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Review article

Cultivating Resilience: Integrating Sustainability, Technology, and Equity for Climate-Resilient Agriculture and Global Food Security

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ABSTRACT

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Climate change poses an increasingly severe threat to global food security, particularly in vulnerable and resource-constrained regions. Addressing this challenge requires a holistic and multidisciplinary approach that integrates sustainable agricultural practices such as crop diversification and agroecology with advanced technologies including genomics, phenomics, enviromics, crop modeling, artificial intelligence, and statistical methods. However, technological innovation alone is insufficient. Ensuring equitable access, education, and inclusive policies is critical to translating scientific advancements into real-world impact. This paper emphasizes the importance of integrating scientific, technological, and social dimensions to build resilient agricultural systems and carve a path toward sustainable, climate-resilient food systems for the future.

Introduction

In an era defined by the profound impacts of climate change, the imperative to foster resilience has never been more pressing. As the global population is projected to reach 9.7 billion by 2050 and 10.34 billion by 2100 (UN 2023), the need to grow more food becomes even more pronounced (Macrotrends 2023). This demographic projection underscores the urgency of addressing the challenges posed by climate change, which not only threatens the stability of agricultural systems but also exacerbates issues of food security on a global scale. With the increasing population, we will have to grow as much as 56% more food in 2050 than we produced in 2010 (Hanson et al. 2018). However, research suggests that climate change has reduced 3.8% and 5.5% of global maize and wheat production, respectively (Lobell et al. 2011, Yadav et al. 2019), and the global yield production may even be reduced to 50% by 2050 in some parts of the globe (IPBES 2018). These impacts are not only regional but global in scale, affecting food availability, accessibility, and stability, particularly in resource-limited and climate-sensitive regions. As our planet grapples with shifting weather patterns, rising temperatures, and escalating environmental challenges, the intricate web connecting sustainable agriculture and global food security becomes increasingly complex (Yadav et al. 2019).

As per the UN, 70% of the 49 least developed countries reside in rural areas and highly depend on agriculture for their livelihood (UN 2009). Climate change will escalate the current state of water stress in some of these poorest, least developed countries, which will highly compromise the agricultural production and food security in the region (UN 2009). The symbiotic relationship between climate change and agriculture is undeniable, as the very ecosystems that support our food production are under siege from the consequences of a warming planet (Calvin et al. 2023). Concurrently, the repercussions are felt on a global scale, reverberating through the intricate tapestry of food security. As we navigate this intricate terrain, it becomes clear that sustainable agricultural practices are not merely an option but a necessity for mitigating the impact of climate change and ensuring a stable food supply for a burgeoning global population.

Climate change has resulted in substantial damage to the ecosystem, resulting in the loss of hundreds of local plant species (Lepcha 2024), and an irreversible effect on the hydrological system driven by the unequivocal thawing of glaciers and Arctic ice (Calvin et al. 2023). At the ecosystem level, the loss of local exotic plant species can result in a surge of risk of invasion by alien plant species and subsequent degradation of local biodiversity (Shelef et al. 2017). This intricate tapestry of climate change has inherently affected crops and livestock by altering temperature, altering growing periods, or other climatic extremes. On average, 30% and 60% of the global ruminant meat and milk production originates from the livestock fed on pastureland or meadow (Godde et al. 2021). The nutrient concentration of pasture is reduced with the increased average growing temperature and increased water stress (Hidalgo-Galvez 2023). Land degradation, biodiversity loss, and climate change have been listed as the most important aspects to be addressed by the IPBES (IPBES 2018). In over three decades from now, global crop production is predicted to reduce by an average of 10% and up to 50% in some regions of Central and South America, sub-Saharan Africa, and Asia due to the combined effect of land degradation and climate change (IPBES 2018). Given these critical circumstances, the need to feed the increasing population with shrinking production resources has created an urgent need to develop new sustainable ways of farming. In this context, cultivating resilience at the nexus of climate change, sustainable agriculture, and global food security emerges as a critical path forward.

This paper aims to forge a path toward a future where the world's food systems not only adapt to the evolving climate but thrive in harmony with the environment. Resilience encompasses both **reactive strategies**, which involve responding to the impacts of climate change, and **proactive strategies**, which aim to reduce its underlying causes. In short, this review explores how climate change, sustainable agriculture, and global food security are connected. Termed "Cultivating Resilience," our inquiry seeks not only to dissect the challenges posed by these interwoven factors but also to illuminate the pathways toward a more resilient and sustainable future for our global food systems.

The study is based on the literature review and the empirical findings of the author(s). A wide range of sources was analysed, including peer-reviewed journal articles, academic books, conference proceedings, newspapers, blogs, and web profiles of national, international, governmental, and non-governmental organizations were thoroughly studied to gather relevant information. All these materials were critically studied to understand and extract relevant information on climate-resilient agriculture, sustainability practices, technological interventions, and global food security.

