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SUSTAINABLE AGRONOMY OF WHEAT (*TRITICUM AESTIVUM L.*): PATHWAYS TOWARD ZERO HUNGER AND CLIMATE RESILIENCE

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Abstract
Wheat (Triticum aestivum L.) is a cornerstone of global food systems, providing nearly 20% of the world's caloric and protein intake. However, its sustainability is under threat from climate variability, soil degradation, and resource constraints. This review synthesizes recent advancements (2023–2025) in sustainable agronomic practices, encompassing climate-smart irrigation, conservation tillage, nutrient and biofortification strategies, and genetic innovations that enhance resilience and nutritional quality. Emerging evidence highlights the integration of water-efficient irrigation, precision nutrient management, and conservation agriculture as synergistic strategies for yield stability, soil health, and environmental resilience. Biofortification initiatives are bridging the gap between food quantity and quality, offering dual solutions for production and nutrition security. The review concludes with policy, socioeconomic, and technological pathways aligning sustainable wheat systems with the United Nations Sustainable Development Goal 2 (Zero Hunger) and broader climate resilience objectives.

1. INTRODUCTION

Wheat (*Triticum aestivum L.*) remains the cornerstone of global food security, cultivated across more than 215 million hectares worldwide and serving as a staple source of carbohydrates, protein, and essential micronutrients for billions of people (FAO, 2024). Beyond its caloric contribution, wheat plays a vital socio-economic role by supporting rural livelihoods, ensuring nutritional adequacy, and driving agricultural economies in both developed and developing nations (Nwadi & Okonkwo, 2025). However, the sustainability of global wheat production faces significant challenges due to escalating climate pressures, land degradation, input dependency, and changing pest and disease dynamics (Ren, Zhang, & Fu, 2024; Guo et al., 2024).

Rising temperatures and altered precipitation regimes are already influencing wheat phenology, reducing grain quality, and reshaping planting suitability across major agro-ecological zones (Guo et al., 2024). Soil fertility depletion, intensive monocropping, and

declining genetic diversity further exacerbate productivity stagnation. At the same time, population growth continues to drive the demand for higher yields under constrained resources, making the need for sustainable and climate-resilient agronomic approaches more urgent than ever (Lubetkin, 2025).

Sustainable agronomy thus embodies a multidimensional approach that integrates genetic innovation, resource-efficient water and nutrient management, soil conservation, and socioeconomic inclusion to enhance both productivity and environmental resilience (Rafiei et al., 2024). Recent interdisciplinary advances emphasize the importance of aligning crop genetics with agronomic and environmental management strategies to sustain wheat yields amid the dual crises of climate change and food insecurity (Akinkuolie, 2025). In this context, this review synthesizes emerging evidence and scientific breakthroughs in the sustainable agronomy of wheat, linking biofortification, soil and water conservation, and climate-smart technologies with the achievement of Sustainable Development Goal 2 (Zero Hunger).

2. Genetic Improvement and Biofortification Strategies

2.1 Genetic Enhancement for Nutritional Quality

Genetic improvement of wheat has long been central to ensuring both yield and nutritional stability, particularly in regions prone to malnutrition and micronutrient deficiencies. Traditional breeding and modern genomic tools have together expanded the potential for biofortification, enhancing the intrinsic nutrient density of wheat grains without compromising productivity. Recent molecular breeding programs have identified quantitative trait loci (QTLs) and gene families regulating grain micronutrient content, particularly iron (Fe) and zinc (Zn) (Nasim et al., 2025).

The success of biofortified wheat varieties such as “Zinc-Shakti” and “Zinc-Ganga” demonstrates the feasibility of combining productivity with nutritional quality, addressing hidden hunger in vulnerable populations (Nasim et al., 2025; Ma et al., 2024). Parallel research using genome-wide association studies (GWAS) has revealed the molecular basis of declining Fe content during conventional wheat breeding, emphasizing the need to incorporate micronutrient-rich germplasm into breeding pipelines (Ma et al., 2024).

