Agricultural Technology in Climate-Smart Maize Systems: Integrating Digital, Agronomic, Biological, and Inclusive Innovations

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ABSTRACT

Agricultural technology is reshaping maize systems, yet its contribution to sustainable intensification depends less on the novelty of individual tools than on their integration across genetics, sensing, agronomy, ecology, institutions, and value chains. This structured critical review synthesizes 70 Scopus-indexed studies published from 2021 to 2025 to assess how recent technologies influence productivity, resource-use efficiency, climate resilience, environmental performance, and farmer welfare. The evidence shows rapid progress in unmanned aerial vehicle imaging, hyperspectral sensing, machine learning, crop modeling, variable-rate management, precision irrigation, and digital extension. These tools improve diagnosis and prediction, but their agronomic value is realized only when linked to actionable management rules. Conservation agriculture, subsurface drip fertigation, optimized nitrogen placement, controlled-release fertilizers, biochar-based amendments, microbial inoculants, and stress-targeted nanomaterials can raise yield or reduce environmental burdens, although performance is strongly conditioned by soil, climate, formulation, and management. Genomic prediction, high-density genotyping, gene editing, and high-throughput phenotyping are also converging toward environment-specific breeding. Across smallholder contexts, adoption is shaped by profitability, credit, market access, organizational membership, risk, and the compatibility of technologies as a package; information alone is rarely sufficient. Important trade-offs include microplastic accumulation from film mulching, nitrate displacement after ammonia-control interventions, uncertain nanoparticle safety, and digital model transferability. The review proposes an integrated framework in which sensing, prediction, intervention, verification, and institutional delivery operate as a closed decision loop. Future research should prioritize interoperable data, multi-location validation, whole-system environmental accounting, affordability, and co-designed technology bundles that deliver measurable gains under real farm constraints across diverse production regions.

Keywords: *agricultural technology, climate-smart maize, digital farming, precision agriculture, sustainable intensification*

I. INTRODUCTION

Maize is an unusually revealing crop through which to examine the direction of agricultural technology. It is simultaneously a staple, feed grain, industrial raw material, bioenergy substrate, breeding platform, and major component of global land-use and nutrient cycles. Because maize is cultivated across highly mechanized commercial regions and resource-constrained smallholder systems, technological change is expressed through very different combinations of sensors, machinery, seed, irrigation, fertilizer, information, labor, and institutions. A review focused only on yield-enhancing devices would therefore miss the central issue. The current transition is not simply from low technology to high technology; it is from fragmented interventions toward connected production systems in which biological and digital information are converted into timely management decisions.

Recent literature demonstrates the breadth of this transition. Digital phenotyping can estimate plant height, biomass, canopy architecture, leaf water status, chlorophyll, disease symptoms, drought stress, and planting dates. Crop models and machine-learning algorithms can turn those observations into irrigation, nitrogen, or seeding recommendations. In parallel, conservation agriculture, subsurface drip fertigation, controlled-release fertilizer, optimized nitrogen placement, biochar, microbial inoculants, gene editing, and engineered nanomaterials are expanding the set of possible interventions. At the institutional level, digital extension, climate information systems, public-private coordination, credit, farmer organizations, and infrastructure influence whether technically promising practices become routine. The result is a technology landscape that is broad but uneven: predictive capability is advancing faster than field-level integration, and controlled experiments are more common than evidence of durable, inclusive scaling.

A first insight from the corpus is that technological performance must be interpreted through genotype-by-environment-by-management interactions. Environment-type analysis showed that temporal variation in drought and heat can exceed spatial variation and that stress-defined environments explain substantially more yield variability than long-term climatic averages alone (Couëdel et al., 2021). This finding has implications well beyond breeding trials. A sensor model, fertilizer schedule, irrigation rule, or conservation practice that performs well in one season may fail under a different sequence of water and heat stress. Likewise, field-scale planting-date reconstructions in the US Corn Belt revealed strong responses to early-season rainfall and soil productivity but no uniform trend toward earlier planting over 2000-2020, illustrating how climate adaptation is constrained by local weather and operational windows rather than driven by temperature signals alone (Deines et al., 2023).

A second insight is that technologies are complements more often than substitutes. In Ghana, simultaneous adoption of zero tillage, row planting, and drought-resistant seed produced the largest yield effect, whereas a different combination generated the largest net-income effect (Asante et al., 2024). In Eastern Ethiopia, improved seed and inorganic fertilizer together increased yield and household welfare more than either technology alone (Ahmed, 2022). In northwestern India, conservation agriculture combined with subsurface drip fertigation delivered higher yield, water productivity, nitrogen-use efficiency, and net returns than the component practices evaluated under conventional configurations (Patra et al., 2023). These studies point toward a portfolio logic: the relevant unit of innovation is often a coordinated bundle that addresses several limiting factors at once.

A third insight is that sustainability gains cannot be inferred from yield gains. Plastic film mulching can improve soil temperature and water capture, yet 32 years of use led to severe macroplastic and microplastic accumulation throughout the soil profile, including deep subsoil layers that are difficult to remediate (S. Li et al., 2022). Nitrogen injection can sharply reduce ammonia volatilization, but the same intervention may increase nitrate leaching in particular soils and seasons (Mencaroni et al., 2021). Biochar can improve water retention and crop performance without consistently changing soil chemical fertility, indicating that claims about mechanism must be aligned with feedstock, pyrolysis conditions, climate, and soil properties (Medyńska-juraszek et al., 2021). Technology evaluation therefore requires multiple outcomes: yield, profitability, water and nutrient efficiency, greenhouse-gas emissions, pollution, resilience, labor, and distributional effects.

A fourth insight concerns the distinction between measurement and management. The accuracy of sensing has improved rapidly. UAV-derived plant height can closely match ground measurements, and multi-source sensing can predict biomass with high coefficients of determination (Teshome et al., 2023; Zhai et al., 2023). Yet information has value only when it changes a decision. Modeling work in Nebraska found that irrigation strategy affected water use and profit more strongly than large errors in soil-moisture information, suggesting that better recommendations may matter more than marginal improvements in sensor precision (Kelly et al., 2021). Similarly, information about certified seed increased farmer knowledge in Uganda but did not causally raise willingness to pay, because affordability and other constraints remained binding (Mastenbroek et al., 2021). The literature thus supports a decision-centered definition of agricultural technology: a tool is useful when it reliably improves the sequence from observation to action under real constraints.

This review updates the discussion of agricultural technology by organizing the supplied evidence into a systems framework. It asks four questions. First, which technology domains have generated the strongest recent evidence for maize productivity, resilience, and resource-use efficiency? Second, how are digital, biological, mechanical, and agronomic technologies becoming integrated? Third, what trade-offs and implementation barriers limit scaling? Fourth, what research and policy architecture is needed to move from isolated technical performance toward resilient and inclusive maize systems? The review contributes by connecting farm-level technologies with breeding, environmental accounting, institutional delivery, postharvest management, and circular value chains. Rather than presenting a catalog of innovations, it identifies the conditions under which technologies reinforce one another, displace environmental burdens, or fail to reach farmers.

II. MATERIALS AND METHODS

2.1 Review Design and Evidence Base

The study was designed as a structured critical review and evidence map. The supplied files contained the same Scopus export in plain-text and RIS formats. Records were reconciled by digital object identifier, producing 70 unique publications. The evidence bases covered 2021-2025 and included field experiments, long-term trials, remote-sensing analyses, machine-learning studies, crop-model simulations, life-cycle assessments, meta-analyses, randomized interventions, econometric adoption studies, and focused reviews. No web searches or external references were added. This restriction preserved citation integrity and ensured that every claim attributed to a study could be traced to the provided title, abstract, and bibliographic metadata.

The corpus was broad by design. Most studies directly examined maize or corn, while several addressed related cereal systems, soil remediation, crop diversity, biochar, nanoparticles, agricultural value chains, or technologies in which maize was a feedstock, substrate, or comparison crop. These adjacent studies were retained when they clarified mechanisms or system-level implications relevant to maize technology. For example, research on plant growth-promoting rhizobacteria under combined salt and metal stress was considered for its evidence on ion homeostasis and microbial stress mitigation, while life-cycle studies of pig production and bioplastics were used to locate maize within downstream environmental burdens and alternative feedstock pathways.