The impact of climate change on agriculture

Agricultural productivity highly depends upon the intricate balance between the different climatic parameters. Global climate change has altered rainfall patterns, fluctuated temperature, and relative humidity, resulting in unpredictable drought and soil moisture (EU 2023, Aydinalp et al. 2008). The effect of climate change has been more revealing in the recent decade.

Fluctuations in average **temperature** have been shown to alter the productivity of different food crops under different production systems (Rasul et al. 2011, Zhao et al. 2017). Since 1880, the Earth's average global temperature has risen by approximately 1°C, with projections indicating a further warming of around 1.5°C by 2050 and a potential increase of 2-4°C thereafter (WDNR 2024, Masson-Delmotte et al. 2019). Under this scenario of continuous global temperature rise, the potential impacts on **food crop productivity** become a significant concern. Higher night temperatures have been reported to result in a surge in respiration and thereby reduce grain yield in wheat and other winter crops (Rasul et al. 2011). In the absence of CO2 fertilization effects, successful adaptation, and genetic enhancements, a one-degree Celsius rise in the global mean temperature would, on average, result in a 6.0% decline in wheat yields, a 3.2% decline in rice yields, a 7.4% decline in maize yields, and a 3.1% drop in soybean yields (Zhao et al. 2017). However, the world will still need a 70 to 100% rise in food production to sustain the growing population by 2050 (Gomiero et al. 2011). Farmers in developing countries are most affected by warming as they are less able to adapt and are more vulnerable to food insecurity resulting from poor agricultural production (Mendelsohn 2009).

Furthermore, erratic **rainfall** resulting from climate change has resulted in unpredictable floods and the destruction of crops and livestock. The sudden flood resulting from the erratic rain swept away to harvest of 325,258 tonnes of paddy worth around 62 million USD in Nepal in 2021 (Prasain 2021). Sudden floods triggered by erratic rainfall in Pakistan destroyed almost half of the cropland, destroying at least 3.6 million acres of crops/orchards across the country in 2022, threatening national food security (Gul 2022). Farmers in developing nations like Nepal, India, Pakistan, and Afghanistan face significant vulnerability to unpredictable rainfall patterns and sudden floods, influenced by the region's topography.

Global warming as a result of climate change is making dry regions drier and wet regions wetter. According to the World Health Organization (WHO), around 55 million people worldwide experience the impact of **droughts** annually, making drought the most significant threat to both livestock and crops across nearly all regions (WHO 2024). Water scarcity resulting from the severe drought impacts 40% of the world's population, particularly in developing countries, and as many as 700 million people are at risk of being displaced as a result of drought by 2030 (WHO 2024). The study presented by Santini (2022) underscores the consistent global impact of complex drought patterns, such as magnitude, frequency, duration, and timing, on key crops like winter wheat, spring wheat, soybean, and the main maize season, revealing vulnerability hotspots and emphasizing escalating yield losses under extreme multiscale drought conditions.

Sudden **pest outbreaks** due to rising temperatures have raised concern among many entomologists and biologists. A sudden invasion by desert locusts in 2020 in Pakistan resulted in a state of national emergency, damaging a major portion of agricultural production (Al Jazeera 2020). Pest outbreak is influenced when the environmental component of the plant disease triangle is compromised, leaving plants more susceptible to attack by virulent pathogens and pests (Figure 1). Global climate warming could **trigger** an expansion of the geographic range of insects, increase the chances of overwintering survival, increase the number of generations, and increase the risk of invasive insect species (Skendžić 2021). Integrated pest management is a holistic approach of suppressing pest populations below the threshold level by adopting every possible pest control tactic (Gyawali et al. 2023). Although the IPM strategies appear promising in papers and policies, the adoption and practicality of these strategies are challenging, as explained by Deguine et al. (2021).

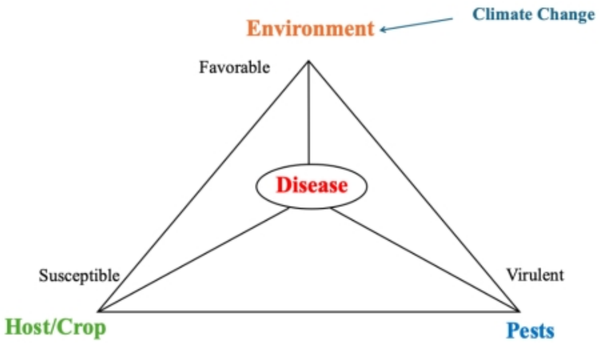

Figure 1. The Disease triangle. The disease triangle represents the interaction between a susceptible host, a virulent pathogen, and a conducive environment, each essential for disease development. Climate change can disrupt this balance, often creating more favourable conditions for pathogens and increasing the risk of disease outbreaks (Garrett et al. 2006, Skendzic 2021).

