Al-Farabi Kazakh National University (KazNU)

Faculty of Biology and Biotechnology

Department of Molecular Biology and Genetics

Discipline: «Modern Problems of Plant Genetics»

Lecture 9

Impact of Genetic Engineering in Agriculture: Achieving UN SDG 2 (Zero Hunger)

Clonal micropropagation, abiotic stress tolerance, biofortification (Golden Rice 2), sustainable feed, smallholder Bt/drought crops, and agro-biofuels

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Aim and Structure of the Lecture

Aim: evaluate how plant tissue culture, transgenic breeding, and genome editing advance UN Sustainable Development Goal 2

KEY FOCUS

Lecture Plan & Modules

Key sections:

1. Global Hunger & SDG 2 Targets
2. Micropropagation & Clean Seed
3. Soil & Climate Stress Engineering
4. Biofortification Breakthroughs
5. Sustainable Feed & Smallholders
6. Biofuels & Circular Bioeconomy

- **Global Hunger & SDG 2 Targets:** FAO SOFI 2024–2025 hunger metrics, «hidden hunger» micronutrient gaps, and 2050 caloric demand
- **Micropropagation & Clean Seed:** Apical meristem culture eliminating systemic viruses in vegetatively propagated staple crops
- **Soil & Climate Stress Engineering:** Aluminum detoxification (TaALMT1), salinity antiporters (NHX1), and drought/flooding tolerance
- **Biofortification Breakthroughs:** Golden Rice 2 (β-carotene), iron/zinc-enriched grains, and nutritionally enhanced functional foods
- **Sustainable Feed & Smallholders:** Low-phytate grain, digestible lignin alfalfa, Bt brinjal in Bangladesh, and Bt cowpea in West Africa
- **Biofuels & Circular Bioeconomy:** From 1st-gen food crops to 2nd-gen lignocellulosic biomass, 3rd-gen microalgae, and NUE crops

The Global Food Challenge and UN SDG 2 Imperative

Climate extremes, conflicts, and soil degradation keep world hunger elevated ahead of the 2030 SDG deadline (FAO SOFI 2024)