2.2 Thematic Coding and Synthesis

To ensure a systematic and transparent synthesis, the selected studies were classified according to their technological focus, agronomic application, reported outcomes, and relevance to climate-smart maize production. The thematic coding process identified six interconnected research domains: digital sensing and artificial intelligence, precision water and nutrient management, soil health and conservation agriculture, biological and genetic innovation, mechanization and postharvest technology, and the socioeconomic dimensions of technology adoption. The complete review and thematic synthesis process is presented in Figure 1.

As illustrated in Figure 1, the review process progressed from data identification and article screening to evidence classification, thematic coding, comparative analysis, and integrated synthesis. This structure enabled the literature to be assessed not only according to individual technological performance but also in terms of interactions among production efficiency, climate resilience, environmental sustainability, and inclusive adoption. The resulting thematic framework therefore served as the analytical basis for organizing the findings and discussion presented in the following sections.

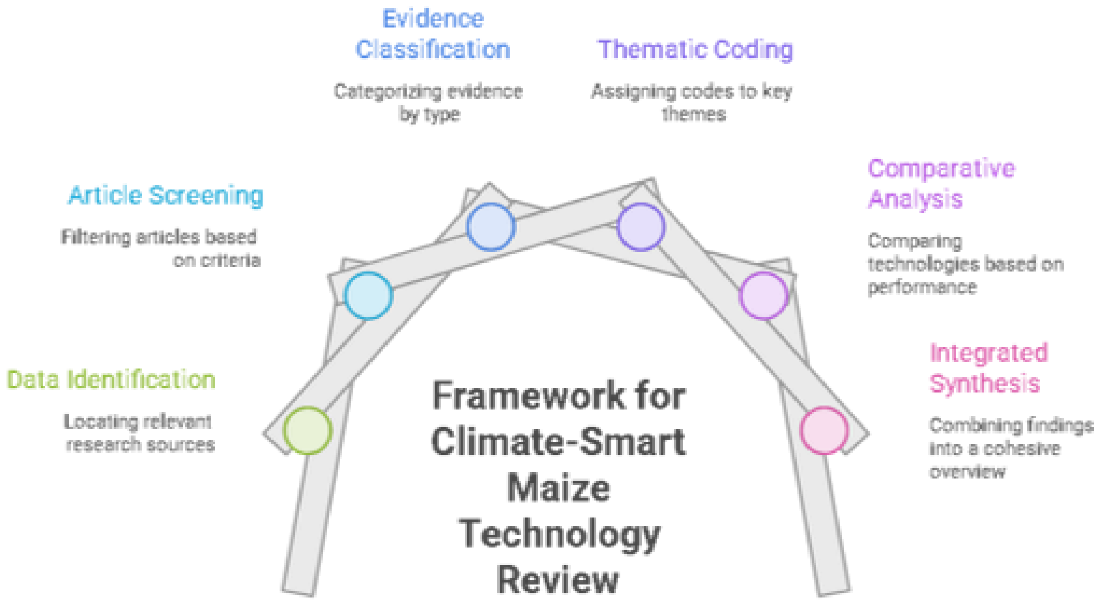

Figure 1. Review and Thematic Synthesis Framework for Agricultural Technology in Climate-Smart Maize Systems

2.3 Interpretation and Limitations

The review gives priority to recent studies and to evidence with clear field, economic, or environmental outcomes. However, the source material consisted of abstracts rather than full articles. Consequently, the synthesis does not independently reassess experimental protocols, statistical power, risk of bias, or complete life-cycle boundaries. Comparisons across studies are interpretive because locations, cultivars, years, input levels, and outcome definitions differ. The review therefore emphasizes convergent patterns and explicit boundary conditions rather than pooled effect sizes, except where a supplied meta-analysis already reported them.

III. RESULTS AND DISCUSSION

3.1 Evidence Landscape: from Discrete Tools to Connected Decision Systems

The 70-study corpus shows a marked concentration in four areas: digital observation and prediction; water and nitrogen management; climate and soil resilience; and adoption or economic performance. The publication pattern also shows a transition from demonstrating that a technology works toward asking when it works, how it should be combined, and who can use it. The most recent study in the corpus, for example, did not merely test nitrogen fertilizer under ridge-furrow mulching; it linked crop growth, water productivity, nitrogen partial factor productivity, economic return, enzyme activity, nitrate residues, and a soil-quality index to identify a multi-objective optimum of 180 kg N ha-1 under the ridge-furrow system (F. Zhang et al., 2025). This is representative of an emerging evaluation standard in which a technology is judged against a vector of outcomes rather than a single yield response.

The evidence also spans scales that are often separated in agricultural research. At the plant scale, sensors and models estimate leaf angle, movement, chlorophyll, water status, disease, biomass, and individual-plant geometry. At the field scale, irrigation, seeding, fertilizer placement, residue retention, and pest control modify resource capture and yield formation. At the landscape scale, remote sensing maps planting dates, drought, residue cover, abandoned cropland, and production potential. At the institutional scale, extension systems, public expenditure, public-private partnerships, farmer organizations, and market conditions affect adoption and green productivity. At the value-chain scale, maize contributes to postharvest losses, animal-feed impacts, starch modification, biochar, biogas, and bioplastic pathways. A top-tier interpretation must therefore connect these scales rather than assume that plant-level accuracy automatically produces system-level sustainability.

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The review organizes this connection as a five-part decision loop. Observation captures crop, soil, weather, and management states. Prediction translates observations into yield, stress, or resource forecasts. Intervention adjusts seed, water, nutrients, crop protection, tillage, or postharvest handling. Verification measures agronomic, economic, and environmental outcomes. Delivery embeds the loop in institutions, skills, finance, infrastructure, and farmer practice. Weakness in any part can break the system. High-resolution sensing without a credible intervention rule produces information overload; an agronomically sound recommendation without finance or market access produces low adoption; a profitable practice without environmental verification can shift burdens to soil, water, or downstream stages.

3.2 Digital Sensing, Machine Learning, and High-throughput Phenotyping

Digital agricultural technologies are strongest where they replace slow, destructive, or spatially sparse measurement. UAV imaging estimated sweet-corn plant height with r2 of 0.99 (Table 1) and mean absolute error of 5 cm, while fresh and dry biomass estimates reached r2 values of 0.75 and 0.70. Machine-learning models further improved the prediction of biomass and height, with algorithm performance depending on the target trait (Teshome et al., 2023). Multi-source fusion produced an additional gain: combining multispectral and thermal data with SPAD measurements and CatBoost achieved biomass-estimation r2 values as high as 0.901 at the big-trumpet stage, outperforming support-vector and random-forest alternatives (Zhai et al., 2023). The implication is not simply that one algorithm is superior. Trait expression changes across growth stages, and sensor fusion can compensate for information missing from individual instruments.

Three-dimensional phenotyping extends the same logic to plant architecture. Euclidean clustering combined with K-means segmentation accurately separated individual maize plants in point clouds, including cross-leaf situations that defeated simpler Euclidean segmentation. Performance remained high in sparse stands but declined under dense canopies, especially at later stages, exposing occlusion as a persistent field constraint (Miao et al., 2023). A robotic stereo-vision platform addressed a related problem by reconstructing leaf angles from side-view images using a deep convolutional pipeline. The system offered a practical alternative to manual protractor measurements and created a pathway for breeding canopy architectures that improve light interception (L. Xiang et al., 2023). Together, these studies show that phenotyping is becoming a data pipeline: image acquisition, object separation, key-point detection, three-dimensional reconstruction, trait extraction, and genetic association.

