality with different rootstocks, limited availability of rootstocks, variability in response to salinity among plants and soils, and the lack of adequate controls in experiments. The most significant outcome of the research should be the highest marketable yield per unit of water or salinity stress, rather than the highest biomass.

Comparative studies of grafted tomatoes demonstrate why rootstock choice must be evaluated beyond seedling survival. Fu *et al*. [14] compared commercial rootstocks for low-temperature and salinity tolerance and assessed the yield and quality of grafted tomato plants. Alqardaeai *et al*. [15] examined novel and commercial rootstocks in saline soilless systems, observing differences in tomato yield, fruit quality and water productivity across rootstocks and growing media. These studies support testing rootstock–scion combinations under the irrigation and production conditions for which they will be recommended.

Therefore, extension and breeding recommendations should give stress intensity and media where benefits were demonstrated. Long-term studies should check if high root vigor leads to faster transpiration and higher irrigation and fertilizer requirements; if fruit flavor, mineral quality and/or ripening are affected; and if other, yet unknown, harmful effects occur. Economic evaluation is particularly important for smallholders and protected cultivation. (Alqardaeai *et al.*, 2024) [16]

Genome editing is a more targeted way of studying and modifying stress pathways. CRISPR experiments with tomatoes have shown the editing of multiple stress pathways. However, transforming commercial varieties will take time due to legal and technical constraints. This is especially the case with polygenic traits. Unintended developmental consequences will also have to be considered. Improving the selection of plants based on high-throughput phenotyping (HTP) techniques, combined with improved (environmental) sensors and/or imaging will help if calibrated against physiological measurements and yield. Improving genomic prediction will require in-depth training on different data types and stresses as well as new, unexplored, environments and populations to avoid overestimating accuracy. The transparency of training data, treatment and stress conditions is therefore essential. (Chavhan *et al.*, 2025) [17]

5. Climate-resilient vegetable crop development

Sweet pepper has provided some examples of genotype-specific antioxidant and developmental responses to drought, and of interactions with beneficial microorganisms. While these cases show potential, they are not always stable across different soils or cropping seasons. Compared to pepper, research on eggplant and tomato has been more extensive, particularly on salinity and heat, and grafting. Tolerant rootstocks for tomato can be sourced from eggplant. Cucurbits and brassicas have different reproductive biology and stress sensitive stages. The priority of the trait to be changed must depend on the crop: for brassicas it could be bolting and for solanums, it could be head formation and firmness. For tomatoes it could be pollen viability, while for cucurbits it could be the percentage of marketable yield. Integrating the requirements of consumers with the stress ecology of a region is important for developing pipelines specific to crops. (Lozo *et al.*, 2022) [18]

Changes in the direction and speed of climatic variables are likely to impact crops more adversely. Selection of crop varieties adapted to different climates will become increasingly critical. Under these circumstances, control treatments should represent conditions likely to yield favorable results. Stresses need to be combined realistically and representative of agricultural conditions in the region. Measurement of crop biomass, especially for weed-like vegetables that are harvested repeatedly, is preferable to a single terminal reading. Often, trade-offs are hidden and require a series of measurements to be determined. Farmers need to be able to choose seeds adapted to various climates, have access to improved germplasm and irrigation, and receive appropriate agronomic assistance. Improved germplasm cannot

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entirely substitute for an adequate climatic and edaphic environment for crop growth. (Saikia *et al.*, 2024) [13]

Table 1. Comparative evaluation of major strategies and practical constraints.