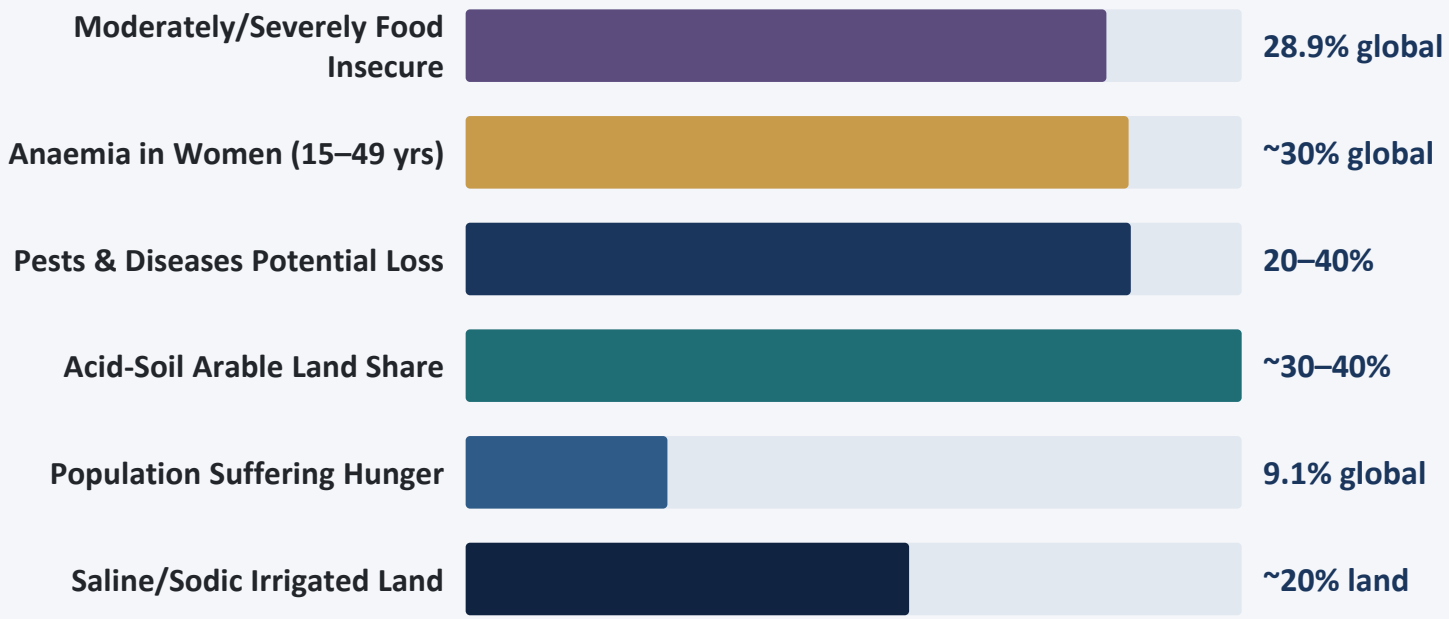
~733M
Undernourished Globally

~2.33B
Food Insecure People

~2B+
Micronutrient Deficient

+50–60%
Food Demand by 2050

Estimated Global Crop Yield Losses & Malnutrition Burden (%)



Why Conventional Yields Alone Fall Short

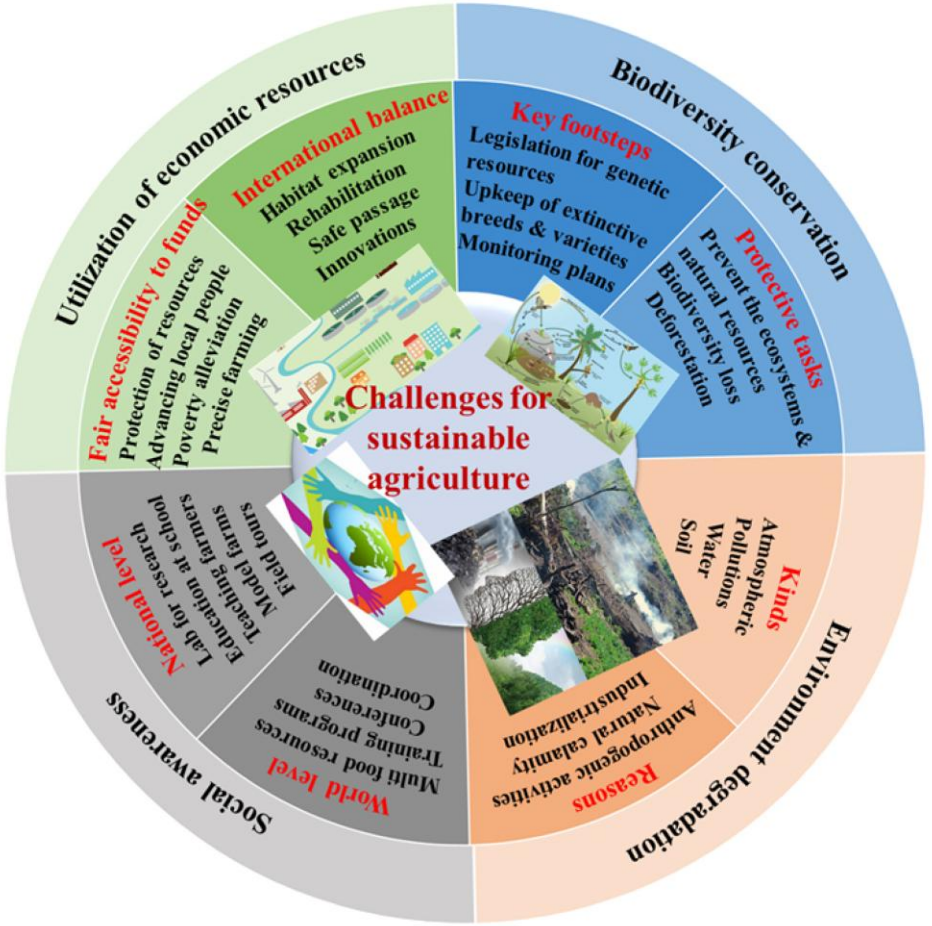
- Annual yield gains in wheat (~0.9%) and rice (~1.0%) lag the ~1.5–2.0% rate needed for 2050
- Arable land cannot expand substantially without destroying carbon-rich forests
- Genetic solutions must raise yield per hectare, nutrient density, and climate stability simultaneously

