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Climate-Resilient Agriculture and Human Rights: Integrating Plant Breeding Innovations, Legal Frameworks, and Sustainable Agribusiness for Food Security

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ABSTRACT

Climate change threatens agricultural productivity, food security, and the realization of the human right to food. Rising temperatures, erratic rainfall, droughts, floods, salinity, and emerging pests and diseases disproportionately affect vulnerable populations, particularly smallholder farmers. This article argues that climate-resilient agriculture should be viewed as a human-rights imperative rather than merely an adaptation strategy. It examines the legal foundations of the right to food, the contribution of modern plant breeding technologies—including marker-assisted selection, genome-wide association studies (GWAS), genomic selection, speed breeding, and gene editing—and the role of sustainable agribusiness in technology dissemination and market inclusion. The study highlights challenges relating to intellectual property rights, technological inequality, governance, and climate justice. It concludes that integrating scientific innovation, rights-based legal frameworks, and sustainable agribusiness strategies is essential for achieving food security and fulfilling international human rights obligations under conditions of climate uncertainty.

KEYWORDS

Climate Change, Human Rights, Food Security, Climate-Resilient Agriculture, Farmers' Rights, Plant Breeding Innovation, Sustainable Agribusiness, Climate Justice, GWAS, Gene Editing.

INTRODUCTION

Climate change has become one of the most serious challenges facing agriculture and food systems worldwide.[1] Agricultural productivity is increasingly affected by heat stress, drought, floods, salinity, and changing pest and disease dynamics.[2] These impacts threaten food

[1] Simon J Vermeulen, Bruce M Campbell and John SI Ingram, 'Climate Change and Food Systems' (2012) 37 Annual Review of Environment and Resources 195.

[2] Asif Shahzad and others, 'Nexus on Climate Change: Agriculture and Possible Solution to Cope Future Climate Change Stresses' (2021) 28(12) Environmental Science and Pollution Research 14211.

availability, accessibility, utilization, and stability, thereby undermining food security and human well-being.

Food security is closely linked to human rights.[3] Adequate food is essential for health, dignity, and socio-economic development. Climate-related disruptions disproportionately affect smallholder farmers, women, indigenous communities, and other vulnerable groups.[4] Consequently, climate-resilient agriculture has emerged as a critical strategy for protecting livelihoods and realizing the right to food.[5]

Advances in plant breeding provide new opportunities for adaptation. Technologies such as marker-assisted selection, GWAS, genomic selection, speed breeding, and gene editing enable the development of crop varieties capable of maintaining productivity under adverse environmental conditions.[6] However, technological progress alone is insufficient. Farmers require access to quality seeds, extension services, finance, and markets. Legal frameworks and sustainable agribusiness systems are therefore essential for ensuring equitable access to innovations.[7]

This article adopts an interdisciplinary approach integrating law, genetics and plant breeding, and commerce and management. It examines international legal frameworks, modern breeding technologies, and sustainable agribusiness strategies, while identifying key challenges and policy priorities.

CLIMATE CHANGE, FOOD SECURITY, AND HUMAN RIGHTS

Food security exists when all people have access to sufficient, safe, nutritious, and affordable food at all times.[8] Climate change threatens each pillar of food security. Reduced yields affect availability, rising

[3] Katrin Mechlem, 'Food Security and the Right to Food in the Discourse of the United Nations' (2004) 10(5) European Law Journal 631.

[4] Anju Adhikari and Sushila Ghimire, 'Gendered Dimensions of Climate Change Impacts: Challenges and Adaptive Strategies' (2025) 13(5) Turkish Journal of Agriculture-Food Science and Technology 1354.

[5] Jon Hellin, Edward Fisher, Mark Taylor, Shweta Bhasme and Ana Maria Loboguerrero, 'Transformative Adaptation: From Climate-Smart to Climate-Resilient Agriculture' (2023) 4(1) CABI Agriculture and Bioscience 30.

[6] Rajesh Kumar and others, 'Advances in Genomic Tools for Plant Breeding: Harnessing DNA Molecular Markers, Genomic Selection, and Genome Editing' (2024) 57(1) Biological Research 80.

[7] Shawn Ferris, Paul Robbins, Rupert Best, David Seville, Andrew Buxton, Jason Shriver and Evelyn Wei, Linking Smallholder Farmers to Markets and the Implications for Extension and Advisory Services (MEAS Brief 4, 2014) 13.