Spectral sensing has also moved from generic vegetation indices toward physiologically interpretable traits. Hyperspectral reflectance in the 900-1700 nm range, combined with fractional-order Savitzky-Golay preprocessing and wavelength selection, predicted maize leaf water content with validation r2 of 0.92 and reduced model complexity to 23 informative wavelengths (Sun et al., 2021). Across maize, mustard, and lentil, red-edge, green, red, and near-infrared combinations were evaluated for leaf chlorophyll and leaf-area index, with radial support-vector regression outperforming linear, polynomial, random-forest, partial-least-squares, and neuro-fuzzy models (Verma et al., 2022). Such studies are important because they shift digital agriculture toward parsimonious sensing. A smaller, mechanistically relevant wavelength set may be easier to deploy in lower-cost sensors than a full hyperspectral instrument.

Remote sensing is particularly valuable when field measurements are impossible at operational scales. MODIS-derived phenological metrics predicted county-level corn yield before harvest, and combining phenology with the most strongly correlated NDVI observation improved performance over a single-index model (Ji et al., 2021). Satellite-derived temperature-vegetation drought indices were more closely related to real available water content than to unadjusted soil-moisture content, and the analysis identified growth periods when maize yield was most sensitive to drought (Wan et al., 2021). Sentinel-2 tillage indices combined with texture features estimated maize residue cover with r2 of 0.783, providing a means to map conservation-practice implementation rather than relying entirely on farmer reports (X. Xiang et al., 2022). At larger scales, Landsat and GF-1 imagery with deep learning identified approximately 1.53 million ha of abandoned cropland in major Chinese grain regions and estimated substantial potential maize, wheat, and rice production (Jiang et al., 2023).

Table 1. Digital, Modeling, and precision-management Evidence Supporting Maize Decision Systems

Technology cluster	Evidence base and context	Main reported outcome	Critical interpretation for deployment	Ref.
UAV crop-surface modeling	Sweet corn under four irrigation levels	Plant height r2 = 0.99; useful biomass and yield estimation	Strong trait measurement; management value depends on decision thresholds	(Teshome et al., 2023)
Multi-source UAV fusion	Multispectral, thermal, and SPAD data across growth stages	CatBoost reached r2 up to 0.901 for biomass	Sensor fusion reduces single-sensor blind spots; stage-specific calibration is essential	(Zhai et al., 2023)
Point-cloud segmentation	Terrestrial laser scans at V5-V6 under sparse and dense planting	Very high segmentation in sparse stands; reduced performance under dense canopy	Occlusion remains a major bottleneck for plant-level phenotyping	(Miao et al., 2023)
Robotic stereo vision	Field-based side-view imaging of maize architecture	Automated leaf-angle and internode characterization	Enables high-throughput architectural breeding but misses occluded organs	(L. Xiang et al., 2023)
Hyperspectral leaf-water sensing	900-1700 nm reflectance with fractional derivatives	Validation r2 = 0.92 using selected wavelengths	Supports lower-dimensional sensor design and early water-stress diagnosis	(Sun et al., 2021)
Spectral chlorophyll and LAI retrieval	Multiple crops under irrigation and fertilizer treatments	Radial SVR was most robust among tested algorithms	Optimal bands and models vary by crop and trait	(Verma et al., 2022)
Phenology-based yield prediction	MODIS NDVI across 314 US Corn Belt counties	Regional models reached r2 = 0.64-0.72	Phenological features add physical meaning to pre-harvest forecasts	(Ji et al., 2021)
Satellite drought monitoring	MODIS vegetation and temperature indices in China	Improved relation with real available water content; sensitive stages identified	Drought products should represent plant-available water, not only surface moisture	(Wan et al., 2021)
Residue-cover mapping	Sentinel-2 tillage indices and texture features	Combined model r2 = 0.783	Can verify conservation-agriculture implementation at scale	(X. Xiang et al., 2022)
Field-scale planting dates	Landsat and weather covariates across 2000-2020	Maize field-level MAE = 7.4 days; state-level r2 = 0.76	Useful for model initialization and adaptation tracking	(Deines et al., 2023)
Abandoned-cropland detection	Landsat-8 and GF-1 with deep learning in China	>87% accuracy; 8.5 Mt total grain potential estimated	Land recovery requires ecological and institutional assessment, not mapping alone	(Jiang et al., 2023)
Disease recognition	Small samples and complex backgrounds	98.84% field-image classification accuracy	Deployment needs external validation and disease-severity estimation	(E. Li et al., 2023)
Leaf-motion sensing	Low-cost inertial sensors attached to plant organs	Real-time detection of normal and stress-induced movement	Promising early-warning signal; attachment and field durability need testing	(Geldhof et al., 2021)
Genotyping-by-target sequencing	High-density maize mSNP and haplotype panels	Improved diversity, LD, and association analysis	Reduces genotyping barriers but requires phenotypic and environmental integration	(Guo et al., 2021)

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The same analytical progression is visible in crop-health monitoring. A deep-learning architecture combining DenseNet121, multi-dilated modules, attention mechanisms, generative augmentation, and transfer learning achieved 98.84% accuracy on maize disease images collected under complex field backgrounds and small-sample conditions (E. Li et al., 2023). A low-cost inertial sensor attached directly to leaves detected both ordinary movement and stress-induced changes, including reduced nutation amplitude, suggesting that continuous plant motion can serve as an early stress signal (Geldhof et al., 2021). These approaches differ in scale and mechanism, but both treat the crop as an active sensor. The plant's color, temperature, geometry, and movement encode stress before final yield loss becomes visible.

Digital observation also supports breeding. High-resolution multiple-SNP arrays generated 40K mSNPs, 251K SNPs, and 690K haplotypes from a target-sequencing platform, improving diversity analysis, linkage disequilibrium assessment, and genome-wide association compared with one-amplicon-one-SNP systems (Guo et al., 2021). Crop-growth models linked with whole-genome prediction improved predictive accuracy for untested genotypes in untested environments relative to conventional genomic prediction, because physiological models could represent time-dependent environmental interactions (Diepenbrock et al., 2022). This convergence of genotyping, digital phenotyping, and process modeling is strategically important. It can reduce the gap between identifying a statistical marker and explaining why a genotype performs under a specific water, heat, or management regime

3.3 Water-smart Irrigation and Nutrient Management

Water and nitrogen management remain the most direct points at which technology can change maize productivity and environmental performance. The literature, however, does not support a single universal irrigation technology. It supports the principle that water delivery, timing, depth, nutrient placement, soil condition, and crop stage must be managed jointly. In northwestern China, alternate surface and subsurface drip irrigation increased two-year mean grain yield to 6,939.5 kg.ha^{-1}, 4.8% above subsurface drip and 13.3% above conventional surface drip (Table 2). The treatment improved grain filling and post-silking biomass contribution, indicating that the benefit arose through crop development rather than water saving alone (Y. Cao et al., 2022). A broader meta-analysis of saline-alkali land found that drip irrigation reduced root-zone salinity by 37.7% and increased crop yield by 37.4% relative to flood irrigation, but outcomes depended on emitter flow, irrigation quota, water salinity, crop, and soil texture (Y. Du et al., 2023). The practical message is that drip irrigation is a control platform, not a guarantee of efficiency.

Subsurface drip becomes especially powerful when integrated with conservation agriculture and fertigation. In a maize-wheat system, residue-retained conservation agriculture with subsurface drip produced 8.2 t.ha^{-1}, saved 54% of irrigation water relative to furrow-irrigated systems, more than doubled water productivity, and improved nitrogen-use efficiency and net return (Patra et al., 2023). This result is important because it demonstrates complementarity between soil cover, root-zone water placement, and split nutrient supply. By contrast, technology assessments that compare drip with flood irrigation while holding residue, fertilizer timing, and soil structure constant may underestimate the potential of integrated systems.

Crop simulation adds a temporal dimension. Long-term DSSAT simulations in an arid Mediterranean environment showed that irrigation frequency and reproductive-stage protection were more important than simply replacing a large fraction of evapotranspiration. Under limited water, applying 40% of evapotranspiration during vegetative growth and 80% during reproduction, or maintaining approximately 30% available water in the upper soil layer, offered a balance between yield and water-use efficiency (Attia et al., 2021). A separate DSSAT-genetic algorithm framework optimized nitrogen scheduling under drip irrigation, raising maize yield by 7-9% and economic benefits by 8.4-12.4% relative to a conventional schedule (Bai & Gao, 2021). These examples illustrate the value of models as scenario engines. Their strongest contribution is not the prediction of one best schedule, but the ability to explore timing and resource trade-offs over weather sequences that cannot be reproduced in short field trials.

