

Integrative Plant Systems Biology: Linking Physiology, Metabolism, Ecology, and Biotechnology for Climate-Resilient Crop Improvement

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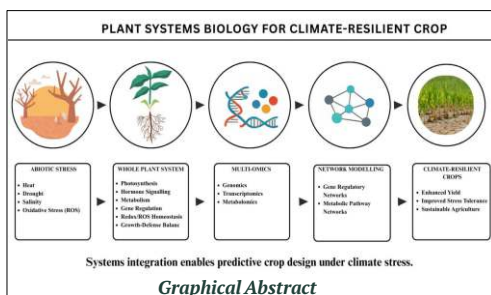
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Abstract

Rapidly advancing climate change is altering plant growth environments with concomitant heat, drought, salinity, and oxidative stresses, compromising crop productivity and ecosystem function alike. These constraints disturb feedback of a network of networks to the regulation of photosynthesis, carbon allocation, hormone signalling, metabolism, and adjustments between plant-environment interactions. Conventional gene-centred improvement approaches are not effective in handling the systemic and multiscale character of plant stress response. Therefore, a conceptual change to integrative plant systems biology is needed. Here, we compile how integrating molecular control, physiological organization, ecological dynamics, and biotechnological advances in simple systems could facilitate the predictive design of crops. Integration of multi-omics and network reconstruction uncovers how gene regulatory circuits, metabolic fluxes, and redox signaling together control growth–defense tradeoffs in response to environmental stress. Ecological and evolutionary considerations also illustrate how gene duplications, network rewiring, and plant–microbe interactions mediate adaptive capacity along environmental gradients. We emphasize emerging predictive strategies to consider genotype × environment × management interactions as a way to shift crop improvement from empirical selection toward system-guided optimization. These include advanced analytics and predictive design at the genome scale, where the emphasis is on network-level knowledge of DNA rather than individual genes. Ecosystem and sustainability principles must be embedded in engineered traits such that they can perform within complex agroecosystems. Through the integration of predictive multi-omics approaches to plant and crop biology, in combination with physiology, metabolism, ecology, and biotechnology, plant systems biology also offers a conceptual framework for the development of climate-resilient crops that can sustainably feed global populations in an increasingly harsh environment.

Keywords: Climate change, Abiotic stress (heat, drought, salinity, oxidative stress), Plant systems biology, Multi-omics integration, Gene regulatory networks, Metabolic flux, Redox signaling, Photosynthesis regulation, Carbon allocation, Hormone signaling.



1. Introduction

Plants serve as the primary interface between the biosphere and atmosphere, sustaining terrestrial life through photosynthesis, carbon capture, nutrient cycling, and ecosystem stability, while crop plants are central to global food security as sources of nutrients, industrial raw materials, and renewable energy (1,2). Beyond agriculture, plants regulate climate, support soil formation, maintain

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hydrological cycles, and preserve biodiversity, making them essential for ecological and economic stability; however, their productivity is increasingly threatened by climate change (3). Rising temperatures, altered precipitation, elevated CO₂, and frequent extreme events impose multiple simultaneous stresses such as drought, heat, salinity, and oxidative stress, which disrupt photosynthesis, metabolism, and plant development, while also intensifying pest and pathogen pressures, leading to yield instability (4). Importantly, plant responses to these stresses are governed by highly integrated molecular, physiological, and ecological networks rather than isolated pathways (5). Traditional crop improvement approaches, including phenotypic selection and gene-centric methods, have achieved significant gains but are limited in addressing complex, multifactorial stress conditions (6). Traits like stress tolerance and metabolic plasticity arise from interconnected regulatory systems spanning multiple biological scales, necessitating a shift from reductionist to systems-level approaches (7,8). Plant systems biology provides this framework by integrating multi-omics technologies with computational modeling and network analysis to understand plants as interconnected systems (9). This approach enables identification of key regulatory hubs, feedback mechanisms, and metabolic constraints governing growth, stress responses, and adaptation, while linking genotype to phenotype across dynamic environments (10). Since plant function operates across hierarchical levels from genes and metabolism to physiology, communities, and ecosystems environmental signals trigger cascading responses that influence resource allocation, development, and productivity (11,12). Advances in phenotyping, big-data analytics, and artificial intelligence now make such multi-scale integration feasible, offering new opportunities to enhance crop resilience and sustainability under changing climatic conditions. Biotechnological innovations further amplify the translational potential of systems biology. Precision genome editing tools, including CRISPR-based technologies, enable targeted modification of genes and regulatory elements identified through network analyses (13). Metabolic engineering and synthetic biology approaches allow the redesign of biochemical pathways to enhance stress tolerance, nutrient content, and yield stability. When combined with ecological insights and predictive modeling, these tools facilitate rational crop design rather than empirical trait selection (14). Such integration is central to developing climate-resilient crops capable of maintaining productivity under environmental uncertainty. Despite remarkable progress in individual domains of physiology, metabolism, ecology, and biotechnology, these disciplines often remain fragmented. A comprehensive framework that explicitly links these dimensions is essential for advancing climate-smart agriculture. Integrative plant systems biology seeks to unify mechanistic understanding with ecological context and technological application, fostering interdisciplinary collaboration and data-driven innovation (15).

