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AGRIVOLTAICS: PIONEERING THE FUTURE OF SUSTAINABLE AGRICULTURE

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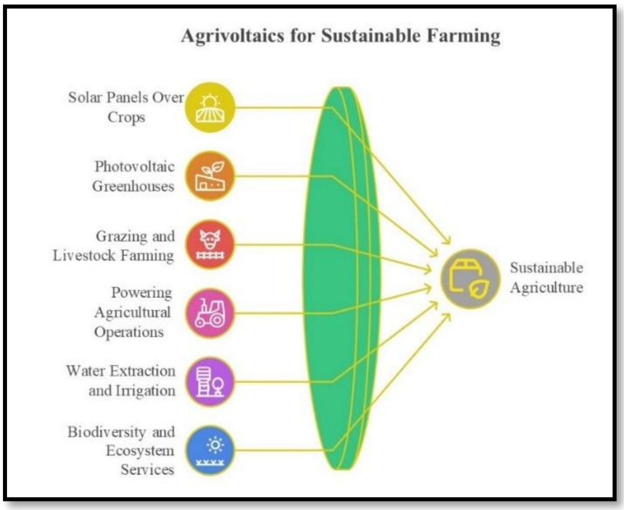
Agrivoltaics is a new way to use land for both farming and solar power. It is also called agrisolar or dual-use solar. This method lets farmers grow crops and produce solar energy on the same land. Solar panels are placed above or between crops or on grazing land. This helps make the most of the land, gives shade to crops, and provides farmers with extra income. It allows food and clean energy to be produced together. By putting solar panels on farmland, it not only creates clean energy but also supports sustainable farming. As climate change becomes a bigger issue and the need for renewable energy grows, agrivoltaics is becoming popular worldwide.

Architecture of Agrivoltaic System

Agrivoltaics, first introduced in the 1980s, is increasingly recognized globally as an innovative approach to cultivate food and generate renewable energy simultaneously. This method is particularly significant for nations such as India, which face constraints in land availability and have substantial energy demands. Agrivoltaics involves the installation of solar panels above crops or grazing areas, where the panels harness sunlight to produce electricity, while the land beneath continues to support plant cultivation or livestock rearing.



- Raised solar panels: Instead of being installed directly on the ground, solar panels are installed on structures that are high enough to allow sunlight and rain to reach the crops below. These raised solar panels in agriculture also enable farmers to easily move their equipment underneath.
- Partial shading: The panels offer shade that protects crops from intense heat and minimizes water loss from the soil and provides a cooler, more stable environment for plant growth, particularly in hot or arid areas.
- Dual land use: With solar panels producing electricity and crops or livestock flourishing below, farmers benefit from both food and clean energy on the same land.
- Electricity for the farm and beyond: The solar power generated on an agrivoltaic farm can supply energy for farm operations, lowering electricity expenses. Any surplus power can be fed back into the grid, providing extra income.

By balancing the demands of agriculture and energy production, agrivoltaics transforms farmland into a multifunctional space that supports sustainable farming and clean energy generation simultaneously.

Applications of Agrivoltaics Farming

Agrivoltaics has the following applications for sustainable farming.

1. **Solar panels over crops:** A prevalent method of agrivoltaics involves placing solar panels above agricultural fields. This arrangement offers partial shading to the crops, enhancing water retention and minimizing heat stress, which is particularly advantageous for dry farming with limited irrigation.

2. **Photovoltaic greenhouses:** Another innovative application of agrivoltaics is the use of photovoltaic greenhouses, where solar panels are installed on the roof or exterior of the greenhouse. These panels function as a canopy, helping to regulate temperature and humidity inside, thereby reducing energy consumption for climate control. The electricity generated is used to power greenhouse operations, lowering costs and enhancing sustainability.
3. **Grazing and livestock farming:** Agrivoltaics extends beyond crop cultivation. Solar installations can be set up over grazing areas, allowing animals like sheep or goats to find shelter beneath the panels. This dual-purpose land use benefits animal welfare by providing shade and decreases the costs associated with vegetation maintenance.
4. **Powering agricultural operations:** Solar energy can be directly utilized on farms to power essential equipment such as irrigation pumps, lighting and fencing. Employing solar energy in agriculture decreases reliance on fossil fuels and reduces energy expenses, enabling farmers to save money and lessen their carbon footprint.
5. **Water extraction and irrigation:** In numerous rural regions, water access is a significant challenge. Agrivoltaic solar power can operate pumps that draw water from wells, facilitating more efficient irrigation systems and supporting crop growth in dry areas. This integration of solar energy with water management is transformative for sustainable agriculture.
6. **Supporting biodiversity and ecosystem services:** Some agrivoltaic farms create pollinator-friendly environments beneath and around solar panels, boosting biodiversity and promoting ecosystem health. This strategy benefits crops dependent on pollination and fosters environmental sustainability.

Schemes and Initiatives Supporting Agrivoltaics in India

National schemes promote agrivoltaics by supporting solar adoption in agriculture and enabling stakeholder collaboration. They aim to boost clean energy while enhancing farm incomes:

1. **India Agrivoltaics Alliance (IAA):** Established by the National Solar Energy Federation of India (NSEFI), it aims to harmonize agriculture and solar energy.
2. **PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan):** Launched in 2019, PM-KUSUM supports farmers in installing solar-powered pumps

and grid-connected solar power plants in different states like Telangana, Maharastra, Gujarat, Haryana, Karnataka and Delhi.

3. **Mukhyamantri Saur Krushi Vahini Yojana (MSKVY):** Maharashtra aims to solarize 1,600 MW of agricultural feeders by 2026 under MSKVY. The state has already installed 500,000 solar pumps, surpassing the rest of India combined. The scheme offers a fixed tariff of ₹3.10 per kWh for solar power projects, with the Maharashtra State Electricity Distribution Company Ltd. (MSEDCL) facilitating implementation.
4. **Suryashakti Kisan Yojana (SKY):** In Gujarat, SKY provides farmers with subsidies and loans to install solar panels on their fields. Farmers can sell surplus electricity to the grid, earning additional income. The scheme offers a feed-in tariff of ₹7 per unit for the first 7 years and ₹3.50 per unit for the next 18 years. The government covers 60% of the installation cost, with the remaining 40% financed through loans.
5. **Surya Raitha Scheme:** This scheme focuses on solarizing agricultural pumps to reduce farmers' dependency on grid electricity and diesel in Karnataka state. It offers financial assistance for installing solar pump sets and encourages farmers to sell excess power back to the grid, providing an additional income stream. The initiative aims to promote renewable energy use in agriculture and enhance sustainability.
6. **Mukhyamantri Kisan Aay Badhotri Solar Yojana:** Under this scheme, Delhi farmers lease their land to developers who install solar panels, generating electricity. This initiative provides farmers with an additional revenue source while promoting solar energy adoption.
7. **The National Solar Energy Federation of India (NSEFI)** is working with local, state, and agricultural institutions to align agrivoltaics with AP's diverse agro-climatic zones. AP is recognized as a leader in solar adoption and is exploring agrivoltaics to strengthen the rural economy.
8. **PM-KUSUM:** The Government of Telangana is actively implementing the PM-KUSUM Component A scheme, which encourages farmers to set up 500 kW to 2 MW solar plants on their land to foster combined agricultural and energy production. The Telangana Renewable Energy Development Corporation Limited (TGREDCO) oversees the deployment of these projects, aligning them with state-level agricultural support, such as the *Rythu Bharosa* initiative and Telangana is also a key focus state for the India Agrivoltaics Alliance (IAA), which is working on establishing pilot projects to validate business models.

