Phenotypic plasticity vs. genetic adaptation in plants under rapid climate change

[1]Praveen Pandey, [2,3,4,5]I. Valentin Petrescu-Mag, [6]Jehanzeb Farooq

[1] Division of Plant Breeding and Genetic Resource Conservation, CSIR - Central Institute of Medicinal and Aromatic Plants, Lucknow, India; [2] Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Cluj-Napoca, Romania; [3] Bioflux SRL, Cluj-Napoca, Romania; [4] Doctoral School of Engineering Science, University of Oradea, Oradea, Romania; [5] WABBA International Bodybuilding and Fitness LTD, London, United Kingdom; [6] Cotton Research Station, AARI, Faisalabad, Pakistan. Corresponding author: J. Farooq, jehanzeb1763@hotmail.com

Abstract. Rapid anthropogenic climate change is reshaping environmental conditions at an unprecedented pace, challenging the capacity of plant populations to persist and adapt. Two fundamental and interconnected processes underpin plant responses to these changes: phenotypic plasticity and genetic adaptation. While phenotypic plasticity enables immediate, within-generation adjustments to environmental variability, genetic adaptation involves heritable changes that determine long-term population persistence. This mini-review synthesizes current theoretical and empirical advances to clarify the dynamic interplay between these processes under rapid and often unpredictable climate change. We examine the conditions under which plasticity is adaptive, maladaptive, or neutral, emphasizing the critical role of environmental predictability, cue reliability, and the temporal scale of stress. Particular attention is given to the mechanisms underlying plastic responses, including emerging evidence on epigenetic regulation, stress priming, and ecological memory, which may extend the influence of plasticity across generations. We further evaluate the costs and limits of plasticity, highlighting context-dependent trade-offs and constraints that can restrict its effectiveness, especially under extreme or fluctuating environments. Building on these insights, we discuss conceptual and methodological advances that distinguish adaptive plasticity from phenotypic noise and genetic change, including reaction norm approaches and selection-based frameworks. Finally, we address a key frontier in plant ecology: the integration of plasticity into predictive models of species responses to climate change. Incorporating reaction norms, trait variability, and eco-evolutionary dynamics into species distribution and vegetation models is essential for improving forecasts of plant persistence, maladaptation, and evolutionary trajectories. Overall, this review emphasizes that phenotypic plasticity and genetic adaptation are not alternative strategies but interacting processes whose balance determines plant responses to rapid environmental change. Understanding when plasticity facilitates persistence, delays adaptation, or contributes to population decline remains central to predicting the future of plant populations in a changing climate.

Keywords: phenotypic plasticity, genetic adaptation, climate change, reaction norms, maladaptation, epigenetics, stress priming, ecological memory, adaptive evolution, plant ecology, species distribution models, eco-evolutionary dynamics.

Introduction. Rapid anthropogenic climate change is imposing unprecedented selective pressures on plant populations by altering temperature regimes, precipitation patterns, and the frequency of extreme events (Oroian et al., 2023; Bordea & Popescu, 2023; Petrescu-Mag et al., 2026). In this context, understanding the mechanisms by which plants respond to environmental change has become a central problem in evolutionary ecology and plant biology (Petrescu-Mag, 2026ab; Bora et al., 2025ab; Oroian et al., 2025). Two primary, yet tightly interconnected, processes underpin these responses: phenotypic plasticity and genetic adaptation (Petrescu-Mag, 2026ab).

Phenotypic plasticity refers to the capacity of a single genotype to produce different phenotypes across varying environmental conditions within an individual’s lifetime (Li et al., 2025; Petrescu-Mag & Proorocu, 2022; Popescu & Papuc, 2025; Gavriloaie, 2023).

This flexibility enables plants to respond immediately to environmental fluctuations through adjustments in morphology, physiology, phenology, and resource allocation (Ashra & Nair, 2022; Laitinen & Nikoloski, 2018; Quevedo-Caraballo & Álvarez-Pérez, 2025). In contrast, genetic adaptation operates across generations, involving heritable changes in allele frequencies that shift population-level trait distributions toward new fitness optima. While plasticity provides a rapid, short-term buffer against environmental variability, genetic adaptation determines long-term population persistence under sustained directional change (Kristensen et al., 2020).

