# SOUVENIR

National Conference on
"Frontier Technologies for Weather and Climate
BasedDecisions in Agriculture and Allied Sectors"

# AGMET - 2025

13th to 15th February, 2025

**Assam Agricultural University**
Jorhat - 785013 (Assam)

*Jointly organized by :*

**Association of Agrometeorologists, Anand**
**&**
**Assam Agricultural University, Jorhat**

SOUVENIR AGMET - 2025 AAU, JORHAT

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# SOUVENIR

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***Souvenir,*** *National Conference on "Frontier Technologies for Weather and Climate Based Decisions in Agriculture and Allied Sectors (AGMET-2025)", is a compilation of articles written by various authors on the occasion of National Conference on "Frontier Technologies for Weather and Climate Based Decisions in Agriculture and Allied Sectors (AGMET-2025)", held from 13th to 15th February, 2025, at Assam Agricultural University, Jorhat, India, and published by the Organizing Secretary, on behalf of the Organizing Committee.*



## Editorial Committee



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ড° হিমন্ত বিশ্ব শৰ্মা
**Dr. Himanta Biswa Sarma**

মুখ্যমন্ত্ৰী, অসম
**Chief Minister, Assam**

সত্যমেৱ জয়তে

CMS.7/2023/ 2522
Dispur
17 Magh, 1431 Bhaskarabda
31st January, 2025

## MESSAGE

I am pleased to extend my warmest greetings to the participants of the National Conference on 'Frontier Technologies for Weather and Climate-Based Decisions in Agriculture and Allied Sectors (AGMET-2025)', organised by Assam Agricultural University, Jorhat in collaboration with the Association of Agrometeorologists, Anand. This gathering represents a pivotal moment in our collective endeavour towards integrating advanced technology and climate insights into the fabric of agricultural decision-making.

AGMET-2025 serves as a crucial crossroads, where the vanguard of scientific innovation converges with the tangible realities of the land. This confluence of the brightest minds - researchers, practitioners and thought leaders – offers an indispensable forum to chart a course toward a future in farming that is not merely enduring but also dynamic and robust. The theme of this conference serves as a clarion call to action, urging us to harness the power of technology, agro meteorology and climate science to strengthen the foundations of our agricultural systems.

By embracing frontier technologies in weather forecasting and climate prediction, we can equip our farmers with the necessary instruments necessary to navigate the capricious tides of climate change. The insights and collaborations nurtured here will sow the seeds for pragmatic, grassroots innovations, empowering our farming communities to thrive amidst the trials of our contemporary age.

My heartfelt congratulations go to Assam Agricultural University and the Association of Agrometeorologists for their commendable efforts in organising this event. I wish all participants an experience replete with success and intellectual enrichment. Your collective dedication to advancing agricultural landscapes is truly inspiring. I look forward to seeing the transformative breakthroughs that will emerge from this gathering.

**(Dr. Himanta Biswa Sarma)**

কেশৱ মহন্ত
মন্ত্ৰী
Keshab Mahanta
MINISTER



সত্যমেৱ জয়তে

ৰাজহ আৰু দুৰ্যোগ ব্যৱস্থাপনা,
তথ্য প্ৰযুক্তি,
বিজ্ঞান, প্ৰযুক্তি আৰু জলবায়ু পৰিৱৰ্তন,
অসম চৰকাৰ

Revenue and Disaster Management,
Information Technology,
Science, Technology & Climate Change,
Government of Assam
Dispur, Guwahati


## MESSAGE

It gives me immense pleasure to learn that Assam Agriculture University is organizing a National Conference on "Frontier Technologies for Weather and Climate Based Decisions in Agriculture and Allied Sectors" (AGMET 2025), jointly with the Association of Agrometeorologists from February 13 to 15, 2025 at AAU, Jorhat.

In an era that witnessed rapid technological growth and shifting climate change dynamics, an event like this would offer an excellent opportunity to the scientific community to navigate the pressing issues of climate change, its impact on the agricultural sector and thereby facilitate making critical decisions to address these pertinent issues.

Climate Change is the defining issue of our time. The effects of climate change- now accelerating all over the world, include unpredictable changes in rainfall patterns- bringing drought, heat-waves, and flooding. Since agriculture relies heavily on factors like temperature, rainfall and sunlight, it is considered highly sensitive to weather and climate changes. As extreme weather becomes more frequent, and destructive events hit farmers harder, the impact on farming will be more and more severe. Climate change reduces crop yields and lower nutrition quality of the produce.

As the global climate continues to evolve, the role of high-tech technologies in weather forecasting becomes increasingly pivotal to cope with the adversities of the changing climate, particularly in the agricultural sector.

I believe, this conference is a testament to the unwavering commitment of the researchers towards fostering innovation, advancing knowledge and addressing climate related risks.

At this momentous juncture, I extend my heartfelt greetings to all the esteemed participants and delegates attending the conference. I would like to laud the organizers for their diligent effort and dedication towards creating such a platform where transformative ideas can take shape. I am confident that the discussions held at the conference will yield significant outcomes and contribute towards achieving a sustainable future.

I wish the event a grand success.

(Keshab Mahanta)


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**Atul Bora**
**Minister**
**Agriculture, Horticulture, Excise,**
**Border Protection & Development,**
**Implementation of Assam Accord.**

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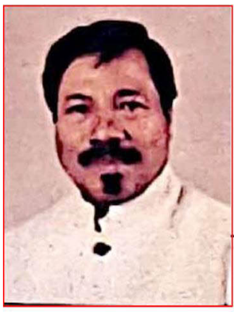

# *MESSAGE*

It gives me great pleasure to extend my warmest greetings to all the participants, distinguished guests and organizers of this **National Conference** themed on **"Frontier Technologies for Weather and Climate Based Decisions in Agriculture and Allied Sectors (AGMET-2025)"** which is being organized jointly by Assam Agricultural University, Jorhat and the Association of Agrometeorologists, Anand from 13th to 15th February, 2025.

In a nation where agriculture forms the backbone of our economy and livelihood sustenance, it is imperative to address the critical challenges posed by changing climate behaviour on agriculture and allied sectors. This Conference will provide an exceptional platform to researchers and stakeholders to exchange ideas on fostering innovative technologies that promote climate resilient agriculture and address the need for policy reforms in response to evolving market dynamics.