Sources: FAO, IFAD, UNICEF, WFP & WHO — The State of Food Security and Nutrition in the World (SOFI 2024); Savary et al. Nature Ecology & Evolution.

Mapping Plant Genetic Engineering to UN SDG 2 Targets

Translating laboratory molecular breakthroughs into measurable progress across SDG indicators

- **End Hunger & Access Food:** High-yielding dwarf hybrids, pathogen-free seed stocks, and shelf-life preservation cut post-harvest loss; Protects staple calories in South Asia, Sub-Saharan Africa, and arid Central Asian steppes
- **End All Forms of Malnutrition:** Vitamin A, iron, zinc, folate, and essential amino acid biofortification targets «hidden hunger»; Delivers nutrition inside daily local staples (rice, cassava, sorghum, banana) without recurring cost
- **Double Smallholder Income:** Trait-embedded seed packages require no specialized capital equipment—scaling cleanly to 1-hectare farms; Cuts pesticide expenditure and manual weeding labor for women and smallholder households
- **Sustainable Resilient Farming:** Nitrogen-use efficiency, salt/Al tolerance, and conservation no-till protect topsoil and watersheds; Reduces agricultural CO_2, N_2O emissions, and acute pesticide poisonings



Mapping plant genetic engineering innovations to UN SDG 2 targets

Clonal Micropropagation and Virus-Free Planting Material

Rapid in vitro multiplication rescues vegetatively propagated staples from yield-crushing systemic viral buildup

1 Elite Selection

- Select high-yielding pathogen-tested stock
- Thermotherapy (37–39°C) slows viral replication

2 Meristem Excision

- Dissect 0.2–0.5 mm apical meristem dome
- Zone largely devoid of phloem-borne viruses

3 Shoot Multiplication

- Murashige–Skoog (MS) medium + high cytokinin
- Exponential clonal axillary bud proliferation

Step 4 Rooting & ELISA

- High-auxin rooting + PCR/ELISA certification
- Confirms freedom from PVY, PVX, PLRV, BBTV