A central challenge in contemporary research is to disentangle when plastic responses are adaptive, effectively tracking shifting environmental optima, and when they are non-adaptive, potentially constraining or misdirecting evolutionary trajectories. Importantly, plasticity and genetic evolution do not represent distinct or sequential processes; rather, they interact dynamically. Plastic responses can modify the strength and direction of natural selection, either facilitating adaptation by maintaining population viability or hindering it by masking genetic variation or producing maladaptive phenotypes (Farooq et al., 2015; Riaz et al 2017).

Under rapid climate change, environmental conditions may exceed the historical range experienced by populations, disrupting the reliability of environmental cues and the correspondence between phenotype and fitness (Parakkasi et al., 2020). Consequently, the effectiveness of plasticity becomes context-dependent, varying with the predictability, magnitude, and temporal structure of environmental change. This raises critical questions regarding the limits of plasticity, its potential costs, and its role in shaping evolutionary responses in increasingly novel and fluctuating environments.

In this mini-review, we synthesize current theoretical and empirical advances to clarify the conditions under which phenotypic plasticity promotes, constrains, or fails to influence adaptive evolution in plants. We further examine the emerging role of epigenetic mechanisms in mediating plastic responses and discuss integrative frameworks that aim to distinguish adaptive plasticity from phenotypic noise and genetic change.

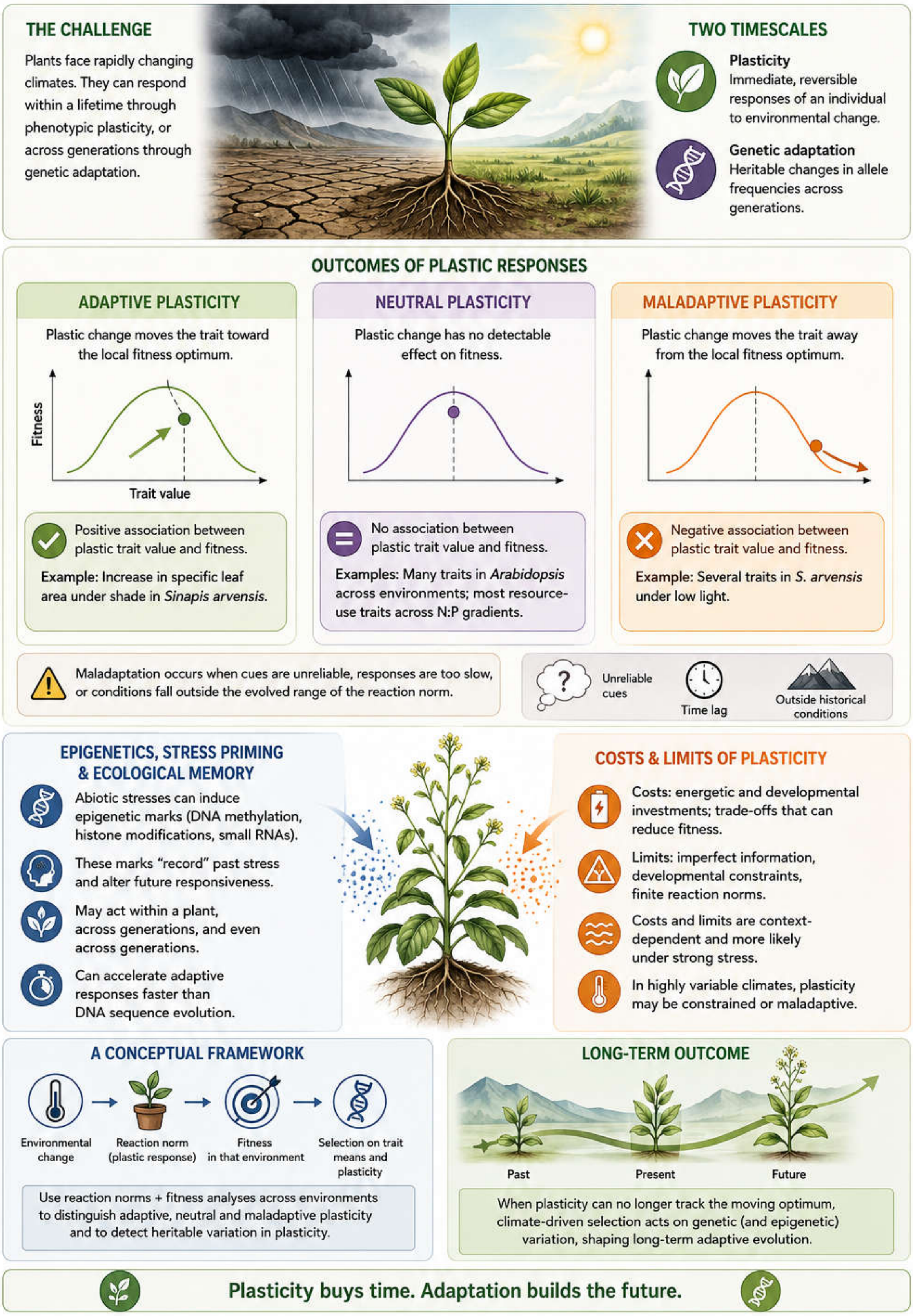
Conceptual Boundary: Where Plasticity Ends and Selection Begins. Plasticity and selection interact rather than forming a sharp boundary. Climate change imposes novel regimes that immediately elicit plastic shifts in phenology, physiology and reproduction, but longer-term persistence depends on evolution of both trait means and plasticity itself (Franks et al., 2013; Nicotra et al., 2010; Matesanz et al., 2010; Scheiner et al., 2019; Schneider et al., 2026).