[8] Elliot M Berry, Sandro Dernini, Barbara Burlingame, Alexandre Meybeck and Paolo Conforti, 'Food Security and Sustainability: Can One Exist Without the Other?' (2015) 18(13) Public Health Nutrition 2293.

prices reduce accessibility, changing environmental conditions affect utilization, and climatic variability undermines stability.[9]

The United Nations increasingly recognizes climate change as a human rights issue because it affects rights to life, health, water, housing, and food.[10] The right to food occupies a central position within this framework because adequate nutrition is indispensable for human dignity.[11] [12]

International human rights law identifies three categories of state obligations regarding food: respect, protect, and fulfill.[13] States must avoid interfering with food access, regulate third parties that may threaten food security, and take positive measures to ensure food availability when individuals cannot secure food themselves.[14] [15]

Agriculture is highly vulnerable to climatic variability. Rising temperatures reduce photosynthesis and reproductive success in major crops.[16] Water scarcity limits productivity in rainfed systems.[17] Salinity affects nutrient uptake and crop growth, while changing climatic conditions facilitate the spread of pests and diseases[18]. Smallholder farmers are particularly vulnerable because they often lack access to

[9] Peter J Gregory, John SI Ingram and Michael Brklacich, 'Climate Change and Food Security' (2005) 360(1463) Philosophical Transactions of the Royal Society B: Biological Sciences 2139.
[10] John H Knox, 'Linking Human Rights and Climate Change at the United Nations' (2009) 33 Harvard Environmental Law Review 477.
[11]Philip Alston, 'International Law and the Human Right to Food' in Philip Alston and Katarina Tomaševski (eds), *The Right to Food* (Martinus Nijhoff Publishers 1984) 9.
[12] Alicia Ely Yamin Ayala and Benjamin Mason Meier, 'A Human Rights Approach to the Health Implications of Food and Nutrition Insecurity' (2017) 38(1) *Public Health Reviews* 10
[13] Susan Randolph and Shareen Hertel, *The Right to Food: A Global Overview* (Economic Rights Working Paper No 19, 2012).
[14] Smita Narula, *The Right to Food: Holding Global Actors Accountable under International Law* (Centre for Human Rights and Global Justice Working Paper, New York University School of Law, 2006).
[15] Barbara L McDonald, *Food Security* (Polity Press 2010).
[16] Elizabeth A Ainsworth and Donald R Ort, 'How Do We Improve Crop Production in a Warming World?' (2010) 154(2) *Plant Physiology* 526.
[17] Johan Rockström, Line Gordon, Suhas P Wani, Jennie Barron, Nuhu Hatibu, Theib Oweis and others, 'Managing Water in Rainfed Agriculture—The Need for a Paradigm Shift' (2010) 97(4) *Agricultural Water Management* 543.
[18] Dennis L Corwin, 'Climate Change Impacts on Soil Salinity in Agricultural Areas' (2021) 72(2) *European Journal of Soil Science* 842.

irrigation, credit, insurance, improved seeds, and extension services.[19] [20] Their dependence on climate-sensitive agriculture increases exposure to environmental shocks. A rights-based approach therefore requires targeted support for vulnerable populations.

Climate-resilient agriculture contributes directly to several Sustainable Development Goals, including Zero Hunger, No Poverty, Climate Action, Responsible Consumption and Production, and Life on Land.[21] By strengthening resilience and protecting livelihoods, it supports both development and human rights objectives.[22]

INTERNATIONAL LEGAL FRAMEWORKS GOVERNING FOOD SECURITY AND FARMERS' RIGHTS

International law provides a strong foundation for linking food security, climate resilience, and human rights.[23] The Universal Declaration of Human Rights recognizes the right to an adequate standard of living, including food. Although not legally binding, it established the normative basis for later human rights instruments.[24] [25] The International Covenant on Economic, Social and Cultural Rights (ICESCR) explicitly recognizes the right to adequate food and freedom from hunger.[26] General Comment No. 12 clarifies that food must be available, accessible, adequate, and sustainable. States are required to respect, protect, and fulfill this right.[27] [28]