I commend the organizers for their innovative and relentless efforts in bringing together experts and scholars for this significant event. I am confident that the discussions to be held in this forum will yield impactful outcomes that aim at empowering our farmers and building a more sustainable and inclusive agricultural landscape besides paving the path for future collaboration and networking opportunities.

I wish the **National Conference** a grand success.

Date : 31st January, 2025

**( ATUL BORA )**

Block - C, Ground Floor, Assam Sachivalaya, Dispur, Guwahati - 781006. Tel. : 0361-2237008 (O). E-mail : ministeratulbora@gmail.com

डॉ. मृत्युंजय महापात्र
मौसम विज्ञान विभाग के महानिदेशक,
विश्व मौसम विज्ञान संगठन में भारत के स्थाई प्रतिनिधि
विश्व मौसम विज्ञान संगठन के तीसरे उपाध्यक्ष

*Dr. Mrutyunjay Mohapatra*
Director General of Meteorology,
Permanent Representative of India to WMO
Third Vice President of WMO



भारत सरकार
पृथ्वी विज्ञान मंत्रालय
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नई दिल्ली–110003
Government of India
Ministry of Earth Sciences
India Meteorological Department
Mausam Bhawan, Lodi Road
New Delhi-110003


## MESSAGE

Climate change and increasing frequency of extreme weather events are constantly threatening the global food security. Under such circumstances, the need for precise, timely and actionable weather and climate information becomes crucial to ensure sustainability in the farming sector. India Meteorological Department (IMD) has consistently been proactive in envisioning the integration of cutting-edge technologies like Artificial Intelligence and Machine Learning to transform weather forecasting, which in turn enable the farmers and stakeholders to make informed decisions in the agriculture sector, thereby enhancing resilience and ensuring food security. IMD is proud to be part of this transformative journey, facilitating the implementation of weather based agro-advisories across various states of the country, all the way down to the Panchayat level.

I am pleased to note that the Association of Agrometeorologists (AAM), Anand and Assam Agricultural University (AAU), Jorhat are jointly organizing the National Conference on Frontier Technologies for Weather and Climate Based Decisions in Agriculture and Allied Sectors (AGMET-2025), from 13th to 15th February, 2025 at AAU, Jorhat campus. This event offers an exceptional platform for engaging discussions and debates on enhancing our understanding of climate-related risks in agriculture and allied sectors, exploring the need for technological advancements and policy reforms with the changing market dynamics as well as exploring climate-resilient agrometeorological practices, among other topics.

I congratulate the organizers for their collective efforts in uniting academicians, experts, vendors of technology and products, and promising young scholars under the banner of AGMET-2025. I am sure the deliberations made in this conference will be helpful for initiating collaborative research projects and developing innovative strategies for the welfare of the farming community.

I extend my best wishes to all the participants and organizers of AGMET-2025 and wish the event a grand success.

**(Mrutyunjay Mohapatra)**


Phone : 91-11-24611842, Fax : 91-11-24611792
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**Dr. Bidyut C. Deka**
**Vice Chancellor**

**ASSAM AGRICULTURAL UNIVERSITY**
**JORHAT-785013, ASSAM (INDIA)**

(Recipient of Sardar Patel Outstanding Institution Award)

## Message

It is a matter of great pride and privilege for Assam Agricultural University (AAU), Jorhat, to host the *National Conference on Frontier Technologies for Weather and Climate-Based Decisions in Agriculture and Allied Sector (AGMET-2025)*, jointly organized with the Association of Agrometeorologists, Anand.

The ever-evolving challenges posed by climate variability, extreme weather events, and their cascading effects on agriculture and allied sectors necessitate the adoption of cutting-edge technologies and scientific innovations. This conference, focusing on themes such as natural resource management, precision agriculture, digital technologies, AI, IoT, crop modelling, and climate-resilient crop improvement, promises to ignite insightful discussions and pave the way for sustainable solutions.

I am delighted that the compendium of abstracts, which serves as the abstract volume for this conference, encapsulates the essence of the research endeavours presented by the participants. This volume not only reflects the depth and diversity of ideas being explored but also acts as a valuable repository of knowledge for the scientific community.

I extend my heartfelt gratitude to the organizers, participants, and contributors for their dedication to this noble cause. I am confident that AGMET-2025, complemented by the insights captured in this abstract volume, will emerge as a milestone in fostering innovation and collaboration in agriculture under changing climatic conditions.

Wishing the conference a grand success.

Vice-Chancellor
Assam Agricultural University, Jorhat

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"Healthy Soils for a healthy life"

Association of Agrometeorologists

## Message

Advancements in agricultural meteorology are transforming the way farmers make decisions about weather and climate, helping them manage their farms more effectively and adapt to the challenges of climate change. As weather patterns become more unpredictable, farmers are increasingly relying on new technologies to improve crop production and protect against climate-related risks. This data-driven approach not only makes farming more efficient, but also increases diversified opportunities to enhance crop yields while reducing environmental constraints. As farmers adopt climate-smart practices backed by meteorological insights, they are building farming systems that are more resilient to changing weather conditions. By combining traditional knowledge with these cutting-edge technologies, agricultural meteorology plays a critical role in ensuring food security, supporting sustainability, and helping farming communities thrive even in the face of a changing climate.

I am delighted to announce that the Association of Agrometeorologists (AAM), Anand, in collaboration with Assam Agricultural University (AAU), Jorhat, is jointly organizing the National Conference on Frontier Technologies for Weather and Climate Based Decisions in Agriculture and Allied Sectors (AGMET-2025) from 13$^{th}$ to 15$^{th}$ February, 2025, at AAU, Jorhat campus. Hosting this important event will enhance academic collaborations among students and faculties, besides fostering greater exposure for other stakeholders.

I hope this platform brings up meaningful discussions and leads the way for thoughtful decisions that drive sustainable agriculture forward.

I wish the event a great success and convey my best regards to all the participants and dedicated organizers of AGMET-2025.