This review synthesizes current advances in integrative plant systems biology and examines how linking physiological regulation, metabolic networks, ecological dynamics, and biotechnological interventions can accelerate climate-resilient crop improvement. We first outline the conceptual foundations and methodological platforms underpinning systems-based plant research. We then explore the regulation of plant physiology and metabolism under environmental stress, highlighting network-level adaptations. Subsequently, we discuss ecological and evolutionary drivers of plant resilience, computational modeling strategies, and emerging biotechnological tools for crop engineering. Finally, we consider translational pathways, policy implications, and future research priorities necessary for sustainable agricultural systems. In the context of accelerating climate change and a rapidly growing global population, advancing integrative plant systems biology is not merely a scientific endeavor but a strategic necessity. By embracing systems-level thinking and cross-disciplinary integration, plant science can transition from reactive stress mitigation to predictive and design-oriented crop development, ensuring agricultural stability and ecological sustainability in an uncertain future.

2. Foundations of Plant Systems Biology

Plant systems biology represents a paradigm shift in plant research, transitioning from reductionist approaches toward integrative frameworks that capture the dynamic complexity of biological systems. Unlike traditional methodologies that examine individual genes or pathways in isolation, systems biology seeks to understand how molecular components interact within regulatory, metabolic, and ecological networks to produce emergent plant traits (16). This holistic perspective is particularly essential in the context of climate change, where plant responses arise from coordinated multi-level interactions rather than single-gene effects (17). Plant function is inherently multiscale, spanning hierarchical levels of biological organization from genes and proteins to cells, tissues, organs, whole organisms, communities, and ecosystems. Environmental signals perceived at the molecular level propagate through signaling cascades and transcriptional networks, reshaping metabolic fluxes and physiological outputs that ultimately determine growth, reproduction, and survival. Systems biology integrates these scales to decipher how genotype translates into phenotype under dynamic environmental conditions (18).

2.1 Concept of Systems Biology in Plant Science

Plant systems biology is built on three core principles: integration, interaction, and prediction, which together enable a comprehensive understanding of plant function. Integration involves combining diverse datasets such as genomic sequences, gene expression profiles, protein interactions, metabolite levels, and phenotypic traits into unified frameworks, allowing a shift from descriptive to mechanistic analysis (19).

Interaction emphasizes that plant traits arise from complex, interconnected networks involving gene regulation, metabolism, hormonal signaling, and environmental feedback, where processes such as carbon metabolism, nitrogen assimilation, and stress responses are tightly coordinated rather than operating in isolation (20).

Prediction, a key feature of systems biology, uses computational modeling and network reconstruction to simulate plant responses, identify regulatory hubs, and forecast phenotypic outcomes, supporting rational crop design and climate adaptation strategies (21). This approach extends across multiple biological scales, from molecular to ecosystem levels, linking gene regulatory networks and protein interactions with metabolic fluxes, physiological processes like photosynthesis and nutrient uptake, and ultimately plant performance and ecosystem dynamics (22). Climate change impacts operate across these scales simultaneously; for example, drought influences cellular signaling, physiological responses, whole-plant carbon allocation, and ecological interactions, highlighting the need for integrated, multiscale analysis (23). Central to this framework is the network-based view of plant function, where genes, proteins, metabolites, and traits are interconnected as nodes within regulatory and metabolic systems. Network analysis enables identification of key hubs, bottlenecks, and functional modules that control stress tolerance and productivity, revealing emergent properties such as robustness and adaptability that cannot be understood through single-gene approaches (24,25).

2.2 Omics Platforms Driving Plant Systems Research

High-throughput omics technologies have become central to plant systems biology by generating comprehensive datasets across multiple layers of biological regulation.

Table 1: Overview of major omics platforms highlighting biological level, key outputs, climate-resilience applications, and main limitations in plant systems biology.