Step 5 Clean Field Yield

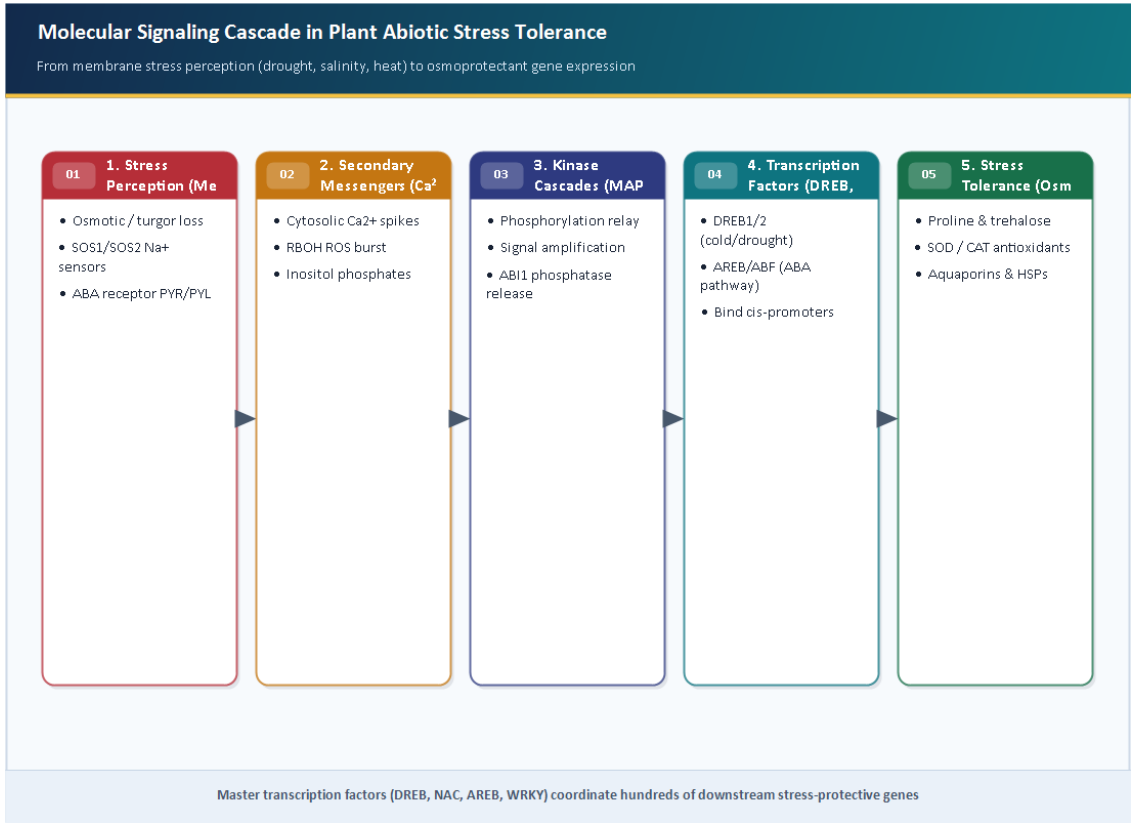
- Greenhouse hardening & tuber/plantlet release
- Restores 30–100% yield in potato, cassava, banana

Micropropagation underpins national seed-potato certification in Kazakhstan and tissue-culture banana systems in East Africa.

Engineering Tolerance to Acid-Soil Al^{3+} Toxicity and Salinity

Unlocking degraded marginal soils through targeted organic-acid efflux and ion-homeostasis genes

- **Aluminum Toxicity Resistance (TaALMT1 & MATE):** At soil pH <5.0, toxic trivalent Al^{3+} ions solubilize and inhibit root tip cell elongation within hours
- TaALMT1 encodes a root-tip malate efflux channel; SbMATE/HvAACT1 export citrate into the rhizosphere
- Secreted malate and citrate tightly chelate free Al^{3+} cations, detoxifying the apoplast around meristems
- Transgenic and MAS introgression of TaALMT1 boosts barley, wheat, and sorghum yields on ~35% acid arable lands
- **Salinity & Ion Homeostasis Engineering:** Excess soil Na^+ causes osmotic water deficit and K^+ displacement poisoning cytosolic enzymes
- AtNHX1 / OsNHX1 vacuolar Na^+/H^+ antiporters sequester toxic Na^+ into vacuoles as an osmoticum



Engineering signaling tolerance to soil salinity, Al3+ toxicity & drought

Metabolic Engineering of Golden Rice 2 Against Vitamin A Deficiency

Restoring an interrupted carotenoid pathway inside rice endosperm prevents childhood blindness (~250k–500k cases/yr)

1 Endosperm Pathway Gap

- Green rice leaves synthesize β-carotene normally
- Polished seed grain silences carotenoid genes

2 First Proof-of-Concept

- Beyer & Potrykus express daffodil psy + bacterial crtI
- Produces ~1.6 µg/g carotenoids in endosperm

5 (GR 2) 23× Efficiency Boost

- Paine et al. swap daffodil psy for maize ZmPSY1
- Reaches up to ~37 µg/g provitamin A (β-carotene)

Imp act Humanitarian Deployment

- Royalty-free humanitarian license (<$10k/yr farms)
- Approved for food/feed safety in 4+ countries & Philippines

A single daily serving (~100 g) of Golden Rice 2 provides >50–60% of a child's Estimated Average Requirement for Vitamin A.