Adaptive plasticity is defined operationally by within-environment selection analyses: if the plastic trait value is positively associated with fitness under the new condition, plasticity is adaptive; negative associations indicate maladaptive plasticity and non-significant associations point to neutral plasticity (Minden et al., 2023; Steinger et al., 2003; Bonser, 2021; Matesanz et al., 2010). Many empirical studies show that plastic responses to global change drivers are common, but clear demonstrations of adaptive plasticity, especially in complex, novel climates, remain relatively scarce (Matesanz et al., 2010; Franks et al., 2013; Nicotra et al., 2010; Bibi et al., 2024) (Table 1, Figure 1).

Table 1

Examples of adaptive, neutral and maladaptive plasticity

Context / trait	*Outcome of plasticity*	*References*
Specific leaf area under shade in Sinapis arvensis	Increase was favoured; adaptive, yet costly	Steinger et al., 2003
Multiple resource-use traits across N:P gradients	Mostly fitness-neutral; a few traits (chlorophyll content, leaf area, root surface area) consistently adaptive	Minden et al., 2023
Eight traits across environments in *Arabidopsis thaliana*	Trait plasticity largely fitness-neutral; no detectable costs	Shamsid-Deen & Whitney, 2026.



THE CHALLENGE

Plants face rapidly changing climates. They can respond within a lifetime through phenotypic plasticity, or across generations through genetic adaptation.

TWO TIMESCALES

Plasticity Immediate, reversible responses of an individual to environmental change.

Genetic adaptation Heritable changes in allele frequencies across generations.

OUTCOMES OF PLASTIC RESPONSES

ADAPTIVE PLASTICITY

Plastic change moves the trait toward the local fitness optimum.

Positive association between plastic trait value and fitness.

Example: Increase in specific leaf area under shade in *Sinapis arvensis*.

NEUTRAL PLASTICITY

Plastic change has no detectable effect on fitness.

No association between plastic trait value and fitness.

Examples: Many traits in *Arabidopsis* across environments; most resource-use traits across N:P gradients.

MALADAPTIVE PLASTICITY

Plastic change moves the trait away from the local fitness optimum.

Negative association between plastic trait value and fitness.

Example: Several traits in *S. arvensis* under low light.

Maladaptation occurs when cues are unreliable, responses are too slow, or conditions fall outside the evolved range of the reaction norm.

EPIGENETICS, STRESS PRIMING & ECOLOGICAL MEMORY

Abiotic stresses can induce epigenetic marks (DNA methylation, histone modifications, small RNAs).

These marks "record" past stress and alter future responsiveness.

May act within a plant, across generations, and even across generations.

Can accelerate adaptive responses faster than DNA sequence evolution.

COSTS & LIMITS OF PLASTICITY

Costs: energetic and developmental investments; trade-offs that can reduce fitness.

Limits: imperfect information, developmental constraints, finite reaction norms.

Costs and limits are context-dependent and more likely under strong stress.

In highly variable climates, plasticity may be constrained or maladaptive.

A CONCEPTUAL FRAMEWORK

Use reaction norms + fitness analyses across environments to distinguish adaptive, neutral and maladaptive plasticity and to detect heritable variation in plasticity.