Sustainable agriculture as a solution

Sustainable Agriculture is a farming technique that focuses on producing food in an **environmentally** friendly, **economically** viable, and **socially** responsible manner by judicious exploitation of limited resources with consideration for **future** needs. Sustainable agricultural systems also depend upon the rational manipulation of the farming components and their interaction to reduce chemical inputs and promote soil health, water conservation, biodiversity, and the overall well-being of ecosystems (Edwards 2020).

Sustainable farming practices, such as the use of cover crops and catch crops, reduction in tillage, augmenting plant diversity, and fertilization with organic materials, help sequester carbon in the soil, reducing greenhouse gas emissions and mitigating climate change (IPOL 2022). As per the IPOL 2022, approximately 55% of the climate mitigation potential in the agricultural sector of 27 European countries lies with agricultural soils and manure management. Approximately 78 Gt of carbon has been released into the atmosphere as a result of the degradation of one-third of the world's soil, which has significantly contributed to global warming (FAO 2017). **Cover crops** can sequester up to 17 Gt of carbon worldwide, Agroforestry system can sequester around 7 tonnes of carbon per hectare per year, and combined application of organic manure with chemical fertilizer can sequester 43% higher soil organic carbon compared to the solo use of inorganic fertilizer in China's arable land (FAO 2017). The combination of **zero-tillage** systems and cover crop management improves soil organic carbon and boosts productivity in soybeans (Wulanningtyas 2021). Conservation agriculture increases wheat yield by 20–40 kg/ha, maize by 10–20 kg/ha, and cowpeas by 0.5–1 kg/ha (Lal 2004). Soil microbial communities can contribute to carbon sequestration and greenhouse gas mitigation, as highlighted by Arora and Chaudhary (2021), and their crucial role in both emissions and potential climate change mitigation strategies. The carbon capture and sequestration (CCS) technology, as explained by Singh et al. (2021), and the advanced bibliometric analysis proposed by Malekli et al. (2022) are some of the promising CO_2 Capture and Storage strategies for carbon sequestration and diminishing greenhouse gas emissions. However, conservation agriculture, adopting zero tillage, cover crops, incorporating organic fertilisers, and crop diversity are easy and reliable practices for improving carbon sequestration for the rural community, from the point of food security and sustainable agriculture (Bhatia et al. 2022).

Various forms of **conservation tillage,** such as zero tillage, two times tillage, and strip tillage, conserve 9.25%, 10.05%, and 35.54% of soil moisture, respectively, as compared to conventional tillage practice (Handiso et al. 2023). For every

1 % rise in soil organic matter, the available soil water per acre can rise by up to 20,000 gallons (Bhadha et al. 2017). Rainwater harvesting and aquaponics also enhance water efficiency and climate resilience (Blidariu and Grozea 2011). **Aquaponics** also boosts the growth of both fish and plants, aligning with the millennial focus on sustainability, resource efficiency, and environmental conservation (Gyawali et al. 2019, Knaus and Palm 2017). However, the **adoption** of such practices by farmers remains uneven due to factors such as limited access to resources, technical knowledge, or initial investment costs. In developing regions, uptake is often higher when farmers observe clear short-term benefits like reduced input costs, improved yields, or community-based support systems (Knowler and Bradshaw 2007).

Climate resilience crops are those crop genotypes that are competent and perform better than other plant genotypes under the same biotic and abiotic stresses driven by rising climate change (Figure 2). On the brink of climate change and increasing hunger and poverty, developing climate-resilient crops should be prioritized for staple crops rich in carbohydrates, such as paddy, wheat, millet, sorghum, maize, etc. Diversification of crops provides smallholder farmers with a diverse diet and improves their income and nutrition security (Mango 2018). Diversification of crops enhances pest and disease suppression, climate variability buffering, and mitigation (Lin 2011). Crop diversification minimizes soil loss and water level depletion by providing proper cover to the open ground and improving soil biodiversity and thus soil nutrition. Additionally, it fosters associated biodiversity by creating a more heterogeneous habitat that supports beneficial organisms such as pollinators, natural pest predators, and decomposers, thereby strengthening ecological balance and reducing dependence on chemical inputs.