Few Agrivoltaics Projects in India

- India's largest agrivoltaics farms in Sagar, Madhya Pradesh. Spanning 16 acres farm grows crops like strawberries and lettuce beneath elevated solar panels, producing about 25,000 units of clean electricity daily.
- In Nashik, Maharashtra, Sahyadri Farms, the largest Farmer Producer Organization in India, runs a pilot agrivoltaics project pairing solar power with grape cultivation to boost farmer earnings and eco-friendly practices.
- The Central Arid Zone Research Institute (CAZRI) in Jodhpur tested a 105 kWp system that improved land productivity and water use in arid regions.
- The Muradpur lift irrigation scheme in Nagpur uses floating solar panels to support irrigation over 465 acres, enabling up to three crops annually while reducing energy costs. These projects showcase agrivoltaics' potential to enhance land use, promote sustainable agriculture, and deliver clean energy to farmers across India.

Benefits of Agrivoltaics Farming

Agrivoltaics farming offers a promising solution by enabling both farming and generation of solar energy simultaneously on the same piece of land, providing numerous environmental, economic, and social benefits. Here are some of the key advantages of agrivoltaics farming:

- Increases land-use efficiency by using agrivoltaics to generate renewable energy while carrying on with their agricultural operations.
- Agrivoltaics can lower electricity costs, supply clean energy to farm operations, and occasionally resell excess power to the grid, boosting the stability of farm income.
- Solar panels provide partial shade and keep soil moisture levels stable, lowers water evaporation and moderates' temperature extremes particularly in hot or arid areas, resulting in increase in yields and less need for irrigation.
- Diversifies income for farmers generate extra income by combining crop or livestock production with solar for agriculture.
- It enhances ecosystem services and biodiversity by preserving native vegetation and establishing habitats for pollinators like bees etc.,

- Agrivoltaics sites can also enhance the health of ecosystems by controlling water runoff and reducing the need for herbicides, these green areas lessen their negative effects on the environment and maintenance expenses.
- Provides grazing opportunities for sheep and chickens etc., that can graze beneath solar agriculture panels, naturally controlling vegetation while enjoying the shade and protection.
- Improves working conditions for farm workers by providing shade and improve comfort and safety by spending extended periods of time outside by shielding them from intense heat and damaging UV rays.
- Agrivoltaics can reduce greenhouse gas emissions and increase climate resilience in agriculture by producing clean, renewable energy and lowering dependency on fossil fuels.

Challenges to Agrivoltaics Farming

Besides its promising potential, agrivoltaics faces several challenges related to technical, economic, agronomic, and institutional that must be addressed for it to scale sustainably.

1. **High capital costs:** Because of their higher structures, higher material requirements, and more complicated installations, agrivoltaics systems are substantially more expensive than ground-mounted solar. Prices per kw can increase by 1.3-2 times. Costs are further increased by lower panel density, wind resistance specifications, and higher panel heights. For small and marginal farmers, this makes Agri photovoltaics financially difficult unless financing options or subsidies are implemented.
2. **Uncertain impact on crop yields:** The way that crops react to solar panel shading varies greatly. While some crops, like leafy greens, benefit yields of staple crops like wheat and rice are frequently lower. Although Land Equivalent Ratio (LER) values can conceal decreases in food production, they may indicate overall gains. Yield results are highly dependent on the panel. Crop type, spacing, orientation, and local agroclimatic conditions, all of which call for site-specific data and trials prior to scaling.
3. **Design and compatibility issues:** Energy production and agricultural requirements must be balanced when designing agrivoltaics systems. For crop health, proper row spacing and enough room for farm equipment, particularly harvesters, are essential. Advanced technologies (like movable or transport panels) are still costly and uncommon in India, and many of the panels and mounting systems that are currently in use are not designed with agriculture in mind.

4. **Operation, maintenance, and safety:** Most farmers lack the technical know-how and routine maintenance needed for Agri photovoltaics systems. Risks include exposed wiring or electrical infrastructure raising safety concerns and unintentional damage to solar equipment while farming. Reliance on outside technicians may result in higher operating expenses and downtime over time.
5. **Soil and water impacts:** Compaction and erosion of the soil may result from the installation of solar structures, particularly if heavy equipment is used or topsoil is removed. The microclimate is changed by shading, which may lower evapotranspiration but also has an impact on water requirements and rainfall distribution. More research is required to determine how different crops will react to these changes.
6. **Grid integration and storage constraints:** Although off-grid systems are less practical than grid-connected ones, many rural areas lack nearby substations or sufficient evacuation infrastructure. Without adequate planning, intermittent solar generation could put strain on the grid. In Indian Agri photovoltaics setups, battery storage is still costly and unproven.
7. **Regulatory and policy barriers:** Clear national regulations pertaining to agrivoltaics are lacking. In some states, dual-use applications may be restricted by land use classifications and farmland protection laws. Solar installation approval procedures on agricultural land are complex and dispersed among several agencies.
8. **Farmer awareness and adoption:** The potential advantages of Agri photovoltaics are unknown to most farmers. The threats to crop yields and disturbances to farming practices are the reasons for non-adoption of agri photovoltaics. Adoption is low due to absence of training, outreach and demonstration initiatives, particularly through Farmer Producer Organizations (FPOs).

Conclusion

Agrivoltaics represents a prime example of human ingenuity in tackling complex environmental and economic issues. By merging agriculture with renewable energy, it offers a promising path toward creating more resilient, sustainable, and economically sound futures in both the food and energy industries. To overcome current challenges and fully harness the transformative potential of agrivoltaics worldwide, ongoing research, supportive policy frameworks, and collaborative efforts are essential.

