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A STEP TOWARDS AGRICULTURE

Agri Roots e-Magazine

"A Smart Approach to Precision Cattle Breeding"

“SHAPING BETTER HERDS THROUGH SMART GENETICS.”

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from the editor

The rapid advancement of reproductive biotechnology is reshaping modern livestock production, and among these innovations, sex-sorted semen stands out as a transformative tool for precision cattle breeding. The Sex-Sorted Semen Revolution: A Smart Approach to Precision Cattle Breeding offers valuable insights into how this technology enables producers to predetermine calf gender, thereby improving genetic progress, enhancing herd productivity, and optimizing economic returns.

This article thoughtfully highlights the scientific principles, practical applications, and future prospects of sex-sorted semen while addressing its role in sustainable dairy and beef systems. At a time when efficiency, resource optimization, and climate-smart agriculture are paramount, such precision breeding approaches represent a significant step forward.

We hope this contribution stimulates informed discussion among researchers, extension professionals, and farmers, and encourages wider adoption of evidence-based reproductive technologies for building resilient and profitable cattle enterprises.

Dr. Deepak Kumar
FOUNDER & EDITOR

The Sex-Sorted Semen Revolution

EXPLORING KNOWLEDGE & DISCOVERING AGRICULTURE

AGRI ROOTS E-MAGAZINE

Overview of precision brrisewing technologies and scale implementation

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The Sex-Sorted Semen Revolution: A Smart Approach to Precision Cattle Breeding

ARTICLE ID: 0331

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Sex-sorted semen (SSS) technology represents a transformative advancement in bovine reproductive biotechnology, enabling preferential production of female calves with accuracy exceeding 90%. In India, increasing mechanization and socio-economic challenges associated with surplus male cattle have accelerated the adoption of this precision breeding approach. Recent indigenous innovations such as the GauSort system, combined with government support under the Rashtriya Gokul Mission, have substantially reduced costs and expanded accessibility. This article reviews the scientific principles of SSS, current technological developments, government interventions, operational guidelines for farmers, and its economic impact on dairy enterprises.

Biological sex determination in bovines traditionally follows a random process, governed by fertilization with either X- or Y-chromosome-bearing spermatozoa. In the present Indian dairy scenario, the approximately 50% probability of male births has become economically unsustainable due to mechanization and increasing stray cattle concerns. Consequently, demand for targeted reproductive technologies has risen sharply.

Sex-sorted semen (SSS) technology employs flow cytometric sorting to separate X- and Y-bearing sperm based on DNA content, enabling production of female offspring with more than 90% accuracy [1]. In *Bos indicus* and *Bos taurus*, X-chromosome-bearing sperm contain approximately 3.8–4.2% more DNA than Y-bearing sperm [3]. Advances in indigenous technology, notably the GauSort system developed by the National Dairy Development Board (NDDB), together with fiscal support under the Rashtriya Gokul Mission (RGM), have significantly improved farmer access to this innovation [2].

This review presents a technical, institutional, and policy-oriented overview of SSS implementation in India.

1. Technology Overview

1.1 Principle of DNA Fluorescence Sorting

Flow cytometry remains the gold standard for sex sorting. The process includes:

- **Stoichiometric Staining:** Semen is treated with Hoechst 33342, a DNA-specific fluorescent dye.
- **Laser Excitation:** A 355-nm ultraviolet laser excites the dye; X-bearing sperm emit higher fluorescence.
- **Droplet Charging And Separation:** Electrically charged droplets containing X-sperm are deflected into collection tubes, while Y-sperm are discarded [4].

1.2 Indigenous Advancement: Gausort

India previously depended on imported technologies such as SexedULTRA 4M® and Sexcel®. During 2024–2025, NDDB introduced GauSort, an indigenous system tailored for Indian breeds.

Key features include:

- Calibration for sperm morphology of Gir, Sahiwal, and Murrah breeds [5].
- Significant cost reduction, with subsidized straw prices decreasing from approximately ₹1,200 to ₹250 [2].

2. Government Schemes and Financial Support (2025–2026)

Multiple national programs facilitate last-mile delivery of SSS technology (Table 1).

Table 1. Government support mechanisms for sex-sorted semen adoption

Scheme	Provision	Target Group
Rashtriya Gokul Mission	50% subsidy on SSS (up to ₹750/pregnancy)	Small & marginal farmers
Assured Pregnancy Incentive	₹5,000 DBT for female calf born via SSS	Breed improvement
Breed Multiplication Farms	50% capital subsidy (up to ₹2 crore)	Entrepreneurs/FPOs
National Livestock Mission	50% subsidy for private semen stations	Private sector
AHIDF	3% interest subvention	Infrastructure
Pashu Sakhi/MAITRI	Training of AI technicians	Doorstep services
State top-ups (UP/Maharashtra)	₹100–200 per straw	Regional affordability
Kisan Credit Card	Enhanced credit limits	Working capital

3. Operational Guidelines for Farmers

3.1 Animal Selection

SSS conception rates are typically 10–15% lower than conventional semen [7].