The water-footprint perspective broadens the boundary further. An assessment of Chinese corn production separated blue, green, and gray water and found that water productivity and water efficiency improved over time but remained spatially heterogeneous. Technology progress reduced water footprints in some regions, while meteorology and planting structure shaped national patterns (X. Cao et al., 2021). This suggests that field-level water-saving technologies should not be evaluated only by irrigation volume. Regional crop relocation, rainwater capture, yield stability, and pollution-related gray water can alter the system outcome. A water-efficient field in an unsuitable region may still be less sustainable than a moderately efficient field in an area with better rainfall and lower environmental pressure.

Nitrogen technologies show a similar shift from dosage to placement, timing, formulation, and system context. Under long-term conservation agriculture, subsurface point placement of both nitrogen splits increased grain yield, nitrogen remobilization, and benefit-cost ratios compared with surface band placement. The intervention was effective because it overcame the physical barrier created by surface residues and placed nitrogen where roots could access it (Nayak et al., 2022). Site-specific fertilizer injection in Italy reduced ammonia loss from maize by 75% with ammonium nitrate and by 96% with organic fertilizer relative to surface broadcasting, but some scenarios increased nitrate leaching. The study therefore argued for whole-nitrogen-flow assessment rather than single-emission optimization (Mencaroni et al., 2021).

Controlled-release formulations provide another route to synchronize supply and demand. In semiarid spring maize, a one-time mixture of controlled-release and granular urea improved economic efficiency and reduced net global-warming potential and carbon footprint relative to split granular urea. Adding straw return increased carbon dioxide and nitrous oxide emissions but built soil organic carbon strongly enough to lower net global-warming potential and carbon footprint overall (J. Bai et al., 2021). The result shows why greenhouse-gas accounting must include both emissions and soil carbon change. A technology can increase gross field emissions while improving the net carbon balance.

Integrated nutrient management also benefits from multi-objective evaluation. In a long-term maize-chickpea system, soil-test-crop-response management using farmyard manure plus 75% of the recommended mineral nutrient rate reduced energy requirements and cultivation cost, lowered carbon footprint, and improved system productivity, energy productivity, and carbon sustainability relative to the general recommended fertilizer dose (Meena et al., 2021). Yet the study also found that high organic-input rates could increase nitrous oxide emissions. Organic inputs should therefore not be treated as inherently low carbon. Their performance depends on substitution of synthetic inputs, yield response, decomposition, and the amount and timing applied.

The 2025 ridge-furrow study adds a soil-quality mechanism to this literature. Ridge-furrow plastic-film planting combined with 180 kg N ha-1 improved growth, yield, water productivity, nitrogen partial factor productivity, economic return, soil enzymes, and an integrated soil-quality index while reducing nitrate residues compared with less suitable combinations (F. Zhang et al., 2025). However, long-term plastic-film evidence requires caution. The productivity benefits of film-based water and heat management must be weighed against persistent plastic contamination documented after decades of use. Biodegradable or recoverable alternatives, improved collection, and whole-life material accounting are therefore central to the future of mulch-enabled maize systems.

The strongest water-nutrient technologies share four design features. They target the root zone, align supply with sensitive growth stages, use feedback from crop or soil status, and evaluate multiple losses. The remaining weakness is often operational. Smallholders may lack pressure-regulated drip systems, maintenance services, soluble fertilizers, or access to model-based recommendations. Large farms may have the infrastructure but still face data fragmentation and labor constraints. Research should therefore compare management packages under realistic maintenance, energy, and financing conditions rather than under ideal technical operation.

3.4 Conservation Agriculture, Soil Health, Carbon, and Pollution Trade-offs

Conservation agriculture is a system based on minimal soil disturbance, permanent soil cover, and crop diversification rather than no-tillage alone. In the Indo-Gangetic Plains, integrating legumes and subsurface drip irrigation improved productivity and profitability while reducing water and energy use, with maize substitution providing substantial water savings (Jat et al., 2021). Similarly, in Brazil, no-tillage alone was insufficient for sustainability without permanent cover and crop diversification (Fuentes-Llanillo et al., 2021). Thus, soil conservation depends on the interaction of multiple complementary practices.

Table 2. Resource-efficient, Biological, and Environmental Technologies in Maize-centered Systems

Technology cluster	Evidence base and context	Main reported outcome	Critical interpretation for deployment	Ref.
Alternate and subsurface drip	Two-year maize field trial in semiarid China	Alternate drip increased yield 4.8% over SDI and 13.3% over surface drip	Water placement affected grain filling; hydraulic design must match soil and roots	(Y. Cao et al., 2022)
Drip on saline-alkali land	Global meta-analysis	Root-zone salinity -37.7%; crop yield +37.4% versus flooding	Benefits depend on emitter flow, quota, water salinity, crop, and texture	(Y. Du et al., 2023)
Deficit-irrigation scheduling	Long-term DSSAT simulation in arid sandy soil	Reproductive-stage protection improved yield-WUE balance	Stage-sensitive rules outperform uniform seasonal deficit	(Attia et al., 2021)
Drip plus N optimization	Field-calibrated DSSAT and genetic algorithm	Yield +7-9%; economic benefit +8.4-12.4%	Models are most useful when connected to weather and operational decisions	(Bai & Gao, 2021)
Conservation agriculture plus SSD fertigation	Two-year maize-wheat field experiment	54% water saving; >2x water productivity; higher yield and return	Demonstrates complementarity among residue, water placement, and split N	(Patra et al., 2023)
Precision N placement	Decade-long conservation-agriculture experiment	Higher yield, N remobilization, and benefit-cost ratio	Residue-retained systems require adapted fertilizer placement	(Nayak et al., 2022)
Controlled-release N plus straw	Semiarid spring maize	Lower carbon footprint and NGWP; straw increased SOC	Net accounting can favor a practice despite higher gross field emissions	(J. Bai et al., 2021)
Integrated nutrient management	Long-term maize-chickpea system	Lower energy and carbon footprint with higher productivity	Organic inputs can raise N2O; optimum mixes matter more than labels	(Meena et al., 2021)
Ridge-furrow mulching and N	Three-year Loess Plateau field study	180 kg N ha-1 optimized yield, efficiency, soil quality, and return	Multi-objective optimum is promising but film legacy must be addressed	(F. Zhang et al., 2025)
Site-specific fertilizer injection	Modeling plus field validation	NH3 reductions up to 96%; possible nitrate-leaching increase	Evaluate all N pathways to avoid burden shifting	(Mencaroni et al., 2021)
Regional water-footprint management	Chinese corn production, 1996-2015	WP and WE improved but varied strongly by region	Crop geography and green/blue/gray water matter alongside field efficiency	(X. Cao et al., 2021)
Conservation agriculture package	Indo-Gangetic cereal systems	Higher productivity and profitability with lower water and energy use	No-till, cover, diversification, and irrigation should be co-designed	(Jat et al., 2021)
National no-till expansion	Brazilian agricultural census	Expansion linked to soybean-maize systems	No-till alone is insufficient without cover and rotation	(Fuentes-Llanillo et al., 2021)
PPP-enabled large-scale management	Commercial maize in North China Plain	Yield 10.4 Mg ha-1; lower carbon footprint and higher ecosystem benefit	Institutional coordination enabled mechanized precision management	(W. Zhang et al., 2022)

The carbon evidence is similarly conditional. A public-private partnership combined with large-scale farming and no-tillage achieved maize yields of 10.4 Mg ha-1, lower carbon footprints, higher net ecosystem carbon budgets, and higher net ecosystem economic benefits than either large-scale or smallholder farming alone. Mechanized application of controlled-release fertilizer without top-dressing was identified as a major driver of the lower footprint (W. Zhang et al., 2022). This case is notable because the institutional arrangement enabled agronomic precision. Scale alone was not the causal mechanism; coordination allowed access to machinery, inputs, and standardized management.