In addition to crop diversification, **the use of localized agrobiodiversity and genetic diversity** plays a pivotal role in promoting sustainable and resilient agriculture. **Cultivar mixtures,** which are the practice of growing multiple genotypes of the same crop in a single field, can significantly reduce disease outbreaks, improve yield stability, and buffer against environmental stress (Zhu et al. 2000, Mundt 2002). Leveraging **locally adapted landraces** and traditional crop varieties has seen to enhance resilience to climatic and ecological conditions while preserving valuable genetic traits for future breeding (FAO 2010). Moreover, **integrated farming systems**, which combine crop production with livestock, aquaculture, or agroforestry, can improve resource use efficiency, diversify farm income, and reduce vulnerability to climate shocks (Pretty et al. 2011). Harnessing agrobiodiversity using different systems, both at the genetic and systems level, is thus a low-cost, ecologically sound, and farmer-centered approach to building resilience in the face of climate change.

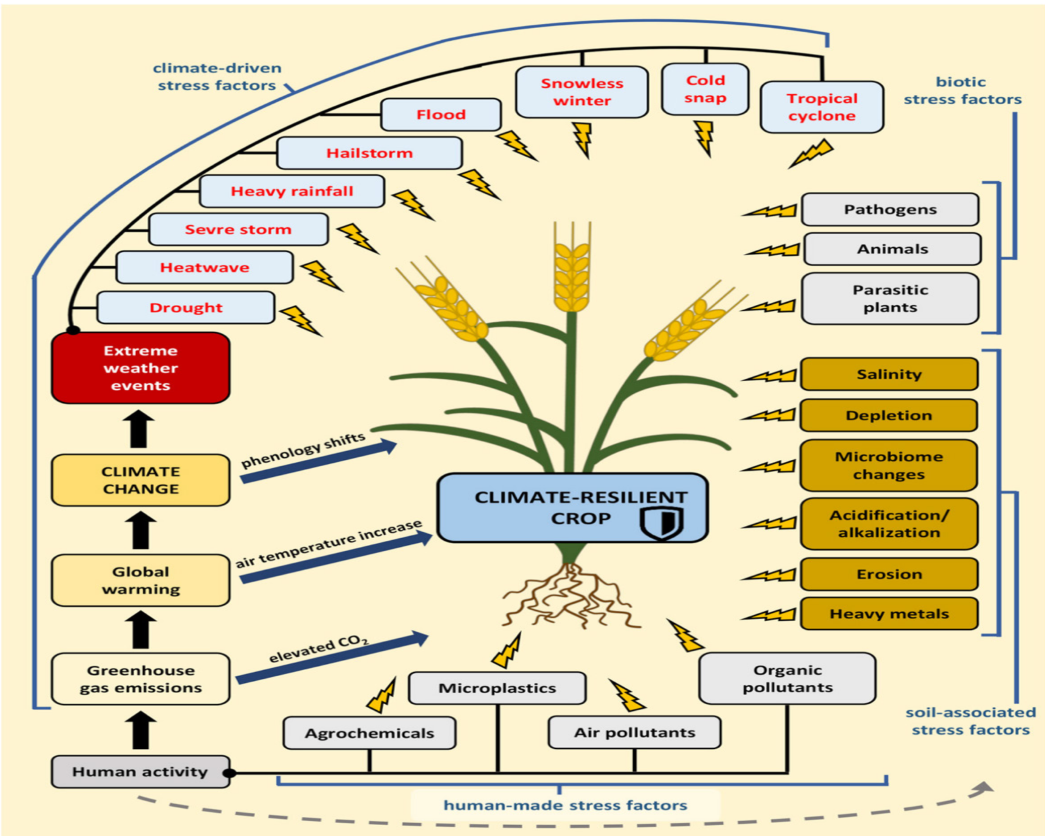

Figure 2. Systematic representation of climate-resilience crop (Kopeć 2024)

In response to climate-driven **pest pressures** discussed in Figure 1. Integrated Pest Management (**IPM**) offers a sustainable and adaptive approach. It combines multiple control strategies, including biological, cultural, mechanical, and chemical control methods, to keep pest populations below economic thresholds while minimizing environmental harm

(Ahmad 2024,requiring strategies that are both effective and sustainable. Integrated Pest Management (IPM Gyawali et al. 2023). It helps to promote ecological balance and reduces chemical use in the field, which loses efficacy under changing climate conditions. Another management practice called Ecological Pest Management (**EPM**), which is based on IPM but emphasizes the restoration of ecological processes like conservation of natural enemies to naturally suppress pests. However, despite the potential of IPM and EPM, widespread adoption remains limited due to socio-economic, institutional, and knowledge barriers (Deguine et al. 2021). To scale up implementation, **policies** must prioritize farmer training, strengthen extension services, and incentivize climate-resilient pest management practices.

Case studies of sustainable agriculture from different regions

Across different continents, sustainable agriculture has been adapted to local environmental and socio-economic realities. Several initiatives stand out for their scale, innovation, and community impact. Some of those are discussed here.