- **Preferred:** Virgin heifers (15–18 months), with 45–50% conception rates [8].
- **Suitable:** First-lactation cows without uterine infections.
- **Avoid:** Repeat breeders and cows beyond fourth lactation.

3.2 Heat Detection and Timing

Due to reduced sperm longevity (~12 hours):

- Artificial insemination should be performed 14–16 hours after onset of standing heat.
- Visual observation during early morning and evening is essential.

3.3 Nutritional and Herd Management

- Provide 50 g chelated mineral mixture daily for 30 days before AI.
- Maintain cold chain strictly; thaw semen at 37°C for 30 seconds in a water bath [5].

4. Cooperative and Institutional Support

Cooperative milk unions such as Amul and Nandini integrate SSS within veterinary outreach programs. NDDB and its subsidiaries provide genetic merit certification of donor bulls, ensuring enhanced milk productivity in female progeny [10].

5. Research Insights and Economic Impact

Economic analyses indicate that although SSS incurs higher initial costs, net present value of dairy enterprises increases by approximately ₹25,000 per animal [9]. Benefits arise from:

- Reduced replacement costs
- Accelerated genetic gain (15–20% improvement per generation)
- Elimination of expenditure on unproductive male calves

Conclusion

Sex-sorted semen technology represents a paradigm shift from traditional cattle rearing to precision dairy entrepreneurship. Indigenous innovations such as GauSort, supported by Rashtriya Gokul Mission subsidies, have democratized access to elite genetics. With proper management, SSS offers Indian farmers a sustainable pathway toward higher productivity, profitability, and herd quality.

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Transformation Technology in Crop Residue Management: A Sustainable Solution to Stubble Burning

ARTICLE ID: 0332

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Crop residue, especially rice stubble, has historically posed an agronomic and environmental challenge in intensive agricultural systems. In regions such as the Indo-Gangetic Plains of India, rice harvesting is immediately followed by wheat sowing, leaving farmers with a narrow time window for field preparation. Consequently, open stubble burning has become a widespread practice due to its speed and low cost. However, this releases large quantities of particulate matter and greenhouse gases, degrades air quality, harms human health, and destroys valuable soil nutrients.

Recent innovations emphasize sustainable residue management through microbial decomposers, biochar production, and in-situ mechanization tools such as the Happy Seeder and Super Straw Management (SMS)/Super Seeder. These technologies reduce environmental damage, improve soil health, and maintain productivity without compromising rapid field turnaround.

The Problem of Stubble Burning

Farmers often have only 15–21 days between rice harvest and wheat sowing, leading to preference for rapid residue removal methods (Näher and Ziulu, 2025). Although burning is quick and inexpensive, it causes:

- Loss of essential nutrients (especially nitrogen and potassium)
- Disruption of beneficial soil microbiota
- Increased emissions of CO_2, CH_4, $PM_{2.5}$ and PM_{10}

These effects contribute to seasonal air-pollution crises in northern India and aggravate climate change and public health risks. Hence, governments, research institutions, NGOs and farmers are exploring transformative crop residue management strategies.

Microbial Decomposers: Accelerating Natural Residue Breakdown

Concept and Mechanism

Microbial decomposers consist of specialized fungi and bacteria that accelerate lignocellulosic residue degradation. Products such as Pusa Decomposer secrete enzymes (ligninase, cellulase and pectinase) that convert tough crop residues into simpler organic compounds.

Developed by ICAR, Pusa Decomposer contains fungal strains such as *Trichoderma* spp., enabling conversion of rice straw into organic matter within 20–25 days, making it compatible with wheat sowing schedules (Asian J. Soil Sci. Plant Nutr., 2025).

Benefits for Sustainable Agriculture

- **Soil Enrichment:** Enhances organic matter and microbial activity; reported yield increases of 12–15%.
- **Reduced Chemical Dependence:** Improved nutrient cycling lowers fertilizer requirement.
- **Environmental Protection:** Prevents burning-related emissions and improves air quality.

Adoption challenges include limited awareness, logistical constraints, and availability, highlighting the need for extension services and coordinated field support.

Biochar: Turning Residue into a Valuable Soil Amendment

What Is Biochar?

Biochar is a carbon-rich product obtained through pyrolysis of biomass under limited oxygen. Unlike burning, pyrolysis converts residues into stable carbon that persists in soil for decades, acting as a carbon sink.

Environmental and Agronomic Advantages

1. **Carbon Sequestration:** Mitigates climate change by locking carbon in soils.
2. **Soil Health Improvement:** Enhances structure, water retention and cation exchange capacity.
3. **Reduced Fertilizer Losses:** Improves nutrient retention and use efficiency.
4. **Versatility:** Can be combined with compost or manure for greater soil benefits.