Sd/-
***Dr. Kamalesh K. Singh***
**(President, AAM)**
**New Delhi**

# Content

# Content

# Editorial

## Harnessing Meteorological and Climatological Insights for Resilient Agriculture

*The intricate interplay between weather, climate, and agriculture has been a defining factor in human history. From rudimentary observations of seasonal patterns to the sophisticated agro-meteorological models of today, understanding this nexus has been fundamental to food security and economic stability. This souvenir, commemorating the event "Frontier Technologies for Weather and Climate Based Decisions in Agriculture and Allied Sectors," underscores the increasing recognition of data-driven decision-making and policy planning in the face of evolving climatic conditions and uncertainties of climate change.*

*Agriculture, inherently linked to natural systems, is particularly susceptible to the impacts of weather variability and long-term climate change. Extreme events like droughts, floods, and heatwaves, coupled with shifts in precipitation patterns and temperature regimes, can severely impact crop yields, livestock productivity, and overall agricultural sustainability and food security. In the context of accelerated climate change, these challenges are becoming more frequent, intense, and unpredictable, necessitating a paradigm shift towards proactive and informed strategies.*

*This event, and this accompanying souvenir, provide a platform for researchers, policymakers, and practitioners to disseminate cutting-edge research, innovative technologies, and best practices related to weather and climate-informed agricultural decision support systems. The contributions herein showcase the diverse facets of this interdisciplinary field, spanning from the development of climate-resilient cultivars and optimization of irrigation scheduling based on evapotranspiration models, to the application of advanced weather forecasting techniques, remote sensing data, and geospatial analysis for precision agriculture.*

*They highlight the importance of integrating meteorological and climatological data with agricultural models to provide actionable insights for stakeholders.*

*The insights presented in this souvenir underscore the imperative of incorporating weather and climate information across the entire agricultural value chain. From pre-planting decisions based on seasonal climate forecasts and soil moisture assessments, to real-time crop monitoring using remote sensing and weather data, and post-harvest management informed by climate risk assessments, data-driven approaches are crucial for maximizing productivity, mitigating risks, and promoting sustainability. Furthermore, these decisions must consider both short-term weather fluctuations, such as rainfall intensity and duration, and long-term climate trends, including changes in temperature and precipitation variability, to enhance resilience and facilitate adaptation.*

*This souvenir is more than a compilation of research papers; it represents a call to action. It advocates for a transition from reactive responses to proactive strategies, leveraging the power of scientific advancements and technological innovation to build a more robust and sustainable agricultural sector. It emphasizes the need for capacity building programs to empower farmers with the skills and knowledge to interpret and utilize weather and climate information effectively. Furthermore, it highlights the importance of developing robust policy frameworks that incentivize the adoption of climate-smart agricultural practices and facilitate access to relevant data and technologies.*

*Looking ahead, the challenges facing agriculture are projected to escalate. However, by embracing scientific rigor, fostering interdisciplinary collaboration, and prioritizing weather and climate-informed decision-making, we can strive towards a future where agriculture not only withstands climate change impacts but also contributes to global food security, economic growth, and environmental stewardship. This souvenir serves as a valuable resource and catalyst for continued dialogue and action in this critical domain.* ●●

*- Editorial Committee*

# Role of Marginal and Small Holding Farmers in Viksit Bharat-2047

**L.S. Rathore***

*Former Director General of Meteorology, Indian Meteorological Department, Govt. of India, New Delhi, Delhi, India*
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**"Considering large number of small and marginal farmers and vast expanse of agriculture area, support from government agencies to this class of farmers for improving farm economic growth will strengthen the economic growth of the country."**

Agrometeorological information and service is vital for small holding agriculture and its productivity performance. The Viksit Bharat @2047 initiative envisions India as a developed nation by the centenary of its independence in 2047. This transformative roadmap emphasizes inclusive development, sustainable progress, and effective governance. Enhancing farm productivity and resilience in Agriculture is among the top nine priorities for generating ample opportunities in line with the strategy set out in the interim budget to achieve Viksit Bharat 2047. These goals cannot be achieved without active participation of farmers particularly the marginal and small as they are one of the key drivers of improving the availability of nutritious food. Different aspects of Viksit Bharat encompass various facets of development such as economic growth, environmental sustainability, social progress and good governance to make India a developed nation by 2047, all of which are weather sensitive. Hence, call for strengthening the agrometeorological service in the country targeting the yet unreached small and marginal farmers.

Small and marginal holdings constitute about 86% of the total holdings in the country. The idea of Viksit Bharat cannot be achieved without enhancing viability of agriculture and increasing income of Small and marginal farmers. Faced with constant productivity and market pressures, agriculture in India needs new tools to enhance its competitiveness and innovation capacity. Considering large number of small and marginal farmers and vast expanse of agriculture area, support from government agencies to this class of farmers for improving farm economic growth will strengthen the economic growth of the country. Also, they have to be made important stakeholders in modulating the existing regulatory framework to save their interests, enabling them to embrace new technologies to foster agricultural innovation leading to income enhancement.

**Table1.** Some attributes related to small and marginal farmers

| Attribute | Marginal Farmer | Small Farmer |
|---|---|---|
| Land holding | Up to 1 Hectare (Average size 0.38 hectares) | 1-2 Hectare |
| Challenges | Limited access to resources and support services, Poverty, Debt cycles, Reliance on non-farm activities and wage labour to sustain their livelihoods | |
| Landholding share in total cultivable land | 24% (approx.) | 62% (approx.) |
| As per assessment survey conducted by National Sample Survey Office (NSO) in 2018-19, the percentage distribution of agricultural households owning less than two hectares of land is 89.4%. | | |

To improve the condition of Small and Marginal there is need to focus on their income enhancement which calls for improved technological solutions inter alia other initiatives. Government of India has taken many initiatives for these categories of farmers which are as under;