LONG-TERM OUTCOME

When plasticity can no longer track the moving optimum, climate-driven selection acts on genetic (and epigenetic) variation, shaping long-term adaptive evolution.

Plasticity buys time. Adaptation builds the future.

Figure 1. Phenotypic plasticity vs genetic adaptation in plants under rapid climate change.

When Does Plasticity Become Maladaptive? Maladaptation emerges when environmental cues cease to predict the selective environment, when response times mismatch stress duration, or when extreme or novel conditions fall outside evolved reaction norms (Nicotra et al., 2010; Matesanz et al., 2010; Chevin & Hoffmann, 2017). Under low light, S. arvensis expressed strong plastic changes in multiple traits, but only increased specific leaf area matched the direction of selection; plasticity in other traits was maladaptive because it shifted phenotypes away from optimal values in that environment (Steinger et al., 2003).

Theoretical and empirical syntheses emphasize that plasticity will not be adaptive when cues are unreliable or when developmental plasticity is too slow or irreversible relative to fluctuating stress, a situation expected under increasingly erratic climates (Matesanz et al., 2010; Chevin & Hoffmann, 2017; Franks et al., 2013). In extreme environments that are rare or confined to marginal habitats, selection on reaction norms is weak; unless genetic correlations link moderate and extreme conditions, plasticity under extremes can be maladaptive or effectively absent (Chevin & Hoffmann, 2017).

Misinterpretation of plasticity is common when plasticity is inferred from fitness or biomass itself: because adaptive plasticity in fitness would require low fitness in some environments, plastic changes in performance traits are rarely adaptive by definition, and their plasticity generally reflects environmental limitation rather than an evolved buffering mechanism (Bonser, 2021).

Epigenetics, Stress Priming, and Ecological Memory. Epigenetic mechanisms provide a key interface between short-term plastic responses and longer-term adaptation. Climate-relevant phenotypes such as flowering time, stress tolerance and resource use show both genetic control and plasticity, with emerging evidence that epigenome-wide changes (e.g. environmentally triggered epialleles) contribute to plastic responses that can arise much faster than DNA sequence evolution (Nicotra et al., 2010; Pozzi et al., 2025; Bibi et al., 2024).

Reviews on stress priming and ecological memory argue that recurrent abiotic stresses induce specific DNA methylation and histone modifications, modulated by hormone signalling and small RNAs, which "record" past stress and alter future responsiveness (Aswathi et al., 2025; Harris et al., 2023; Zhang et al., 2026). These epigenetic marks can underpin somatic memory within a plant, intergenerational carry-over, and, in some cases, transgenerational inheritance, thereby potentially accelerating population-level adaptive trajectories under pulsed or rapidly shifting climates (Aswathi et al., 2025; Harris et al., 2023; Zhang et al., 2026).

Nonetheless, causal links between specific epigenetic modifications, altered gene expression and fitness under recurrent stress remain only partly demonstrated; new "reverse epigenetics" tools are being promoted to test whether particular priming-induced marks truly enhance performance under realistic climate scenarios (Harris et al., 2023; Nicotra et al., 2010; Pozzi et al., 2025).

Hidden Costs and Limits of Plasticity in Fluctuating Environments. Adaptive plasticity is predicted to evolve only when benefits across environments exceed its costs and limits. Costs include energetic or developmental investments in sensory and regulatory machinery, or pleiotropic trade-offs that reduce fitness when plasticity is expressed, even if trait values are held constant statistically (Schneider, 2022; Steinger et al., 2003; Auld et al., 2010; Scheiner et al., 2019; Matesanz et al., 2010). Limits reflect imperfect matching between phenotype and environment due to genetic, developmental or information constraints (Schneider, 2022; Matesanz et al., 2010; Auld et al., 2010).

Empirical evidence for direct fitness costs is mixed. In S. arvensis, families with higher plasticity in specific leaf area had lower fitness than less plastic families under low light after controlling for trait values, indicating a real cost of plasticity that was environment-dependent (Steinger et al., 2003). In contrast, a multi-environment Arabidopsis study detected no costs and no strong link between trait plasticity and seed output, suggesting widespread fitness-neutral plasticity in that setting (Shamsid-Deen & Whitney, 2026). A multi-species nutrient experiment found that plasticity costs appeared mainly under phosphorus variation, again highlighting that costs are context-specific and more likely where stress strongly reduces fitness (Minden et al., 2023).