Biochar vs. Burning

While burning causes nutrient loss and degradation, biochar retains carbon and nutrients within the farming system, promoting circular agriculture. However, widespread adoption faces constraints related to equipment cost and logistics. Community pyrolysis units and subsidies could accelerate uptake.

In-Situ Mechanization: Happy Seeder, SMS and Super Seeder

Happy Seeder: Revolutionizing Direct Sowing

The Happy Seeder allows direct wheat sowing into standing rice residue. It cuts stubble, opens seed furrows and deposits straw as mulch, eliminating the need for burning.

Key benefits include:

- Reduced soil disturbance and erosion
- Improved moisture retention and microclimate
- Up to 78% reduction in greenhouse gas emissions
- Long-term economic gains through lower labor and input costs

Government subsidies (up to 80%) have promoted adoption in Punjab, Haryana and Uttar Pradesh.

Super Straw Management (SMS) and Super Seeder

SMS attachments on combine harvesters evenly chop and spread residues, facilitating subsequent sowing. The Super Seeder integrates residue cutting and crop sowing in a single operation. Field trials show maintained or improved yields due to better seed placement and mulch benefits.

Integrated Benefits of Transformation Technologies

The combined use of microbial decomposers, biochar and mechanization provides:

- **Environmental Gains:** Reduced pollution, enhanced carbon storage and healthier soils
- **Economic Benefits:** Lower fuel and labor costs, improved yields and value-added residue products
- **Social Outcomes:** Cleaner air, improved public health and farmer livelihoods
- **Policy Alignment:** Strong synergy with government incentives and climate-smart agriculture goals

Challenges and Future Directions

Major constraints include:

- High machinery costs for smallholders
- Need for farmer training and awareness
- Limited infrastructure for biochar and microbial inputs
- Requirement for consistent policy support

Future research should prioritize region-specific microbial formulations, low-cost biochar technologies and multifunctional machinery.

Conclusion

Transformation technologies provide sustainable alternatives to stubble burning. Microbial decomposers enable rapid residue breakdown, biochar enhances soil fertility while sequestering carbon, and mechanization tools facilitate residue-retained sowing. Together, these approaches improve soil health, reduce emissions and build resilient cropping systems. Strategic investment in innovation, infrastructure and education, supported by enabling policies, can make crop residue management a cornerstone of sustainable agriculture in India and beyond.

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Self-Help Groups and Farmer Producer Organizations: Empowering Women and Youth in Rural India

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In rural India, women and youth play a central role in agricultural production, household food security, and livelihoods. Despite their contributions, structural barriers such as limited access to land, finance, technology, and markets constrain their economic participation. Self-Help Groups (SHGs) and Farmer Producer Organizations (FPOs) have emerged as grassroots institutions addressing these challenges through collective action, capacity building, and market integration. This article examines the complementary roles of SHGs and FPOs in promoting inclusive rural development, with a case study of Raskum Mahila Sajiv Khet Utpadak Mandali Farmer Producer Company Limited (RASKUM), Gujarat, highlighting their impact on income enhancement, social empowerment, and youth engagement.

Women and youth are integral to India's rural economy, contributing significantly to agriculture and allied sectors. However, persistent constraints—limited asset ownership, inadequate credit access, weak market linkages, and low participation in decision-making—restrict their potential. In response, institutional mechanisms such as SHGs and FPOs have gained prominence as vehicles of collective empowerment, enabling marginalized groups to access resources, build skills, and engage more effectively with markets.

Self-Help Groups: Engines of Inclusion and Empowerment

Self-Help Groups, promoted under NABARD and the Deendayal Antyodaya Yojana–National Rural Livelihoods Mission (DAY-NRLM), form the backbone of women-centric rural development initiatives. Typically comprising 10–20 women, SHGs encourage regular savings and provide internal lending based on mutual trust and collective decision-making.

India hosts over 76 lakh SHGs with more than 8 crore women members (NRLM, 2023). Participation in SHGs has enhanced financial inclusion, increased access to institutional credit, and diversified livelihoods through activities such as dairy, poultry, tailoring, food processing, and micro-enterprise development. Beyond economic benefits, SHGs foster social empowerment by strengthening confidence, leadership, communication skills, and participation in household and community governance (NABARD, 2022).

Moreover, SHGs act as platforms for addressing broader social concerns, including health, nutrition, sanitation, education, and gender equity, thereby functioning as agents of social transformation.

FPOs: Platforms for Market Linkages, Skills and Youth Participation

Farmer Producer Organizations are collective enterprises designed to strengthen small and marginal farmers through aggregation, value addition, and market integration. Supported by SFAC, NABARD, and state governments, FPOs facilitate access to quality inputs, improved technologies, and structured markets while reducing transaction costs and price exploitation.

FPOs are increasingly important for attracting rural youth by promoting agribusiness orientation, entrepreneurship, digital tools, and value-chain participation. Leadership roles within FPOs provide opportunities to develop managerial and organizational competencies.