Strategy	Main opportunity	Limitation to address
Conventional breeding	Combines multiple traits	Time and linkage drag
Genomic selection	Predicts polygenic performance	Training-set transferability
Genome editing	Tests defined regulators	Complex trait interactions
Rootstock grafting	Rapid deployment in preferred scions	Compatibility and cost

6. Comparative evidence, research gaps, and future prospects

Inconsistencies in drought definitions, temperature regimes, crop stages and units of measure make it challenging to compare studies. For example, one study may define tolerance as leaf survival, another as relative yield, and a third as ion exclusion. These endpoints are not interchangeable. Multi-omics data have expanded rapidly, but causal genes are observed less frequently than correlated candidate genes. Meta-analysis would benefit from publicly available phenotypic data associated with genotypes, treatment schedules, and environments. These data should also include replication and handling. Multi-location partnerships should report both average productivity and yield stability in addition to the extent to which their crops are impacted by extreme events. Such reporting would facilitate a move away from overstated claims regarding the improvement of crops and breeding progress. (Gisbert-Mullor *et al.*, 2023) [10]

A pragmatic approach to crop improvement begins with germplasm and risk assessment and is followed by replicated field phenotyping, genotyping, marker or sequence analysis, refinement, crossing or editing, and multiple season selection. In the case of stress treatments, individual exposures should be the norm prior to combined stress. Maintaining product quality should be the objective throughout. In the case of time-of-the-essence needs, grafting or management changes may be used in conjunction with cultivar improvement. Public breeding should prioritize germplasm aligned with locally available seed systems, and assessment under low-input conditions. Future research should address seeds and breeding in a fiscally equitable manner. A technically robust cultivar provides no food security benefit to farmers if they cannot gain access to the seed. (Hubab *et al.*, 2025) [19]

Knowing the local farmers' priorities, a selection index could be developed using relative marketable yield under stress, yield penalty under control conditions, fruit quality and physiological measurements. Factors such as longer breeding cycles and higher risk of rare extreme events should be included in economic analysis. More transparent indices make competing strategies easier to compare and communicate.

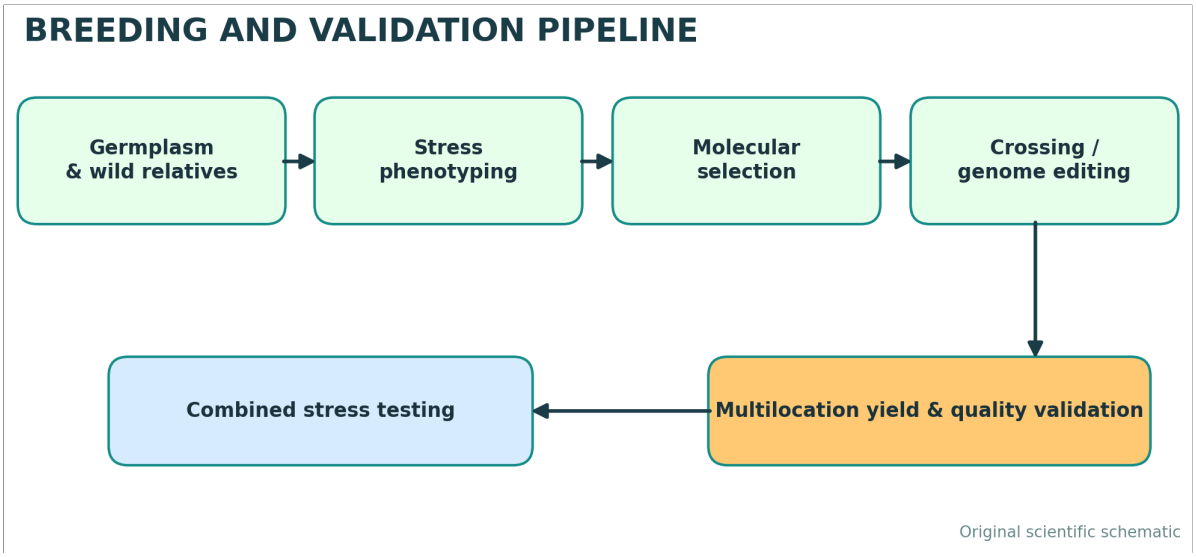


Figure 2. An integrated pipeline for germplasm evaluation, stress phenotyping, genomic improvement, and multilocation validation of climate-resilient vegetables.