At a broader scale, meta-analytic work shows that plasticity increases with climatic variability only for some trait classes (e.g. allocation), and that physiological plasticity can be limited under cold stress, suggesting that stressful conditions may constrain rather than promote plasticity (Stotz et al., 2021; Matesanz et al., 2010; Chevin & Hoffmann, 2017). Reviews of costs and limits warn that statistical collinearity between trait means and plasticities often obscures cost estimates, and that many putative "costs" may instead reflect underlying limits in the ability to track rapid or irregular fluctuations (Auld et al., 2010; Schneider, 2022; Chevin & Hoffmann, 2017).

Towards a Conceptual Framework: Separating Adaptive Plasticity from Phenotypic Noise. Several conceptual and methodological advances help distinguish adaptive plasticity from non-adaptive "noise" and from genetic adaptation. Random regression mixed models allow reaction norms to be estimated across continuous climatic gradients, separating population-level responses from among-genotype variation in slopes and curvatures, thus exposing heritable variation in plasticity itself (Arnold et al., 2019; Schneider et al., 2026; Franks et al., 2013). Selection analyses within each environment then reveal whether observed plastic shifts align with local fitness optima (adaptive), oppose them (maladaptive), or have no detectable fitness consequences (neutral) (Minden et al., 2023; Steinger et al., 2003; Bonser, 2021; Matesanz et al., 2010).

Theoretical work on the genetics of plasticity under climate change shows that evolving plasticity can enhance persistence when not too costly, but that its benefit depends on the magnitude of plastic responses relative to environmental change and on the rate at which new genetic variation for plasticity arises (Scheiner et al., 2019; Schneider, 2022; Chevin & Hoffmann, 2017). Global-change focused reviews emphasize that adaptive plasticity has been best documented in simple, single-factor manipulations, whereas under realistic, multifactorial and fluctuating climates much plasticity remains untested for adaptive value and may be neutral or even maladaptive (Matesanz et al., 2010; Nicotra et al., 2010; Franks et al., 2013; Fox et al., 2019; Bibi et al., 2024).

In this integrated view, plasticity "ends" and selection "begins" where reaction norms systematically fail to keep phenotypes close to the moving optimum, either because cues are unreliable, environments lie outside historical variation, or costs and limits restrict further plastic evolution. Under such conditions, climate-driven selection increasingly acts on standing and newly generated genetic (and possibly epigenetic) variation for both trait means and plasticities, shaping the longer-term adaptive landscape of plant populations (Nicotra et al., 2010; Franks et al., 2013; Scheiner et al., 2019; Pozzi et al., 2025; Zhang et al., 2026).

While these frameworks improve our ability to classify plastic responses, a critical next step is to integrate such insights into predictive models capable of forecasting plant responses under ongoing climate change.

Predicting Plant Responses: Integrating Plasticity into Climate Change Models. A major frontier in plant evolutionary ecology is not only to describe phenotypic plasticity and genetic adaptation, but to incorporate these processes into predictive frameworks capable of forecasting plant responses to ongoing climate change. Despite substantial advances in documenting plastic responses across traits and environments, most large-scale ecological and distribution models still rely on static trait values or assume fixed species niches, thereby underestimating the dynamic nature of plant responses.

Species distribution models (SDMs) and dynamic global vegetation models (DGVMs) traditionally treat species as ecologically invariant entities, implicitly assuming that observed trait–environment relationships remain constant under future climates. However, phenotypic plasticity can decouple instantaneous phenotype–environment relationships from long-term genetic adaptation, allowing individuals to persist temporarily in conditions that would otherwise be outside their realized niche. As a result, models that ignore plasticity may overestimate extinction risk in the short term, while simultaneously underestimating the potential for maladaptive persistence or delayed evolutionary responses.

Recent efforts aim to integrate plasticity explicitly into predictive models by incorporating reaction norms, trait variability, and environment-dependent performance functions. Reaction norm approaches allow trait values to vary continuously along environmental gradients, providing a more realistic representation of how plants respond to fluctuating and novel conditions. When combined with fitness landscapes, these models can distinguish whether plastic responses track shifting optima or generate mismatches that reduce population viability.

A key challenge lies in scaling from individual-level plastic responses to population and community-level dynamics. Plasticity can buffer populations against environmental change, effectively "buying time" for genetic adaptation, but this buffering capacity depends on the magnitude, reversibility, and costs of plastic responses. In highly variable or unpredictable climates, plasticity may instead increase demographic instability, particularly when environmental cues are unreliable or when response lags exceed the temporal scale of stress events.