Women-led and women-inclusive FPOs further enhance bargaining power and visibility in markets, contributing to income growth and resilience among smallholders (Singh et al., 2019).

Combined Impact: Social Capital, Livelihoods and Rural Transformation

SHGs and FPOs operate synergistically: SHGs focus on household-level financial inclusion and social cohesion, while FPOs strengthen community-level entrepreneurship and market engagement. Together, they build social capital, enhance collective bargaining, generate employment, stabilize incomes, and reduce distress migration.

Despite their success, challenges persist, including limited access to advanced training, inadequate working capital, weak governance, low digital literacy, and gender gaps in leadership. Addressing these constraints through targeted capacity building and institutional support remains critical.

Case Study: Raskum Mahila Sajiv Khet Utpadak Mandali Farmer Producer Company Limited (RASKUM), Gujarat

Established in July 2021 in Dahod district under DAY-NRLM, RASKUM exemplifies effective SHG–FPO convergence in empowering tribal women farmers (Jha & Singh, 2025). Originating from women-led SHG networks, RASKUM transitioned into a registered producer company, enabling collective participation in markets.

Initially mobilizing over 100 tribal women farmers engaged mainly in maize cultivation, RASKUM facilitated aggregation and collective marketing, improving price realization and reducing intermediary dependence (Singh et al., 2019; Anand et al., 2023). Capacity-building initiatives in input procurement, post-harvest management, grading, storage, bookkeeping, and marketing enhanced operational efficiency. Participating households reported income increases of 20–30%.

An example of enterprise diversification emerged when a women's group associated with RASKUM provided catering services for an event at the Institute of Rural Management Anand (IRMA), demonstrating how SHG skills linked with FPO market exposure can generate non-farm income (Jha & Singh, 2025).

Outcomes

Economic Gains: Access to institutional credit, quality inputs, storage, and collective transport shifted farming from subsistence to commercial orientation (Biswas et al., 2025; Kumar et al., 2023).

Social Empowerment: SHG foundations strengthened financial literacy, leadership capabilities, and confidence among women members.

Institutional Synergy: RASKUM illustrates how SHGs build social cohesion and savings discipline, while FPOs provide scale, formal market access, and business orientation—aligning with broader empirical evidence (Singh et al., 2019; Anand et al., 2023).

Conclusion

SHGs and FPOs have emerged as pivotal grassroots institutions advancing inclusive rural development by enabling women and youth to overcome constraints related to finance, skills, technology, and markets. While SHGs enhance social capital and household-level empowerment, FPOs offer community-level scale and entrepreneurial opportunities. The RASKUM case demonstrates how SHG–FPO linkages translate into higher farm incomes, enterprise diversification, youth engagement, and strengthened decision-making power for tribal women. Strengthening governance, working capital access, digital inclusion, and gender-responsive support systems will be essential to scale such models and position SHGs and FPOs as pillars of sustainable rural transformation in India.

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Biochemical Composition and Bioactive Compounds of Wood Apple (*Limonia acidissima* L.)

ARTICLE ID: 0334

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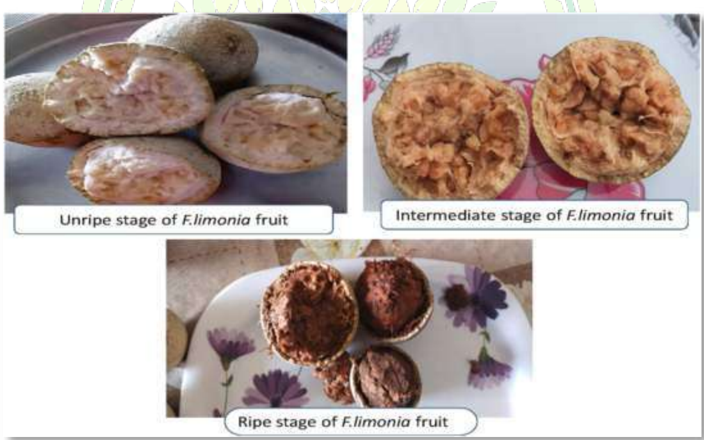
Wood apple (*Limonia acidissima* L.; synonym *Feronia limonia*) is a perennial underutilized fruit tree belonging to the family Rutaceae. Native to the Indian subcontinent, it is widely distributed across India, Bangladesh, Sri Lanka, and Southeast Asia. The fruit is traditionally valued for its distinctive flavor and medicinal applications in Ayurveda and other ethnomedicinal systems.



Wood apple is nutritionally rich and possesses considerable antioxidant potential. Various plant parts exhibit curative properties due to the presence of proteins, carbohydrates, dietary fiber, calcium, phosphorus, and diverse phytochemicals. Fruit composition varies with genotype, environmental conditions, soil type, and maturity stage. In India, fruits mature during October–November, with ripening extending from January to June.