[19] Bashir Jama and Gloria Pizarro, 'Agriculture in Africa: Strategies to Improve and Sustain Smallholder Production Systems' (2008) 1136(1) *Annals of the New York Academy of Sciences* 218.
[20] Augustine Langyintuo, 'Smallholder Farmers' Access to Inputs and Finance in Africa' in Suresh Babu and Sieglinde Snapp (eds), *The Role of Smallholder Farms in Food and Nutrition Security* (Springer International Publishing 2020) 133.
[21] Muhammad Farooq, 'Conservation Agriculture and Sustainable Development Goals' (2023) 60(3) *Pakistan Journal of Agricultural Sciences*.
[22] Sophia Huyer, Elisabeth Simelton, Nitya Chanana, Amanda A Mulema and Elena Marty, 'Expanding Opportunities: A Framework for Gender and Socially-Inclusive Climate Resilient Agriculture' (2021) 3 *Frontiers in Climate* 718240.
[23] Harry Johnson, *International Agricultural Law and Policy: A Rights-Based Approach to Food Security* (Edward Elgar Publishing 2018).
[24] Mary Ann Glendon, 'Knowing the Universal Declaration of Human Rights' (1999) 73(5) *Notre Dame Law Review* 1153.
[25] Gordon Brown (ed), *The Universal Declaration of Human Rights in the 21st Century: A Living Document in a Changing World* (vol 2, Open Book Publishers 2016).
[26] A Butt and AH Sethi, 'The International Covenant on Economic, Social and Cultural Rights (ICESCR)' (6 June 2024) *Social and Cultural Rights (ICESCR)*.
[27] Stefan Söllner, 'The Breakthrough of the Right to Food: The Meaning of General Comment No 12 and the Voluntary Guidelines for the Interpretation of the Human Right to Food' (2007) 11(1) *Max Planck Yearbook of United Nations Law* 391.
[28] Peter M Rukundo and Ruth K Oniang'o, 'Twenty-Five Years of the United Nations General Comment Number 12 on the Human Right to Adequate Food—Malnutrition

The Convention on Biological Diversity (CBD) emphasizes conservation of biodiversity, sustainable use of biological resources, and equitable sharing of benefits arising from genetic resources.[29] Agricultural biodiversity is essential for developing climate-resilient crop varieties.[30] The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) facilitates access to genetic resources and recognizes Farmers' Rights, including protection of traditional knowledge, participation in decision-making, and equitable benefit sharing.[31] [32] [33] The Treaty's multilateral system supports international cooperation in crop improvement.[34]

The United Nations Declaration on the Rights of Peasants (UNDROP) strengthens recognition of rights relating to seeds, land, participation, and food sovereignty.[35] These provisions are particularly important for smallholder farmers and rural communities.[36] The Paris Agreement establishes a global goal on adaptation and recognizes the importance of human rights in climate action.[37] Climate-resilient agriculture contributes directly to adaptation objectives by reducing vulnerability and enhancing resilience.[38] Together, these frameworks establish that

Continues to Surge' (2024) 24(10) *African Journal of Food, Agriculture, Nutrition and Development* 24698.

[29] Michael R Muller, *Genetic Resources as Natural Information: Implications for the Convention on Biological Diversity and Nagoya Protocol* (Routledge 2015).

[30] EJ Zuza and others, 'Crop Species Diversity: A Key Strategy for Sustainable Food System Transformation and Climate Resilience' (2024) 13(3) *Food and Energy Security* e558

[31] Regine Andersen, 'The International Treaty on Plant Genetic Resources for Food and Agriculture: Toward the Realization of Farmers' Rights as a Means of Protecting and Enhancing Crop Genetic Diversity' in Michael Bowman, Peter Davies and Edward Goodwin (eds), *Routledge Handbook of Biodiversity and the Law* (Routledge 2017) 135.

[32] Michael Halewood and Kent Nnadozie, 'Giving Priority to the Commons: The International Treaty on Plant Genetic Resources for Food and Agriculture' in Geoff Tansey and Tasmin Rajotte (eds), *The Future Control of Food* (Routledge 2012) 115.

[33] Elsa Tsioumani, 'International Treaty on Plant Genetic Resources for Food and Agriculture: Legal and Policy Questions from Adoption to Implementation' (2004) 15(1) *Yearbook of International Environmental Law* 119.

[34] Tatiana Rivera and others, 'How the International Treaty on Plant Genetic Resources for Food and Agriculture Can Support Effective Germplasm Exchange: Four Colombian Case Studies' (2026) *Food Security* 1.