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PLANS TO SUPPORT CLIMATE CHANGE ADAPTATION, PRIVATE SECTOR & CIVIL SOCIETY INITIATIVES

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Climate change poses serious threats to agriculture and rural livelihoods, making adaptation essential for sustaining productivity and ensuring food security. Adaptation involves adjusting agricultural practices—such as crop diversification, efficient irrigation, and stress-tolerant varieties—while mitigation focuses on reducing greenhouse gas emissions. Both approaches are complementary and necessary for long-term climate resilience.

Effective adaptation requires coordinated efforts among governments, the private sector, civil society, and international institutions. Governments provide policy support and infrastructure, the private sector drives innovation and financial solutions, and civil society promotes community-based action and capacity building. A collaborative, multi-stakeholder approach is crucial to building resilient agricultural systems and safeguarding sustainable rural development.

Climate change poses a serious threat to global agriculture, natural resources, and rural livelihoods. Increasingly unpredictable rainfall, prolonged droughts, and frequent extreme weather events have made it essential for all sectors to take proactive steps toward adaptation. Climate change adaptation involves developing and implementing strategies that help individuals, communities, and systems adjust to the impacts of a changing climate while maintaining productivity and sustainability.

To achieve this, coordinated action among multiple stakeholders—governments, private sector actors, and civil society organizations—is crucial. Governments provide the foundation for adaptation through supportive policies, climate-resilient infrastructure, and financial mechanisms that empower farmers and rural communities. The private sector contributes by investing in climate-smart technologies, research and development, and strengthening market systems that promote sustainable and inclusive growth.

Meanwhile, civil society organizations play an equally important role in bridging policy and practice. They focus on capacity building, awareness creation, and community-based adaptation strategies that ensure inclusivity and social equity. By integrating the efforts of these three pillars—public institutions, private enterprises, and community organizations—climate change adaptation plans can effectively enhance resilience, protect livelihoods, and promote long-term sustainability in both agriculture and the broader environment.

Adaptation vs. Mitigation

Adaptation refers to adjustments in agricultural systems and practices to minimize the adverse effects of climate change. Farmers adopt strategies such as crop diversification, efficient irrigation systems, soil conservation, and the use of stress-tolerant varieties to cope with temperature variations and erratic rainfall.

Mitigation, on the other hand, focuses on reducing greenhouse gas emissions through actions like renewable energy use, improved manure management, and agroforestry.

Government & Institutional Plans

National Adaptation Plans (NAPs)

National Adaptation Plans (NAPs) provide a structured framework that helps governments systematically integrate climate adaptation measures into their long-term national development agendas. These plans focus on identifying vulnerabilities and designing targeted strategies to reduce climate-related risks across various sectors. They prioritize critical areas such as agriculture, water resources, health, and energy—sectors that are highly sensitive to climate variability and essential for sustainable growth. Moreover, NAPs are aligned with the commitments of the United Nations Framework Convention on Climate Change (UNFCCC), enabling countries to access international finance, technical assistance, and global cooperation mechanisms to strengthen national adaptation capacity.

Climate-Smart Agriculture (CSA) Programs

Climate-Smart Agriculture (CSA) is an integrated approach aimed at achieving three main objectives—enhancing agricultural productivity, building resilience against climate shocks, and reducing greenhouse gas emissions. CSA promotes practical interventions such as crop diversification, soil and water conservation, integrated farming systems, and the use of ICT-based weather and market advisories to help farmers make informed decisions. Institutional support plays a major role in its implementation; for instance, programs like the National Innovations on Climate Resilient Agriculture (NICRA) in India and various FAO initiatives worldwide provide on-field demonstrations, capacity-building training, and extension services to promote sustainable farming practices and improve livelihood resilience.

Disaster Preparedness & Early Warning Systems

Effective disaster preparedness and early warning systems are crucial in minimizing the adverse impacts of extreme weather events on agriculture and rural livelihoods. Real-time weather forecasts and advisories issued by institutions like the India Meteorological Department (IMD) through mobile applications and SMS alerts help farmers make timely decisions on crop management. Early warning systems that provide alerts for floods, droughts, and cyclones enable proactive measures, reducing potential losses and ensuring safety. In addition, community-level preparedness initiatives, including local disaster management committees and training programs, enhance the collective capacity of rural communities to respond quickly and efficiently during emergencies.

Policy Incentives for Adaptation

Policy incentives are essential to motivate farmers and stakeholders to adopt climate-resilient practices. Financial incentives such as subsidies for solar-powered irrigation systems, drip irrigation, and renewable energy technologies help reduce the cost burden for smallholders. Market-based instruments like Minimum Support Price (MSP) and procurement policies ensure stable income and protect farmers from market fluctuations. Additionally, investments in infrastructure—such as irrigation networks, cold storage facilities, and rural electrification—create an enabling environment for long-term adaptation. These measures collectively enhance the adaptive capacity of the agricultural sector, ensuring food security and sustainable rural development.

Private Sector Role

Importance of Private Sector Participation

The private sector plays a vital role in advancing climate change adaptation efforts by bringing in financial, technological, and managerial expertise. One of its key contributions lies in capital investment, where private enterprises mobilize financial resources to scale up adaptive technologies and infrastructure that improve agricultural resilience. These investments help introduce innovative solutions—such as precision agriculture tools, renewable energy systems, and sustainable irrigation methods—at a much larger scale.

Another crucial area is technology development, where private companies engage in extensive research and development (R&D) to produce climate-resilient seeds, improved fertilizers, and advanced farm mechanization tools. These innovations not only enhance productivity but also enable farmers to cope with temperature fluctuations, pest outbreaks, and water scarcity.

In addition, the private sector plays a significant role in market linkages, connecting farmers to broader supply chains and value-added markets. By providing assured markets and fair pricing mechanisms, agribusiness firms encourage sustainable production and reduce the vulnerability of farmers to market shocks. Through these contributions, the private sector serves as a key driver of climate-resilient agricultural growth.

Insurance & Financial Innovations

Insurance and innovative financial mechanisms are essential tools for managing the economic risks associated with climate variability. Weather-index insurance is one of the most effective instruments, providing quick and transparent compensation to farmers based on specific weather parameters such as rainfall or temperature deviations. This reduces disputes and administrative delays common in traditional claim-based systems, ensuring timely support during adverse events.

Green bonds and climate funds represent another important innovation, as they attract private investment toward large-scale adaptation projects such as renewable energy deployment, watershed management, and climate-resilient infrastructure. These financial instruments create new avenues for sustainable funding beyond government budgets.

Furthermore, microfinance models play a critical role in empowering smallholder farmers. By offering customized credit schemes, microfinance institutions enable farmers to invest in climate-resilient inputs, improved irrigation systems, and sustainable farming technologies. Collectively, these financial innovations enhance the adaptive capacity of rural communities and ensure the long-term sustainability of agricultural systems in the face of climate change.