The pulp contains substantial amounts of polyphenols, tannins, vitamins, amino acids, and flavonoids, contributing to health benefits such as reduced risks of cardiovascular diseases, cancer, and diabetes. Recent scientific investigations have focused on validating these traditional claims through biochemical and phytochemical analyses.

Botanical Description and Uses

Limonia acidissima is a medium-to-large deciduous tree characterized by rough bark and thorny branches. The fruit possesses a hard woody shell enclosing sticky brown pulp with embedded seeds.

The pulp is consumed fresh or processed into beverages, jams, sweets, and traditional remedies. Fruits, leaves, bark, and seeds are extensively used in herbal medicine due to their rich phytochemical profile and bioactivity.

Proximate and Nutritional Composition

Macronutrients

Proximate analysis of wood apple pulp reveals:

- **Carbohydrates:** ~24.74% (dry weight)
- **Proteins:** ~9.30%
- **Fat:** ~0.99%
- **Crude Fiber:** ~3.32%
- **Ash:** ~2.73%

Fresh pulp contains approximately 79% moisture, with protein (8.3–8.35%), fat (1–2%), and total sugars (~6.4%). These values vary with maturity and growing conditions.

Sugars and Organic Acids

Chromatographic studies have identified:

- **Major Sugars:** Fructose (~16.40%) and glucose (~14.23%)
- **Organic Acids:** D-tartaric, citric, and ascorbic acids
- **Vitamin C:** Approximately 2.55 mg/g in certain varieties

These compounds contribute to the characteristic sweet–sour taste of the fruit.

Mineral Content

Wood apple pulp contains essential minerals including:

- **Calcium and Phosphorus:** Important for bone health
- **Iron:** Supports hematopoiesis
- **Potassium, Magnesium, And Zinc:** Maintain electrolyte balance and enzymatic functions

The potassium–sodium ratio suggests potential benefits for blood pressure regulation.

Fatty Acid Profile

Although total lipid content is low, nutritionally valuable fatty acids are present:

- **Saturated:** Palmitic and stearic acids
- **Unsaturated:** Oleic (~23.89%), α-linolenic (~16.55%), and linoleic (~10.02%)

These unsaturated fatty acids contribute to cardiovascular and anti-inflammatory benefits.

Bioactive Phytochemicals

Wood apple contains diverse secondary metabolites responsible for its pharmacological properties.

Phenolic Compounds and Flavonoids

- High total phenolic content
- Presence of quercetin and related flavonoids
- Strong correlation with antioxidant activity

Coumarins

Compounds such as psoralen and umbelliferone exhibit antimicrobial and dermatological bioactivities.

Alkaloids, Tannins, and Steroids

Phytochemical screening confirms the presence of:

- Alkaloids
- Tannins
- Steroids and terpenoids
- Saponins

These constituents contribute to antimicrobial, antidiarrheal, and metabolic effects.

Other Bioactive Classes

Additional compounds include quinones, lignans, triterpenoids, and essential oils, indicating broad chemical diversity.

Functional Properties and Bioactivities

Antioxidant Activity

Phenolics and flavonoids provide strong free-radical scavenging capacity, reducing oxidative stress.

Antimicrobial and Antidiabetic Effects

Traditional applications and experimental studies suggest antimicrobial and antidiabetic potential arising from synergistic phytochemical interactions.

Pharmacological Activities of *Limonia acidissima*

- **Anti-inflammatory:** Helps reduce cardiovascular risk and enhances immunity
- **Anti-ulcer:** Phenolic compounds protect gastric mucosa and reduce leukocyte infiltration
- **Ayurvedic formulations containing Kapitha (Wood Apple):**
  - *Vajra Kapat Rasa* – diarrhea and malabsorption
  - *Nyagrodhadi Choorna* – urinary disorders and diabetes
  - *Dashamoolarishta* – anemia, postpartum care, cold, cough, and digestive disorders

Conclusion

Limonia acidissima exhibits a rich biochemical composition comprising carbohydrates, proteins, minerals, unsaturated fatty acids, vitamins, and diverse bioactive phytochemicals. Phenolics, flavonoids, coumarins, alkaloids, and terpenoids contribute to its antioxidant, antimicrobial, anti-inflammatory, and gastroprotective properties.

These nutritional and pharmacological attributes validate traditional uses and highlight the fruit's potential for incorporation into functional foods, nutraceuticals, and herbal formulations. Further clinical investigations are required to establish therapeutic efficacy and safety in humans.