Europe: Spain – Conservation agriculture in Andalusia

In southern Spain, over 2.2 million hectares are managed under conservation agriculture. Farmers apply minimal soil disturbance, crop rotation, and cover cropping practices that have reduced erosion by 45%, improved soil organic matter, increased water-use efficiency (WUE) by 20-25%, and improved biodiversity indicators like pollinator species richness (Asin 2023). Also, Triviño-Tarradas et al. (2020) observed a 27.3% increment in crop yields within only 4 years of implementation of these soil conservation practices.

North America: United States – Community-driven sustainable farming

A nonprofit project in Vermont is transforming a 101-acre property into a model for climate-resilient agriculture and community education. The initiative integrates greenhouses for year-round cultivation, pollinator meadows to boost biodiversity, sustainable forestry, and small-scale animal husbandry. Educational programs engage the local community, promoting the adoption of sustainable practices and reinforcing the link between agriculture and environmental stewardship. (Sustainable Vermont Farming 2024).

South-east Asia: Nepal – Agroecology in Karnali Province

In Nepal's remote Karnali region, the Himalayan Permaculture Centre has led a decade-long agroecology initiative using low-input, appropriate technologies, reaching over 800 households and expanding across 10 districts (Yadav et al. 2023). Through agroforestry, organic soil management, and local cottage industries, the project has improved farm resilience and livelihoods by increasing 20-30% higher yields 20-30% increased gross income, benefit-cost ratio of 2.5 for medicinal plant cultivation (Evans 2020, Yadav et al. 2023)

Africa: Burkina Faso – Reviving traditional water management (Zaï technique)

Facing land degradation and water scarcity, farmers in Burkina Faso have revitalized the ancient Zaï method, which involves digging compost-filled pits to trap rainwater and restore barren land. Combined with improved seed systems and soil fertility management, this low-cost innovation has improved food security in arid regions (UNDP 2024). More importantly, even though this method was costlier mainly due to being labour intensive, the increased yield covered that way up with more than three times higher gross margin for zaï millet (101,085 FCFA) than the conventional system (23,030 FCFA) (Schuler et al. 2016)based on data gathered through two surveys in the\nOuahigouya region. A survey among 101 farmers concentrated\nmainly on adoption rates and household characteristics. Later, 16 farmers from the first survey were interviewed with respect to their adoption of the zaï technique for soil restoration. Farm data was collected to cover the farms' and households' expenses and revenues for the year 2011. Material and labor input, as well as the\nobtained yields, were analyzed using the economic farm model\nOLYMPE. The results reflect the positive economic benefits of zaï cereal production at field and farm level when compared to conventional cultivation, but also point out the constraints to its further\nexpansion. Despite higher input costs mostly related to external\nlabor, the increased yields led to a more than three times higher gross margin per hectare for zaï millet (101,085 FCFA.

Eastern Asia: Indonesia – Integrated, water-saving rice cultivation

In Indonesia, the national IPHA program based on SRI and AWD principles has been adopted across multiple provinces. Between 2002 and 2006, approximately **9,429 ha** were trials tested under the System of Rice Intensification (SRI), delivering an **average 78% yield increase** (~3.3 t/ha) alongside **40% reductions in water use**, **50% reduction in fertilizer**, and a **20% decrease in production costs (Hasan and Sato 2007)**. More recent field data show **up to 169% productivity gains** over conventional practices and **40% less irrigation water (Mallareddy et al. 2023)**. Alternate Wetting and Drying (**AWD**) alone has been shown to **reduce water use by 30–40%** and raise yields by **6–20%,** all while reducing methane emissions by up to **85%** (IRRI 2009)**.**

These diverse case studies serve as compelling evidence that sustainable agriculture is not a one-size-fits-all model but a dynamic set of practices that can be shaped to local ecological, economic, and cultural contexts. From the water-saving rice systems in Indonesia to agroecological transitions in Nepal and land restoration in Burkina Faso, each initiative demonstrates tangible gains in productivity, input efficiency, income, and resilience. Collectively, they highlight how climate-smart agriculture, grounded in local knowledge and supported by innovative technologies, can generate scalable, community-centered solutions that strengthen global food systems while safeguarding environmental health and livelihoods.

The role of technology in resilient agriculture

While the adoption of sustainable practices such as carbon and water management, diversification of crops, capacity building, IPM practices, and so on, as discussed in the above sections, lays a strong foundation for resilient agriculture, technology must not be overlooked in this era of rapid innovation in technology. In this section, we will discuss different technological advancements that can be leveraged to fight climate change and their use in developing resilient varieties that can perform well in an unknown future environment.

Climate-smart breeding and genomics

Breeding tools and techniques have always played a critical role in crop improvement by leveraging genetic diversity, experimental designs, crossing techniques, varietal selection, biotechnological approaches, phenotyping, crop management, genomic information, environmental information, and so on. Integrating novel techniques to assess resilient varieties across multiple environments can significantly enhance agricultural resilience.