Another emerging direction involves coupling eco-evolutionary models with epigenetic dynamics. Incorporating mechanisms such as stress-induced epigenetic memory or transgenerational effects may improve predictions of short-term population resilience under pulsed environmental stress. However, empirical parameterization remains limited, and the persistence and reversibility of epigenetic marks under natural conditions are still insufficiently quantified for robust model integration.

Ultimately, improving predictive accuracy requires integrative frameworks that combine plasticity, genetic variation, demographic processes, and environmental heterogeneity. Such models must account not only for mean trait values, but also for variance, covariance, and the capacity for plastic and evolutionary change. Bridging empirical studies with modeling approaches will be essential for identifying when plasticity enhances persistence, when it delays adaptation, and when it contributes to population decline under rapid climate change.

Conclusions. This mini-review consolidates current knowledge on the diversity, adaptive strategies, and functional significance of extremophilic organisms, highlighting their relevance as model systems for understanding the limits of life. By integrating physiological, molecular, and ecological perspectives, it becomes evident that extremophiles are not merely biological curiosities, but key contributors to fundamental and applied scientific domains.

One of the central insights emerging from this work is the remarkable convergence of adaptive mechanisms across phylogenetically distant taxa. Whether through membrane restructuring, protein stabilization, osmolyte accumulation, or highly specialized metabolic pathways, extremophiles demonstrate that evolutionary innovation is both constrained by physicochemical limits and remarkably flexible in its execution. These adaptations underline the importance of studying life under extreme conditions as a means to refine our understanding of evolutionary processes and biochemical resilience.

Furthermore, the ecological roles of extremophiles extend beyond survival in isolated niches. Many of these organisms actively shape their environments, participating in biogeochemical cycles under conditions previously thought to be incompatible with sustained biological activity. This has significant implications for ecosystem functioning, particularly in extreme or rapidly changing habitats, and suggests that their contribution to global processes may be underestimated.

From an applied perspective, extremophiles represent a valuable reservoir of biomolecules with exceptional stability and efficiency. Enzymes derived from these organisms continue to drive innovation in biotechnology, industrial processes, and environmental remediation. In addition, their study provides critical insights for astrobiology, expanding the framework for identifying potentially habitable environments beyond Earth.

Finally, despite substantial progress, several gaps remain. Future research should prioritize integrative omics approaches, in situ studies, and the exploration of under-investigated extremophilic systems. Particular attention should be given to the interplay between genetic isolation, environmental pressures, and microevolutionary dynamics, especially in spatially fragmented habitats such as cave systems or hypersaline basins.

As a final remark, extremophiles challenge traditional paradigms of habitability and biological function. Their study not only broadens the conceptual boundaries of life but also offers tangible benefits across multiple scientific and technological disciplines. Continued interdisciplinary research will be essential for fully unlocking their potential and for advancing our understanding of life in its most resilient forms.

Acknowledgements. OpenAI ChatGPT-5.3 - https://openai.com - was used for plate editing. An AI-powered search engine for research - https://consensus.app – Consensus NLP, Inc – was used to summarize data in a table.

Authors Contributions. IVPM wrote the manuscript; PP and JF read and revised the manuscript.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This research received no external funding.

References

Arnold, P., Kruuk, L., & Nicotra, A. (2019). How to analyse plant phenotypic plasticity in response to a changing climate. *The New Phytologist, 222(3)*, 1235-1241.

Ashra, H., & Nair, S. (2022). Review: Trait plasticity during plant-insect interactions: From molecular mechanisms to impact on community dynamics. *Plant Science: An International Journal of Experimental Plant Biology 317*, 111188.

Aswathi, K., Ul-Allah, S., Puthur, J., Siddique, K., Frei, M., & Farooq, M. (2025). The plant mind: unraveling abiotic stress priming, memory, and adaptation. *Physiologia Plantarum, 177*(4), e70372.

Auld, J., Agrawal, A., & Relyea, R. (2010). Re-evaluating the costs and limits of adaptive phenotypic plasticity. *Proceedings of the Royal Society B: Biological Sciences, 277*, 503-511.

Bibi, Z., Maqsood, M., Idrees, A., Rafique, H., Butt, A., Ali, R., Arif, Z., & Nabi, M. (2024). Exploring the role of phenotypic plasticity in plant adaptation to changing climate: A review. *Asian Journal of Research in Crop Science, 9*(1), 1-9.