[35] Priscilla Claeys and Marc Edelman, 'The United Nations Declaration on the Rights of Peasants and Other People Working in Rural Areas' (2020) 47(1) *Journal of Peasant Studies* 1.

[36] Marco Alabrese, Adriana Bessa, Michele Brunori and Pier Filippo Giuggioli (eds), *The United Nations' Declaration on Peasants' Rights* (Routledge 2022).

[37] Alexandra Lesnikowski, James Ford, Robbert Biesbroek, Lea Berrang-Ford, Melissa Maillet, Marina Araos and Sarah E Austin, 'What Does the Paris Agreement Mean for Adaptation?' (2017) 17(7) *Climate Policy* 825.

[38] Jon Hellin, Edward Fisher, Mark Taylor, Shweta Bhasme and Ana Maria

food security is not merely an agricultural objective but also a legal entitlement. States therefore have obligations to support climate adaptation, protect farmers' rights, and promote sustainable agricultural development.

PLANT BREEDING INNOVATIONS FOR CLIMATE-RESILIENT AGRICULTURE

Plant breeding has historically contributed to agricultural productivity and remains central to climate adaptation.[39] The development of climate-resilient varieties helps maintain food production under adverse environmental conditions and supports the realization of the right to food.[40] Conventional breeding remains the foundation of crop improvement.[41] By utilizing landraces, wild relatives, and germplasm collections, breeders develop varieties with improved tolerance to heat, drought, salinity, pests, and diseases.[42] Conventional approaches are widely accepted and compatible with diverse farming systems, although they can be time-consuming.[43] Marker-assisted selection (MAS) uses DNA markers linked to desirable traits, allowing breeders to select superior plants without waiting for phenotypic expression.[44] MAS improves efficiency, shortens breeding cycles, and supports the development of stress-tolerant varieties.[45] [46] Genome-Wide Association Studies (GWAS) identify genomic regions associated with complex traits. GWAS has been widely used to discover genes related to drought tolerance, heat tolerance, disease resistance, root architecture, and yield

Loboguerrero, 'Transformative Adaptation: From Climate-Smart to Climate-Resilient Agriculture' (2023) 4(1) *CABI Agriculture and Bioscience* 30.

[39] SC Chapman, S Chakraborty, MF Dreccer and SM Howden, 'Plant Adaptation to Climate Change—Opportunities and Priorities in Breeding' (2012) 63(3) *Crop and Pasture Science* 251.

[40] Rajesh Kumar and others, 'Traditional and Emerging Climate-Resilient Agricultural Practices for Enhancing Food Production and Nutritional Quality' in *New Frontiers in Plant-Environment Interactions: Innovative Technologies and Developments* (Springer Nature Switzerland 2023) 551.

[41] Prem P Jauhar, 'Modern Biotechnology as an Integral Supplement to Conventional Plant Breeding: The Prospects and Challenges' (2006) 46(5) *Crop Science* 1841.

[42] Eleni Lazaridi and others, 'Crop Landraces and Indigenous Varieties: A Valuable Source of Genes for Plant Breeding' (2024) 13(6) *Plants* 758.

[43] National Research Council and Committee on the Role of Alternative Farming Methods in Modern Production Agriculture, *Alternative Agriculture* (National Academies Press 1989).

[44] Guo-Liang Jiang, 'Molecular Marker-Assisted Breeding: A Plant Breeder's Review' in Rajeev K Varshney and Roberto Tuberosa (eds), *Advances in Plant Breeding Strategies: Breeding, Biotechnology and Molecular Tools* (Springer International Publishing 2015) 431.

[45] X Li and others, 'Integrating Genetic Diversity and Agronomic Innovations for Climate-Resilient Maize Systems' (2025) 14(10) *Plants* 1552.

[46] H Gao and H Li, 'Marker-Assisted Selection (MAS) in Soybean Breeding' (2025) 16 *Molecular Plant Breeding*.

stability.[47] These insights facilitate precision breeding and accelerate crop improvement.