Platform	Level	Output	Application (Climate)	Limitation
Genomics	DNA	SNPs, variants	Adaptive genes, genome editing	Complex genomes
Transcriptomics	RNA	Gene expression	Stress gene discovery	Time-dependent changes
Proteomics	Protein	Protein abundance, PTMs	Signaling & enzyme control	Low coverage
Metabolomics	Metabolites	Primary/secondary compounds	Stress biomarkers	Chemical instability
Phenomics	Whole plant	Traits	Genotype–phenotype link	Environmental noise
Epigenomics	Chromatin	DNA methylation	Stress memory	Context dependent
Metagenomics	Microbiome	Microbial diversity	Microbiome resilience	Environmental variation

3. Regulation of Plant Physiology and Metabolism

Plant survival, productivity, and resilience depend on tightly coordinated physiological and metabolic processes that regulate energy capture, allocation, and utilization through interconnected networks rather than isolated reactions. Photosynthesis, respiration, and metabolic fluxes are dynamically controlled by environmental signals, developmental cues, and stress conditions, making systems-level understanding essential for improving crop performance under climate variability (34). Photosynthesis drives plant productivity by converting solar energy into chemical energy, with its efficiency influenced by factors such as temperature, light, water availability, and atmospheric

Genomics provides the foundational blueprint by decoding genome sequences and identifying genetic variation linked to adaptive traits, supporting genome-wide association studies and network reconstruction (26).

Transcriptomics captures global gene expression patterns under developmental and stress conditions, enabling identification of regulatory networks and stress-responsive genes (27). Proteomics adds a functional layer by analyzing protein abundance, modifications, and interactions, offering insights into signaling pathways beyond transcript levels (28). Metabolomics links molecular activity to phenotype by profiling small molecules involved in primary and secondary metabolism, revealing metabolic reprogramming under stress (29). Phenomics integrates imaging and sensor-based technologies to quantify plant traits such as growth, biomass, and stress responses at the field scale, bridging molecular data with real-world performance (30). While each omics layer provides valuable information, their integration is essential for a systems-level understanding of plant biology. However, challenges such as data heterogeneity, differences in scale, computational demands, and lack of standardization limit effective integration (31). Advances in machine learning, network modeling, and cloud-based platforms are overcoming these barriers by enabling multidimensional data analysis, predictive modeling, and accelerated gene discovery (32). Integrative databases and digital platforms further support data sharing and reproducibility, allowing reconstruction of complex regulatory networks. The convergence of multi-omics and computational tools is transforming plant science from fragmented analysis to predictive, systems-level frameworks, providing a strong foundation for improving crop resilience and productivity (33).

CO₂ (35). At the molecular level, coordinated regulation of photosystems, electron transport chains, and the Calvin–Benson cycle, along with factors like Rubisco activity, chlorophyll stability, and membrane organization, determines carbon fixation efficiency (36). Under stress, especially heat and drought, photosynthesis is impaired, leading to reduced carbon assimilation and increased reactive oxygen species, which plants counter through antioxidant systems, non-photochemical quenching, and stomatal adjustments (37). Respiration complements photosynthesis by generating ATP and reducing power, with mitochondrial pathways closely linked to carbon metabolism and redox balance (38).

During stress, respiratory pathways are reprogrammed, and mechanisms such as the alternative oxidase pathway help maintain electron flow and reduce oxidative damage (39). Energy regulation is further controlled by central sensors like TOR and SnRK1, where TOR promotes growth under favorable conditions, and SnRK1 activates stress-responsive, catabolic pathways during energy limitation, integrating nutrient, carbon, and stress signals to balance growth and defense (40–42). Climate change further impacts this energy balance by increasing photorespiration at higher temperatures and altering carbon assimilation under elevated CO₂, highlighting the importance of systems-level modeling to optimize carbon-use efficiency and maintain yield stability under changing environmental conditions (43).

3.1 Primary and Secondary Metabolism Networks

Plant metabolism consists of interconnected primary and secondary pathways that collectively support growth, development, and environmental adaptation. Primary metabolism, including carbohydrate metabolism (glycolysis and TCA cycle), nitrogen assimilation, lipid biosynthesis, and amino acid synthesis, provides energy, reducing power, and essential cellular components, with tight coordination between carbon and nitrogen metabolism determining biomass accumulation and nutrient-use efficiency (44). Under stress conditions, these pathways are dynamically reprogrammed; for example, drought promotes the accumulation of osmoprotectants such as proline and soluble sugars, while heat stress alters membrane lipid composition to maintain stability, reflecting metabolic plasticity. Systems-level analyses, including flux balance and isotope-labeling studies, show that these pathways function as integrated networks where disturbances in one pathway affect overall energy balance and redox homeostasis, enabling identification of key metabolic bottlenecks (45). Secondary metabolism, involving compounds such as phenolics, flavonoids, alkaloids, terpenoids, and glucosinolates, plays essential roles in defense, signaling, and stress tolerance, often induced by environmental stress through hormonal pathways like jasmonic acid, salicylic acid, and abscisic acid (46,47). These pathways are closely linked to primary metabolism through shared precursors, such as the phenylpropanoid pathway derived from phenylalanine, and reflect a dynamic trade-off between growth and defense (48,49). At the network level, plant metabolism exhibits modular organization, feedback regulation, and redundancy, ensuring robustness under fluctuating conditions. Integration of multi-omics data has enabled the development of genome-scale metabolic models that predict flux redistribution and guide metabolic engineering, emphasizing that enhancing stress tolerance without yield loss requires coordinated reprogramming of metabolic networks rather than modification of individual genes (50).