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Role of GM and Genome-Edited Crops in Enhancing Stress Tolerance and Nutrient Use Efficiency

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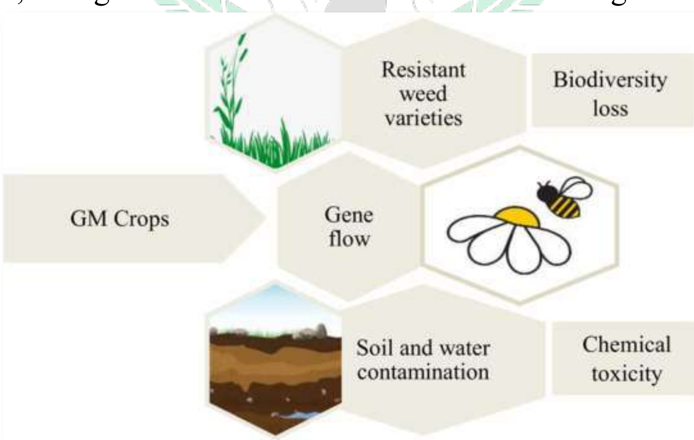
Global agriculture faces increasing pressure from climate change, land degradation and rising food demand. Abiotic stresses such as drought, salinity and heat, along with inefficient nutrient utilization, significantly limit crop productivity. Conventional breeding approaches are often slow and constrained by genetic variability. Advances in genetic modification (GM) and genome editing technologies offer precise tools to improve stress tolerance and nutrient use efficiency (NtUE) in crops. This article reviews the role of GM and genome-edited crops in enhancing resilience to abiotic stresses and improving nutrient utilization. Mechanisms, case studies and future prospects are discussed, highlighting their potential contribution to sustainable agriculture and global food security.



Global agriculture faces unprecedented challenges from climate change, land degradation and a growing human population. Increased incidence of drought, salinity, heat stress and nutrient depletion are among the major constraints limiting crop productivity and food security. Traditional breeding methods have historically improved yield and stress tolerance traits, but they are relatively slow and limited by genetic variability within breeding populations.

Recent advances in biotechnology have paved the way for genetically modified (GM) and genome-edited crops, offering precise and robust solutions to enhance stress tolerance and nutrient use efficiency (NtUE). This article explores how these technologies contribute to sustainable crop improvement, examines specific examples, discusses mechanisms of action and considers broader implications for agriculture.

Genetic Modification and Genome Editing: Background

GM crops involve introducing foreign genetic material into a plant genome to confer desired traits such as insect resistance or herbicide tolerance. Examples include Bt cotton and herbicide-tolerant soybean.

Genome editing utilizes tools such as CRISPR/Cas9, TALENs and ZFNs to induce precise changes in native DNA without necessarily introducing foreign genes. These approaches enable gene knock-out, insertion or modification with high accuracy.

Unlike GM crops, genome-edited plants may be indistinguishable from naturally occurring variants except at the nucleotide level, allowing potential regulatory flexibility. Both technologies offer powerful avenues for improving stress tolerance and NtUE.

Enhancing Stress Tolerance

Understanding Stress Factors

Plants experience multiple abiotic stresses including drought, salinity, heat and cold. These stresses trigger ROS accumulation, cellular dehydration and hormonal imbalance. Improvement of stress tolerance focuses on genes involved in perception, signalling, osmotic regulation and antioxidant defence.

GM Approaches to Stress Tolerance

Transgenic strategies commonly introduce stress-responsive genes or transcription factors such as DREB**,** enhancing water-use efficiency and osmotic balance.

HB4 wheat, containing a sunflower gene, exhibits improved drought tolerance and biomass retention under water stress, providing yield stability in drought-prone environments.

Genome Editing for Stress Resilience

Genome editing modifies endogenous genes controlling stress responses. CRISPR-Cas9 mediated disruption of stress-sensitivity genes improves tolerance to drought, salinity and cold.

Edited rice MYB genes enhanced cold tolerance, while MAPK and ARF gene modifications improved heat and salinity tolerance. Kumar et al. (2024) reported that genome editing targets regulatory networks enabling superior abiotic stress resilience.

Mechanisms Underlying Stress Tolerance

- Regulation of stress signalling pathways
- Improved osmotic balance and water-use efficiency
- Enhanced antioxidant defence reducing oxidative damage

These mechanisms collectively support crop productivity under adverse environments.

Improving Nutrient Use Efficiency (NtUE)

Importance of NtUE

NtUE reflects a plant's ability to acquire and utilize nutrients efficiently. Improved NtUE reduces fertilizer demand, lowers production costs and minimizes environmental pollution.

GM Approaches to NtUE

GM cereals have demonstrated higher nitrogen uptake efficiency and grain yield per unit nitrogen applied. Meta-analyses show improved NUpE in rice, maize and wheat without increased fertilizer input.

Genome Editing for Nutrient Efficiency

Genome editing targets nutrient transporters, root architecture genes and regulatory pathways to enhance uptake and utilization. Editing negative regulators of nutrient signalling offers promising strategies for low-input agriculture.

Biofortification and Dual Benefits

Genome editing supports biofortification (e.g., β-carotene enriched rice) and indirectly influences nutrient metabolism, linking human nutrition with crop efficiency.