Genomic selection uses genome-wide marker information to predict breeding values.[48] Unlike MAS, which targets specific loci, genomic selection captures small effects across the genome. It is especially useful for complex climate-resilience traits and can significantly increase genetic gain. Speed breeding accelerates crop improvement by manipulating environmental conditions such as photoperiod and temperature.[49] Multiple generations can be produced each year, reducing variety development time. When combined with MAS, GWAS, genomic selection, and gene editing, speed breeding dramatically enhances breeding efficiency. Gene editing, particularly CRISPR-based technologies, allows precise modification of plant genomes. Applications include drought tolerance, disease resistance, nutritional improvement, and yield enhancement.[50]

While highly promising, gene editing raises regulatory and ethical questions regarding biosafety, intellectual property, and public acceptance.[51] Climate-resilient breeding has produced important advances in wheat, rice, maize, and oilseed crops. Heat-tolerant wheat, drought-tolerant maize, salinity-tolerant rice, and resilient mustard varieties demonstrate the practical value of breeding innovations. Agricultural biodiversity remains the foundation of all breeding efforts.[52] Gene banks and germplasm collections preserve genetic resources needed for future adaptation.[53] Conserving biodiversity is therefore both a scientific necessity and a policy priority. Plant breeding directly contributes to food availability, income stability, and resilience. As

[47] W Huang, 'The Current Situation and Future of Using GWAS Strategies to Accelerate the Improvement of Crop Stress Resistance Traits' (2024) 15 *Molecular Plant Breeding*.
[48] Zewdie A Desta and Rodomiro Ortiz, 'Genomic Selection: Genome-Wide Prediction in Plant Improvement' (2014) 19(9) *Trends in Plant Science* 592.
[49] M Ćeran and others, 'Genomics-Assisted Speed Breeding for Crop Improvement: Present and Future' (2024) 8 *Frontiers in Sustainable Food Systems* 1383302.
[50] F Chen and others, 'Recent Advances of CRISPR-Based Genome Editing for Enhancing Staple Crops' (2024) 15 *Frontiers in Plant Science* 1478398.
[51] Anika Shukla-Jones, Steffi Friedrichs and David E Winickoff, 'Gene Editing in an International Context: Scientific, Economic and Social Issues across Sectors' (OECD Science, Technology and Industry Working Papers No 2018/04, OECD Publishing 2018).
[52] Helen Anne Curry, 'Breeding Uniformity and Banking Diversity: The Genescapes of Industrial Agriculture, 1935–1970' (2017) 10(1) *Global Environment* 83.
[53] MM Aribi, 'Plant Gene Banks: Conservation of Genetic Resources' in *Sustainable Utilization and Conservation of Plant Genetic Diversity* (Springer Nature Singapore 2024) 753.

climate risks intensify, breeding innovations should be recognized not only as scientific achievements but also as mechanisms for advancing human rights and sustainable development.

SUSTAINABLE AGRIBUSINESS AND EQUITABLE TECHNOLOGY DISSEMINATION

Scientific innovation generates solutions, but agribusiness systems determine whether those solutions reach farmers and consumers.[54] Sustainable agribusiness therefore plays a critical role in climate-resilient agriculture. Agribusiness encompasses input supply, seed production, financing, extension services, processing, transportation, marketing, and retailing.[55] Climate change affects every stage of these value chains. Strengthening resilience across the chain is essential for maintaining food security.[56]

A rights-based approach to agribusiness recognizes that business activities influence access to food, employment, health, and development.[57] The United Nations Guiding Principles on Business and Human Rights emphasize the state duty to protect, corporate responsibility to respect human rights, and access to remedies.[58] Climate-resilient value chains require reliable access to improved seeds, efficient production systems, effective storage, resilient transportation networks, and sustainable market systems.[59] [60] Reducing post-harvest losses and strengthening infrastructure can significantly improve food availability.[61]

Seed systems are particularly important because they determine whether

[54] CJ Shultz and MR Edwards, 'Reframing Agribusiness: Moving from Farm to Market Centric' (2005) 23(1) *Journal of Agribusiness*.
[55] Jay T Akridge, Jeremy C Foltz, Elizabeth A Yeager, Brian E Brewer and Timothy Malone, *Agribusiness Management* (Routledge 2025).
[56] Kyle F Davis, Shauna Downs and Jessica A Gephart, 'Towards Food Supply Chain Resilience to Environmental Shocks' (2021) 2(1) *Nature Food* 54.
[57] Molly D Anderson, 'Rights-Based Food Systems and the Goals of Food Systems Reform' (2008) 25(4) *Agriculture and Human Values* 593.
[58] Maria Mercedes Barnes, 'The United Nations Guiding Principles on Business and Human Rights, the State Duty to Protect Human Rights and the State-Business Nexus' (2018) 15(2) *Revista de Direito Internacional* 41.
[59] BF Chirombo and I Pangapanga-Phiri, 'Adaptive Practices and Governance Structures for Building Climate Resilient Agrifood Systems Value Chains in Sub-Saharan Africa' (2025) 6(1) *Discover Sustainability* 879.
[60] A Alawode, 'The Role of Agricultural Value Chains in Enhancing Food Security and Economic Development' (2025) *International Research Journal of Modernization in Engineering Technology and Science*.
[61] B Nath, G Chen, CM O'Sullivan and D Zare, 'Research and Technologies to Reduce Grain Postharvest Losses: A Review' (2024) 13(12) *Foods* 1875.