3.2 Hormonal Signaling and Growth Regulation

Plant hormones act as central integrators of environmental signals and developmental programs, coordinating growth, metabolism, and defense through interconnected signaling networks rather than independent pathways (51). Key hormones, including auxins, cytokinins, gibberellins (GAs), abscisic acid (ABA), ethylene, jasmonates (JA), salicylic acid (SA), and brassinosteroids, regulate processes such as cell division, elongation, organ formation, and stress adaptation via tightly controlled transcriptional and signaling mechanisms (52,53). Hormonal cross-talk is essential for balancing plant responses; for example, ABA suppresses GA-driven growth during drought, JA and SA interact to regulate defense against pathogens, and auxin–cytokinin balance determines root–shoot architecture (54,55). These interactions form dynamic regulatory hubs embedded within broader metabolic and gene networks, enabling plants to efficiently allocate resources under changing environmental conditions (56). A critical outcome of this integration is the growth–defense trade-off, where favorable conditions promote growth through anabolic pathways and TOR signaling, while stress activates energy-sensing pathways such as SnRK1, shifting metabolism toward defense responses often mediated by ABA and JA (57,58). Understanding and manipulating these hormonal networks allows targeted improvement of stress tolerance while maintaining yield stability, with genome editing of key signaling components offering promising strategies for developing climate-resilient crops (59).

3.3 Stress Physiology and Metabolic Plasticity

Plants exposed to climate change face multiple simultaneous stresses, and their survival depends on physiological resilience and metabolic plasticity, the ability to dynamically reconfigure biochemical pathways in response to environmental changes (60). Abiotic stresses such as drought, heat, and salinity disrupt water balance, membrane stability, and redox homeostasis, but plants counter these effects through coordinated responses including stomatal closure, accumulation of osmolytes like proline and soluble sugars, and activation of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidases, along with heat shock proteins and membrane lipid remodeling to maintain cellular integrity (61). Stress conditions also elevate reactive oxygen species (ROS), which, although harmful at high levels, function as signaling molecules that interact with hormonal pathways, calcium signaling, and transcription factors to regulate adaptive responses, making ROS central integrators of stress signaling networks (62). Metabolic plasticity enables redistribution of carbon and nitrogen resources, such as increased synthesis of osmoprotectants during drought, activation of defense-related pathways like phenylpropanoid metabolism during pathogen attack, and lipid adjustments under temperature stress, with genome-scale metabolic models showing coordinated flux changes that maintain energy balance and redox homeostasis (63–65).

Additionally, plants develop stress memory through epigenetic and metabolic changes, allowing faster and stronger responses to recurring stress, a process known as priming (66). From a systems biology perspective, stress adaptation involves integrated regulation of gene networks, metabolic pathways, and signaling systems, and identifying key regulatory hubs and interactions enables the development of crops with enhanced resilience while maintaining growth and productivity under changing environmental conditions (67,68).

Table 2: Summary of major stress-responsive metabolic and regulatory pathways showing their stress context, functional role in plant stress tolerance, and potential targets for crop improvement

Pathway	Stress	Role	Improvement Target
Calvin Cycle	Heat, drought	Carbon fixation	↑ Photosynthesis (69)
Photorespiration	High temp	Redox balance	Yield enhancement (70)
TCA Cycle	Multiple	ATP supply	Respiratory flexibility (71)
Osmolytes	Drought, salinity	Osmotic balance	Osmoprotection (72)
Phenylpropanoid	UV, pathogens	Antioxidant defense	↑ Defense capacity (73)
Terpenoids	Heat, ROS	Membrane protection	Protective metabolites (74)
ROS Network	All stresses	Detox & signaling	Oxidative tolerance (75)
ABA	Drought	Stomatal control	ABA sensitivity tuning (76)
JA	Biotic stress	Defense activation	Pest resistance (77)
SA	Pathogens	Systemic resistance	Disease resistance (78)
TOR	Nutrient-rich	Growth promotion	Growth optimization (79)
SnRK1	Energy stress	Stress adaptation	Growth–defense balance (80)
HSPs	Heat	Protein stability	Thermotolerance (81)