The **traditional breeding approaches** are still in practice and can also play an important role in developing resilient varieties. Some of the practices involve bringing together diverse germplasm, making crosses, selecting desirable traits (such as drought resistance, high yield potential, reproductive performance of animals, growth rate and adaptability), phenotypic and molecular marker analysis, field trials, heritability, correlation, and direct-indirect effect estimation (Sah 2025, Abderrahmane and Abidine 2013, Ghimire et al. 2020), population improvement, participatory breeding (Sperling et al. 2001) and so on. The utilization of germplasm and gene banks around the world can be an effective way to bring important traits like drought, cold, disease, and stress resistance which are certainly needed traits for resilient agriculture (Wang et al. 2017). For bringing those traits, researchers have been using both traditional and modern breeding approaches; however, modern approaches can accelerate the process and might be able to fulfill the requirements of the growing population.

Modern genomic approaches are accelerating the breeding process and increasing precision. Innovative biotechnological tools can facilitate the introduction of cross-species traits into agriculturally important ones. The utilization of molecular markers linked to specific genes or loci associated with target traits (Marker Assisted Breeding) is also being globally utilized breeding strategy. **Marker assisted selection** (MAS) is a very important tool to track down and include traits that are controlled by a few major genes (qualitative genes) and for quantitative traits-those controlled by many genes ranging from a couple of genes to hundreds, genomic selection can be leveraged (Collard et al. 2005, Goddard and Hayes 2007, Foolad and and Panthee 2012)Solanum lycopersicum L., is the second most consumed vegetable crop after potato and unquestionably the most popular garden crop in the world. There are more varieties of tomato sold worldwide than any other vegetable crop. Most of the commercial cultivars of tomato have been developed through phenotypic selection and traditional breeding. However, with the advent of molecular markers and marker-assisted selection (MAS. The past couple of decades have been an era of genomic advancement, which has led to much cheaper genotyping facilities and made possible the integration of genomic data into plant and animal improvement. Wallace et al. (2018) discussed different breeding versions, and soon the ability to combine any known alleles to obtain a desired combination (Breeding 4.0) will be achieved for many crops, which would be possible due to biotechnological advancements and the use of advanced phenotyping and machine learning approaches. The paper also mentions Breeding 5.0, which is too far from the current research but would be a key in helping fight climate change issues in the future. The time has come to explore phenomics and utilize the knowledge and information we can gather from high-throughput phenotyping (**HTP**) of plants and animals.

Digital agriculture

Digital agriculture is transforming the way we understand, manage, and optimize agricultural systems by integrating cutting-edge sensing technologies, data analytics, and decision support tools. At the heart of this transformation lies genomics, phenomics, as well as enviromics. Genomics deciphers the genetic makeup of crops, phenomics enables high-throughput measurement of observable traits, and enviromics captures environmental variability through sensor networks and modeling. Together, these fields help unravel the complex interactions between genotype, environment, and phenotype (G×E×P), enabling more precise, predictive, and resilient agricultural decision-making.

While genomics has been flourishing for more than two decades, phenomics has more recently emerged as a promising field in agricultural research. Leveraging high-throughput sensing technologies**, phenomics** provides a scalable means to characterize plant traits and understand the complex relationships between genetic and environmental factors to shape their impact on observable characteristics (Pieruschka and Schurr 2019). Phenomics, employing advanced phenotyping and sensing technologies, has been developing rapidly in the last decade (Hall et al. 2022) and has shown significant potential for enhancing crop and animal improvement in recent research (Figure 3) (Sishodia et al. 2020, Yang et al. 2017, Teramoto and Uga 2022).

High Throughput Phenotyping (**HTP**) can measure traits at a large scale with great precision and spatiotemporal resolution. Remote Sensing (**RS**) and Unmanned Aerial Vehicles (UAVs) provide valuable canopy-level information, allowing researchers to monitor large-scale plant health, growth patterns, and stress responses (Yang et al. 2017). **Proximal sensing** and Light Detection and Ranging (LIDAR) technologies capture detailed sub-canopy information, including plant architecture and leaf area index (Wang and Fang 2020). Additionally, underground rovers equipped with cameras are used to gather root-level information, offering insights into root system architecture and soil interactions (Sishodia et al. 2020). Other under- and above-ground imaging techniques using Rhizotron (Mohamed et al. 2017), Minirhizotron (Rajurkar et al. 2022), and isotope tracing (Hobson 2008) have been used to observe and track plant and animal systems. Collecting information through these diverse sensing and imaging techniques for ecosystem analysis, from the canopy to root level, provides a comprehensive understanding of the biological mechanisms of plants. This multi-level data collection helps to better fit models that bridge the gap between mechanistic (process-based) and **black-box** approaches (data-driven), leading to more accurate predictions and effective interventions.