Civil Society & Community Initiatives

Role of NGOs and FPOs

Non-Governmental Organizations (NGOs) and Farmer Producer Organizations (FPOs) play a crucial role in promoting climate change adaptation at the grassroots level by empowering farmers through capacity-building initiatives, collective action, and policy engagement. NGOs conduct training programs focused on organic farming, efficient water management, soil conservation, and sustainable agricultural techniques that help farmers reduce their vulnerability to climate risks. These efforts build farmers' technical skills and awareness, enabling them to adopt eco-friendly and resilient practices.

In addition to training, NGOs actively engage in policy advocacy, representing the voices and concerns of farmers in regional, national, and even international policy forums. Through advocacy, they ensure that farmers' needs are integrated into agricultural and climate policies, particularly those concerning subsidies, insurance, and rural infrastructure.

Farmer Producer Organizations (FPOs) strengthen the collective bargaining power of farmers by uniting them under common business and production interests. FPOs enhance access to markets, inputs, and credit facilities, while also fostering social capital and cooperation among members. By combining advocacy with action, NGOs and FPOs serve as critical bridges between local communities and institutional systems, ensuring equitable participation in climate adaptation efforts.

Community-Based Adaptation

Community-Based Adaptation (CBA) emphasizes locally driven, participatory approaches to address climate change challenges. It relies on local resource management, where communities take collective responsibility for the sustainable use and preservation of natural resources such as water bodies, forests, and grazing lands. This decentralized approach ensures that adaptation strategies are built upon local knowledge and traditional practices.

Communities also lead the way in adopting innovative practices like rainwater harvesting, mangrove restoration, contour bunding, and micro-irrigation systems that enhance resilience to droughts and floods. These practices are not only cost-effective but also environmentally sustainable.

Furthermore, community-based initiatives enhance empowerment by making adaptation solutions culturally relevant and widely accepted. Local participation ensures ownership, accountability, and long-term sustainability of interventions. By integrating traditional wisdom with modern science, community-based adaptation strengthens resilience from the bottom up.

Knowledge Sharing & Farmer Networks

Knowledge sharing and networking among farmers are fundamental to the success of climate change adaptation. Farmer Field Schools (FFS) serve as effective platforms for participatory learning, where farmers gain hands-on experience in adopting adaptive agricultural technologies and management practices. These schools help farmers experiment, observe results, and make informed decisions that suit their local conditions.

Peer learning further enhances adaptation by facilitating the exchange of innovative ideas and practical techniques between experienced and novice farmers. Such farmer-to-farmer communication builds confidence and encourages replication of successful practices across communities.

In addition, information networks—supported by Information and Communication Technologies (ICTs)—link farmers with extension agencies, researchers, and market information systems. These digital platforms provide timely weather forecasts, pest alerts, and advisory services, enabling farmers to plan effectively. Altogether, knowledge exchange and collaborative learning promote continuous adaptation and innovation within farming communities.

International Support

UNFCCC & Global Frameworks

The United Nations Framework Convention on Climate Change (UNFCCC) serves as the cornerstone of global efforts to combat climate change, providing a platform for cooperation among nations to promote both mitigation and adaptation. The Paris Agreement (2015), established under the UNFCCC, emphasizes the inclusion of adaptation strategies within countries' Nationally Determined Contributions (NDCs), ensuring that adaptation becomes an integral part of national climate policies and development plans. Through this framework, countries are encouraged to enhance resilience, reduce vulnerability, and support sustainable livelihoods.

The global goals under the UNFCCC aim to strengthen resilience, promote equity, and ensure sustainability, particularly for developing nations that are disproportionately affected by climate impacts. Moreover, international cooperation plays a pivotal role in facilitating the exchange of technologies, policy experiences, and best practices across countries. This collaborative approach enables knowledge transfer, capacity building, and the alignment of global efforts toward achieving climate-resilient development.

Funding Mechanisms

Financial support is essential to implement adaptation projects, especially in developing and vulnerable countries. Several international mechanisms have been established to channel resources toward climate resilience. The Green Climate Fund (GCF) is one of the largest and most influential financing instruments, supporting both adaptation and mitigation initiatives through grants and concessional loans. It assists countries in developing projects related to renewable energy, agriculture, and ecosystem restoration.

The Adaptation Fund, created under the Kyoto Protocol, focuses primarily on small-scale, community-level projects that directly benefit vulnerable populations. These initiatives often involve sustainable land management, water conservation, and local infrastructure development.

Similarly, the Global Environment Facility (GEF) provides funding to NGOs, governments, and private-sector entities for projects that enhance environmental sustainability and climate adaptation. By promoting partnerships between multiple stakeholders, these funding mechanisms ensure that financial flows are directed toward building climate resilience in the most at-risk regions of the world.

Global Knowledge Networks

Global knowledge networks play a vital role in advancing scientific understanding and promoting innovation in climate adaptation strategies. The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is a prominent global initiative that conducts interdisciplinary research on climate-smart agriculture, focusing on improving productivity while reducing vulnerability to climate stress.

The Global Commission on Adaptation (GCA) serves as a high-level platform advocating for stronger and faster adaptation measures worldwide. It mobilizes political commitment, supports policy reforms, and facilitates partnerships to accelerate action across governments and the private sector.

In addition, South-South Cooperation fosters collaboration among developing nations by facilitating the exchange of successful adaptation practices, technologies, and policy experiences. This mutual learning process helps countries facing similar climate challenges to implement proven solutions more effectively. Together, these global networks contribute to the creation of a shared pool of knowledge and resources that strengthens the collective capacity to adapt to a changing climate.

Conclusion

Climate change adaptation requires coordinated action from governments, the private sector, and civil society. Governments must provide supportive policies, financial mechanisms, and resilient infrastructure, while the private sector contributes through innovation, technology development, and improved market systems. Civil society organizations ensure that adaptation efforts are inclusive and responsive to the needs of vulnerable communities.

Building resilient agriculture is essential for ensuring food security and sustainable rural livelihoods. A holistic approach that integrates institutional support, technological advancement, and community participation will strengthen adaptive capacity and safeguard resources for future generations.

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INDIGENOUS PLANT-BASED PESTICIDES IN ORGANIC FARMING: LOW-COST SOLUTIONS FOR SUSTAINABLE CROP PROTECTION

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In recent decades, excessive dependence on synthetic chemical pesticides has become a major concern in Indian agriculture. While these chemicals initially provided quick and visible results, their continuous and indiscriminate use has led to serious problems such as pest resistance, resurgence of secondary pests, environmental contamination, and harmful residues in food products (Pimentel, 2005; Isman, 2006). Rising input costs have further increased the burden on small and marginal farmers, making crop protection an expensive component of cultivation.