4. Ecological and Evolutionary Dimensions of Plant Function

Plant function cannot be fully understood in isolation from its ecological and evolutionary context, as long-term adaptation and resilience arise from continuous interactions with environmental gradients, microbial communities, neighboring plants, and evolutionary pressures (82). Although molecular and physiological networks regulate immediate plant responses, integrating these with ecological processes is essential to understand how plants perform under real-world, heterogeneous environments (83). Environmental gradients such as temperature, precipitation, soil salinity, nutrient availability, and light intensity strongly influence plant distribution, growth, and metabolism, and adaptation to these gradients depends on both genetic diversity and phenotypic plasticity. Natural populations harbor extensive allelic variation in regulatory genes, transcription factors, and metabolic enzymes, enabling local adaptation, such as improved water-use efficiency, deeper root systems, and altered stomatal sensitivity in drought-adapted plants (84). Systems biology approaches integrated with genome-wide association studies and ecological datasets allow identification of adaptive loci and improve prediction of genotype–environment interactions under future climate scenarios (85). In parallel, phenotypic plasticity enables plants to dynamically adjust physiological and metabolic processes, including photosynthesis, root architecture, osmolyte accumulation, and membrane composition, providing short-term resilience without genetic change (86). Evolutionary diversification of regulatory networks, including expansion of transcription factors and signaling proteins, further enhances species-specific adaptation, while conserved stress-response pathways provide common resilience mechanisms that can be

exploited for crop improvement (87).

Plant performance is also profoundly shaped by biotic interactions within ecological systems. The plant microbiome, including rhizosphere bacteria, mycorrhizal fungi, endophytes, and phyllosphere communities, plays a critical role in nutrient acquisition, stress tolerance, and disease resistance (88). For example, mycorrhizal associations enhance water and nutrient uptake, while nitrogen-fixing bacteria improve nitrogen assimilation, and beneficial microbes can modulate hormone signaling and activate systemic resistance pathways (89). Systems-level analyses reveal complex bidirectional communication between plants and microbes mediated by metabolites, signaling molecules, and small RNAs, while environmental stress can reshape microbial communities, influencing plant resilience (90). In addition to plant–microbe interactions, plant–plant interactions such as competition, facilitation, and allelopathy influence growth strategies, resource allocation, and stress adaptation. Plants communicate through volatile organic compounds, root exudates, and hormonal signals that can prime defense responses in neighboring plants, enhancing community-level resilience (91,92). These ecological interactions are further shaped by agricultural practices, where monocultures often reduce diversity and increase vulnerability, while strategies such as crop rotation, intercropping, and microbiome management improve system stability and stress tolerance (93). Thus, integrating ecological interactions with systems biology provides a comprehensive understanding of plant adaptation and supports the development of climate-resilient and sustainable agricultural systems.

Plant metabolic pathways and traits have evolved over millions of years under environmental pressures and ecological interactions, enabling plants to sustain growth, reproduction, and adaptation to changing conditions (94). This evolution is largely driven by gene duplication events such as whole-genome, tandem, and segmental duplications, which expand genes encoding enzymes and regulatory proteins, followed by neofunctionalization, subfunctionalization, or regulatory divergence, leading to diversification of metabolic pathways, including phenylpropanoids, alkaloids, terpenoids, and glucosinolates that enhance tolerance to biotic and abiotic stresses (95). These secondary metabolites play a key role in plant defense and adaptation (96). Environmental stresses have further shaped these pathways, as seen in the independent evolution of C4 and CAM photosynthesis for hot and arid climates, lipid modifications for cold tolerance, and osmoprotectant accumulation in saline environments (97). Many stress-responsive networks originated from conserved ancestral systems and were later modified across lineages (98). Evolution also involves network rewiring through changes in promoters, transcription factor binding, and epigenetic regulation, altering metabolic flux and generating new adaptive traits while improving robustness, flexibility, and redundancy in plant systems (99).

These insights help identify targets for crop improvement using advanced breeding and genome editing (100). Crop resilience is influenced by the interaction between genetic architecture and ecological factors such as climate variability, soil conditions, and pathogen pressure, which select for traits like deep root systems, efficient nutrient use, and strong immune responses (101). Integrating ecological and genomic data helps identify adaptive trait combinations for specific environments (102). Soil microbes further enhance resilience through improved nutrient uptake, hormone production, and stress resistance (103). Additionally, agroecosystem structure plays a critical role, with diversified systems like intercropping and agroforestry improving resilience compared to monocultures (104). Modern approaches integrating genomics, ecological data, and machine learning enable prediction of genotype–environment interactions for designing climate-resilient crops (105).