Figure 3. Application of phenomics technology at multiple levels (canopy, sub-canopy, and underground), figure created by the authors using Microsoft PowerPoint stock images.

Beyond phenomics, **precision agriculture** is another major component of digital agriculture. **Precision agriculture**, also known as precision farming or smart farming, involves the use of advanced technologies to optimise crop production while minimizing inputs such as water, fertilizers, and pesticides. It utilizes tools such as GPS-guided tractors, drones, and sensors that we discussed above to collect data on soil conditions, crop health, and environmental factors in real-time. This data is then analysed using machine learning algorithms to make informed decisions on planting, irrigation, and pest management, resulting in higher yields and reduced environmental impact. These tools not only improve efficiency and reduce waste but also enhance environmental sustainability and climate resilience. Precision farming thus serves as a bridge between ecological knowledge, technology, and on-ground implementation, aligning with the goals of sustainable and resilient agriculture.

Importantly, this **digital framework** also contributes directly to genetic improvement. As described in the breeder's equation (equation 1 below), genetic gain over time can be enhanced by both increasing selection intensity and selection accuracy while shortening the breeding cycle and maximizing additive genetic variance. The phenomics utilizing High Throughput Phenotyping (HTP), sensors, imaging systems, and precision agriculture can enhance genetic gain by increasing both selection intensity and selection accuracy while at the same time reducing the breeding cycle (Bhandari et al. 2023).

$$\frac{Selection\ Intensity\ (i)\ \times\ Selection\ Accuracy\ (r)\ \times\ Additive\ Genetic\ Variance\ (\sigma A)\ )}{Years\ per\ Cycle\ (Y)} \quad .....(1)$$

Statistics and modeling for climate-resilient agriculture

The increasing complexity and variability of agricultural systems under climate change necessitate advanced modeling and statistical approaches to support informed decision-making. Modeling frameworks and statistical tools enable researchers to simulate, predict, and optimize plant and animal performance under various environmental scenarios, making them indispensable in building climate-resilient agricultural systems.

Process-based models such as **DSSAT** (Decision Support System for Agrotechnology Transfer) and **APSIM** (Agricultural Production Systems sIMulator) simulate physiological crop development and yield as functions of genotype, environment, and management (G×E×M) interactions. These models help to evaluate the impact of climate variability, soil conditions, and agronomic practices on crop performance and resource use efficiency. By integrating these tools with weather projections, remote sensing, and field phenotyping, researchers can forecast crop responses and design site-specific management strategies to mitigate climate risks (Elias et al. 2016, Ittersum et al. 2003), which can help farmers make immediate interventions as well. In livestock systems, similar biophysical models assess feed intake, growth, and heat stress responses, enabling producers to adapt breeding and nutrition programs to changing environments. For example, the Integrated Farm System Model (IFSM) has been successfully applied to simulate the productivity and environmental footprint of dairy systems under various climate scenarios in the U.S., helping farmers adjust forage systems and herd management practices (Rotz et al. 2019). These livestock models are critical tools for improving resilience and sustainability in animal agriculture under climate uncertainty.

Predictive analytics and **machine learning (ML)** techniques such as random forests, support vector machines, and deep learning are increasingly employed to extract patterns from large-scale, high-dimensional datasets, including genomic, phenomic, and environmental data. These tools are used to forecast yield, detect diseases, estimate evapotranspiration, and even recommend optimal planting or harvesting windows. ML models can complement mechanistic (process-based) models by learning nonlinear interactions and hidden patterns not easily captured by rule-based systems. Hybrid modeling approaches, where ML is used to calibrate or refine mechanistic models, are proving powerful in improving accuracy and adaptability across diverse agroecological zones (Reichstein et al. 2019).

While machine learning (ML) offers great potential to uncover complex patterns and make accurate predictions in agriculture, it often operates as a “black box,” requires vast amounts of data, and sometimes lacks transparency in decision-making processes. For developing more realistic and interpretable agricultural systems, **Bayesian statistical approaches** can be particularly valuable. Bayesian methods, especially when combined with Markov Chain Monte Carlo (MCMC) techniques, enable the integration of prior knowledge and explicitly quantify uncertainty in model predictions. This is crucial for agriculture, where environmental variability and incomplete data often challenge reliable forecasting. Bayesian models excel in genomic selection by capturing the stochastic nature of gene expression, epistatic interactions, and genotype-by-environment effects, while also aiding risk assessment related to crop failure, pest outbreaks, or economic variability. Although Bayesian methods pose computational challenges, especially with large-scale data from UAVs, remote sensing, and multi-environment trials, recent advances in cloud computing, high-performance computing, and scalable MCMC algorithms are helping to overcome these hurdles, making Bayesian frameworks increasingly accessible for climate-resilient agriculture (Bayesian Models 2015, Besag and Higdon, 1999, Technow et al. 2015)