Diversification can also improve the energy and carbon profile of landscapes. Replacing maize- and rice-dominated traditional systems with groundnut-based rotations in the eastern Indian Himalayas reduced non-renewable energy inputs, increased system and water productivity, raised soil carbon and enzyme activity, and improved a soil-quality index (Ansari et al., 2021). The broader lesson is that technology assessment should include cropping-system redesign. Precision management of a poorly diversified system may optimize an ecologically narrow baseline, whereas rotations can alter nutrient cycling, labor distribution, pest pressure, and income stability.

Biochar occupies a central but contested position in soil technology. A broad review described biochar-based fertilizers as a circular-economy pathway that can improve structure, sorption, nutrient retention, water-holding capacity, contaminant immobilization, and greenhouse-gas mitigation (Samoraj et al., 2022). Field evidence in temperate maize showed a more restrained picture: pinewood biochar improved physical properties, water retention, crop growth, and yield during hot dry summers but had limited effects on chemical soil properties and fertility (Medyńska-juraszek et al., 2021). The contrast is productive. Biochar should be specified by feedstock, pyrolysis temperature, dose, nutrient content, surface chemistry, soil type, and target function. Treating all biochars as one input obscures why some materials act mainly as physical conditioners while others supply nutrients or immobilize metals.

Contaminated-soil studies illustrate the possibility of engineered amendment combinations. Mixed bacteria loaded onto corn-stalk biochar reduced extractable uranium and cadmium more strongly than biochar or bacteria alone and promoted plant growth, indicating that sorption and microbial colonization can be combined (Qi et al., 2021). In maize grown under lead and zinc contamination, combinations of mesquite biochar, zeolite, and bentonite reduced metal concentrations in leaves and roots, lowered bioavailable soil fractions, and improved antioxidant responses (Afzal et al., 2024). Heavy-metal-resistant Streptomyces isolated from polluted environments removed multiple metals and improved maize growth under arsenic and chromium stress, offering a microbial route for remediation and plant protection (AL-Huqail & El-Bondkly, 2022). These technologies are promising, but the pathway from pot or controlled studies to safe food production requires long-term field monitoring of metal speciation, microbial persistence, and transfer into edible grain.

Soil microbiomes can also reveal unintended effects of conventional improvement. A chronosequence of maize germplasm showed that more recently developed lines recruited fewer microbial taxa with the potential for sustainable nitrogen provisioning and more taxa associated with nitrogen loss (Favela et al., 2021). Long-term copper contamination, meanwhile, altered fungal diversity and network structure, with moderate contamination strengthening some interactions and severe contamination weakening them; Penicillium emerged as a potential keystone taxon for tolerance and detoxification (X. Zhang et al., 2022). These findings suggest that breeding, fertilizer management, and pollution control influence not only plant traits and soil chemistry but also ecological networks that regulate nutrient cycling and resilience.

A major unresolved issue is burden shifting. Plastic film mulching can enhance water and nutrient performance, yet persistent fragments accumulate vertically through the soil profile. Fertilizer placement can lower gaseous loss but move nitrogen toward leaching pathways. Biochar production can stabilize carbon, but feedstock sourcing, pyrolysis energy, contaminants, and transport influence net benefit. Conservation agriculture can reduce tillage energy and erosion, but herbicide dependence, residue competition, or specialized seeding equipment may create new constraints. A credible sustainability claim therefore needs a defined system boundary, a counterfactual, and transparent treatment of displaced burdens.

Life-cycle assessment helps establish these boundaries. The environmental impact of small-scale intensive pig production in China was dominated by feed production, with maize identified as a major hotspot because of high

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consumption and processing energy (Liu et al., 2021). In a comparison of polyhydroxyalkanoate pathways, photoautotrophic production from carbon dioxide outperformed a corn-glucose pathway across assessed impact categories, while solvent-based extraction remained a major hotspot for both systems (Koch et al., 2023). These studies do not imply that maize should be removed from all value chains. They show that downstream demand and processing technology determine the environmental meaning of upstream yield gains. Producing more maize efficiently is not automatically sustainable if it supports a high-impact conversion pathway.

3.5 Genetic, Microbial, and Nano-enabled Resilience

Climate resilience is increasingly pursued through technologies that modify the crop's capacity to perceive, avoid, or tolerate stress. Conventional breeding remains central, but the reviewed studies show a convergence of genome editing, genomic prediction, high-throughput phenotyping, microbiome management, and nano-enabled physiology. This convergence changes the meaning of a stress-tolerant variety. Rather than selecting only for yield under a broadly defined drought treatment, breeders can identify physiological traits, predict performance across stress sequences, manipulate target genes, and monitor plant responses continuously.

Gene editing provides the most direct intervention (Table 3). Editing the trehalase substrate-binding domain increased drought tolerance in Arabidopsis, and the study also established a transient maize-leaf transformation system and a vector platform intended for monocot and dicot editing (Nuñez-Muñoz et al., 2021). The maize result was methodological rather than a field-ready drought-tolerant hybrid, but it illustrates a route from comparative biology to targeted crop improvement. The main bottleneck is no longer the conceptual possibility of precise modification; it is the translation of edited traits into stable, high-yielding genotypes across environments, together with regulatory, stewardship, and public-acceptance frameworks.

The case for broader genetic diversity remains equally strong. A review of crop diversity and de novo domestication argued that next-generation sequencing, metabolomics, high-throughput phenotyping, and targeted editing can expand the range of crops and traits used under climate uncertainty (Zsögön et al., 2022). For maize, this means avoiding an overly narrow focus on elite germplasm performance under favorable management. Diversity in root architecture, phenology, heat response, disease resistance, and microbiome recruitment may become more valuable as stress combinations become less predictable. Digital physiology can help identify these traits, but breeding objectives must also incorporate farmer-preferred characteristics, maturity windows, grain quality, and compatibility with mechanization or intercropping.

Genetically modified crop technology provides evidence at a much larger adoption scale. Global farm-level estimates for 1996-2020 attributed substantial income and production gains to GM soybean, maize, cotton, and canola, with a large share of benefits arising from yield and production rather than cost savings. The analysis estimated that GM technology added hundreds of millions of tonnes to global maize production and generated higher average returns per dollar invested in developing countries (Brookes, 2022). These aggregate findings support the productivity potential of genetic technology, but they do not resolve trait-specific environmental effects, market concentration, seed access, resistance management, or distribution of benefits. Future assessments should separate herbicide-tolerance, insect-resistance, drought, and quality traits and evaluate them within specific management systems.

Microbial and nanotechnology approaches offer complementary strategies for enhancing plant resilience by targeting the plant–soil interface and physiological processes. Plant growth-promoting rhizobacteria isolated from metal- and salt-affected maize rhizospheres improved nutrient acquisition and reduced sodium and cadmium uptake through ion homeostasis, with mechanisms including phosphorus solubilization, ACC deaminase activity, and auxin production (Daraz et al., 2023). However, field effectiveness of microbial inoculants may depend on native microbial communities, soil chemistry, formulation, storage, and post-application competition. Meanwhile, engineered nanoparticles have been explored for pathogen detection, plant-health monitoring, antimicrobial activity, nutrient delivery, and reducing chemical inputs (Kumar et al., 2022). Under salinity stress, nanoparticles can affect ion balance, antioxidant systems, osmolytes, hormones, and gene expression, although their effects remain dose dependent and mechanistically incompletely understood (Etesami et al., 2021). In cereals, interactions among nanoparticles, phytohormones, nitric oxide, antioxidant systems, nutrient homeostasis, and xenobiotic transport may enhance stress tolerance, but inappropriate concentrations or application methods can cause phytotoxicity (Banerjee & Roychoudhury, 2022).