climate-resilient varieties reach farmers.[62] Formal systems provide quality assurance and large-scale distribution, while informal systems support affordability, biodiversity conservation, and local adaptation.[63] Integrating both systems can improve accessibility and resilience. Technology adoption depends on profitability, institutional support, social acceptance, and risk perceptions. Farmers are more likely to adopt innovations when they have access to extension services, training, finance, and reliable information.[64] [65] Digital agriculture is transforming agricultural management. Mobile advisory services, climate information systems, remote sensing, and artificial intelligence can improve decision-making and resilience.[66] However, unequal access to digital infrastructure may widen existing disparities. Sustainable supply chain management seeks to balance economic efficiency with environmental and social objectives.[67] Increasingly, businesses are adopting environmentally responsible practices, supporting fair labor standards, and promoting community development.[68]

Public-private partnerships are valuable mechanisms for accelerating agricultural innovation.[69] Collaborative initiatives involving governments, research institutions, universities, civil society organizations, and private enterprises can facilitate technology transfer, capacity building, and infrastructure development. Environmental, Social, and Governance (ESG) frameworks provide tools for aligning

[62] Niels P Louwaars and G Manicad, 'Seed Systems Resilience—An Overview' (2022) 1(4) *Seeds* 340.
[63] Willem S de Boef, Hannes Dempewolf, JM Byakweli and JMM Engels, 'Integrating Genetic Resource Conservation and Sustainable Development into Strategies to Increase the Robustness of Seed Systems' (2010) 34(5) *Journal of Sustainable Agriculture* 504.
[64] Mahama A Akudugu, Paul K Nkegbe, Charles A Wongnaa and KK Millar, 'Technology Adoption Behaviors of Farmers during Crises: What Are the Key Factors to Consider?' (2023) 14 *Journal of Agriculture and Food Research* 100694.
[65] George W Norton and Jeffrey Alwang, 'Changes in Agricultural Extension and Implications for Farmer Adoption of New Practices' (2020) 42(1) *Applied Economic Perspectives and Policy* 8.
[66] K Khatana and others, 'Adaptation to Achieve Climate Resilience Through Advanced Techniques like Remote Sensing and Machine Learning' in *Climate Resilience: Impact of Quantum Computing and Artificial Intelligence on Urban Planning* (Springer Nature Switzerland 2025) 293.
[67] SS Panigrahi, BB Bahinipati and V Jain, 'Sustainable Supply Chain Management: A Review of Literature and Implications for Future Research' (2019) 30(5) *Management of Environmental Quality* 1001.
[68] Peter A Heslin and JD Ochoa, 'Understanding and Developing Strategic Corporate Social Responsibility' (2008) 37 *Organizational Dynamics* 125.
[69] David J Spielman, Frank Hartwich and Klaus von Grebmer, 'Public–Private Partnerships and Developing-Country Agriculture: Evidence from the International Agricultural Research System' (2010) 30(4) *Public Administration and Development* 261.

business strategies with sustainability goals.[70] By integrating environmental stewardship, social responsibility, and transparent governance, agribusinesses can contribute to resilient and inclusive food systems.[71] Smallholder inclusion remains essential. Contract farming, producer organizations, and inclusive business models can improve market access, strengthen bargaining power, and enhance rural livelihoods.[72] [73] Sustainable agribusiness therefore serves as a bridge between scientific innovation and human development outcomes.[74]