- Enhancement in budget allocation by more than 4.35 times to Rs. 1,31,612.41 crore in 2023-24 in last 10 years
- Income support to farmers through PM KISAN providing [1] 6000 per year
- Pradhan Mantri Fasal Bima Yojana (PMFBY)
- Institutional credit for agriculture sector
- Fixing of Minimum Support Price (MSP) at one-and-a half times the cost of production
- Promotion of organic farming in the country
- Per Drop More Crop (So far, an area of around 70 lakh hectares has been covered)
- Micro Irrigation Fund (A corpus has been created with NABARD)
- Promotion of Farmer Producer Organizations (FPOs)
- A National Beekeeping and Honey Mission (NBHM)
- Agricultural Mechanization: (18,824 custom hiring centres, 403 high-tech hubs, 16,791 farm machinery banks, 2804 CHCs, 12 Hi-tech hubs and 1260 Village Level Farm Machinery Banks have been established)
- Providing Soil Health Cards to farmers
- Setting up of National Agriculture Market (e-NAM) extension Platform (1260 mandis of 22 States and 03 UTs have been integrated)
- Launch of the National Mission for Edible Oils and Oil Palm (NMEO)
- Setting up Agri Infrastructure Fund (AIF)
- Improvement in farm produce logistics, introduction of Kisan Rail
- Creation of a Start-up Eco system in agriculture and allied sector
- Achievement in Export of Agri and Allied Agri- Commodities

The efforts of Government at positive implementation of these schemes have yielded remarkable results towards augmenting the income of the farmers. Most importantly, it is essential that these farmers may be provided credit support not just for crops but also for allied activities.

Agrometeorology plays significant role in many of above scheme such as PMFBY, promotion of organic farming in the country, Per Drop More Crop, Micro Irrigation Fund, promotion of FPOs, NBHM, Providing Soil Health Cards to farmers, setting up of e-NAM, launch of NMEO, creation of a Start-up Eco system in agriculture and allied sector, achievement in Export of Agri and Allied Agri-Commodities etc. The contribution to output is higher for marginal and small farmers as compared to their share in area. The share of these farmers was 46.1% in land possessed but they contribute 51.2% to the total output of the country (S Mahendra Dev. 2012). Considering higher efficiency of small holdings than large holdings they should be targeted as prime recipient of agrometeorological information support.

The main crops sown by farmers in both the kharif and the rabi seasons for self-consumption as well as for selling are cereals. While paddy dominated in both kharif (all India) and rabi (in southern and eastern states), wheat was the preferred rabi crop in the northern states. Gram (chana), maize and cotton followed close next choices of these farmers. It highlights the fact that there is ample scope for their income enhancement if crops generating more profit are cultivated by them. But as they are largely engaged in non-agricultural activities like wage labour and livestock management to supplement their income, they are unable to concentrate on cultivation of non-traditional crops.

These 126 million farmers owned 0.6 hectares holding each on average, which is not enough to produce surpluses which can financially sustain their families. To supplement the meagre income from cultivation, 68.3 percent of the marginal farmers are engaged in other income generating activities such as daily wage labour (78 percent), vocational business (60 percent) non-agricultural business (18 percent) and animal husbandry (12 percent) and salaried employment (12 percent). According to the study, average landholding size is around 1.22 acres among marginal farmers. Only 56 percent of marginal farmers have access to irrigation and practice only rainfed agriculture. Around 69 percent farmers sold crops or byproducts with an average annual sale at Rs 60,510, and the median annual sales from farming is estimated at Rs. 40,000 (Source: devdiscourse).

Climate change is another challenge for this group of farmers as it is severely impacting their production efficiency, food security and livelihoods. Climate change is expected to have adverse impact on the living conditions of farmers particularly those living in already fragile environments. They may face an immediate risk of increased crop failure and loss of livestock. Also, capability of this group for adaptation and mitigation strategies to climate change is poor. Similarly, small and marginal farmers depend more on ground water compared to large farmers which is fast depleting. Hence, they are going to face more problems regarding water in future. Their capability for integrated pest management calls for strengthening. Therefore, weather-based water management is going to be crucial for these farmers. Among many issues and challenges faced by marginal and small farmers poor access to suitable agrometeorological services restricting suitable decisions regarding cultivation practices, input management, weather sensitive technology use, poorer land and water management are very important. Hence, there is need to carry out study on usage of agrometeorological information by small and marginal farmers to further strategize the service delivery to them. ●●

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# Agrometeorological Research in India- Its Inception and Journey So Far

**Santanu Kumar Bal, Sarath Chandran M.A. and Vinod Kumar Singh***
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**"Agrometeorological Research in agricultural research institutions in India had its beginning in the earlier years of the 20th century with research efforts on evaporation, soil temperature, soil moisture, and soil gases, at the then Imperial Agricultural Research Institute at Pusa, the predecessor of the present Indian Agricultural Research Institute (IARI) at New Delhi."**

Agrometeorological Research in agricultural research institutions in India had its beginning in the earlier years of the 20th century with research efforts on evaporation, soil temperature, soil moisture, and soil gases, at the then Imperial Agricultural Research Institute at Pusa, the predecessor of the present Indian Agricultural Research Institute (IARI) at New Delhi. Consequent to the recommendations of the Royal Commission on Agriculture, the activities in this discipline took a concrete shape with the establishment of the Division of Agricultural Meteorology in 1932 in the offices of the India Meteorological Department (IMD) at Pune. Dr. L.A. Ramdas, India's 'Father of Agricultural Meteorology', headed the unit. The main objectives of the unit were to link meteorology and agriculture; and to provide research facilities for post-graduate students to investigate borderline problems like soil science, plant physiology, and agricultural meteorology.

The major works of Dr. L.A. Ramdas include the role of solar radiation, surface conditions, soil conductivity, convection process and radiation from the earth's surface and adjacent air layers, wind movements, limits of surface climate, evaporation, the water vapour content in the atmosphere, and dew fall. studied Monsoon and weather abnormalities, such as floods, droughts, cyclonic storms, thunderstorms, hailstorms, dust storms, cold waves, and frost hazards. He was also a pioneer in the field of Solar and Wind energy in India.

This work paved the way for formulating an All India Crop Weather Scheme in 1945 in collaboration with the Indian Council for Agricultural Research (ICAR), the Indian Central Cotton Committee, and the Indian Central Sugarcane Committees. A network of agrometeorological observatories was started at the State Agricultural Farms, which also carried out field experiments under the crop-weather scheme for developing crop-weather relations. Major crops like rice, wheat, sugarcane, and cotton, raised under rainfed conditions were covered by this scheme. The Agromet division at Pune also participated in the SITE Program and later, an Agromet Advisory Service bulletin was started at 17 centres for the farming community.