Biofortified Biotech & Edited Crops Targeting «Hidden Hunger»

Genetic engineering reaches micronutrient levels unachievable by conventional breeding in polished cereals & bananas

Crop	Target Nutrient	Genetic Engineering Strategy	Nutritional & Health Outcome
Golden Rice 2	Provitamin A (β-carotene)	Endosperm-specific ZmPSY1 + Pantoea ananatis crtI (Glu1 promoter)	Up to ~37 µg/g carotenoids; prevents xerophthalmia & mortality
Golden Banana (BG2)	Provitamin A (β-carotene)	Endosperm/pulp Fe'i banana PSY2a expressed in East African cultivars	Addresses >30% child VAD burden in Uganda & Great Lakes region
High-Fe/Zn Rice	Iron (Fe) & Zinc (Zn)	Overexpression of OsNAS2 nicotianamine synthase + soybean ferritin	2–4× higher Fe (15 µg/g) & Zn (45 µg/g) in polished white grain
Biofortified Cassava	Fe, Zn & Provitamin A	Stacked VIT1 iron vacuolar transporter, FER1, DXS & crtB	Reaches 30–40% Fe/Zn EAR and provitamin A simultaneously in roots
High-Folate Tomato/Rice	Vitamin B_9 (Folate)	Overexpression of Arabidopsis GTPCHI + ADCS folate pathway genes	Up to 25–100× folate enrichment, preventing neural tube defects
Sicilian Rouge Tomato	GABA (neuro-relaxant)	CRISPR-Cas9 truncation of autoinhibitory SlGAD3 C-terminal domain	4–5× GABA accumulation; supports healthy blood pressure (Japan sold)

Improving Livestock Feed Efficiency and Cutting Runoff

Genetic engineering tackles indigestible phytate and recalcitrant lignin—reducing agricultural water pollution

Low-Phytate & Phytase-Expressing Grain Feed

- Monogastric livestock (poultry, swine) cannot digest phytic acid (IP_6), which binds 60–80% of seed phosphorus
- Undigested phytate passes into manure, causing freshwater eutrophication and algal blooms
- Expressing fungal/bacterial phytase (phyA) in maize/soybean endosperm or knocking out IPK1 raises bioavailable P
- Simultaneously boosts Zn/Fe mineral absorption without mineral-supplement additives

Reduced-Lignin Forage & Fiber Crops

- Cell-wall lignin shields cellulose from rumen microbial cellulases, limiting milk and meat conversion
- RNAi downregulation of CCoAOMT, COMT, or CAD enzymes cuts recalcitrant lignin 15–20% (HarvXtra alfalfa)
- Increases rumen neutral detergent fiber digestibility (NDFD) by ~10–15% per ton of forage
- Allows delayed harvests for higher biomass yield while curbing enteric methane per unit milk

Public-Sector Bt and Drought-Resilient Crops for Smallholders

Public partnerships deliver stress resilience directly to resource-poor farmers in Asia and Africa

- **Smallholder Bt Vegetables & Legumes:** Bt Brinjal (Eggplant, Bangladesh, since 2014): Cry1Ac stops fruit-and-shoot borer without 50–80 seasonal sprays
- Field surveys confirm >60% pesticide reduction, dramatically lower acute farmer poisoning, and ~6× net return
- **PBR Cowpea (Nigeria & Ghana, Cry1Ab):** resists Maruca pod borer, protecting vital dietary protein for 200M people
- **TELA Maize (Africa):** stacks Bt protection with water-use efficiency under royalty-free public breeding
- **Drought & Submergence Tolerance Genes:** DroughtGard Maize (cspB RNA chaperone): stabilizes mRNA translation under episodic flowering drought (+6% yield)
- HB4 Drought-Tolerant Wheat (sunflower HaHB4 transcription factor): boosts arid yields ~16–20% (Argentina/Brazil/USA)