Case Studies and Examples

Drought and Salt Tolerance

- CRISPR-edited rice (OsDREB1A) showed improved drought survival.
- Maize with modified ZmNHX1 exhibited enhanced salinity tolerance.

Enhanced NtUE

- GM cereals demonstrated significant improvements in nitrogen uptake efficiency.
- CRISPR targets regulating nutrient uptake show future potential under poor soil conditions.

Integration of Stress and NtUE Traits

Stress tolerance and nutrient efficiency share overlapping molecular pathways. Advanced genome editing allows multiplexed trait improvement, producing crops capable of maintaining productivity under combined stress and nutrient limitation.

Challenges and Considerations

Regulatory and Ethical Issues

Genome-edited crops may face relaxed regulations in some regions; however, biosafety and public acceptance remain crucial.

Environmental Concerns

Potential off-target effects and ecological impacts necessitate rigorous evaluation.

Socio-Economic Impacts

Equitable access, farmer training and intellectual property considerations must be addressed to ensure inclusive benefits.

Conclusion

GM and genome-edited crops are transformative technologies for modern agriculture. They enhance abiotic stress tolerance and nutrient use efficiency, reducing fertilizer dependency and environmental impact. Genome editing, particularly CRISPR-Cas systems, provides unprecedented precision and speed. As climate challenges intensify, these tools will play a vital role in sustainable crop production and global food security.

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Adaptation Strategies to Heat Stress for Sustaining Wheat Crop Yield

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Rising temperatures under climate change increasingly expose wheat (*Triticum aestivum* L.) to heat stress (HS), causing severe yield and quality losses, particularly when stress coincides with reproductive and grain-filling stages. Wheat responds through a complex network of morphological, physiological, molecular, biochemical, epigenetic, and priming-mediated adaptations that collectively determine thermotolerance and yield stability. This review synthesizes current understanding of these mechanisms and highlights key traits and management options that can be exploited in breeding and agronomy to safeguard wheat productivity in heat-prone environments.

Wheat is the most widely grown rabi cereal and a major source of calories and protein for the global population, contributing nearly 20% of dietary protein [2,3]. Projections indicate that global wheat demand will rise by approximately 198 million tonnes by 2050, yet a large proportion of wheat-growing regions, particularly in low latitudes, already experience frequent heat stress during critical growth stages [2]. Crop modelling across multiple environments has shown yield reductions ranging from 1–28% for each 2 °C rise in temperature and 6–55% for a 4 °C increase [2,3]. Globally, wheat production is estimated to decline by around 6% per 1 °C rise in temperature [2,3]. In India, a 1 °C increase in mean temperature during March–April can reduce wheat yield by about 400 kg ha^{-1}, largely due to terminal heat stress during grain filling when temperatures exceed 31 °C [4,5].

Heat stress affects wheat growth, development, photosynthesis, hormonal balance, metabolism, water relations and reproductive success, mainly through excessive generation of reactive oxygen species (ROS) and stress hormones such as ethylene [1,4]. To survive and produce grain under high temperature, wheat relies on a hierarchy of adaptive mechanisms operating from the whole-plant to molecular and epigenetic levels. Understanding these adaptations is essential for designing climate-smart wheat production systems [1].

Effects of Heat Stress on Wheat Growth, Yield and Quality:

a. Vegetative stage

Heat stress at the vegetative stage primarily affects seed germination and early seedling establishment. Temperatures around 45 °C severely damage mitochondria in imbibing embryos, reduce ATP synthesis and oxygen uptake, and alter protein expression, resulting in poor seed vigor and weak plant stands [1,5]. Elevated temperatures (around 30/25 °C day/night) suppress biomass accumulation by restricting leaf development and productive tiller formation [1]. Although higher temperature increases leaf appearance and elongation rate, it shortens the elongation period, leading to reduced final leaf size, plant height and biomass [1,5].

Photosynthesis is one of the earliest and most heat-sensitive processes. High temperature disrupts Rubisco and Rubisco activase activity, damages thylakoid membranes and impairs photosystem II, reducing CO_2 fixation [1,4]. Increased photorespiration under high temperature further lowers net photosynthesis, while accelerated leaf senescence above 34 °C is associated with chlorophyll degradation and cellular dehydration [1,4].

b. Reproductive Stage And Yield Formation

Heat stress during flowering and grain filling is far more damaging than during vegetative growth. A rise of just 1 °C during this period can cause severe yield losses [2,4]. Flowering and grain filling are optimal between 12 and 22 °C; heat stress during meiosis or anthesis disrupts pollen development, pollen tube growth and fertilization, causing floral abortion and reduced grain number [1,4]. Grain filling depends on both the rate and duration of dry matter accumulation, and even a 1–2 °C rise shortens grain-filling duration, reducing grain weight [1,4]. Short episodes of heat stress can reduce grain yield by up to about 23%, while reduced grain number also lowers harvest index [4,5].

c. Grain Quality

Heat stress alters both starch and protein composition of wheat grains. Activities of ADP-glucose pyrophosphorylase and starch synthase decline under heat stress, causing up to one-third reduction in endosperm starch [1,4]. Heat stress increases amylose content and the amylose: amylopectin ratio, altering starch functionality [1]. Protein concentration and soluble sugars often increase due to smaller kernel size and altered nitrogen remobilization, but protein quality and bread-making properties may deteriorate, particularly when heat stress occurs early during grain filling [4,5].