Experimental evidence with nitrogen-doped, polyacrylic-acid-modified carbon dots demonstrates both the attraction and the uncertainty of this field. Foliar application at 5 mg L-1 under drought reduced reactive oxygen species, increased net photosynthesis by 206.8%, and raised abscisic acid and proline in maize roots, supporting water uptake and osmotic adjustment (C. Wang et al., 2022). The study provided a mechanistic chain from nanoparticle design to cellular penetration, signaling, root function, and growth recovery. Yet field-scale questions remain: persistence, transformation, non-target effects, residue in grain and soil, production cost, repeated exposure, and regulation. Nano-enabled agriculture should therefore advance through a safety-by-design framework in which agronomic efficacy and environmental fate are assessed together.

Genetic, microbial, and nano-enabled approaches should not be framed as competing solutions. Genetic improvement can provide baseline tolerance; microbial inoculants can modify nutrient and stress responses; nanomaterials can supply targeted short-term protection or diagnostics; and digital phenotyping can verify response. The challenge is to identify combinations that are biologically compatible and economically defensible. A drought-tolerant genotype may reduce the marginal value of a nanoparticle treatment under moderate stress but increase its value under severe stress if the two act on different physiological bottlenecks. Conversely, a treatment that improves photosynthesis without protecting reproductive development may produce limited yield benefit. Multi-stage phenotyping and crop modeling are needed to distinguish these cases.

3.6 Mechanization, Crop Protection, Postharvest Technology, and Circular Value Chains

Agricultural technology continues after crop establishment and does not end at harvest. Mechanization, pest management, storage, processing, and residue use determine how much biological yield becomes food, income, or environmental burden. These stages are especially important for maize because field losses, insect damage, drying and storage constraints, feed demand, and bulky residues can erase gains achieved through precision production.

Mechanical harvesting illustrates the need for joint machine-crop-management design. A review of nearly 3,000 observations from major Chinese maize regions reported average combine losses of about 3.5% of yield, with extreme cases much higher. Ear dropping, lodging, pest and disease damage, harvest date, cultivar, field condition, header design, forward speed, threshing configuration, and operator skill all contributed (K. Wang et al., 2021). Reducing loss therefore requires more than purchasing a newer combine. Varieties must be suitable for grain harvest and resistant to lodging; planting density, row spacing, drying, and harvest timing must match local heat accumulation; machinery must be adjusted to field conditions; and operators require training. Mechanization is a socio-technical system in which biological uniformity and human skill affect machine performance.

Crop protection can also be integrated with irrigation infrastructure. Drip-applied chlorantraniliprole control fall armyworm for approximately 40 days, transported effectively from stems to upper leaves, and was not detected in maize tissues at harvest in the reported study (X. Li et al., 2021). This delivery method can reduce spray drift and operator exposure while targeting a pest that damages upper canopy tissue. However, systemic chemigation also raises questions about resistance selection, non-target exposure through soil and water, compatibility with irrigation schedules, and dependence on a single active ingredient. Precision delivery should therefore be embedded in integrated pest management and resistance stewardship.

Postharvest storage is a lower-cost technology with direct welfare effects. Among small-scale maize farmers in northwestern Ethiopia, Purdue Improved Crop Storage hermetic bags had the highest gross margin and marginal rate of return and generated additional net cash flow after storage. Adoption was influenced by information, initial cost, and available storage capacity (Alemu et al., 2021). Hermetic storage demonstrates that sophisticated sensing is not always the highest-value intervention. Where insect losses and seasonal price variation are large, an airtight bag can improve food security and market timing with limited infrastructure. The appropriate technology portfolio depends on the dominant loss point.

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Table 3. Scaling, Value-chain, and Institutional Evidence for Agricultural Technology

Technology cluster	Evidence base and context	Main reported outcome	Critical interpretation for deployment	Ref.
Gene editing for drought tolerance	Trehalase editing and maize transformation platform	Edited plants showed higher drought tolerance in model species	Field-ready maize traits require stable transformation and multi-environment testing	(Nuñez-Muñoz et al., 2021)
Crop diversity and de novo domestication	Review of future climate-resilient crops	Sequencing, phenotyping, and editing can broaden crop options	Diversity should complement, not be displaced by, elite-crop optimization	(Zsögön et al., 2022)
GM crop adoption	Global farm-income analysis, 1996-2020	Large cumulative income and production gains	Trait-specific impacts, access, and resistance stewardship need separation	(Brookes, 2022)
PGPR for combined stress	Bacteria from maize rhizosphere tested under salt and Cd stress	Improved ion homeostasis and plant growth	Formulation and survival in field soils determine reliability	(Daraz et al., 2023)
Nanoparticle disease management	Critical review of diagnostics and control	Potential for sensitive detection and lower chemical use	Commercialization needs regulation, fate, and non-target assessment	(Kumar et al., 2022)
Nanoparticles under salinity	Physiological and molecular review	Potential effects on ion balance, antioxidants, and gene regulation	Responses are material-, dose-, species-, and environment-specific	(Etesami et al., 2021)
Nanoparticle signaling in cereals	Review of hormones, antioxidants, and nutrient homeostasis	Potential stress tolerance and biofortification	Overdosing can produce phytotoxicity; safety-by-design is essential	(Banerjee & Roychoudhury, 2022)
Carbon dots for maize drought	Controlled physiological study	Photosynthesis +206.8%; ABA and proline increased	Strong mechanism evidence; field fate, cost, and residues remain open	(C. Wang et al., 2022)
Combine-harvest optimization	Review and 2,987 field observations	Average loss about 3.5% of yield	Cultivar, crop condition, machine settings, and operator skill must align	(K. Wang et al., 2021)
Drip-delivered insecticide	Fall armyworm control in maize	Approximately 40-day control; no detection at harvest	Embed chemigation in IPM and resistance management	(X. Li et al., 2021)
Hermetic grain storage	450 Ethiopian smallholders	Highest gross margin and marginal rate of return among storage options	Initial cost and supply-chain access constrain adoption	(Alemu et al., 2021)
Green-productivity public spending	Twenty Chinese corn provinces	Infrastructure mediated productivity gains	Enabling public goods can outperform narrow input subsidies	(Deng et al., 2023)
Integrated seed-fertilizer package	Smallholders in Eastern Ethiopia	Combined adoption improved yield and welfare most	Complementary inputs should be promoted and financed together	(Ahmed, 2022)

Processing technologies can add value while altering environmental performance. Combined ultrasound and microwave treatment modified corn starch rapidly and was presented as an efficient, lower-impact physical method relative to conventional chemical modification routes (Yılmaz & Tugrul, 2023). The evidence was focused on physicochemical properties, so industrial sustainability would still require energy measurement, scale-up, product functionality, and comparison with existing processing. Nonetheless, the study illustrates how agricultural technology extends into material functionality: value can be created by changing starch structure rather than only increasing grain quantity.

Residue technologies are particularly relevant to circular agriculture. A simplified Anaerobic Digestion Model No. 1 reproduced biogas production and key intermediates using maize silage, other crops, manure, and industrial residues with fewer parameters than the full model, making model-based monitoring more practical for agricultural biogas plants (Weinrich et al., 2021). Another study coupled anaerobic fermentation and pyrolysis of corn stalks to produce fermented liquid feed and biologically modified biochar. Fermentation improved feed characteristics, while the resulting biochar had a cadmium sorption capacity 2.1 times that of pristine corn-stalk biochar (Tao et al., 2021). These examples show how residues can generate feed, energy, soil amendments, or remediation materials, but they also reveal competition among uses. Retaining residues for soil cover may conflict with removal for bioenergy or biochar. System design should allocate residues according to erosion risk, soil-carbon need, transport distance, contamination, and product value.

The value-chain perspective also changes how production technologies are prioritized. If harvest loss is 3.5%, a yield-enhancing input that raises production by 3% may deliver no net food gain unless harvesting improves. If storage insects remove a substantial share of grain, hermetic storage can outperform additional fertilizer in economic terms. If maize is routed into a high-impact feed or material pathway, upstream carbon efficiency may be insufficient. Agricultural technology strategy should therefore begin with a loss and value map that identifies where biomass, nutrients, energy, labor, and revenue are dissipated.

