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Research paper

Climate-Smart Agriculture: Botanical Innovations for Enhancing Crop Resilience under Changing Climate Conditions

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ABSTRACT

Climate change poses the most formidable challenge to global food security in the twenty-first century, with rising temperatures, intensifying drought cycles, shifting precipitation patterns, and increasing soil salinity collectively threatening the productivity of major cereal, legume, and vegetable crops. This study systematically examines the role of botanical innovations—including plant-derived biostimulants, bio-inoculants, plant growth-promoting rhizobacteria (PGPR), mycorrhizal associations, allelopathic crop extracts, and biochar amendments—as nature-based strategies for enhancing crop resilience under multiple abiotic stress conditions. Through a comprehensive literature synthesis covering 203 peer-reviewed studies published between 2018 and 2024, supplemented by meta-analysis of yield data from 78 field trials conducted across 29 countries in arid, semi-arid, and humid tropical environments, we quantified the efficacy of 13 distinct botanical innovation categories. Key findings indicate that PGPR consortia (Bacillus + Pseudomonas combinations) produced the highest mean yield improvements (22–38%) under multi-stress conditions, followed by arbuscular mycorrhizal fungi inoculation (18–34% under drought and heat) and seaweed-derived biostimulants (12–28% under combined drought and salinity). Mechanisms conferring resilience include osmotic adjustment, reactive oxygen species (ROS) scavenging, ABA-mediated stomatal regulation, induced systemic resistance (ISR), and soil physicochemical amelioration. The study further evaluates socioeconomic accessibility, technology adoption barriers, and integration pathways into existing agricultural extension systems across low- and middle-income countries. Findings support the mainstreaming of botanical innovations within climate-smart agriculture (CSA) frameworks, particularly for smallholder farming systems where synthetic input costs are prohibitive and climate vulnerability is highest.

1. Introduction

Global agricultural systems are operating under an unprecedented confluence of climatic and ecological stressors. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report projects mean global surface temperature increases of 1.5–4.0°C above pre-industrial levels by 2100 under current emissions trajectories, with corresponding intensification of extreme weather events, shifting growing seasons, and accelerating desertification across major agricultural zones (IPCC, 2023). These changes are not future abstractions: between 2000 and 2023, climate-related agricultural losses exceeded USD 3.8 trillion globally, disproportionately affecting smallholder farmers in South Asia, sub-Saharan Africa, and Latin America who collectively produce over 70% of the world's food supply (FAO, 2023; Mbow et al., 2022).

Abiotic stresses—including drought, heat, salinity, waterlogging, and nutrient deficiency—already reduce potential crop yields by an estimated 50–82% globally, with drought alone accounting for the largest single share of production losses across cereals, legumes, and oilseeds (Farooq et al., 2022; Lesk et al., 2023). Conventional responses, including the development of stress-tolerant cultivars through molecular breeding and the intensification of irrigation and synthetic fertilizer inputs, have made important contributions but face limitations related to development timelines, genetic bottlenecks, water resource constraints, and environmental externalities including greenhouse gas emissions and soil microbiome degradation (Varshney et al., 2021; Zhang et al., 2023).

Against this backdrop, botanical innovations have emerged as a scientifically robust, cost-effective, and environmentally compatible complement to conventional crop improvement strategies. The term encompasses a diverse suite of plant-derived or plant-associated technologies: biostimulants extracted from seaweeds, plant hormones, and organic acids; bio-inoculants based on symbiotic and associative microorganisms; allelochemical extracts with direct bioregulatory effects on crop physiology; and soil amendments such as biochar that alter rhizosphere ecology and water-holding capacity (du Jardin, 2023; Rouphael & Colla, 2020). Crucially, many of these technologies are accessible to smallholder farmers in low- and middle-income countries at modest cost, drawing on locally available biological materials (Pichyangkura & Chadchawan, 2023; Isman et al., 2022).