CHALLENGES, ETHICAL CONCERNS, AND POLICY RECOMMENDATIONS

Despite significant progress, climate-resilient agriculture faces numerous challenges. One major issue concerns the relationship between intellectual property rights and farmers' rights. Intellectual property protections encourage innovation and private-sector investment, but excessive protection may restrict access to improved seeds, increase costs, and limit traditional seed-saving practices.[75] [76]Policymakers must balance incentives for innovation with accessibility and equity. Technological inequality presents another challenge. Advanced breeding technologies are concentrated in a limited number of countries and institutions.[77] Resource-poor farmers often face barriers related to cost,

[70] T Dathe, M Helmold, R Dathe and I Dathe, *Implementing Environmental, Social and Governance (ESG) Principles for Sustainable Businesses: A Practical Guide in Sustainability Management* (Springer Nature 2024).
[71] A Zavhorodnii and others, 'Selective Management in Sustainable Agri-Food Systems' (2024) 13(4) *TEM Journal* 2931.
[72] Rachel Smalley, *Plantations, Contract Farming and Commercial Farming Areas in Africa: A Comparative Review* (Future Agricultures Working Paper No 55, 2013).
[73] Prabhu Pingali, Anaka Aiyar, Mathew Abraham and Andaleeb Rahman, 'Linking Farms to Markets: Reducing Transaction Costs and Enhancing Bargaining Power' in *Transforming Food Systems for a Rising India* (Springer International Publishing 2019) 193.
[74] Jennifer Gaffney, Matthew Challender, Kevin Califf and Karen Harden, 'Building Bridges between Agribusiness Innovation and Smallholder Farmers: A Review' (2019) 20 *Global Food Security* 60.
[75] Margaret Mascarenhas and Lawrence Busch, 'Seeds of Change: Intellectual Property Rights, Genetically Modified Soybeans and Seed Saving in the United States' (2006) 46(2) *Sociologia Ruralis* 122.
[76] Niels P Louwaars and others, *Impacts of Strengthened Intellectual Property Rights Regimes on the Plant Breeding Industry in Developing Countries* (Report commissioned by the World Bank, Wageningen 2005).
[77] Derek Byerlee and Keith Fischer, 'Accessing Modern Science: Policy and Institutional Options for Agricultural Biotechnology in Developing Countries' (2002) 30(6) *World Development* 931.

infrastructure, information, and technical support.[78] [79] Without targeted interventions, innovations may disproportionately benefit wealthier producers.

Emerging technologies such as gene editing raise ethical and regulatory concerns. Questions regarding biosafety, environmental impacts, consumer acceptance, and governance require careful consideration. Regulatory systems should balance precaution with the need to encourage beneficial innovation. Climate justice highlights unequal exposure to climate risks. Smallholder farmers, despite contributing little to global emissions, often bear the greatest burdens.[80] Adaptation policies should therefore prioritize vulnerable populations and promote equitable access to resources and technologies.

Governance challenges include institutional fragmentation, regulatory uncertainty, and inadequate accountability mechanisms.[81] [82] Effective climate-resilient agriculture requires coordination among agriculture, environment, trade, research, and rural development agencies. Financing remains a critical constraint. Public investment supports research, germplasm conservation, extension services, and capacity building. Private investment contributes innovation and commercialization. International climate finance can further support adaptation efforts, particularly in developing countries.

Key policy recommendations include:

[78] S Vasavi and others, 'Challenges and Strategies of Resource Poor Farmers in Adoption of Innovative Farming Technologies: A Comprehensive Review' (2025) 227 *Agricultural Systems* 104355.
[79] O Shemfe and S Modirwa, 'Barriers to the Adoption of Information and Communication Technology (ICT) for Accessing Agricultural Information by Small-Scale Farmers in Mahikeng, Northwest Province' (2026) 54(1) *South African Journal of Agricultural Extension* 190.
[80] John A Dixon, David P Gibbon and Aidan Gulliver, *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World* (Food and Agriculture Organization 2001).

[81]J Li, 'Governing High-Risk Technologies in a Fragmented World: Geopolitical Tensions, Regulatory Gaps, and Institutional Barriers to Global Cooperation' (2026) 19(1) *Fudan Journal of the Humanities and Social Sciences* 113.
[82] Delia Rodrigo, Lorenzo Allio and Pedro Andres-Amo, *Multi-Level Regulatory Governance: Policies, Institutions and Tools for Regulatory Quality and Policy Coherence* (OECD Working Papers on Public Governance No 13, OECD Publishing 2009).