Beyond Fe and Zn, recent studies have advanced selenium (Se) biofortification through both genetic and agronomic pathways. Selenium-enriched genotypes, developed through conventional and transgenic breeding, achieved up to 42% higher Se accumulation without negative yield effects, indicating compatibility between biofortification and productivity targets (Sunic, K., & Spanic, V. 2024). Moreover, integrating molecular tools such as CRISPR-Cas9 has accelerated the incorporation of genes conferring drought tolerance and enhanced nutrient uptake, thereby supporting climate-resilient and nutritionally superior wheat (Zhang et al., 2025).

2.2 Agronomic Biofortification and Nutrient Synergies

While genetic enhancement provides a long-term solution, agronomic biofortification offers an immediate and scalable approach to improve grain nutrient content through targeted nutrient application. Field-based experiments have shown that foliar supplementation of Zn (0.5%) and Fe (0.3%) at key growth stages significantly enhances grain micronutrient concentrations and yield stability under diverse agro-climatic conditions (Jafarnejadi & Vishkaee, 2024). Such results underscore the synergistic potential of integrating micronutrient management with conventional NPK fertilization.

Tripathi et al. (2024) demonstrated that combined foliar sprays of nitrogen, potassium, sulfur, and zinc improved both yield and grain nutrient composition, highlighting the role of balanced nutrition in maintaining soil fertility and economic viability. Similarly, Xi et al. (2024) reported that nutrient-efficient cultivars show improved biomass partitioning and resource-use efficiency, suggesting that optimized nutrient inputs can reinforce genetic gains.

Integrating both genetic and agronomic biofortification thus presents a dual pathway where breeding programs provide inherent nutrient density and agronomic practices enhance bioavailability and uptake efficiency. Such an integrated model is critical for closing the nutrient gap in resource-constrained regions while supporting sustainable production goals

aligned with global food security frameworks (FAO, 2024; Lubetkin, 2025).

3. Water-Use Efficiency and Climate-Smart Irrigation

Water scarcity remains one of the most pressing constraints in wheat-producing regions, especially under the combined pressures of population growth and climate change. Efficient irrigation practices play a pivotal role in optimizing water productivity without compromising yield. Recent meta-analyses across semi-arid regions of China demonstrated that water-saving irrigation (WSI) technologies—such as micro-sprinkler and drip systems, reduced total irrigation water use by approximately 35%, improved water-use efficiency (WUE) by 18%, and maintained yields within ±5% of fully irrigated control plots (Zhao et al., 2024).

Similarly, deficit irrigation strategies supplying 60–80% of the crop's full water requirement, have proven optimal for balancing yield stability and water conservation (Li et al., 2023). These approaches, when coupled with real-time soil moisture sensors and decision-support systems, can significantly reduce wastage and improve irrigation scheduling accuracy. Integration of remote sensing tools and AI-based forecasting is further enabling site-specific irrigation management under variable rainfall conditions (Peng et al., 2024).

Table 1. Comparative Effectiveness of Water Management Strategies in Wheat

Irrigation Method	Water Reduction	Yield Effect	WUE Change	Reference
Drip irrigation	35% ↓	−3%	+18%	Zhao et al., 2024
Micro-sprinkler	30% ↓	−2%	+15%	Li et al., 2023
Deficit irrigation (70%)	–	Stable	+12%	Peng et al., 2024

4. Conservation Tillage and Soil Health Restoration

Conservation agriculture (CA) encompassing zero or minimum tillage, crop residue retention, and crop rotation is widely recognized as a cornerstone of sustainable agronomy. In the Indo-Gangetic Plains, adoption of zero tillage with residue retention improved soil organic carbon by 12%, enhanced aggregate stability, and suppressed weed emergence (Tripathi et al., 2024; Panghaal & Sangwan, 2024). Moreover, these practices mitigated soil erosion and reduced greenhouse gas emissions by 15–20% compared to conventional tillage (Singh et al., 2023). The positive feedback loop of improved soil structure, enhanced microbial activity, and increased infiltration under CA systems contributes to long-term yield stability, especially under water-limited conditions. However, successful implementation requires adaptive weed and pest management strategies to counter shifts in ecological niches resulting from reduced tillage intensity.