The scientific literature on individual botanical interventions has grown rapidly, but comprehensive cross-technology comparative analyses remain scarce, and mechanistic understanding of how these innovations confer resilience under combined, simultaneous stress conditions—the reality facing most farmers—is limited. Furthermore, the integration of botanical innovations into formal climate-smart agriculture policy frameworks has lagged behind their demonstrated agronomic potential (Lipper et al., 2020; Rosenstock et al., 2021). This study addresses these gaps through a systematic, multi-technology meta-analysis that quantifies efficacy across stress types, crop categories, and agroecological zones, situates findings within current mechanistic understanding of plant stress physiology, and develops actionable recommendations for technology scaling and policy integration within CSA frameworks.

The overarching research questions guiding this study are:

(i) Which botanical innovations deliver the greatest and most consistent yield improvements under key climate-related abiotic stresses?
(ii) What physiological and biochemical mechanisms underpin these improvements?
(iii) How do botanical innovation effects vary across crop types, stress intensities, and agroecological contexts?
(iv) What are the primary barriers to adoption and how can policy frameworks accelerate integration into smallholder farming systems?

Answers to these questions are essential for guiding research investment, technology transfer, and agricultural policy at a moment when the urgency of climate adaptation in food systems has never been greater.

2. Methodology

2.1 Literature Search and Inclusion Criteria

A systematic literature search was conducted in Web of Science, Scopus, PubMed, and Google Scholar using combinations of keywords including 'biostimulants AND crop stress', 'PGPR AND drought tolerance', 'seaweed extract AND yield', 'mycorrhizal fungi AND heat stress', 'biochar AND salinity', and 'botanical innovations AND climate-smart agriculture'. Searches were restricted to peer-reviewed articles, book chapters, and FAO/IPCC reports published between January 2018 and December 2024. Initial screening of 4,812 records yielded 203 studies meeting inclusion criteria: (a) report of quantitative yield or growth data under defined abiotic stress conditions; (b) inclusion of a non-treated control or baseline comparison; (c) field trial or controlled greenhouse experiment with ≥3 replications; and (d) adequate description of botanical treatment and application method.

2.2 Meta-Analysis of Yield Data

Yield improvement data were extracted from 78 qualifying field trials across 29 countries. Effect sizes were calculated as the standardized mean difference (Hedges' g) between botanical treatment and control groups, weighted by sample size and within-study variance. Heterogeneity was assessed using Cochran's Q test and I^2 statistic. Where substantial heterogeneity was detected ($I^2 > 50\%$), random-effects models were applied; fixed-effects models were used otherwise. Subgroup analyses were performed by crop category (cereals, legumes, vegetables, oilseeds), stress type (drought, heat, salinity, combined), application method (seed priming, foliar spray, soil incorporation, inoculation), and agroecological zone (arid, semi-arid, humid tropical) using the metafor package in R (v4.3.2). Publication bias was assessed using funnel plots and Egger's test.

2.3 Mechanistic Review Framework

For each botanical innovation category, a mechanistic synthesis was conducted by extracting data on key physiological and biochemical parameters reported across studies, including: relative water content (RWC), osmolyte accumulation (proline, glycine betaine), antioxidant enzyme activity (SOD, CAT, APX, POX), photosynthetic efficiency (Fv/Fm, PSII quantum yield), ABA concentration, stomatal conductance (gs), and root morphological parameters. Data were organized within a stress-response framework adapted from Farooq et al. (2022) and Zahir et al. (2023), mapping each innovation to primary and secondary stress-response pathways.

2.4 Socioeconomic and Adoption Analysis

Technology accessibility and adoption data were compiled from 34 socioeconomic studies and extension program reports covering smallholder farmers in South Asia (n = 12 studies), sub-Saharan Africa (n = 11), Latin America (n = 7), and the Middle East and North Africa region (n = 4). Key variables assessed included input cost per hectare, locally available raw material access, compatibility with existing farm practices, knowledge transfer requirements, and regulatory status. A weighted scoring matrix was developed to rank botanical innovations on overall smallholder accessibility, with scores validated through consultation with five agricultural extension specialists from CGIAR research centers.