3.7 Adoption, Economics, Institutions, and Inclusive scaling

The adoption evidence is consistent on one point: information is necessary but rarely sufficient. Farmers make technology decisions under liquidity constraints, uncertain prices, heterogeneous soils, labor bottlenecks, land tenure, market distance, and exposure to drought, pests, and policy change. A technology that is profitable on average may still be rejected when downside risk is high or benefits arrive after a delay. Adoption studies therefore provide an essential counterweight to experimental agronomy.

In northern Uganda, an information treatment improved knowledge of certified seed but did not increase willingness to pay; only 14% of farmers were willing to pay the market price (Mastenbroek et al., 2021). The result warns against interpreting low adoption as a knowledge deficit. Farmers may understand the benefit but lack cash, trust, complementary fertilizer, access to output markets, or confidence that seed quality is genuine. By contrast, an audiovisual extension intervention in eastern Uganda improved knowledge, practice adoption, fertilizer use, and self-reported maize yield by about 10.5%, while adding interactive voice response and SMS reminders produced little incremental effect (Van Campenhout et al., 2021). Communication format, credibility, timing, and cognitive load matter; more digital channels do not automatically produce more behavior change.

Digital decision support can improve management when it incorporates economics. In northern Nigeria, site-specific nutrient recommendations improved fertilizer practices and maize yield without necessarily increasing total fertilizer use. Adding information about output-price variability and expected returns induced somewhat larger and more persistent fertilizer investments, although overall revenue effects were modest (Oyinbo et al., 2022). This is a critical design lesson. Agronomic recommendations should present expected return, uncertainty, and downside exposure, not only the technically optimal rate. A farmer's objective is not maximum simulated yield but acceptable profit and risk under household constraints.

Input and output prices can sharply narrow the economically relevant yield gap. Across sub-Saharan Africa, machine-learning and mechanistic analyses found that the average economic yield gap was only about one-quarter of the ecological yield gap. Maize yields could be profitably increased, but fertilizer and grain prices weakened incentives for intensification (Bonilla-Cedrez et al., 2021). This result challenges technology narratives based on attainable yield alone. Closing a biophysical gap may be irrational where fertilizer is expensive, output prices are low or volatile, and soil response is uncertain. Site-specific agronomy must therefore be accompanied by lower transaction costs, soil-health improvement, reliable markets, and finance.

Smallholder yield gaps are also heterogeneous. In Zambia, actual maize yield was approximately 2.4 t ha-1, or about 20% of water-limited potential. Technology, efficiency, and resource gaps differed across farm types, but better sowing time, plant population, fertilizer use, weed control, soil moisture conservation, and soil health could more than double current yields. The authors emphasized geographic targeting and farm typologies rather than a uniform national recommendation (Silva et al., 2023). This supports a segmentation approach to agricultural technology. Packages should be designed for market-oriented producers, net buyers, marginal maize growers, women farmers, remote communities, and water-limited zones rather than for an average farmer who does not exist.

Climate-smart agriculture studies further demonstrate the importance of bundles and context. In KwaZulu-Natal, drought exposure, on-farm income, household size, education, income source, and marital status influenced adoption or intensity of climate-smart practices (Mthethwa et al., 2022). In Ghana, farmer-organization membership, education, land constraints, market access, pest pressure, and drought influenced adoption of zero tillage, row planting, and drought-resistant seed, while the combination maximizing yield differed from the combination maximizing income (Asante et al., 2024). In Nigeria, sustainable land-management adoption and productivity were associated with gender, education, experience, credit, extension, association membership, and land ownership (Kolapo et al., 2022). These findings make technology inclusion a measurable design requirement, not a later dissemination task.

Evidence from mountainous northern Vietnam also shows that adoption effects are heterogeneous and can be counterintuitive. New seed varieties were associated with higher technical efficiency, and soil-erosion control improved productivity, but the measured effect of integrated pest-management advice was negative in the study context. Cooperative membership and organic-fertilizer use were associated with greater adoption of improved seed (Lampach et al., 2021). Such results should not be dismissed as anomalies. They may reflect poor implementation, selection into advisory programs, labor costs, unsuitable recommendations, or measurement limitations. Scaling programs need feedback systems capable of detecting when promoted practices do not improve performance.

Institutions can enable technology integration at larger scales. The public-private partnership and large-scale farming model discussed earlier aligned machinery, controlled-release fertilizer, and no-till management with economic and environmental goals (W. Zhang et al., 2022). Public expenditure in Chinese corn-producing provinces had an insignificant direct relationship with green productivity but a significant indirect effect through rural infrastructure, with larger gains in smaller producing provinces (Deng et al., 2023). The distinction between direct subsidy and enabling infrastructure is important. Roads, irrigation networks, power, mobile connectivity, machinery services, laboratories, and extension capacity can increase the return to many technologies simultaneously.

Digital climate services provide another institutional layer. Indonesia's integrated cropping calendar translated climate variability into recommendations on planting time, crop pattern, varieties, fertilizer, machinery, and risk. Adoption was moderate to high, but continued usefulness depended on local updates and active provincial task forces (Apriyana et al., 2021). A static platform becomes obsolete when seed portfolios, prices, climate patterns, or farmer needs change. Digital public goods require governance, maintenance, validation, and responsibility for errors.

The adoption literature leads to six practical principles. First, assess the farmer's binding constraint before selecting a technology. Second, present profitability and risk alongside agronomic performance. Third, design bundles with complementary inputs and services. Fourth, segment recommendations by farm type and environment. Fifth, use trusted organizations and service providers for delivery. Sixth, monitor actual use and outcomes rather than counting devices distributed or farmers trained. These principles shift scaling from technology promotion toward service-system design.

3.8 An Integrated Framework for Agricultural Technology Portfolios

The evidence supports a shift from isolated technology lists toward integrated technology architectures. Such an architecture should begin with a clearly defined production objective and the principal process limiting maize performance. Where yield is constrained by uncertain water availability, for example, the technological portfolio may combine drought-resilient genetics, soil-cover management, stage-sensitive irrigation, root-zone moisture sensing, and a climate-informed planting calendar. Where nitrogen loss is the dominant constraint, the portfolio may integrate crop-responsive application rates, subsurface placement, controlled-release formulations, residue management, and simultaneous monitoring of ammonia, nitrate, nitrous oxide, and soil carbon. Similarly, where smallholder adoption remains low, a technically simpler intervention supported by credit, trusted advisory services, market information, and risk-sharing mechanisms may be more effective than the addition of another sensor or digital device.

The five-part loop introduced earlier can be operationalized within this architecture. Observation should focus only on variables capable of changing a management decision. Prediction should communicate uncertainty and identify the specific management lever that can be adjusted. Intervention should remain feasible under the available equipment, labor, skills, and financial resources. Verification should evaluate agronomic, economic, and environmental outcomes, while delivery should clarify who maintains the system, updates recommendations, finances adoption, and bears operational risk. This structure addresses a common weakness in digital agriculture, namely the pursuit of high predictive accuracy for variables that have no clear or feasible management response.

Technology portfolios should also be modular. A core package can establish minimum agronomic performance, while optional modules can be added to address location-specific constraints. Improved seed, timely planting, appropriate plant population, effective weed control, and balanced nutrition may constitute the core package. A water-management module may add drip irrigation or deficit-irrigation scheduling, while a soil-management module may incorporate residue retention, organic amendments, or conservation practices.

A digital module may introduce remote sensing, field sensors, and decision-support systems, whereas a risk-management module may provide insurance, price information, credit, or improved storage. Modularity reduces capital barriers and permits staged adoption; however, the interfaces among modules must be standardized so that they can exchange data, support compatible decisions, and avoid biological or operational conflicts.

These relationships are synthesized in Figure 2, which presents an integrated agricultural technology framework for sustainable and inclusive climate-smart maize systems. The framework connects digital intelligence, precision agronomy, biological innovation, and inclusive scaling within a common technology architecture. Rather than treating these components as independent interventions, Figure 2 illustrates how they interact through observation, prediction, intervention, verification, and delivery to generate improvements in productivity, resource-use efficiency, climate resilience, environmental performance, and farmer inclusion.