Morphological and Physiological Adaptation Strategies

Morphological adaptations

Wheat exhibits several architectural modifications under heat stress that help sustain productivity. Rapid early seedling emergence and ground cover reduce soil evaporation and improve water availability for transpiration cooling [1,5]. Leaf rolling, thickening, and increased wax and hairs on leaves and stems reduce radiation load and heat absorption [1]. Flag leaf area and awn length are positively correlated with grain yield under heat stress because of their role in assimilate supply to grains [1,4]. Early-maturing genotypes escape terminal heat stress, while traits such as days to heading, maturity duration, plant height, effective tillers and biomass become important yield determinants under late-sown conditions [4,5].

Physiological adaptations

Physiological tolerance is strongly associated with membrane stability, water relations and canopy cooling. Heat-tolerant genotypes maintain cell membrane integrity, reflected in lower electrolyte leakage and more stable osmotic potential [1,4]. Deep root systems and high transpiration capacity allow plants to access deeper soil moisture and maintain cooler canopies. Canopy temperature is negatively correlated with transpiration and grain yield, making it a valuable selection trait [1,5].

High-throughput tools such as infrared thermometers (canopy temperature), Green Seeker (NDVI), SPAD meters (chlorophyll) and porometers (stomatal conductance) facilitate screening for heat tolerance [1]. The stay-green trait is particularly important: tolerant genotypes retain chlorophyll longer, delay senescence and maintain photosynthesis, improving grain filling under heat stress [1,4]. Osmolytes such as proline, soluble sugars, glycine betaine and GABA stabilize proteins and membranes and improve redox balance [1,5].

Molecular, Biochemical and Epigenetic Adaptations:

Heat shock signalling

Heat stress disrupts membrane fluidity and ionic balance, triggering Ca^{2+} influx, phosphatidic acid and PIP_2 signalling, and activation of MAPKs and calcium-dependent protein kinases [1]. These cascades activate heat shock transcription factors (HSFs), which induce heat shock proteins (HSPs) and other protective genes. Transcriptomic studies have identified numerous HS-responsive genes in wheat, including HSFs, HSPs and stress-related transcription factors. The transcription factor TaHsfA6f regulates multiple HSPs and enhances thermotolerance [1].

Biochemical and Hormonal Regulation

Rubisco activase (Rca) is highly temperature sensitive; wheat expresses multiple isoforms, including a thermostable form (Rca1β) that is rapidly induced during heat stress [1]. Phytohormones such as abscisic acid (ABA), salicylic acid (SA) and cytokinins regulate stress responses. ABA controls stomatal closure and grain filling, SA modulates photosynthesis and HSP expression, and cytokinins promote stay-green and delay senescence [1,4].

Heat stress increases ROS production, necessitating efficient antioxidant systems. Enzymes such as superoxide dismutase, catalase, ascorbate peroxidase and glutathione reductase, together with non-enzymatic antioxidants, protect cellular structures from oxidative damage [1,5].

Epigenetic Regulation And Stress Memory

DNA methylation, histone modifications and chromatin remodelling contribute to heat stress adaptation and stress memory. In wheat, several DNA methyltransferase genes and histone acetyltransferases (e.g., TaGCN5) regulate the expression of heatresponsive genes. These epigenetic changes enable plants and their progeny to remember previous heat exposure and respond more efficiently to subsequent stress [1].

Heat Stress Priming and Yield Stability

Heat stress priming—exposure to mild heat stress—induces protective memory that enhances tolerance to later severe stress. Priming during early reproductive stages improves grain yield and photosynthesis under subsequent heat stress. Primed plants and their progeny show higher expression of HSPs and antioxidant genes due to epigenetic memory [1,5].

Breeding and Management Perspectives

Breeding for heat tolerance should focus on early vigor, cooler canopy temperature, high NDVI and chlorophyll, deep roots, strong stay-green and osmolyte accumulation [1,4]. These traits can be integrated with molecular markers and genomic selection. Agronomic strategies such as adjusting sowing dates, selecting suitable maturity groups, providing irrigation for canopy cooling and optimizing nutrition to support antioxidant systems are critical for sustaining yields under heat stress [4,5].

Conclusion

Heat stress is a major threat to wheat production under climate change. However, wheat possesses a wide range of adaptive mechanisms from morphology to epigenetics. Integrating physiological traits, molecular tools and agronomic practices offers a realistic pathway to sustaining wheat yield in heat-stressed environments.

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