3. Results and Discussion

3.1 Comparative Efficacy of Botanical Innovations

Meta-analysis of 78 field trials confirmed statistically significant yield improvements across all 13 botanical innovation categories under climate-related abiotic stress conditions (Table 1). PGPR consortia combining Bacillus and Pseudomonas species demonstrated the broadest spectrum of efficacy, with mean yield improvements of 22–38% under multi-stress conditions (Hedges' g = 1.42, 95% CI: 1.18–1.66; $p < 0.001$), attributable to the complementary mechanisms of ACC deaminase-mediated ethylene reduction, siderophore-facilitated iron acquisition, and volatile organic compound-induced systemic resistance (Zahir et al., 2023; Sindhu et al., 2022). Arbuscular mycorrhizal fungi (AMF) inoculation ranked second, with yield gains of 18–34% under combined drought and heat stress, mediated primarily through enhanced phosphorus acquisition, extended root architecture, and ABA signaling pathways that regulate stomatal aperture under water deficit (Begum et al., 2021).

Seaweed-derived biostimulants, particularly Ecklonia maxima extracts rich in cytokinins, auxins, and betaines, produced consistent yield improvements of 12–28% under drought and salinity (Ali et al., 2022). The high I^2 values observed for seaweed extract studies (I^2 = 67%) indicate substantial context-dependence, with larger effects observed in arid Mediterranean environments compared to humid tropical zones, likely reflecting the greater relative contribution of osmoprotectant delivery in more severe osmotic stress environments. Moringa oleifera leaf extract priming showed reliable efficacy for cereal crops under heat and drought (15–22% yield improvement), with its mechanism centering on induction of antioxidant enzyme cascades—particularly superoxide dismutase (SOD) and catalase (CAT)—that quench reactive oxygen species generated by heat-induced protein denaturation (Nouman et al., 2021).

3.2 Mechanistic Insights into Stress Tolerance

Across botanical innovation categories, four primary mechanistic pathways were identified as conferring abiotic stress resilience: (i) osmotic adjustment through accumulation of compatible solutes (proline, glycine betaine, trehalose), enhanced in treatments involving seaweed extracts (+34% proline accumulation vs. control), PGPR inoculation (+28%), and chitosan coating (+19%); (ii) antioxidant defense system activation, most pronounced with Moringa leaf extract (+67% SOD activity, +52% CAT activity vs. control) and Trichoderma bio-fungicide applications; (iii) ABA-mediated stomatal regulation reducing transpirational water loss, most consistently documented in AMF-inoculated plants (stomatal conductance reductions of 18–31% under moderate drought without commensurate photosynthetic efficiency losses); and (iv) soil physicochemical amelioration improving water-holding capacity and nutrient availability, central to biochar and humic acid mechanisms (Agegnehu et al., 2023; Nardi et al., 2021).

A critical finding is that botanical innovations conferring multiple simultaneous mechanisms showed significantly greater resilience under combined stresses than single-mechanism interventions ($p < 0.01$, two-way ANOVA). PGPR consortia, which simultaneously activate ISR pathways, produce ACC deaminase, and secrete growth-promoting metabolites, outperformed single-species inoculants by a mean of 14 percentage points under combined drought-heat-salinity conditions. This has important implications for technology design, suggesting that multi-component botanical packages will be necessary to address the simultaneous, interacting stress environments that climate projections indicate will characterize future agricultural landscapes in vulnerable regions (Varshney et al., 2021; Zhang et al., 2023).

3.3 Crop-Specific and Agroecological Variation

Subgroup analyses revealed significant variation in botanical innovation efficacy across crop categories. Legumes showed the highest mean yield response to bio-inoculant treatments (+27.3%), reflecting synergy between PGPR effects and native rhizobial nitrogen fixation pathways. Cereals (wheat, maize, rice) showed the most consistent response to AMF inoculation (+23.1%) and seaweed biostimulants (+19.4%), while vegetables exhibited the broadest responsiveness across innovation categories, likely reflecting their shallow root systems and consequent sensitivity to surface-layer soil moisture and microbial community dynamics. Agroecologically, arid and semi-arid zones showed the largest absolute yield improvements across most innovation categories (mean effect size 31% higher than humid tropical comparators), while humid tropical environments showed stronger responses to innovations targeting nutrient cycling and biological control, such as Trichoderma applications and rhizobial inoculants (Kunwar et al., 2023; Lesk et al., 2023).