Table 3: Summary of evolutionary and ecological drivers influencing crop resilience under climate change, highlighting their system-level impacts and implications for sustainable crop improvement

Category	Driver	System Impact	Crop Improvement Focus
Evolutionary	Gene duplication & polyploidy	Network robustness & gene diversification	Use duplicated stress genes in breeding (106)
Evolutionary	Regulatory rewiring	Altered stress signaling	Edit key regulatory hubs (107)
Evolutionary	C4/CAM evolution	Better water & N-use efficiency	Engineer C4 traits into C3 crops (108)
Evolutionary	Secondary metabolite diversification	Stronger defense mechanisms	Engineer protective metabolites (109)
Ecological	Environmental gradients	Local adaptation & plasticity	Region-specific cultivars (110)
Ecological	Soil nutrient variability	Nutrient-use efficiency	Low-input crop breeding (111)
Ecological	Plant–microbiome interaction	Stress buffering & nutrient uptake	Microbiome-based management (112)
Ecological	Plant competition/facilitation	Community resilience	Intercropping systems (113)
Ecological	Agroecosystem diversity	Climatic stability	Diversified cropping (114)
Integrated (Eco–Evo)	G×E interaction	Climate-dependent trait variation	AI-assisted predictive breeding (115)

5. Bioinformatics and Computational Modeling in Plant Science

The rapid expansion of high-throughput omics technologies has generated vast plant biological datasets, whose value depends on effective integration and interpretation across molecular, physiological, and ecological levels. Bioinformatics and computational modeling form the backbone of plant systems biology by transforming these datasets into predictive frameworks for crop improvement (116,117). Systems modeling represents plant processes as interconnected networks of genes, proteins, and metabolites, where gene regulatory network analysis identifies key transcription factors and regulatory hubs, and genome-scale metabolic models combined with flux balance analysis simulate carbon and nitrogen allocation and reveal metabolic constraints (118,119). Dynamic and multiscale models further integrate multi-omics data to connect molecular interactions with whole-plant physiology and field performance under stress conditions (120).

Artificial intelligence and machine learning enhance these approaches by analyzing complex datasets to predict breeding values, capture genotype × environment interactions, and improve crop trait prediction, while also supporting high-throughput phenotyping and precision agriculture (121). Integrative databases and digital plant platforms enable efficient data organization, interoperability, and genotype–phenotype mapping, while digital twin technologies allow in silico simulation of plant growth, stress responses, and management strategies (122). Despite these advances, challenges such as data heterogeneity, lack of standardization, high computational demands, limited field datasets, and issues of model interpretability constrain predictive accuracy and application (123). Addressing these limitations through standardized frameworks, open-access resources, and interdisciplinary collaboration will strengthen the integration of mechanistic modeling with AI-driven analytics, ultimately enabling data-driven crop design and accelerating the development of climate-resilient, high-productivity agricultural systems (124).

Table 4. Major bioinformatics tools and digital platforms enabling integrative plant systems biology and climate-resilient crop development.

Category	Core Function	Climate-Relevant Application
Genome Databases	Genome annotation & SNP analysis	Stress gene identification & marker-assisted breeding
Transcriptomics Tools	Gene expression & network analysis	Discover drought/heat tolerance genes
Proteomics Platforms	Protein quantification & PTM analysis	Improve stress signaling pathways
Metabolomics Databases	Metabolite profiling & pathway mapping	Identify resilience biomarkers
Metabolic Modeling (GEM, FBA)	Flux simulation	Optimize carbon & nitrogen efficiency
GRN Tools	Regulatory network inference	Target master stress regulators
Phenomic Platforms	Trait imaging & field quantification	Genotype–phenotype linkage & early stress detection
AI / ML Platforms	Predictive modeling & genomic selection	Accelerated climate-adaptive breeding
Plant–Microbiome Databases	Microbial profiling	Microbiome-assisted stress tolerance
Digital Twin Models	Virtual plant simulation	Predictive design of resilient cultivars
Multi-Omics Portals	Cross-omics data integration	Systems-level crop improvement

6. Biotechnology and Metabolic Engineering for Crop Improvement

Advances in plant systems biology have enabled a detailed understanding of regulatory networks, metabolic pathways, and stress-response mechanisms, which can now be translated into crop improvement through biotechnology and metabolic engineering. Modern approaches have shifted from single-gene modifications to systems-guided strategies, focusing on regulatory hubs, metabolic flux optimization, and hormonal balance to enhance productivity, resilience, and nutritional quality (125). Genome editing technologies such as CRISPR–Cas allow precise gene modifications, including targeted mutations, promoter tuning, and multiplex editing, enabling fine control of stress responses like drought tolerance through pathways such as abscisic acid (ABA) signaling. Emerging tools like base and prime editing further improve accuracy, while systems biology helps identify key targets such as transcription factors and signaling nodes for coordinated trait improvement (126).