Bonser, S. (2021). Misinterpreting the adaptive value of phenotypic plasticity in studies on plant adaptation to new and variable environments. *Plant Biology 23*, 683-685.

Bora, F. D., Rusu, T., Popescu, M., Coroian, C. O., & Petrescu-Mag, I. V. (2025a) Extremotolerant pioneer species for cold, arid, oligotrophic, low-pressure environments. *ELBA Bioflux, 17*(1), 15-21.

Bora, F. D., Rusu, T., Popescu, M., Petrescu-Mag, I. V., Păsărin, B., Dăescu, A. M., & Oroian, I. G., (2025b). Shade-tolerant plants and their adaptation to low-light environments. *ELBA Bioflux, 17*(1), 22-27.

Bordea, D., & Popescu, M. (2023). The impact of climate change on plant physiology and adaptation mechanisms. *AAB Bioflux, 15*(2), 135-139.

Chevin, L., & Hoffmann, A. (2017). Evolution of phenotypic plasticity in extreme environments. *Philosophical Transactions of the Royal Society B: Biological Sciences, 372*(1723), 20160138.

Farooq, J., Mahmood, K., Waseem akram, M., Rehman, A. U., Javaid, M. I., Petrescu-Mag, I. V., & Nawaz, B. (2015). High temperature stress in cotton *Gossypium hirsutum* L. *ELBA Bioflux, 7*(1), 34-44.

Fox, R., Donelson, J., Schunter, C., Ravasi, T., & Gaitán-Espitia, J. (2019). Beyond buying time: the role of plasticity in phenotypic adaptation to rapid environmental change. *Philosophical Transactions of the Royal Society B, 374*(1768), 20180174.

Franks, S., Weber, J., & Aitken, S. (2013). Evolutionary and plastic responses to climate change in terrestrial plant populations. *Evolutionary Applications, 7*, 123-139.

Gavriloaie, C. (2023). The contribution of the diversity of Poeciliid fishes and their genetic plasticity to the development of the aquarium hobby and the aquarium market. *Poeciliid Research, 13*(1), 1-8.

Harris, C., Amtmann, A., Ton, J., Springer, N., & Saze, H. (2023). Epigenetic processes in plant stress priming: Open questions and new approaches. *Current Opinion in Plant Biology, 75*, 102432.

Kristensen, T. N., Ketola, T., & Kronholm, I. (2020). Adaptation to environmental stress at different timescales. *Annals of the New York Academy of Sciences*, *1476*(1), 5-22.

Laitinen, R., Nikoloski, Z., (2018): Genetic basis of plasticity in plants. *Journal of Experimental Botany, 70*(3), 739-745.

Li, P., An, Z., Xu, N., Li, J., Li, Q., He, C. (2025). Phenotypic plasticity and stability in plants: Genetic mechanisms, environmental adaptation, evolutionary implications, and future directions. *Plant, 48*, 5847-5860.

Matesanz, S., Gianoli, E., & Valladares, F. (2010). Global change and the evolution of phenotypic plasticity in plants. *Annals of the New York Academy of Sciences, 1206*: 35-55.

Minden, V., Verhoeven, K., & Venterink, H. (2023). Adaptive plasticity and fitness costs of endangered, nonendangered, and invasive plants in response to variation in nitrogen and phosphorus availabilities. *Ecology and Evolution, 13*, e10075

Nicotra, A., Atkin, O., Bonser, S., Davidson, A., Finnegan, E., Mathesius, U., Poot, P., Purugganan, M., Richards, C., Valladares, F., & Kleunen, M. (2010). Plant phenotypic plasticity in a changing climate. *Trends in Plant Science, 15(12)*, 684-692.

Oroian, C., Balint, C., Popescu, M., Bora, F. D., Petrescu-Mag, I. V., Rusu, T., Voicu, D. (2025). Evolutionary compatibility in lichen symbiosis. *ELBA Bioflux, 17*(1), 41-47.

Oroian, F. C., Kovacs, E., Bora, F. D., Popescu, M. (2023). Adapting agricultural crops to new regional climates post-climate change. *AAB Bioflux, 15*(2), 115-121.