Stress memory and recovery research are other frontiers. Plants may withstand an initial stress event and still recover poorly or not at all, resulting in less than optimal or no yield for a prolonged period of time. Repetitive and extreme environmental conditions can enable and accelerate selection for different traits than those traditionally bred. Continuous laboratory or greenhouse treatments for abiotic stresses may not adequately represent field conditions, especially stresses that are not continuous (pulse stresses) and repeatedly intermittent (e.g. episodic stresses). Determining when a plant is stressed (e.g. at peak stress, at the end of stress, or during recovery) is key to identifying damage or repair mechanisms. The ability to measure recovery or stress-induced damage will help support research on avoiding stress-induced damage. Long-term datasets are essential for pepper, tomato, and cucumber, particularly where harvest continues after an initial stress.

The interaction of genetics with resilience of the soil (e.g. soil salinity, organic matter) is another research frontier. A favorable drought-tolerance trait may not protect against oxygen deprivation after flooding.

Preserving genetic diversity is important in any breeding program. Narrow selection for one stress may reduce performance against other stresses. Documented wild relatives and regional germplasm banks, as well as participatory selection, can be of great help. It is important to acknowledge that adaptation is a continuing process. Climate may change, leading to a different stress environment during the growing period. A new range of pests and diseases may attack crops and the

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agricultural production system may be improved. Release materials need to be regularly evaluated to ensure they still meet the criteria of the original selection.

Agronomic and genetic resilience have to be studied together. Mulching, drainage, and irrigation can be used to reduce stress. Genotypes ranked based on performance under one management regime may not be stable under another. It may be helpful to conduct factorial trials with different management regimes. These findings may lead to better recommendations and complementarities. It may also provide a basis for better integration of breeding and agronomy.

There are many constraints to research. Local circumstances affect the level of impact research may have. To better understand the impact research may have, it would be helpful if future research studies explicitly outlined the methods and limits of the research. Local production constraints should be considered when assessing the potential impact of research. It is also important for research to be cost constrained to aid in making responsible farming decisions. More research in this area may help understand the level of impact research may have.

7. Conclusion

Resiliency to varying climates calls for the genetics of adaptation at multiple levels. This includes heat and water tolerance, as well as balance in ion transport, antioxidant levels, and disease resistance. Often these occur in tandem, but efficacy depends on the crop and situation. Trade-offs, however, are to be expected. In the case of improving heat tolerance, for example, decreases in water-use efficiency could occur. Understood through the lens of modern breeding, complementary strategies include conventional and molecular breeding, and the use of wild relatives and genome editing. The key is evidence of stable yield and quality under combined stress conditions. There are a host of options at all levels to test and improve the resiliency of vegetable crops. Integrating multiple strategies including plant breeding with improvement of land, water, and disease management will be critical for implementing climate change mitigation strategies. (Wang *et al.*, 2024) [20]

Additional literature considered for this review is documented in the supplementary reference section: [20] (Park *et al.*, 2025; Ton *et al.*, 2025; Thingujam *et al.*, 2025; Mohammed *et al.*, 2025; Kopeć *et al.*, 2024; Davosir *et al.*, 2025; Abbas *et al.*, 2023; Ackah *et al.*, 2021; Agliassa *et al.*, 2021; Ahmad *et al.*, 2023; Lone *et al.*, 2022; Akcay *et al.*, 2023; Ali *et al.*, 2020; Arafa *et al.*, 2021; Bwambale *et al.*, 2022; Cha *et al.*, 2020; Hanlon *et al.*, 2021; He *et al.*, 2021; Hu *et al.*, 2024; Huang *et al.*, 2022; Ichwan *et al.*, 2022; Istanbuli *et al.*, 2024; Mahmood *et al.*, 2021; Maszkowska *et al.*, 2021; Meng *et al.*, 2023; Meng *et al.*, 2021; Molinari *et al.*, 2020; Mukherjee *et al.*, 2023; Muthusamy *et al.*, 2020; Nawaz *et al.*, 2021; Urbutis *et al.*, 2024; Varshney *et al.*, 2022; Wang *et al.*, 2021; Shaik *et al.*, 2025; Biermann *et al.*, 2025; An *et al.*, 2025; Shen *et al.*, 2025; Kim *et al.*, 2025; Zhang *et al.*, 2024) [21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59]

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