Engineering stress tolerance involves integrated manipulation of hormonal pathways, antioxidant systems, and metabolic processes. Enhancing enzymes like superoxide dismutase and catalase improves redox balance, while accumulation of osmoprotectants such as proline and sugars supports tolerance to drought and salinity (127). At the same time, optimizing root architecture enhances water and nutrient uptake. These modifications require careful systems-level tuning to balance growth and stress defense. Metabolic redesign also plays a crucial role in improving yield and nutrition by enhancing photosynthesis, optimizing carbon partitioning toward grains or storage tissues, and enabling biofortification with essential micronutrients. Systems modeling ensures that such modifications maintain overall metabolic stability and avoid trade-offs (128).

Synthetic biology further advances crop improvement by enabling the design of programmable genetic circuits and engineered pathways. Stress-inducible systems allow crops to activate protective responses only under adverse conditions, minimizing growth penalties (129). The development of “smart crops,” equipped with biosensors and responsive regulatory systems, enables real-time adaptation to environmental changes. When combined with computational modeling and digital agriculture, this creates an iterative design framework where predictions guide genetic modifications and field data refine future strategies (130). Integrating genome editing, metabolic engineering, synthetic biology, and systems modeling enables proactive development of climate-resilient, high-yielding, and nutritionally enhanced crops, supporting sustainable agriculture under changing environmental conditions (131).

7. Plant Responses to Climate Change

Climate change exposes plants to multiple interacting stresses such as drought, heat, salinity, and elevated CO₂, which collectively disrupt metabolism, growth, and

productivity across molecular, physiological, and ecological levels. Unlike single-stress laboratory conditions, plants in natural environments face combined stresses that require coordinated, system-level responses involving stress signaling pathways, metabolic plasticity, and ecological interactions (132). Drought and salinity impair water and ion balance, while heat stress affects protein stability and photosynthesis; all these stresses generate oxidative stress regulated by antioxidant systems and hormones like abscisic acid (ABA). Plants respond through osmoprotectant accumulation, metabolic reprogramming, and activation of stress-responsive genes, but their combined effects are complex and best understood using systems biology approaches (133).

Climate change also significantly alters carbon balance and plant productivity. Elevated CO₂ can enhance photosynthesis in C3 plants, but this benefit is often limited by nutrient availability, water scarcity, and acclimation responses. At the same time, rising temperatures increase respiration rates, leading to carbon loss and reduced biomass accumulation (134). Environmental stresses modify carbon allocation between roots and shoots, often reducing reproductive efficiency and yield. These physiological changes extend to ecosystem levels, influencing carbon sequestration, soil processes, and climate feedbacks. Therefore, integrating carbon–nitrogen interactions and metabolic fluxes through systems-level models is essential for predicting crop performance under future climate conditions (135).

To address these challenges, predictive modeling frameworks integrate genomic, physiological, metabolic, and environmental data to simulate plant responses across diverse scenarios. Modeling genotype × environment × management (G×E×M) interactions, combined with artificial intelligence and machine learning, enables the identification of region-specific, climate-resilient cultivars. Advanced tools such as crop simulation models and digital twin technologies allow *in silico* testing of genetic modifications and stress conditions, accelerating crop improvement while reducing field trial costs (136).

Ultimately, achieving climate-resilient agriculture requires integrative strategies that combine systems breeding, multi-omics approaches, and climate-smart agricultural practices with ecological sustainability and supportive policies. Enhancing multiple traits simultaneously, such as root architecture, carbon-use efficiency, and stress tolerance, ensures stable productivity under variable climates (137). Sustainable practices like precision irrigation, nutrient management, crop diversification, and soil microbiome enhancement complement genetic improvements. Ensuring equitable access to technology, regulatory harmonization, and global collaboration is also essential (138). By integrating systems biology, AI-driven prediction, and sustainable management, agriculture can shift from reactive stress responses to proactive climate adaptation, ensuring long-term resilience and global food security.

8. Translational Applications and Future Directions

Integrative plant systems biology is transforming crop science by linking mechanistic understanding with practical agricultural applications. The focus is shifting from single-trait improvement to systems-based breeding, which integrates multi-omics data, gene regulatory networks, and genotype \times environment \times management interactions (139). This approach enables the identification of key regulatory hubs and coordinated trait networks, allowing crops to develop synchronized stress responses. Artificial intelligence and predictive modeling further enhance breeding efficiency by simulating trait combinations and identifying climate-resilient cultivars. When combined with climate-smart agricultural practices such as precision irrigation, nutrient optimization, and conservation strategies, these innovations improve productivity while minimizing environmental impact (140).