Parakkasi, P., Rani, C., Syam, R., Zainuddin, Achmad, M. (2020). Growth response and quality of seaweed *Kappaphycus alvarezii* cultivated in various coastal ecosystems in the waters of West Sulawesi, Indonesia. *AACL Bioflux, 13*(2), 627-639.

Petrescu-Mag, I. V. (2026a). Rapid reorganization of plant communities in geological time: context for anthropocene vegetation change. *Studia Universitatis Vasile Goldiș Seria Științele Vieții, Vol.36*. (in press).

Petrescu-Mag, I. V. (2026b). How animals shape plant evolution: an ecological and evolutionary synthesis. *Analele Universităţii din Oradea, Fascicula Biologie* (in press).

Petrescu-Mag, I. V., & Proorocu, M. (2022). Sex chromosomes and genetic plasticity in Poeciliid fishes. *Poeciliid Research, 12*(1), 14-16.

Petrescu-Mag, R. M., Petrescu, D. C., Rastegari, H., Ivan, A., & Petrescu-Mag, I. V. (2026). Climate change boredom: Exploring its predictors and the psychological factors that influence intention to act. *PLoS One, 21*(5): e0348574.

Popescu, M., & Papuc, T. (2025). Behavioural plasticity in female colour preference induced by diet cues in *Poecilia reticulata*. *Poeciliid Research* *15*(1), 1-3.

Pozzi, C., Gaiti, A., & Spada, A. (2025). Climate change and plant genomic plasticity. *TAG. Theoretical and Applied Genetics. Theoretische Und Angewandte Genetik, 138*, 231

Riaz, M., Farooq, J., Scheffler, J. A., Ayoub, M., Chattha, W. S., & Ahmad, S. (2017). Assessment of genetic variation against CLCuD in introduced USDA cotton germplasm. *ELBA Bioflux, 9*(1), 1-8.

Quevedo-Caraballo, S., & Álvarez-Pérez, S. (2025). The role of phenotypic plasticity and within-environment trait variability in the assembly of the nectar microbiome and plant–microbe–animal interactions. *Ecology and Evolution, 15*: e71059.

Scheiner, S., Barfield, M., & Holt, R. (2019). The genetics of phenotypic plasticity. XVII. Response to climate change. *Evolutionary Applications, 13*, 388-399.

Schneider, H. (2022). Characterization, costs, cues and future perspectives of phenotypic plasticity. *Annals of Botany, 130*, 131-148.

Schneider, R., Bäurle, I., Nikoloski, Z., & Lenhard, M. (2026). Plant phenotypic plasticity: From molecular mechanisms to breeding and climate change adaptation. *Annual Review of Plant Biology*, *77*:707-731.

Shamsid-Deen, M., & Whitney, K. (2026). Phenotypic plasticity in *Arabidopsis thaliana* is fitness-neutral, and costs are lacking across experimental environments. *Ecology and Evolution, 16*(4), e73427.

Steinger, T., Roy, B., Roy, B., & Stanton, M. (2003). Evolution in stressful environments II: adaptive value and costs of plasticity in response to low light in *Sinapis arvensis*. *Journal of Evolutionary Biology, 16*(2), 313-323.

Stotz, G., Salgado-Luarte, C., Escobedo, V., Valladares, F., & Gianoli, E. (2021). Global trends in phenotypic plasticity of plants. *Ecology Letters, 24*, 2267-2281.

Zhang, J., Song, M., Zhang, L., Tian, W., Guo, B., Zhou, S., & Ma, C. (2026). Ecological memory in plants: Epigenetic integration of abiotic stress and climate change. *Plants, 15*(4), 534.

Received: 15 April 2026. Accepted: 01 June 2026. Published online: 01 June 2026.

Authors:
Praveen Pandey (PP), Division of Plant Breeding and Genetic Resource Conservation, CSIR - Central Institute of Medicinal and Aromatic Plants, Lucknow-226015, India, e-mail: pandeypraveen1986@yahoo.com
Ioan Valentin Petrescu-Mag (IVPM), Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Calea Mănăștur street, 400372 Cluj-Napoca, Romania, e-mail: ioan.mag@usamvcluj.ro
Jehanzeb Farooq (JF), Cotton Research Station, AARI, Faisalabad, Pakistan, e-mail: jehanzeb1763@hotmail.com

How to cite this article:
Pandey P., Petrescu-Mag I. V., Farooq J., 2026 Phenotypic plasticity vs. genetic adaptation in plants under rapid climate change. AES Bioflux 18(1):49-57.