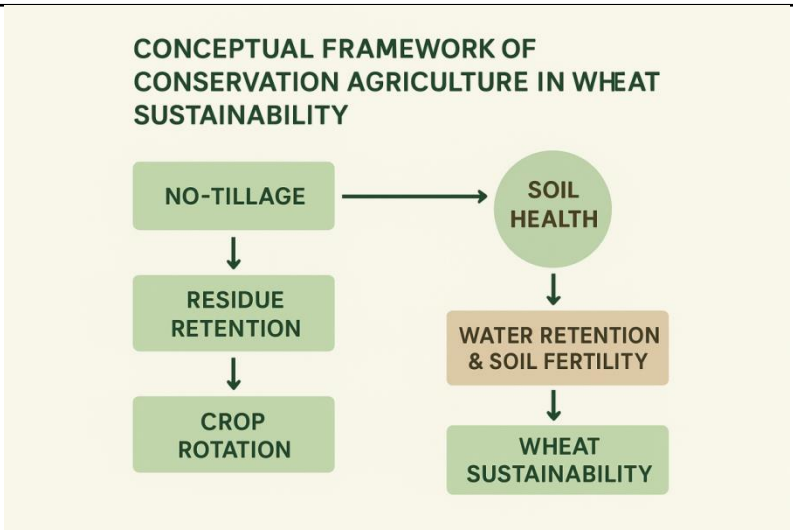


Figure 1. Conceptual Framework of Conservation Agriculture in Wheat Sustainability.

5. Integrated Nutrient and Water Management

Integration of nutrient management with efficient irrigation scheduling amplifies the benefits of both systems. Balanced NPK fertilization, when synchronized with micro-irrigation and foliar micronutrient sprays, enhances nutrient uptake, reduces leaching losses, and improves nitrogen-use efficiency (NUE) by up to 25% (Tripathi et al., 2024). The combined approach promotes stable yields even under erratic rainfall patterns.

Integrated Nutrient Management (INM) involving organic amendments such as compost, green manure, vermicompost, and biofertilizers improves soil microbial diversity and enzymatic activity (Verma et al., 2024). These organic components act synergistically with mineral fertilizers, enhancing nutrient cycling and soil buffering capacity. When integrated with drip or sprinkler irrigation, INM systems significantly improve both water and nutrient use efficiency, reinforcing soil health resilience.

6. Genetic and Agronomic Integration for Climate Resilience

The intersection of genetic improvement and adaptive agronomy forms the foundation of climate-resilient wheat production. Breeding programs are increasingly utilizing genomic selection, marker-assisted selection (MAS), and CRISPR-Cas9 genome editing to introduce drought tolerance, heat resilience, and micronutrient efficiency traits (Zhang et al., 2025; Nasim et al., 2025).

Recent advances in biofortification—such as the incorporation of Fe- and Zn-enriched alleles have substantially improved the nutritional value of wheat without yield penalties (Jafarnejadi & Vishkaee, 2024). The synergy between genetic biofortification and climate-smart agronomic practices (e.g., deficit irrigation, conservation tillage) ensures that these enhanced traits are effectively expressed under field conditions.

Table 2. Recent Advances in Wheat Biofortification and Nutrient Management (2023–2025)

Study & Year	Intervention	Key Findings	Region	Reference
Nasim et al. (2025)	Genetic mapping (Fe, Zn QTLs)	Identified >25 QTLs controlling grain micronutrient traits	China	*Int. J. Mol. Sci.*, 26(5):2178
Jafarnejadi & Vishkaee (2024)	Zn + Fe fertilization	+100% Zn, +95% Fe in grains	Iran	*J. Plant Nutr.*
Tripathi et al. (2024)	Foliar N, K, S, Zn sprays	Improved yield & quality across cultivars	India	*J. Plant Nutr.*, 47(19):3685–3700

Study & Year	Intervention	Key Findings	Region	Reference
Anonymous et al. (2024)	Selenium biofortification	42% Se increase, no yield loss	Europe	*Plants*, 13(13):1816

7. Policy, Socioeconomic, and Equity Considerations

Adoption of sustainable agronomic innovations is deeply intertwined with policy, economic, and social factors. Policies promoting micro-irrigation subsidies, biofortified seed distribution, and farmer training programs significantly enhance adoption rates (FAO, 2024).