At the same time, growing awareness about food safety, ecological balance, and sustainable farming practices has renewed interest in traditional and eco-friendly pest management approaches. Long before the introduction of synthetic pesticides, farmers relied on locally available plant materials such as neem, garlic, tobacco, papaya leaves, and cow urine to protect crops from insects and diseases. These indigenous plant-based preparations were affordable, biodegradable, and relatively safe to humans and beneficial organisms (Isman, 2006; FAO, 2018).

In the context of organic farming, where the use of synthetic chemicals is restricted, these botanical pesticides offer practical and sustainable alternatives. Reviving and standardizing indigenous plant-based formulations can empower farmers to reduce production costs, minimize environmental risks, and promote healthier agricultural systems. This article highlights some commonly used plant-based pesticides that can be prepared easily using locally available materials and applied effectively in organic crop production.

Why Indigenous Plant-Based Pesticides?

Indigenous plant-based pesticides occupy an important place in organic farming because they combine traditional knowledge with ecological sustainability. Unlike synthetic chemicals that often act as broad-spectrum toxins, botanical extracts generally function as repellents, antifeedants, growth regulators, or mild contact poisons (Isman, 2006; Pavela, 2016). This means they interfere with pest behaviour and life cycles without causing severe disruption to the agro-ecosystem.

One of the primary advantages of plant-based pesticides is their local availability. Materials such as neem seeds, garlic, chillies, papaya leaves, tobacco leaves, buttermilk, and cow urine are easily accessible in rural areas. Farmers can prepare these formulations at home with minimal investment, reducing dependence on costly commercial pesticides. For small and marginal farmers, this significantly lowers the cost of crop protection.

Another major benefit is environmental safety. Botanical pesticides are biodegradable in nature and break down rapidly in soil and water, leaving minimal harmful residues. This reduces the risk of contamination of groundwater, soil microflora, and non-target organisms such as pollinators and natural enemies. Their use aligns well with the principles of organic certification and sustainable agriculture.

In addition, indigenous formulations often strengthen plant health. Some extracts, particularly those based on neem and cow urine, not only suppress pests but also enhance plant vigor and resistance. Regular application can contribute to balanced pest management rather than complete eradication, which is more ecologically sound.

However, these botanical pesticides require proper preparation, timely application, and repeated spraying for effective results. When used scientifically and consistently, they serve as reliable, low-cost tools for eco-friendly pest management in organic farming systems.

Major Indigenous Plant-Based Pesticides Used in Organic Farming

1. Neem seed kernel extract (NSKE)

Neem (*Azadirachta indica*) has long been recognized as one of the most effective botanical pesticides in Indian agriculture. The active compounds present in neem kernels, particularly azadirachtin, act as antifeedants, repellents, and insect growth regulators (Schmutterer, 1990; Mordue & Nisbet, 2000). Instead of killing pests instantly, neem disrupts their feeding and reproductive behavior, gradually reducing pest populations.

NSKE can be prepared by crushing shade-dried neem seed kernels and soaking the powder in water overnight. The extract is filtered, diluted appropriately, and sprayed on crops during early morning or evening hours. A small quantity of mild soap is often added to improve adhesion on leaf surfaces.

It is effective against aphids, whiteflies, jassids, thrips, caterpillars, and pod borers in crops such as vegetables, pulses, cotton, paddy, and tobacco. Regular application at 10–15 day intervals helps maintain pest levels below economic threshold limits.

2. Garlic-chilli extract

Garlic and chilli are common kitchen ingredients with strong insect-repellent properties. Garlic contains sulfur compounds, while chilli contains capsaicin, both of which irritate and repel insects (Pavela, 2016). Together, they act as a natural contact insecticide and feeding deterrent.

The extract is prepared by grinding garlic cloves and green chillies into a paste, soaking the mixture in water, filtering it, and diluting before spraying. A small amount of soap solution improves its effectiveness.

This formulation is particularly useful against aphids, thrips, mites, caterpillars, and whiteflies in vegetable and fruit crops. Due to its strong odor and pungency, it effectively discourages pest infestation when applied regularly.

3. Buttermilk and asafoetida spray

Fermented buttermilk combined with asafoetida (hing) serves as a mild repellent and antifungal spray. The fermentation process enhances its microbial activity, which can suppress certain fungal pathogens and deter insect pests.

Sour buttermilk is allowed to ferment further, mixed with dissolved asafoetida, diluted with water, and filtered before spraying. This preparation is commonly used against powdery mildew, leaf spots, aphids, and whiteflies.

It is inexpensive, safe, and suitable for use in vegetable crops and orchards, particularly during early stages of pest or disease incidence.

4. Tobacco leaf extract

Tobacco contains nicotine, a naturally occurring alkaloid (Ware & Whitacre, 2004) that acts as a strong contact poison against insects. Though natural, it is potent and must be handled carefully.

The extract is prepared by soaking crushed dried tobacco leaves in water, boiling the mixture briefly, cooling, filtering, and diluting before application. A small amount of mild soap can be added to improve spreading on leaf surfaces.

Tobacco extract is effective against aphids, caterpillars, leaf miners, thrips, and whiteflies in vegetable and ornamental crops. However, it should not be sprayed close to harvest due to its toxicity. Protective handling is essential during preparation and spraying.

When used cautiously and in recommended dilution, it serves as a powerful botanical alternative in organic pest management systems.

5. Cow urine-based extract (gomutra spray)

Cow urine has been traditionally used in natural farming systems as both a plant growth enhancer and pest repellent (NCOF, 2015). When fermented and combined with botanical ingredients such as neem leaves, garlic, or chillies, its effectiveness increases.

Fresh cow urine is stored in a closed container for several days to enhance its potency. Crushed neem leaves or other plant materials may be added and soaked before filtering and dilution. The solution is then sprayed uniformly on crop foliage.

This preparation acts as a repellent, mild insecticide, and antifungal agent. It is commonly used against aphids, whiteflies, thrips, and caterpillars. In addition to pest control, it has been reported to improve plant vigor and resistance.

Its low cost and easy availability make it especially valuable for small and marginal farmers practicing organic agriculture.

6. Papaya leaf extract

Papaya leaves contain bioactive compounds that act as insect repellents and growth regulators. The extract is prepared by crushing fresh leaves, soaking the paste in water, filtering, and diluting before spraying.

Papaya leaf extract is effective against sucking pests such as aphids, mites, and whiteflies, as well as certain leaf-eating caterpillars. It is suitable for vegetables, fruit crops, and ornamental plants.