During the 1970s the status of agrometeorological studies in India was reviewed by the National Commission on Agriculture constituted by the Government of India which recommended the delineation of the country into Agroclimatic zones taking yield and spread of crops into consideration, and strengthening of the research and human resources development through establishment of Departments of Agricultural Meteorology in the State Agricultural Universities (SAUs).

Under a UNDP program, a Centre for Advanced Studies in Agrometeorology (CASAM) was established at the College of Agriculture, Pune functioning under the Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra to strengthen post-graduate teaching & training. Department of Science and Technology (DST), Government of India installed a supercomputer and established the National Centre for Medium-Range Weather Forecasting (NCMRWF) as a major component of services to the agricultural community. Five-day weather forecasts were put out and a weather-based 'Agromet Advisory Services' scheme was initiated in the year 1991 on a trial basis. The ICAR, the IMD, and SAUS are active partners in this ongoing scheme. Agrometeorological Advisory Service Units (AASUS) were opened at 127 NARP (National Agricultural Research Program, ICAR) centres located in the different Agroclimatic zones. Presently, 127 are functioning and receiving medium-range weather forecasts once/twice a week and formulating weather-based agro-advisories with local expertise which are being finally disseminated to the farming community through various mass media and personal contacts. Based on efforts made by various organizations and scientists in the field of agrometeorology, regular weather forecasts (2-day outlook & medium-range weather predictions) are being used by agricultural scientists to provide local advisory to farmers. This scheme is reviewed annually, which provides periodical feedback. This service has created awareness among farmers about the benefits and use of weather-based information and advisories for their field operations.

Meanwhile, the Planning Commission was also concerned about drought occurrence in the country from time to time and started the Agroclimatological Regional Planning Project and started an Agroclimatic Regional Planning Unit (ARPU) at Ahmedabad in 1988. This institute has been carrying out natural resource and socio-economic analysis for planning economic strategies for diversified agriculture encompassing horticulture, dairying, poultry, fishery, livestock, agro-processing, and crop husbandry, based on Agroclimatic zones and sub-zones. The National Bureau of Soil Survey and Land Use Planning (NBSSLUP) of ICAR with headquarters at Nagpur, took up delineation of Agro-Ecological zones supplementing the Agroclimatic zones to include information on soil-physico-chemical characteristics for determining land suitability for cropping systems and land use planning in the country.

The DST has been funding research projects in agricultural meteorology since the establishment of NCMRWF under the Monsoon and Tropical Climate, Agrometeorology and Monsoon Mission Programs with a focus on crop-weather modelling, the impact of climatic variations and change on agriculture and also in support of the weather-based agro-advisory services. Projects seeking to explore new methodologies and new frontiers of research in Agrometeorology are also being supported. Several projects related to agrometeorology completed their tenure. A major step was the creation of a Data Bank in Agrometeorology by DST in cooperation with ICAR at the Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad.

**Coordinated program for research on Agrometeorology in India**

In the year 1983, under the VI Plan, the ICAR initiated an All India Coordinated Research Project in Agrometeorology (AICRPAM). The coordinating unit of AICRPAM was established at the Central Research Institute for Dryland Agriculture, Hyderabad, and 12 Cooperating Centres at various State Agricultural Universities in 1983. After a detailed review and evaluation of the progress made by the project and realizing the importance of agrometeorological research support for enhancing food production, ICAR extended the Cooperating Centres to an additional 13 Agricultural Universities of the country w.e.f. April 1995. In 2023, five new voluntary centres viz., Barapani, Bikaner, Jhansi, Shimoga, and Srinagar were included in the existing network. At present, AICRPAM undertakes research and extension work on five themes viz., agroclimatic characterization, crop-weather relationships, crop growth modelling, weather effects on pests and diseases, and agromet advisory services.

AICRPAM has conducted extensive agroclimatic characterization of the states where it's cooperating centres are working and has come out with agroclimatic atlases using block-level climate data. All the cooperating centres are quantifying crop-weather relationships and publishing as agrometeorology of crops. AICRPAM has also improved IMD's crop weather calendar by adding more components to it *viz.*, standard meteorological week-wise optimum range of weather parameters for obtaining higher yield and conducive range of weather parameters for incidence of pests and diseases. Further, the project has developed the 'Dynamic Crop Weather Calendar', a software that guides favourable sowing and irrigation decisions based on soil moisture dynamics based on historical, real-time, and forecast weather. The DCWC is proposed to be linked to the Decision Support System (DSS) of the India Meteorological Department (IMD) for the automation of agromet advisory services (Vijaya Kumar *et al.*, 2021). Under crop growth modelling, location and crop-specific genetic coefficients are being calibrated and validated for various crops and the impact of projected climate was assessed using crop simulation models like DSSAT and InfoCrop. Location-specific thumb rules are being developed for the fore-warning of pest/disease incidence. In collaboration with IMD, AICRPAM is also issuing the 'National Agromet Advisory Services' bulletin (NAAS) based on the Extended Range Weather Forecast (ERFS) every Friday.

Besides this, AICRPAM developed a software viz., Weathercock for bringing uniformity in carrying out the agroclimatic analysis. It has various features for data management viz., date conversion, bulk file renaming, unit conversion, data quality checking, agricultural and meteorological drought analysis, rainfall probability analysis, analysis of extreme weather events like heat waves, and cold waves, estimation of length of growing period, climatic water balance etc. (Rao, 2011). This software is being used by many researchers and scholars across the world for carrying out agroclimatic analysis.

**History of agromet advisory services in India**

The need for disseminating the agromet research output to the end users, especially farmers was felt and the India Meteorological Department started issuing Farmers' Weather Bulletins (FWBs) regularly in 1945. Later it was entrusted to Regional Meteorological Centres viz., New Delhi, Mumbai, Kolkata, Chennai, and Nagpur. These FWBs contained a weather forecast for the next 36 hours and an outlook for another two days. All India Radio used to broadcast FEBs every evening in regional languages to reach every part of the country. The concept of agromet advisory services was introduced in 1977. The Government of India initiated the National Centre for Medium Range Weather Forecast (NCMRWF) in 1988.