1. Adopting rights-based agricultural governance emphasizing participation, transparency, accountability, and non-discrimination.[83]
2. Strengthening public agricultural research, particularly in plant breeding, genomics, and climate adaptation.[84]
3. Expanding climate-resilient seed systems and supporting community seed banks.[85]
4. Enhancing extension services, credit access, insurance programs, and training for smallholder farmers.[86]
5. Promoting responsible agribusiness practices aligned with ESG principles and human rights standards.[87]
6. Strengthening public-private partnerships to accelerate innovation dissemination.[88]
7. Expanding international cooperation in research, technology transfer, capacity building, and climate finance.[89]
8. Promoting sustainable agricultural intensification through climate-smart practices, biodiversity conservation, and efficient resource management.[90]

These measures can help reconcile scientific innovation with equity, sustainability, and human rights objectives.

CONCLUSION

Climate change poses a profound threat to global food security and the

[83] Adriana Bessa, *The Normative Dimension of Food Sustainability: A Human Rights-Based Approach to Food Systems Governance* (Bern Open Repository and Information System 2019).
[84] G Galluzzi, A Seyoum, Michael Halewood, Isabel Lopez Noriega and EW Welch, 'The Role of Genetic Resources in Breeding for Climate Change: The Case of Public Breeding Programmes in Eighteen Developing Countries' (2020) 9(9) *Plants* 1129.
[85] Ronnie Vernooy, Bhuwon Sthapit, Geoffrey Otieno, Pratap Shrestha and Anil Gupta, 'The Roles of Community Seed Banks in Climate Change Adaptation' (2017) 27(3) *Development in Practice* 316.
[86] NK Priya and others, 'The Important Role of Extension Services in Strengthening the Capacity of Farmers' Resilience to Climate Change in India' (2025) 47(3) *Journal of Experimental Agriculture International* 204.
[87] DJ Julkovski, S Sehnem and EAF Stenger, 'ESG Guidelines for Agribusiness: Actions and Opportunities in Integration Systems' (2023) 17(4) *Revista Pensamento Contemporâneo em Administração* 74.
[88] S Subrahmanyam, 'Strategic Collaboration and Partnerships in R&D for Innovation' in *Research and Development Practices in Innovation* (IGI Global Scientific Publishing 2025) 283.
[89] Y Chen, F Wu and D Zhang, 'Global Climate Finance Architecture: Institutional Development' in *Climate Finance: Supporting a Sustainable Energy Transition* (Springer Nature Singapore 2024) 51.
[90] W Kabato, GT Getnet, T Sinore, A Nemeth and Z Molnár, 'Towards Climate-Smart Agriculture: Strategies for Sustainable Agricultural Production, Food Security, and Greenhouse Gas Reduction' (2025) 15(3) *Agronomy* 565.

realization of fundamental human rights. Rising temperatures, water scarcity, salinity, land degradation, and emerging pests and diseases undermine agricultural productivity and disproportionately affect vulnerable populations.

This article has argued that climate-resilient agriculture should be understood as a human-rights imperative. The realization of the right to food increasingly depends upon the capacity of societies to develop resilient agricultural systems that can withstand environmental uncertainty while ensuring equitable access to resources and opportunities.

International legal frameworks, including the UDHR, ICESCR, CBD, ITPGRFA, UNDROP, and the Paris Agreement, establish a strong normative foundation linking food security, climate resilience, and human rights. These instruments require states to protect vulnerable populations and promote sustainable agricultural development.

Plant breeding innovations—including conventional breeding, marker-assisted selection, GWAS, genomic selection, speed breeding, and gene editing—provide powerful tools for developing resilient crop varieties. These technologies support food availability, agricultural productivity, and climate adaptation.

However, innovation alone is insufficient. Sustainable agribusiness systems are essential for disseminating technologies, strengthening value chains, improving market access, and promoting inclusive development. Responsible business practices, effective seed systems, digital technologies, and collaborative partnerships all contribute to resilient food systems.

Significant challenges remain, including intellectual property disputes, technological inequalities, governance gaps, financing constraints, and climate justice concerns. Addressing these issues requires integrated policies that balance innovation with equity and sustainability.

Ultimately, climate-resilient agriculture represents a convergence of science, law, and development policy. By integrating plant breeding innovations, rights-based legal frameworks, and sustainable agribusiness strategies, governments and stakeholders can strengthen food security, enhance resilience, and promote human dignity in an era of climate uncertainty.