Integrating process-based models with precision agriculture tools, biotechnology, breeding, ML/AI approaches, and Bayesian frameworks can enable researchers to better understand the complex biological system of G*E*M*T (equation 2 below) and develop improved plants and animal genotypes (Elias et al. 2016, Maas, 1988, Technow et al. 2015). Van Voorn et al. 2023 discussed utilizing G*E*M interactions to allow better prediction of existing and new genotypes across a wide range of environments. The use of all these technological advancements we discussed in this section can be leveraged to dissect the G*E*M*T interaction, which can open the door for plant and animal advancements.

$$Phenotype\ (P) \sim Genotype(G) \times Environment(E) \times Management(M) \times Time(T) \quad ....(2)$$

At this point, it is clear that no single discipline alone can overcome these complex challenges posed by climate change. We need much more interdisciplinary research and technological advancement than ever to fight this issue together. Shen et al. (2022) discussed interdisciplinary work combining genomics, phenomics, panomics (multi-omics), bioinformatics, systems biology, modeling, and machine learning that can result in innovative solutions in breeding. These interdisciplinary approaches are not theoretical; they are already reshaping breeding outcomes on the ground.

For instance, in **maize**, an integrated phenomic (multimodal imaging) and genomic (Genotype-by-Sequencing) approach enabled GWAS of over 10,000 image-derived traits, uncovering 4,322 **locus-trait** associations and validating key drought-tolerance genes such as ZmcPGM2 and ZmFAB1A (Wu et al. 2021). Similarly, Zou et al. (2025) utilized multi-omics (genomics, phenomics, enviromics) with statistical (frequentist and Bayesian) and machine learning (neural network based genomic prediction model) approaches to predict complex trait (**wheat** yield) with an exceptionally high prediction accuracy of 99.98% with a mean squared error of just 29 tonnes, demonstrating the power of AI-driven breeding in identifying climate-resilient varieties. Collectively, all these interdisciplinary strategies enhance the precision and efficiency of both plant and animal breeding, accelerating the development of climate-smart, high-performing genotypes needed to meet global food security challenges.

Cultivating resilience and future outlook

Cultivating resilience is a goal to be achieved in both the short-term and long-term to strengthen the individual and community towards the changing climatic conditions for better nutrition, food, environment, and survival. In agriculture, cultivating resilience implies the development of practical and strategic approaches to address diverse challenges, including securing food, fiber, healthy diets, environmental sustainability, and livelihood, while strengthening local communities through diversification and adoption of new resilient technologies.

However, cultivating resilience is not as easy and straightforward or easily achievable as it seems, particularly to the farmers and low-income rural communities of developing nations. While technological advancements and modeling tools offer tremendous promise, their real-world impact hinges on effective translation from research laboratories to the hands of farmers, especially those in low-income and marginalized rural communities in developing nations. Many newly developed technologies remain confined to experimental settings or are difficult to access due to **socioeconomic, infrastructural, and educational barriers.**

To truly cultivate resilience, it is essential to prioritize inclusive strategies that address these challenges. Ultimately, the most effective climate-resilient agriculture will integrate the wisdom of **traditional** systems with the power of **modern science**, guided by interdisciplinary collaboration and a commitment to equity and sustainability. Building resilience is not only a scientific endeavour but a collective human effort grounded in shared knowledge, sustained investment, and adaptive action. Building resilience is not only a scientific endeavour but a collective human effort that requires interdisciplinary collaboration, sustained investment, and commitment to equity and sustainability.

Conclusion

Climate change presents an urgent challenge to global food security. Cultivating resilience in agriculture demands a multidisciplinary approach combining sustainable practices, such as conservation agriculture, agroecology, agroforestry, circular agriculture, and integrated farming, with cutting-edge tools such as panomics, systems biology, computational biology, and advanced statistical methods. To make these innovations impactful, equitable access and inclusive implementation are equally essential because true resilience requires not only technological advancement but also education, policy support, and community empowerment. Ultimately, building a climate-resilient agricultural system is a shared responsibility that is grounded in science, strengthened by collaboration, and driven by a commitment to sustainability and equity. Embracing the strategies outlined in this paper paves the way for a more resilient and sustainable future, ensuring food security despite the growing uncertainties of a changing climate.

Author responsibility

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Conflict of interest declaration

The authors declare that there is no conflict of interest with this publication.

Declaration on the use of generative AI tools

Generative AI tools (such as ChatGPT by OpenAI) were used solely to improve the grammar and formatting of the manuscript. The content was critically reviewed and edited by the authors to ensure academic accuracy and integrity.

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