Genomic selection deploying stress-resilient crops for smallholders

Representative Biotech & Marker-Assisted Crops Advancing SDG 2

Integrating transgenic traits, precision editing, and genomic breeding across diverse agroecologies

Crop & Line	Key Gene / Method	Primary Geography	Verified SDG 2 Benefit
Bt Brinjal (BARI)	cry1Ac (Transgenic)	Bangladesh (60k+ farmers)	Cuts toxic organophosphate sprays >60%; raises farm income
PBR Bt Cowpea	cry1Ab (Transgenic)	Nigeria & Ghana	Protects Maruca-vulnerable protein pods; +20–30% grain yield
HB4 Wheat	HaHB4 TF (Transgenic)	Argentina, Brazil, Australia	Improves yield stability under terminal water stress (+16%)
Swarna-Sub1 Rice	SUB1A (MABC breeding)	India, Bangladesh, Nepal	Survives 14-day complete flash-flooding; zero yield penalty
Rainbow Papaya	PRSV coat protein (RNAi)	Hawaii & Asia	Rescued regional industry from Papaya Ringspot Virus collapse
Late-Blight Potato	3R-gene stack (Rpi-vnt1)	East Africa / EU trials	Confers durable resistance to Phytophthora infestans without fungicides

★ Key Takeaway

- Integrating transgenic traits, precision editing, and genomic breeding across diverse agroecologies
- **Comparison scope (6):** Bt Brinjal (BARI); PBR Bt Cowpea; HB4 Wheat; Swarna-Sub1 Rice; Rainbow Papaya; Late-Blight Potato
- **Priority synthesis:** Late-Blight Potato — Confers durable resistance to Phytophthora infestans without fungicides

Evolution of Agro-Biofuels: From Food Crops to Engineered Algae

Decoupling renewable bioenergy from arable land competition through biomass and lipid genetics

01 **1st Gen — Food-Crop Biomass:** Maize grain ethanol & sugarcane sucrose fermentation; Soy/rapeseed biodiesel — competes directly with food land

02 **2nd Gen — Lignocellulosic Residues:** Corn stover, straw, poplar, Miscanthus & switchgrass; Engineered low-lignin & endoglucanase stems aid saccharification

03 **3rd Gen — Microalgae Factories:** Nannochloropsis & Chlamydomonas on saline/non-arable ponds; Up to 30–60% dry-weight TAG lipids + rapid CO_2 capture

04 **4th Gen — Synthetic & Photobiol:** CRISPR-tuned cyanobacterial & algal carbon fixation; Direct photosynthetic secretion of drop-in aviation fuels

Nutrient-Use Efficiency (NUE) and Regenerative Carbon Footprints

Producing more calories per kilogram of nitrogen and hectare of land protects climate and biodiversity

Engineering Nitrogen & Photosynthetic Efficiency

- Over 50% of applied synthetic urea is lost to leaching and volatilization, generating potent N_2O greenhouse gas
- AlaAT (alanine aminotransferase) root expression improves NUE in rice, canola, and wheat under reduced N
- NRT1.1B nitrate transporter and OsDREB1C dual-boost both grain yield and nitrogen remobilization
- C4 Rice & RuBisCO/Photorespiratory bypasses seek 30–50% higher solar-to-biomass conversion efficiency

Conserving Forests & Soil Carbon Sinks

- Higher yields per hectare avoid plowing ~23+ million additional hectares of wild grassland and tropical forest
- Herbicide-tolerant conservation tillage keeps crop residue intact, locking carbon in topsoil and preventing erosion
- Combined drought + NUE traits build resilience for Central Asian rain-fed wheat zones
- **Supports circular agriculture:** crop residues converted to bioenergy & biochar rather than burned