Being biodegradable and locally available, papaya leaf extract represents a simple yet effective component of indigenous pest management practices.

Table 1: Comparative overview of indigenous botanical pesticides

Botanical extract	Major target pests	Mode of action	Recommended spray interval
Neem (NSKE)	Aphids, whiteflies, caterpillars, jassids	Antifeedant, growth regulator	10-15 days
Garlic-chilli extract	Thrips, mites, aphids	Repellent, contact action	7-10 days
Buttermilk + asafoetida	Powdery mildew, leaf spots	Antifungal, repellent	7-10 days
Tobacco extract	Caterpillars, leaf miners	Contact poison	10-15 days
Cow urine extract	Sucking pests, fungal pathogens	Repellent, mild insecticide	7-10 days
Papaya leaf extract	Aphids, mites, leaf-eating insects	Repellent, growth regulator	7-10 days

Advantages and Practical Considerations

Indigenous plant-based pesticides offer several advantages in organic farming systems. First and foremost, they are cost-effective. Since most of the raw materials such as neem seeds, garlic, chillies, papaya leaves, and cow urine are locally available, farmers can prepare these formulations with minimal expenditure. This significantly reduces the overall cost of crop protection.

Secondly, these botanical preparations are biodegradable and environmentally safe. They decompose rapidly without leaving harmful residues in soil or water. Compared to synthetic chemicals, they pose relatively lower risks to non-target organisms such as pollinators, earthworms, and natural enemies of pests. This makes them highly suitable for organic certification and sustainable agricultural practices.

Another important advantage is reduced risk of pest resistance. Synthetic pesticides often act on a single target site, leading to rapid resistance development. In contrast, plant-based extracts contain multiple bioactive compounds that affect pests in different ways, such as repelling, inhibiting feeding, or interfering with growth and reproduction. This multi-action effect slows down resistance development (Georghiou, 1990; Isman, 2006).

However, practical considerations must be kept in mind. Botanical pesticides generally have a shorter shelf life and should be used soon after preparation. Proper filtration is essential to prevent clogging of sprayer nozzles. Spraying should be done during early morning or late evening hours for better effectiveness and to avoid leaf burn. Repeated applications at 7–15 day intervals may be necessary depending on pest intensity (FAO, 2018; ICAR, 2018).

Farmers must also understand that these formulations are preventive and suppressive rather than instant killers. Consistent and timely application is the key to achieving satisfactory results.

Fig. 1: Step-by-step preparation cycle of indigenous plant-based pesticides used in organic farming

Conclusion

Indigenous plant-based pesticides represent a valuable blend of traditional wisdom and ecological science. At a time when agriculture faces challenges such as rising input costs, environmental degradation, pesticide resistance, and food safety concerns, these locally prepared botanical formulations offer practical and sustainable solutions.

Reviving and promoting such indigenous practices can empower farmers to reduce dependency on synthetic chemicals while maintaining crop health and productivity. When used scientifically and systematically, plant-based pesticides not only protect crops but also preserve soil health, biodiversity, and environmental balance.

Strengthening awareness, training farmers in proper preparation methods, and integrating these botanical extracts into organic farming systems can contribute significantly to sustainable crop protection and long-term agricultural resilience.

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SYNTHETIC BIOLOGY IN AGRICULTURE

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Agriculture is facing unprecedented challenges due to rapid population growth, climate change, declining soil fertility, and increasing pest and disease pressures. Traditional breeding and even advanced molecular techniques, while effective, often require long timeframes and may not be sufficient to address complex agricultural problems. In this context, Synthetic Biology has emerged as a revolutionary approach that combines biology, engineering, genetics, and computational science to design and construct new biological systems or redesign existing ones for useful purposes.

Unlike conventional genetic engineering, synthetic biology goes a step further by enabling scientists to create entirely new genetic circuits, metabolic pathways, and even synthetic organisms. In agriculture, this opens up transformative possibilities such as developing crops with enhanced productivity, engineering microbes for sustainable farming, and reducing reliance on chemical inputs.

Objectives of Synthetic Biology in Agriculture

The application of synthetic biology in agriculture is guided by several important objectives:

- **Enhancing Crop Productivity:** To develop crops that can produce higher yields under varying environmental conditions.
- **Improving Stress Tolerance:** To engineer plants that can withstand abiotic stresses such as drought, salinity, heat, and flooding.
- **Sustainable Nutrient Management:** To reduce dependency on chemical fertilizers by developing biological alternatives like nitrogen-fixing crops and engineered soil microbes.
- **Eco-friendly Pest and Disease Control:** To create biological systems that can naturally resist pests and pathogens, minimizing pesticide use.

- **Nutritional Enhancement (Biofortification):** To improve the nutritional content of crops by increasing vitamins, minerals, and essential amino acids.
- **Environmental Protection:** To reduce greenhouse gas emissions and promote carbon sequestration through engineered plants and microbes.

Description / Applications of Synthetic Biology in Agriculture

Engineering Crops with Novel Traits

Synthetic biology allows the introduction of new genetic circuits into plants to control traits such as growth, flowering time, and stress responses. By designing synthetic promoters and regulatory elements, scientists can precisely control gene expression in crops.

For example, crops can be engineered to activate drought-resistance genes only under water stress conditions, thereby conserving energy and improving efficiency.

Artificial Nitrogen Fixation

One of the most promising applications is the development of crops capable of fixing atmospheric nitrogen. Currently, nitrogen fixation is limited to certain bacteria. Synthetic biology aims to transfer or recreate this ability in non-leguminous crops like rice and wheat.

This innovation could significantly reduce the use of nitrogen fertilizers, lowering production costs and minimizing environmental pollution.

Engineering Plant-Associated Microbiomes

Plants interact with a wide range of microorganisms in the soil and on their surfaces. Synthetic biology enables the design of beneficial microbes that can:

Enhance nutrient uptake
Promote plant growth
Protect against pathogens

This approach, often linked with Microbiome Engineering, supports sustainable agriculture by improving soil health and reducing chemical inputs.

Development of Bio-based Pest Control

Synthetic biology can be used to engineer biological agents such as bacteria, fungi, or viruses to specifically target agricultural pests. Additionally, crops can be designed to produce natural pest-repelling compounds.

This reduces reliance on harmful chemical pesticides and contributes to environmentally friendly pest management systems.

Metabolic Engineering for Value-added Products

Through synthetic biology, plants can be modified to produce high-value compounds such as pharmaceuticals, biofuels, and industrial enzymes. This transforms crops into biofactories, creating new economic opportunities for farmers.

For example, oilseed crops can be engineered to produce specialized fatty acids used in industry.