Gender-sensitive extension models and community-based seed systems empower smallholder and women farmers, fostering inclusive participation in climate-resilient value chains (Kumar et al., 2023). Moreover, integrating sustainability goals within national agricultural frameworks aligns local practices with global objectives such as Sustainable Development Goal (SDG) 2: Zero Hunger.

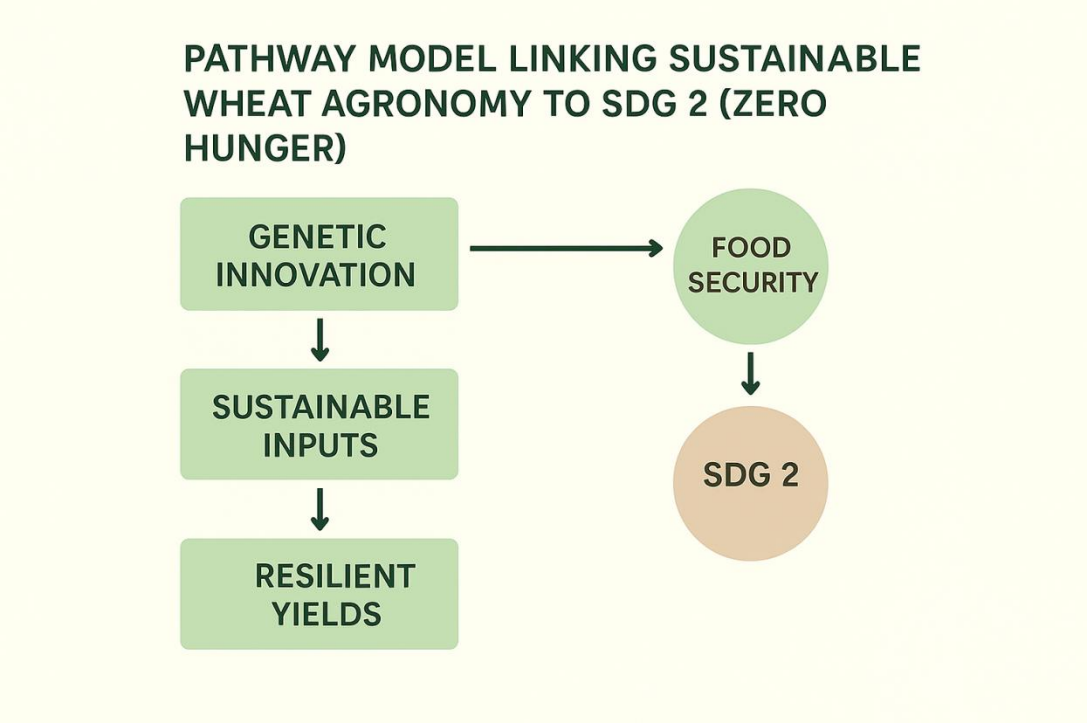


Figure 2. Pathway Model Linking Sustainable Wheat Agronomy to SDG 2 (Zero Hunger).

8. Future Research Directions

- Long-term experiments integrating tillage, irrigation, and nutrient management to quantify cumulative effects on soil organic carbon and productivity.
- Multi-location evaluations of biofortified wheat genotypes under diverse agroecological zones and stress conditions.
- Development of low-cost precision sensors and AI-driven platforms for smallholder decision-making.

- Socioeconomic analyses of sustainable agronomy adoption impacts on gender equity, income distribution, and rural livelihoods.

9. Conclusion

Sustainable wheat agronomy necessitates a holistic integration of genetics, water, nutrient, and soil management within enabling policy environments. The convergence of biofortification technologies, climate-smart irrigation, and conservation tillage offers a transformative pathway toward resource-efficient and nutritionally secure wheat systems. Achieving this vision requires interdisciplinary collaboration, scalable innovations, and context-specific adaptations to ensure that sustainability translates from research to every farmer's field and ultimately, to every plate.

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