Overcoming Barriers to Humanitarian Deployment

Science succeeds only when paired with seed systems, sensible rules, and local agricultural extension

KEY FOCUS

Core Analytical Focus

Key sections:
1. Humanitarian IP Licensing
2. Regulatory Proportionality
3. Seed Quality & Last-Mile
4. Synergy with Agroecology

- **Humanitarian IP Licensing:** Public-Private Partnerships (AATF, WEMA/TELA, Golden Rice Humanitarian Board) grant royalty-free traits; Ensures smallholder access without restricting national seed autonomy
- **Regulatory Proportionality:** Streamlining gene-editing oversight unlocks local university breeding of millet, chickpea, and sesame; Reallocates public funds from redundant testing toward farmer seed multiplication
- **Seed Quality & Last-Mile:** Strengthening community seed banks, diagnostic ELISA testing, and cold-chain storage; Ensures clean micropropagated plantlets and certified varieties reach remote rural districts
- **Synergy with Agroecology:** Biotech seeds complement—never replace—crop rotation, cover cropping, drip irrigation, and soil microbiomes; Integrates precision genetics cleanly into climate-smart integrated farming systems

Control Questions and Key Takeaways

Linking molecular breeding directly to UN SDG 2 Zero Hunger and climate sustainability

? Control & Review Questions

- 1. Why do plant tissue culture and apical meristem excision restore yields in vegetatively propagated crops?
- 2. Explain the biochemical mechanisms of TaALMT1 aluminum tolerance and NHX1 salinity tolerance.
- 3. What enzymatic bottleneck did Golden Rice 2 overcome compared with Golden Rice 1?
- 4. How do low-phytate grains and reduced-lignin alfalfa reduce environmental pollution from livestock?
- 5. Contrast 1st-, 2nd-, and 3rd-generation agro-biofuels with respect to land use and genetic engineering.

✓ Key Takeaways

- With ~733M people facing hunger and +50–60% demand by 2050, multi-trait genetics is essential to SDG 2.
- Biofortification (Golden Rice 2, Fe/Zn rice, GABA tomato) embeds micronutrients directly inside daily diets.
- Smallholder Bt brinjal, Bt cowpea, and Sub1/HB4 crops prove biotech reduces pesticides and weather losses.
- Lignocellulosic engineering, microalgae lipids, and NUE genes transition farming toward low-carbon bioeconomies.

Recommended Literature and SDG Policy Reports

Key scientific papers and UN global nutrition benchmarks

1 Main Literature

- 1. FAO, IFAD, UNICEF, WFP & WHO (2024). The State of Food Security and Nutrition in the World (SOFI 2024): Financing to End Hunger and Malnutrition.
- 2. Qaim, M. (2020). Role of New Plant Breeding Technologies for Food Security and Sustainable Agricultural Development. Applied Economic Perspectives and Policy 42(2): 129–150.
- 3. Paine, J.A. et al. (2005). Improving the nutritional value of Golden Rice through increased pro-vitamin A content. Nature Biotechnology 23: 482–487.
- 4. Zaidi, S.S. et al. (2019). New plant breeding technologies for food security. Science 363(6434): 1390–1391.

2 Additional Literature & Databases

- 1. Bailey-Serres, J., Parker, J.E., Ainsworth, E.A., Oldroyd, G.E.D., Schroeder, J.I. (2019). Genetic strategies for improving crop yields. Nature 575: 109–118.
- 2. Shelton, A.M. et al. (2020). Bt Eggplant Project in Bangladesh: History, Adoption, and Impact. Frontiers in Bioengineering and Biotechnology 8: 980.
- 3. Sasaki, T. et al. (2004). A wheat gene encoding an aluminum-activated malate transporter (TaALMT1). Plant Journal 37: 645–653.
- 4. HarvestPlus Global Biofortification Hub & IRRI Golden Rice Resources.

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