Since 1991, the National Centre for Medium Range Weather Forecast (NCMRWF) has been providing quantitative weather forecasts for a total of 5 agrometeorological field units (AMFUs) with a spatial resolution of 250 km in the medium range (3 days). In 1993, the spatial resolution was improved to 150 km, and in 1999, it was further improved to 75 km. At the agro-climatic zone level, the temporal resolution of the forecast was extended from three to five days in 2006. As the AMFU network grew from 5 units in 1991 to 130 units in 2007 to cover all the agroclimatic zones, these two systems (the forecast system of IMD and NCMRWF) combined into one single system in 2007. IMD began issuing multi-model ensemble weather forecasts (50 km spatial resolution and 5-day temporal resolution) at the district level on June 1, 2008. AAS is currently a multi-institutional and multi-disciplinary endeavour. It includes the Indian Council of Agricultural Research (ICAR), state agricultural institutions, state agricultural departments, non-governmental organizations, the media, and others, in addition to IMD. In 2018, IMD in collaboration with IITM, Pune, and NCMRWF started issuing forecasts for extreme weather events using an ensemble prediction system.

**Way forward**

Agrometeorological research has immense promise in addressing the challenge of global food security under climate change and resource constraints. Advancements in precision agriculture, satellite-based remote sensing, and big data analytics provide a possibility for the provision of real-time, location-specific information on crop-weather interactions in agromet research. The application of artificial intelligence and machine learning improves the predictability of crop models to predict better yields, outbreaks of pests and diseases, and extreme weather conditions. This will also support the development of adaptive management approaches targeted toward different agroecosystems. Meteorologists, agronomists, and data scientists need to collaborate to build resilient agricultural systems enhancing the efficiency of resource(s) use, reducing risks, and improving sustainability in productivity. Once these digital platforms and IoT-based technologies are more accessible, the provision of actionable agromet advisories to farmers will become an integral part of grassroots-level decision-making processes that connect science with the application.●●

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# Advancements in Agrometeorological Advisory Services: Harnessing Technology for Agricultural Resilience

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**"The integration of real-time data from various sources, including ground-based weather stations, satellite imagery, radar networks, and mobile platforms, has greatly improved the accuracy and timeliness of agrometeorological advisories."**

India's Agrometeorological Advisory Services (AAS) have evolved significantly in recent years, integrating advanced technologies and methodologies to support farmers in managing climate-related risks and improving agricultural productivity and sustainability. These advancements have been driven by a combination of technological innovations, real-time data collection, and localized weather forecasting systems that allow for a more accurate and tailored approach to agricultural advisory services. The key developments in AAS have focused on improving weather data accuracy and reliability, enhancing the delivery of information, and fostering climate-smart agricultural practices that help farmers adapt to changing weather patterns.

The establishment of Automated Weather Stations (AWS) across the country represents one of the most important strides in the enhancement of agrometeorological services. These stations provide real-time data on critical weather parameters, including temperature, rainfall, wind speed, and humidity. The data collected by these stations is essential for generating weather forecasts that are not only more accurate but also highly localized. Unlike traditional weather forecasting models, which often provide generalized predictions for large regions, AWS allows meteorologists to offer hyper-localized forecasts for specific districts, towns, or even villages. This granularity is vital for farmers, who rely on highly specific and precise weather information to make informed decisions about crop management, irrigation, pest control, and harvesting. For example, in a drought-prone area, an AWS might detect a sudden drop in soil moisture and trigger a weather advisory that recommends water-efficient irrigation techniques, helping farmers minimize water wastage and protect their crops.

Along with AWS, the integration of satellite-based observations has revolutionized the collection of weather data for agrometeorology. Satellites provide valuable high-resolution imagery and data that helps monitor large-scale weather phenomena such as cyclones, cloud formations, drought conditions, and storm development. Through satellite data, meteorologists are able to track the movement of weather systems and issue more accurate forecasts, which gives farmers sufficient time to prepare for extreme weather events. For instance, the ability to track cyclonic storms with satellite imagery enables timely warnings, which allow farmers to take preventative actions such as securing crops or adjusting their farming schedules. Similarly, satellite-based monitoring of drought conditions can inform farmers about potential water shortages, helping them plan crop selection and irrigation strategies in advance. This shift towards using satellite data has significantly enhanced the accuracy of weather predictions, particularly in regions that lack traditional weather stations.

The role of Artificial Intelligence (AI) and Machine Learning (ML) in improving the accuracy and precision of weather forecasting has become increasingly important. AI and ML technologies enable the processing of vast quantities of data, including historical weather patterns, satellite and radar images, and real-time weather station readings. By analysing these large datasets, AI models can identify trends and patterns that were previously undetectable, leading to more accurate long-term weather predictions. For example, AI models can analyse seasonal climate data to predict changes in the monsoon or the likelihood of extreme weather events, providing farmers with critical information on how to adapt their farming practices. These models are especially valuable for forecasting climate variability and long-term weather patterns, helping farmers make better decisions about crop rotations, planting schedules, and resource allocation. Additionally, AI-powered systems can simulate different weather scenarios and recommend adaptive strategies for farmers, such as switching to drought-resistant crops or adjusting planting dates to avoid unfavourable weather conditions.

The advent of mobile and web-based platforms has also played a pivotal role in the delivery of agrometeorological advisories. Platforms such as Meghdoot, Mausam, Kisan Suvidha and Damini have made weather and agricultural advisory services more accessible to farmers, particularly in rural and remote areas. These platforms provide weather forecasts, real-time updates on weather conditions and warnings, and advice on pest control, irrigation, and crop management directly to farmers via their smartphones. These apps have been designed to deliver localized weather information, allowing farmers to receive region-specific advisories, which are far more relevant to their day-to-day farming activities than generalized forecasts. For example, through these platforms, farmers can receive notifications about impending rainfall or temperature fluctuations, helping them take preventive measures such as protecting crops from frost or avoiding over-irrigation during rainy spells. In regions with poor internet connectivity, many of these platforms also offer offline functionalities, enabling farmers to access important weather information even when they are not connected to the internet.