Climate-Resilient Agriculture

With increasing climate variability, synthetic biology plays a crucial role in developing crops that can adapt to extreme conditions. By integrating stress-responsive genetic circuits, crops can better survive unpredictable weather patterns.

This aligns closely with the goals of Climate-Smart Agriculture, ensuring long-term agricultural sustainability.

Biosensors and Smart Farming

Synthetic biology can be used to develop biological sensors that detect soil nutrients, pathogens, or environmental stress. These biosensors can provide real-time information to farmers, enabling precise and timely interventions.

When integrated with modern technologies, this contributes to smarter and more efficient agricultural practices.

Challenges and Ethical Considerations

Despite its vast potential, synthetic biology in agriculture faces several challenges:

- **Biosafety Risks**: Concerns about unintended effects on ecosystems

- **Regulatory Issues**: Lack of clear global policies for synthetic organisms
- **Public Acceptance**: Ethical concerns regarding genetically modified and synthetic organisms
- **Technical Complexity**: Designing stable and predictable biological systems remains challenging

Addressing these issues requires interdisciplinary collaboration, robust regulatory frameworks, and transparent communication with stakeholders.

Conclusion

Synthetic biology represents a paradigm shift in agricultural science, offering innovative solutions to some of the most pressing challenges in food production and environmental sustainability. By enabling the design and construction of novel biological systems, it provides unprecedented opportunities to enhance crop productivity, reduce chemical inputs, and develop climate-resilient agricultural systems.

However, the successful implementation of synthetic biology in agriculture depends on careful consideration of biosafety, ethical concerns, and regulatory frameworks. With responsible development and proper governance, synthetic biology has the potential to revolutionize agriculture and contribute significantly to global food security and sustainable development.

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THE FUTURE OF FARMING: BLENDING AI AND AGRONOMY FOR HEALTHIER SOILS AND SMARTER WATER USE

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Indian agriculture is currently battling a silent crisis characterized by widespread soil fatigue, salinity, and a dangerously distorted NPK consumption ratio that hovers near 7:2.8:1. This paper explores the transformative potential of "Agri-Intelligence," marking a paradigm shift from simple digitization to "Agentic AI" autonomous systems that act as a farm brain to execute real-time decisions. We examine the synergistic integration of AI with Agronomy to address "Hidden Hunger" through hyperspectral "Digital Twins" that detect nutrient stress days before visible symptoms appear. The study further details Agentic Irrigation technologies, such as weather-locked scheduling and crop-demand modelling, which have demonstrated water savings of 40–50% in arid regions. Highlighting success stories like Telangana's "Saagu Baagu" project, we envision a roadmap for 2047 where technology elevates the farmer to a "Manager of Biological Intelligence," securing a resilient future for Indian food systems.

The Farm Crisis and the "Agentic" Hope

In the verdant granaries of Punjab and Haryana, a silent crisis is unfolding beneath our feet. A farmer stands knee-deep in a field that is thirsty, yet yielding less with every harvest. Despite a record heavy investment in inputs, the soil feels lifeless a victim of soil fatigue and salinity. This is not an isolated anecdote; it is the statistical reality of Indian agriculture in 2026.

For decades, we have treated soil like an inert factory floor, pumping in chemicals to extract maximum grain. The result is a dangerously distorted NPK (Nitrogen-Phosphorus-Potassium) consumption ratio. Against the ideal 4:2:1, current national averages hover near 7:2.8:1, with some intensive districts reaching a staggering 30:8:1 (Dhanashree Crop Solutions, 2024). This chemical imbalance has rendered nearly 30% of India's land area (approx. 120 million hectares) degraded, stripping it of the organic carbon essential for life (ICAR, 2025).

But a new dawn is breaking. We are exiting the era of simple digitization and entering the age of "Agri-Intelligence" and Agentic AI. Unlike the passive tools of the past that merely displayed data, Agentic AI acts as an autonomous farm brain (Srinivasu et al., 2026). It doesn't just tell a farmer that the soil is dry; it calculates the exact liters of water needed based on tomorrow's weather forecast and triggers the irrigation valves automatically. By partnering this computational power with the "soil wisdom" of Agronomy, we are building a holy trifecta: regenerative soils, hyper-efficient water use, and climate-resilient yields. We are moving from farms that struggle to survive to farms that think and heal themselves (Kalra, 2025).

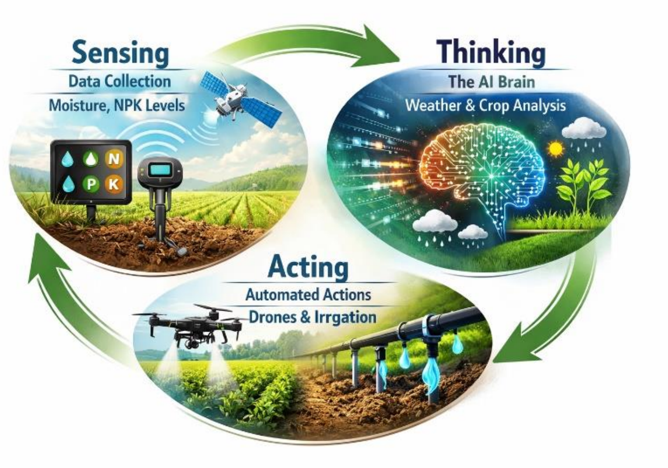

Fig. 1: The Agentic AI Loop – From sensing soil needs to autonomous action.

The Soil Revival Revolution: Decoding "Hidden Hunger"

The most insidious threat to Indian agriculture is Hidden Hunger the depletion of micronutrients (Zinc, Boron, Iron) that goes unnoticed until yield collapses. Traditional soil testing is slow, often taking weeks to return results.

The AI Solution: Hyperspectral "Digital Twins"

The modern agronomy toolkit now includes Hyperspectral Imaging (HSI). Mounted on drones or handheld devices, these sensors capture light signatures invisible to the human eye. Healthy soil reflects light differently than stressed soil, and AI algorithms analyse these spectral signatures to create a "Digital Twin" a virtual 3D map of the farm's soil health (Srinivasu et al., 2026). Instead of waiting for leaves to turn yellow (chlorosis), the AI detects nutrient stress 10–15 days in advance, allowing for Precision Nutrigation (Quyoom et al., 2026).

Biologicals and the "Wood Wide Web"

Agronomy is simultaneously rediscovering the power of the soil microbiome. New "Bio-Ag" protocols use microbial consortia (mycorrhizae and rhizobacteria) to unlock nutrients naturally. In a recent pilot in Karnataka's Aland taluk, sugarcane farmers used AI to monitor soil carbon levels and replaced 25% of their chemical urea with AI-prescribed "bio-stimulants" (Vaimanika Aerospace, 2025). The result was a measurable rise in Soil Organic Carbon (SOC) from 0.3% to 0.6% in just two seasons.