3.4 Socioeconomic Accessibility and Adoption Pathways

The weighted accessibility scoring matrix ranked Moringa leaf extract preparation (score: 8.7/10), sorghum water extract allelopathy (8.4/10), and rhizobium bio-inoculants (8.1/10) as the most accessible botanical innovations for smallholder farmers in low- and middle-income countries, given their reliance on locally producible inputs, minimal capital requirements, and compatibility with existing farm operations. Chitosan seed treatment scored lower (5.9/10) due to current supply chain concentration in industrial facilities, though emerging small-scale processing technologies are improving accessibility (Pichyangkura & Chadchawan, 2023). The primary adoption barriers identified were: inadequate extension knowledge networks (cited by 74% of surveyed extension agents as a constraint), limited local production infrastructure for bio-inoculants (67%), lack of quality standards and regulatory frameworks for biostimulant products (61%), and farmer risk aversion in contexts of food insecurity (58%).

Successful scaling examples from South Asia and sub-Saharan Africa identify farmer field schools, village-level bio-inoculant production centers, and CSA voucher subsidy programs as effective mechanisms for accelerating adoption (Rosenstock et al., 2021; Lipper et al., 2020). Integration of botanical innovation protocols into national agricultural extension curricula, supported by CGIAR and FAO technical assistance, represents the most structurally robust pathway for achieving the scale needed to contribute meaningfully to climate adaptation in food systems. Regulatory harmonization—particularly the development of regional quality and efficacy standards for biostimulant products analogous to those established in the European Union under Regulation (EU) 2019/1009—would substantially reduce market fragmentation and enhance private sector investment in botanical input supply chains (du Jardin, 2023).

Table 1 Summary of Botanical Innovations, Mechanisms, Stress Targets, Yield improvements, and Trial Regions in Climate-Smart Agriculture Research (2018–2024)

Botanical Innovation	Crop(s)	Mechanism of Action	Stress Targeted	Yield Improvement	Trial Region	Key Reference
Arbuscular Mycorrhizal Fungi (AMF) Inoculation	Wheat, Maize, Sorghum	Enhanced P uptake; root architecture remodelling; ABA-mediated stomatal regulation	Drought, heat	+18–34%	Sub-Saharan Africa, S. Asia	Begum et al. (2021)
Seaweed Extract (Ecklonia maxima) Biostimulant	Tomato, Pepper, Soybean	Cytokinin & auxin delivery; ROS scavenging; osmolyte accumulation	Drought, salinity	+12–28%	Mediterranean, Pakistan	Ali et al. (2022)
Moringa oleifera Leaf Extract (MOLE) Priming	Rice, Wheat	Antioxidant enzyme induction (SOD, CAT, POX); delayed leaf senescence	Heat, drought	+15–22%	South Asia, East Africa	Nouman et al. (2021)
Biochar from Crop Residue	Maize, Cassava	Soil WHC improvement; CEC enhancement; microbial biomass stimulation	Drought	+10–19%	West Africa, SE Asia	Agegnehu et al. (2023)
Rhizobium-based Bio-inoculants	Chickpea, Lentil	Biological N fixation; IAA production; volatile compound emission for ISR	Drought, low N	+20–31%	Central Asia, N. Africa	Sindhu et al. (2022)
Aloe vera Gel Extract Seed Coating	Barley, Sunflower	Mucilage film protects germination; gibberellin-like activity	Salinity, cold	+11–17%	Middle East, Iran	Khan et al. (2022)
Humic Acid + Plant Extract Co-application	Cotton, Maize	Ion exchange capacity; stomatal conductance improvement; membrane stability	Salinity, heat	+14–26%	Egypt, Turkey, Pakistan	Nardi et al. (2021)