The integration of real-time data from various sources, including ground-based weather stations, satellite imagery, radar networks, and mobile platforms, has greatly improved the accuracy and timeliness of agrometeorological advisories. One such example is the Agro-AWS network, which integrates data from weather stations, soil moisture and soil temperature sensors, and satellite-based observations to provide farmers with a comprehensive understanding of the weather conditions affecting their crops. This combined approach allows for more precise weather forecasting and the development of tailored recommendations for individual farms, such as advice on irrigation, pest management, and crop selection. For instance, if a weather station detects a high likelihood of rainfall in a particular area, it can trigger an advisory recommending that farmers delay their irrigation schedules to prevent waterlogging. Similarly, during periods of drought, farmers may receive guidance on water-efficient irrigation techniques or the adoption of drought-resistant crops.

Public-private partnerships (PPPs) have been instrumental in the further development and expansion of agrometeorological advisory services. Collaborations between government agencies such as the India Meteorological Department (IMD) and private technology firms specializing in agriculture have enabled the integration of advanced tools such as cloud computing, big data analytics, and precision agriculture technologies. These partnerships have resulted in the creation of tools that enable farmers to make better use of weather data in conjunction with other agricultural technologies. For example, private tech companies have developed precision farming solutions that integrate weather data with soil health monitoring systems, giving farmers a more comprehensive view of their field conditions. Recently, IMD launched the Panchayat Mausam Sewa portal (https://www.greenalerts.in/), a joint initiative of IMD-MoES, MoPR, and Greenalerts under PPP mode. It provides block-level weather forecasts in Hindi, English, and regional languages. Local leaders receive alerts via SMS or WhatsApp, enabling quick dissemination to farmers. Daily block-wise forecasts ensure region-specific weather insights. AICRPAM (All India Coordinated Research Project on Agrometeorology) can play a crucial role in the development of tools for AAS by leveraging its extensive research network and field-level data. By collaborating with IMD and private partners, AICRPAM can help refine weather-based advisories through improved modeling techniques, validation of localized forecasts, and integration with decision support systems tailored to different agro-climatic zones. This will enhance the accuracy and relevance of advisories, ensuring that farmers receive precise, actionable information for climate-resilient agriculture. Such tools help farmers make decisions that not only improve crop yields but also reduce their environmental footprint, making agriculture more sustainable in the face of climate change.

In recent years, there has been a significant shift toward promoting climate-smart agriculture, and agrometeorological advisory services have played a critical role in this transition. Climate-smart agriculture involves adopting practices that increase resilience to climate change, reduce greenhouse gas emissions, and improve food security. Advancements in weather forecasting have enabled the development of agricultural advisories that encourage farmers to adopt climate-resilient practices. For example, farmers in drought-prone areas are advised to plant drought-resistant crop varieties, implement water-conserving irrigation techniques such as drip irrigation, and use organic fertilizers that improve soil health. Similarly, in flood-prone areas, farmers may receive recommendations on how to build more resilient infrastructure, such as raised beds for crops, to protect against flood damage. By providing tailored climate-smart agricultural practices, agrometeorological services are helping farmers adapt to the realities of a changing climate, reducing crop losses, and ensuring food security.

Training and capacity-building programs have been crucial in helping farmers better understand and utilize agrometeorological data. Through workshops, extension services, and community-based training programs, intermediaries and farmers are taught how to interpret weather forecasts, understand the implications of different weather patterns, and apply this knowledge to their farming practices. For example, training programs have helped farmers understand the significance of weather maps, learn how to interpret rainfall predictions, and make informed decisions about when to plant or harvest crops. These efforts have not only enhanced the adoption of weather-based decision-making but have also facilitated a greater exchange of knowledge among farmers. Through community-based participatory approaches, farmers have the opportunity to share their experiences and best practices, thereby fostering a collaborative learning environment that enhances the effectiveness of AAS.

Mission Mausam, led by the Ministry of Earth Sciences and primarily implemented by the India Meteorological Department (IMD), is a national initiative designed to transform weather and climate forecasting in India. Approved by the Union Cabinet with a budget of ₹ 2,000 crore for Phase I (2024-2026), Mission Mausam aims to make India "weather-ready and climate-smart." It addresses the complexities of tropical weather forecasting, particularly in regions where observational data is sparse, and model resolutions are coarse, challenges that are exacerbated by climate change. Through the development of advanced weather surveillance technologies, next-generation radars and satellites, and the enhancement of Earth system models, Mission Mausam will significantly improve the accuracy and granularity of weather forecasts, particularly at the gram panchayat level.

This mission will be instrumental in enhancing AAS by providing hyperlocal weather forecasts and real-time advisories tailored to specific agricultural needs. By improving the horizontal resolution of Numerical Weather Prediction (NWP) models from 12 km to 6 km, the mission will enable the delivery of weather information at much finer scales, empowering farmers to make more informed decisions about irrigation, pest management, fertilizer application, and harvesting. Additionally, the incorporation of cutting-edge technologies such as Artificial Intelligence (AI), Machine Learning (ML), and high-performance computing (HPC) will enable better predictions for extreme weather events, including floods and droughts, which are crucial for minimizing crop losses and supporting resilience against climate variability.

Mission Mausam's integration of Doppler Weather Radars, wind profilers, radiosondes, and advanced satellite payloads will further support the refinement of agromet advisories. The real-time updates and impact-based forecasting tools offered by the mission will allow farmers to receive timely alerts for extreme weather, thus improving disaster preparedness and response. The mission's emphasis on capacity-building initiatives, such as the establishment of incubation centers and collaboration among academia, industry, and government, will ensure that the agricultural community has the knowledge and tools necessary to adapt to the changing climate. Overall, Mission Mausam is poised to be a transformative force in India's agricultural landscape, significantly enhancing AAS and enabling farmers to navigate climate-related challenges with greater efficiency and resilience.

Advancements in weather forecasting, driven by the integration of AI/ML, satellite imagery, and hyper-localized data from AWS, have positioned India's AAS for even greater improvements in the future. With continued advancements, weather predictions will become more precise and capable of predicting not only immediate weather conditions but also long-term climatic shifts. The ability to forecast extreme events like droughts, floods, and cyclones with even greater accuracy will provide farmers with more time to adapt and take preventive measures, ultimately reducing crop losses and safeguarding livelihoods. Additionally, with innovations in data processing and forecasting technology, the reach and effectiveness of weather services will continue to grow, ensuring that farmers have access to real-time, actionable information at the most crucial times.