Water Wisdom: From "More Water" to "Virtual Water"

Agriculture consumes 84% of India's available fresh water, a figure that is unsustainable in a warming world (NITI Aayog, 2025). The old paradigm was "flood irrigation"; the new paradigm is "Predictive Precision."

The Rise of Agentic Irrigation

New irrigation systems are no longer just pipes; they are intelligent agents.

1. **Weather-Locked Scheduling:** The AI system connects to local weather stations. If the forecast predicts rain within 48 hours, the system autonomously delays irrigation, preventing waterlogging and saving thousands of liters (Srinivasu et al., 2026).
2. **Crop-Demand Modelling:** Using evapotranspiration sensors, the system calculates the "thirst" of the crop in real-time. It delivers water directly to the root zone via subsurface drips, reducing evaporation losses by 40–50% (Kalra, 2025).

Success Story: Rajasthan's Millet Miracle

In the arid districts of Rajasthan, pilot projects have deployed these "smart drips" for millet and bajra. By synchronizing water delivery with the crop's physiological growth stages, farmers achieved a double victory: they used 35% less water while increasing grain filling by 18% (NITI Aayog, 2025).

The Trifecta Synergy: Nutrients, Soil, Water United

The true power of Agri-Intelligence lies in the "Resource Matrix" a holistic approach where AI orchestrates the interaction between all inputs. You cannot fix the soil if you over-water it; you cannot optimize water if the nutrients are imbalanced.

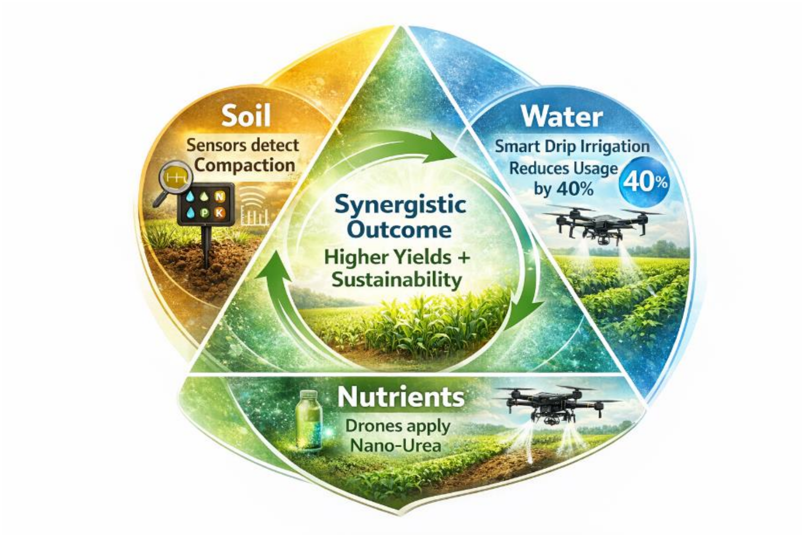

Fig. 2: The Resource Matrix – How AI synchronizes Soil, Water, and Nutrients for maximum efficiency.

Table 1: The Resource Matrix – AI-Driven Optimization

Resource	The Agronomy Challenge	The Agentic AI Solution	The Synergistic Outcome
Nutrients	Volatilization of Nitrogen and fixation of Phosphorus.	AI adjusts fertilizer application timing based on soil moisture and temperature data (Srinivasu et al., 2026).	30% reduction in fertilizer use; prevented groundwater nitrate pollution.
Soil Structure	Compaction due to heavy machinery and tillage.	Satellite radar (SAR) detects compaction zones; AI recommends "Bio-Tillage" with deep-rooted cover crops (Dhanashree Crop Solutions, 2024).	Improved root penetration; enhanced water infiltration rates.
Water	Salinity buildup from poor quality irrigation.	AI monitors soil EC (Electrical Conductivity) and schedules "leaching fractions" to flush salts (NITI Aayog, 2025).	Reclamation of saline soils; sustained long-term fertility.

Real Farms, Real Results: Stories from the Field

This is not science fiction; it is happening now.

- **The *Saagu Baagu* Revolution (Telangana):**

In collaboration with the World Economic Forum, the Telangana government launched the *Saagu Baagu* (Agricultural Advancement) project. Using AI-based pest management tools, 7,000 chili farmers received real-time alerts on their phones. Pesticide spraying was reduced by 9%, while yields jumped by 21% (Kalra, 2025). The AI successfully predicted pest attacks (like thrips) weeks before they decimated the crop.

- **The "Drone Didi" Effect:**

Across rural India, the "Namo Drone Didi" scheme is empowering women to become pilots of agronomy. In Madhya Pradesh, drone-led nano-urea spraying has reduced the quantity of urea needed by 50% (PIB, 2026). The drone's turbulence flips the leaves, ensuring the nutrient is absorbed by the stomata on the underside, maximizing efficiency.

- **Kisan e-Mitra:**

The language barrier is being broken by GenAI. The government's Kisan e-Mitra chatbot, powered by advanced Large Language Models (LLMs), answers queries in 11 local languages. As of late 2025, it has resolved over 90 lakh queries, democratizing access to top-tier agronomic advice that was once available only to wealthy corporate farms (PIB, 2026).

Challenges and the Path Forward

We must address the hurdles to scale this revolution:

1. **The Digital Divide:** Smallholder farmers (86% of India’s farming population) cannot afford high-end sensors. The solution lies in "Farming as a Service" (FaaS), where Custom Hiring Centers rent out AI tools just like tractors (Kalra, 2025).
2. **Data Sovereignty:** Who owns the data generated by a farmer's field? Robust policies are needed to ensure farmers retain ownership of their "Digital Soil Health Cards."
3. **Localizing AI:** Models trained on American corn fields often fail in Indian paddy fields. We need "Desi Data" to train AI models that understand Indian soil diversity (Srinivasu et al., 2026).

Conclusion: Farming’s Bright Horizon

The fusion of AI and Agronomy is not a replacement for the farmer; it is an elevation of the profession. It transitions the farmer from a labourer battling the elements to a Manager of Biological Intelligence. By 2047, the Indian farm will stand as a sophisticated hub where technology amplifies tradition. Sensors will decode the soil's silent language, drones will execute precision care, and decisions will be driven by data-backed foresight rather than uncertain guesswork. While the "Farm Crisis" is a reality, the "Tech Hope" offers a stronger resolve. As we seamlessly blend silicon chips with soil organic carbon, we are doing more than just securing our food and we are cultivating a resilient future.

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