A critical advancement in crop biotechnology is the integration of ecological context into genetic innovation. Traits optimized under laboratory conditions often behave differently in dynamic field environments, making ecological compatibility essential for long-term performance (141). Incorporating ecological modeling ensures stability of engineered traits across diverse conditions and supports balanced nutrient cycling. The plant microbiome represents a promising frontier, where crops can be engineered to recruit beneficial microbes that enhance stress tolerance, nutrient uptake, and disease resistance. Additionally, adopting landscape-level approaches that connect molecular traits with ecosystem processes can improve biodiversity, resilience, and sustainability in agricultural systems (142).

Future progress in plant systems biology depends on coordinated advancements across scientific, technological, and policy domains. Priorities include developing standardized frameworks for multi-omics data integration, expanding multi-location phenotyping to capture environmental variability, and improving the interpretability of AI-driven models (143). Integrating ecological and socio-economic data into crop design will enable context-specific innovations suited to regional conditions. At the same time, harmonized regulatory frameworks for genome-edited crops are necessary to accelerate deployment while ensuring biosafety and public trust. Strong interdisciplinary collaboration will be essential to build predictive, adaptive, and sustainable agricultural systems (144).

Crop improvement is increasingly moving toward multi-omics guided design, which combines genomics, transcriptomics, proteomics, metabolomics, and phenomics with environmental data to construct high-resolution genotype–phenotype relationships. This approach shifts breeding from empirical trial-and-error methods to rational, predictive engineering (145). Instead of targeting individual genes, it focuses on network-level components such as regulatory hubs, metabolic pathways, and coordinated stress-response systems.

By integrating environmental and climate data, multi-omics approaches enable the development of region-specific cultivars with enhanced resilience and reduced input requirements, aligning crop design with sustainability and climate adaptation goals (146).

Technological innovation alone is insufficient to achieve climate-resilient agriculture; it must be supported by effective policies, equitable access, and sustainable practices. Regulatory harmonization for genome-edited crops is essential to facilitate global deployment while maintaining biosafety standards (147). Future agricultural strategies should prioritize reduced reliance on fertilizers and pesticides, improved water-use efficiency, soil health, biodiversity conservation, and nutritional enhancement through biofortification. Ensuring global food security also requires investment in underutilized crops, open-access genomic resources, and international research collaboration (148). Furthermore, addressing potential inequalities in access to digital agriculture and AI technologies is critical. A systems-based approach that integrates scientific innovation, ecological sustainability, and socio-economic equity will be key to achieving long-term agricultural stability and food security under changing climate conditions (149).

9. Conclusion

Climate change poses significant challenges to agricultural productivity, ecosystem resilience, and global food security, necessitating integrative approaches in plant science. Integrative plant systems biology bridges molecular, physiological, and ecological dimensions, linking genomics, metabolism, and environmental interactions to understand plant adaptation as a coordinated system rather than isolated processes. Multi-omics technologies have enabled reconstruction of gene regulatory networks and metabolic pathways, while physiological processes such as photosynthesis, respiration, hormonal signaling, and redox balance collectively determine plant responses to stresses like drought, heat, salinity, and oxidative damage. At the ecological level, plant–microbe interactions and environmental variability further shape resilience and productivity, emphasizing the need for a holistic perspective. Advances in bioinformatics, artificial intelligence, and computational modeling have transformed plant science from descriptive to predictive and design-oriented research. Tools such as genome-scale metabolic models, gene network analysis, and machine learning-based genomic selection enable accurate modeling of genotype \times environment \times management interactions, accelerating the development of climate-resilient crops. Biotechnology and synthetic biology further enhance this potential through precision genome editing and metabolic engineering, allowing targeted improvement of stress tolerance, carbon allocation, and nutritional traits. Importantly, integrating ecological principles ensures that engineered traits function effectively within real agroecosystems.

Achieving climate-resilient agriculture requires strong interdisciplinary collaboration among biologists, ecologists, computational scientists, agronomists, and policymakers. Open-access data systems, standardized frameworks, and global research networks are essential to support innovation and equitable technology dissemination. Future crop improvement must move beyond single-trait selection toward network-level optimization, focusing on multi-stress tolerance, resource-use efficiency, and ecosystem compatibility. Overall, integrative plant systems biology provides both a conceptual framework and a practical pathway for shifting agriculture from reactive stress management to proactive design of resilient crops, ensuring long-term sustainability and global food security under changing climate conditions.

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