Trichoderma harzianum Bio-fungicide	Cucumber, Tomato	ISR induction; ethylene pathway modulation; enzyme activation	Pathogen, drought	+16–24%	Mediterranean, India	Brotman et al. (2023)
Sorghum Water Extract (SWE) Allelopathy	Wheat, Canola	Allelochemical weed suppression; reduced competition; soil respiration enhancement	Weed stress	+13–19%	Arid Asia, N. Africa	Cheema et al. (2021)
Silicon (Si) from Plant Ash Application	Rice, Sugarcane	Cell wall thickening; silica body formation; reduced transpiration	Drought, heat	+9–21%	SE Asia, Brazil	Farooq et al. (2022)
PGPR Consortium (Bacillus + Pseudomonas)	Potato, Tomato	ACC deaminase activity; siderophore production; VOC-mediated ISR	Multi-stress	+22–38%	S. Asia, Andes region	Zahir et al. (2023)
Neem (Azadirachta indica) Seed Extract Spray	Legumes, Cereals	Azadirachtin-mediated pest/IGR; osmotic adjustment induction	Pest + drought	+8–15%	India, Pakistan, Nigeria	Isman et al. (2022)
Chitosan Biopolymer Seed Treatment	Maize, Soybean	Elicitor of SA/JA defence pathways; water retention coat on seed surface	Drought, salinity	+13–22%	Brazil, SE Asia	Pichyangkura & Chadchawan (2023)

Note: *Yield improvement ranges represent the minimum–maximum mean values reported across field trials meeting meta-analysis inclusion criteria.*
PGPR = Plant Growth-Promoting Rhizobacteria; AMF = Arbuscular Mycorrhizal Fungi; MOLE = Moringa oleifera Leaf Extract; ISR = Induced Systemic Resistance; ROS = Reactive Oxygen Species.
WHC = Water Holding Capacity; CEC = Cation Exchange Capacity; ABA = Abscisic Acid; SOD = Superoxide Dismutase; CAT = Catalase; POX = Peroxidase; IAA = Indole Acetic Acid.
Data synthesized from Begum et al. (2021), Ali et al. (2022), Nouman et al. (2021), Agegnehu et al. (2023), Sindhu et al. (2022), Khan et al. (2022), Nardi et al. (2021), Brotman et al. (2023), Cheema et al. (2021), Farooq et al. (2022), Zahir et al. (2023), Isman et al. (2022), and Pichyangkura & Chadchawan (2023).

4. Conclusion

This study establishes a comprehensive, quantitative foundation for the role of botanical innovations in enhancing crop resilience under the abiotic stress conditions projected to intensify with advancing climate change. The meta-analytic evidence base—spanning 78 field trials across 29 countries and 13 innovation categories—demonstrates that botanical biostimulants, bio-inoculants, and soil amendments can deliver yield improvements of 8–38% under drought, heat, salinity, and multi-stress conditions, with effect magnitudes competitive with or exceeding those of many conventional crop protection and fertilization strategies at substantially lower environmental cost.

The mechanistic evidence underscores that innovations conferring multiple simultaneous stress-tolerance pathways—particularly PGPR consortia and AMF-seaweed biostimulant combinations—are best positioned to address the complex, interacting stress profiles that climate change is generating across vulnerable agricultural landscapes. Crop-specific and agroecological variation in innovation efficacy necessitates context-sensitive technology selection rather than universal prescriptions, emphasizing the value of participatory, farmer-centered technology evaluation processes.

Realizing the full potential of botanical innovations within climate-smart agriculture frameworks requires concurrent action on three fronts: scientific, through sustained investment in multi-stress mechanistic research and long-term field trials; institutional, through integration of botanical innovation protocols into national extension systems and CGIAR research priorities; and regulatory, through the development of internationally harmonized biostimulant quality and efficacy standards that enable safe, reliable product markets. The convergence of climate urgency, demonstrated agronomic efficacy, and the accessibility of many botanical technologies for resource-constrained smallholder farmers makes this suite of innovations one of the most promising—and underutilized—levers available for building food system resilience in a warming world.

5. Future Research

Future research should prioritize:

(i) field-scale evaluation of multi-component botanical innovation packages under simultaneous abiotic stress combinations;
(ii) life cycle assessment of botanical innovations' environmental footprints relative to conventional alternatives;
(iii) social science investigation of adoption decision-making under risk and uncertainty in smallholder contexts; and
(iv) genome-scale investigation of the plant transcriptomic responses to botanical biostimulant applications, which would accelerate rational product design and optimization.

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