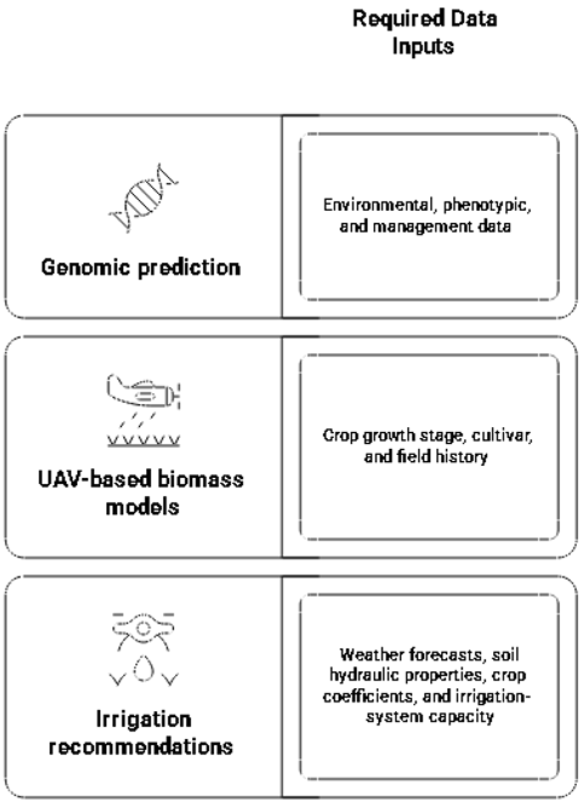

Figure 2. Integrated Agricultural Technology Framework for Sustainable and Inclusive Climate-Smart Maize Systems

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As shown in Figure 2, interoperability becomes increasingly important as digital, agronomic, and biological technologies converge. Genomic prediction requires environmental, phenotypic, and management data. UAV-based biomass models depend on information concerning crop growth stage, cultivar, and field history. Irrigation recommendations require weather forecasts, soil hydraulic properties, crop coefficients, and irrigation-system capacity. Nanoparticle- or microbial-based treatments require reliable records of dose, timing, stress diagnosis, field response, and safety. A common farm data model could therefore connect genotype, field conditions, farming operations, sensor observations, input applications, production outcomes, and uncertainty. Without such interoperability, each technology is likely to remain an isolated pilot project with limited capacity for cumulative learning or large-scale adaptation.

The integrated portfolio represented in Figure 2 also strengthens environmental governance. Each intervention should be assessed across upstream production, field application, persistence, and downstream consequences. Film mulch requires material-recovery systems and microplastic monitoring. Nanomaterials require evaluation of environmental fate and non-target effects. Biochar requires accounting for feedstock origin, pyrolysis conditions, and carbon balance. Irrigation technologies require consideration of energy demand and salinity risk, while nitrogen-management technologies require whole-flow nutrient accounting. Residue-conversion technologies should also be compared with alternative uses that preserve soil cover and carbon. These assessments are not administrative additions to technological development; they are necessary safeguards against efficiency gains that may later produce persistent environmental liabilities.

Finally, the integrated framework requires clear institutional specialization. Public agencies are well positioned to provide climate information, infrastructure, technical standards, environmental monitoring, and basic extension services. Private firms can supply machinery, digital analytics, improved seed, agricultural inputs, and maintenance services. Farmer organizations can aggregate demand, facilitate machinery sharing, validate recommendations, and strengthen market bargaining power.

Universities and research institutes can undertake multi-location trials, develop open benchmarks, and independently evaluate technological performance. Financial institutions can support seasonal credit, equipment leasing, insurance, and risk-sharing arrangements. The evidence indicates that integrated agricultural technology systems are most effective when these institutional roles are aligned, rather than when a single actor attempts to provide and manage the entire technological portfolio.

3.9 Research Priorities for the Next Generation of Maize Technology

The first priority is multi-environment validation. Many algorithms and biological interventions are tested in one location, season, or cultivar. Future studies should use stress-defined environment types, common validation protocols, and external test sites. Reporting should separate calibration, internal validation, temporal transfer, spatial transfer, and cultivar transfer. For digital models, uncertainty intervals and failure cases are as important as average r2. For agronomic technologies, performance distributions across years matter more than a single mean.

The second priority is causal integration. Studies often measure a sensor trait and separately report yield, but do not show that acting on the sensor information improves yield or resource efficiency. Randomized or adaptive trials should compare decision rules, not just prediction models. A moisture sensor should be evaluated through the irrigation schedule it triggers. A disease classifier should be evaluated through treatment timing, pesticide reduction, and yield protection. A digital extension platform should be evaluated through behavior, profit, and inclusion.

The third priority is whole-system accounting. Yield, water productivity, nitrogen-use efficiency, carbon footprint, soil carbon, pollution, labor, and profit should be measured within a consistent boundary. Particular attention is needed for rebound effects. Water-saving irrigation can support area expansion; yield gains can increase fertilizer demand; reduced ammonia can increase nitrate loss; residue harvest can reduce soil protection; and digital services can exclude farmers without connectivity. Multi-criteria decision analysis should make these trade-offs explicit rather than collapse them into a single sustainability score without transparent weights.

The fourth priority is affordability and serviceability. Researchers should report capital cost, operating cost, maintenance, energy demand, replacement cycle, calibration burden, and required skills. A high-accuracy sensor that fails after one season or cannot be repaired locally may have lower value than a simpler instrument. Business models such as custom hiring, pay-per-use analytics, cooperative ownership, leasing, and embedded advisory services should be tested alongside the technology.

The fifth priority is biological safety and ecological persistence. Microbial inoculants, gene-edited crops, engineered nanoparticles, pesticides delivered through irrigation, and soil amendments all require monitoring beyond immediate efficacy. Studies should track persistence, transformation, non-target organisms, resistance evolution, residue, food safety, and interactions with native microbiomes. Safety assessment should be proportional to plausible exposure but integrated early enough to guide material and formulation design.

The sixth priority is inclusion. Technology trials should disaggregate outcomes by farm size, gender, wealth, market orientation, tenure, and agroecology. Co-design should involve users in selecting the problem, defining acceptable risk, and determining the delivery model. Adoption should be measured as sustained correct use rather than initial uptake. Programs should also monitor who is excluded when a technology raises capital, data, or certification requirements.

The seventh priority is open evidence infrastructure. Shared datasets, benchmark fields, transparent algorithms, documented metadata, and common outcome definitions would accelerate cumulative learning. Proprietary systems can still compete on service quality, but core agronomic validation should be reproducible. Open environmental and performance benchmarks are particularly important when public funds support technology development or deployment.

IV. CONCLUSION

The recent literature portrays agricultural technology in maize as an increasingly connected system of sensing, prediction, biological and agronomic intervention, environmental verification, and institutional delivery. Digital technologies have achieved impressive accuracy in phenotyping, drought and disease monitoring, biomass estimation, planting-date reconstruction, and field mapping. Their practical contribution, however, depends on whether information is converted into reliable decisions. The strongest agronomic evidence comes from integrated water, nutrient, and soil-management packages that place resources in the root zone, protect sensitive growth stages, adapt to residue and soil conditions, and measure several environmental pathways at once.

Biological innovation is broadening the intervention space through genomic prediction, gene editing, microbiome management, biochar, engineered amendments, and nanomaterials. These approaches can strengthen stress tolerance and resource capture, but field transfer, safety, persistence, and cost remain decisive. Mechanization, crop protection, storage, processing, and residue conversion show that technology performance must be assessed across the value chain; gains at production can be lost during harvest or storage, and efficient maize production can still support environmentally intensive downstream pathways.

Across smallholder systems, adoption is shaped by affordability, price risk, credit, market access, farmer organizations, extension quality, and the complementarity of technology bundles. Information alone does not remove these constraints. The central implication is that future maize innovation should be designed as a portfolio rather than a product. Technology packages must be environment-specific, modular, interoperable, economically credible, and verified against yield, resilience, profitability, resource use, and environmental persistence. Progress will depend less on maximizing the performance of isolated tools and more on building accountable decision systems that remain effective under variable climates and real farm conditions.

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