In conclusion, the advancements in AAS have significantly improved agricultural resilience by integrating technologies like Automated Weather Stations (AWS), satellite observations, AI, and ML. These innovations provide farmers with hyper-localized, real-time weather forecasts and tailored advisories, enabling informed decisions that enhance crop management and promote climate-smart practices. PPP and initiatives like Mission Mausam have further strengthened AAS, ensuring that even remote farmers benefit from accurate, actionable weather information. As technology continues to evolve, AAS will empower farmers to adapt to climate change and extreme weather events, supporting sustainable agriculture and food security. ●●

# Role of Advanced Computing in Restructuring the Weather Services in India

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**"Since the atmosphere and ocean system has chaotic internal variability, ensemble prediction is essential to bring out the predictable signal from the unpredictable chaotic noise."**

**Introduction**

Weather and climate modeling (e.g. coupled ocean-atmosphere-biosphere-cryospere models) and associated data assimilation (e.g. 4D-VAR) are highly compute intensive jobs. Availability of High Performance Computers (HPC) has been the backbone of the remarkable improvement of skill of extratropical weather forecasts over the past two decades (Fig.1, right panel). While better understanding of the physical system coupled with better data coverage (specially coming from satellites) for initializing the models contributed to this progress, the R & D that went into improving the models and the operational forecasting with those improved high resolution models could not have been achieved without the availability of HPC facilities at leading NWP Centres located in extratropical region. The availability of a supercomputer was deemed crucial for the core function of using an Atmospheric General Circulation Model (AGCM) to produce medium-range Numerical Weather Prediction (NWP) forecasts. With the acquisition of state-of-the-art High-Performance Computer (HPC), the Cray XMP-14, in 1988, NCMRWF entered the arena of NWP. To enhance research and development capabilities and to promote the use of indigenous technology in NWP, NCMRWF collaborated with Bhabha Atomic Research Centre (BARC) and Centre for Development of Advanced Computing (CDAC) to develop Anupam-Alpha system and the PARAM-10000 system respectively in the turn of the century.

An essential factor for progress in atmosphere-ocean-earth system simulations has been the increase of resolution allowed by the development of high performance computing. It is confirmed by leading research institutes that increasing resolution will resolve clouds better than the coarser resolution models. This trend will continue in the next ten years. Increasing the resolution of a simulation is not the end of the story. As the length-scale of the simulation is reduced, the time-step between computations must also be reduced. If the resolution is doubled in each direction then, at the minimum, one has to use a time-step which is less than half the duration of its predecessor. For example, scaling from 100km to 10km resolution, the simulation time-step must be reduced by a factor of 10, meaning that a 10-fold increase in resolution leads to a 1000-fold increase in computation events. Further, the leading climate centers in the world have developed earth system models and it is expected that these models will reduce the uncertainties in the climate change projections. To incorporate some basic elements such as carbon cycle, aerosol and cloud interaction in the existing ocean-atmosphere coupled models, about 800-fold increased computational power is required to run these models at existing resolution.

Since the atmosphere and ocean system has chaotic internal variability, ensemble prediction is essential to bring out the predictable signal from the unpredictable chaotic noise. A 50 member ensemble for weather forecasts is routinely used in major Centers. To make the models more realistic, models have become very high resolution. But for real time forecasting, the forecasting Centers have to create the ensemble forecasts before the deadline for producing the forecasts on a particular day. Repeating the high resolution model forecasts 50 times for generating one forecast demands very high computing facility. With current MoES HPC facility, we are able to run up to 21 ensemble per day/per cycle. One such run requires about 450 TF computations and 22TB data is generated. The history of high performance computing (HPC) systems at NCMRWF is shown in figure 1. and the commensurate advancement in the NWP model resolution is shown in figure 2. There are various factors of a NWP system which stresses the computational requirements.

## Data Assimilation

Since weather is an initial value problem, accuracy of the initial condition is as important as the accuracy of the model. Thus, data assimilation is a crucial component of weather and climate predictions. As conventional data coverage is spatially and temporally limited, satellite data provides much better coverage in both space and time and if properly assimilated could play an important role in improving skill of forecasts. In fact, the major improvement in the skill of weather forecasts in southern hemisphere is entirely due to satellite radiance data assimilation in recent years. However, satellite data comes in non-standard time and requires 4-dimensional data assimilation. 4-D data assimilation such as the 4-D VAR is a very complex process involving solving the adjoint of the original model and is highly computational intensive. In fact, at the major weather prediction centers, the data assimilation part seems to take even more time than creating the actual forecasts. In addition, it has been now shown that assimilation of land-surface data (e.g. soil moisture, vegetation etc) improves weather and climate forecasts. Any such thing, further adds computational burden. Assimilation technique of 4D VAR in global model is highly computationally demanding and requires huge computational resources.

For climate forecasts, ocean data assimilation such as those coming from ARGO or moored buoys is very important. Eventually, coupled ocean-atmosphere models must evolve coupled data assimilation strategy. All these requirements, while crucial for making significant progress, are highly computation intensive. Hence, if we are serious about improving the weather and climate forecasts, we must invest in the HPC infrastructure that is required for state-of-the-art data assimilation.

## Model Development, improvement

While weather and climate models have come a long way since 1960's, they still have some significant errors or biases in representing the observed weather or climate, affecting the skill of weather and climate prediction. In order to improve the skill of prediction models, continuous effort is essential to reduce the systematic biases of the model. For example, almost all models produce the peak of diurnal cycle of precipitation over land about 3 hours ahead of observed peak time. This introduces serious errors in prediction of rainfall in weather prediction models. How can the models be formulated to improve it? Also the simulation of the MJO or the northward propagating summer monsoon intraseasonal oscillations are erroneous in most models. Some of these errors may be related to resolution of the model. But, largely they are related to inadequacy of formulation of physical processes (e.g. clouds, boundary layer turbulence, radiation balance, land-surface processes etc). Thus, extensive experimentation with different improved formulations of these processes is an integral part of this R & D to improve models. Large number of relatively long integrations required for this purpose with the same high resolution model demands large computing facility.

Another aspect of model development is to increase the realism of the model by taking it towards an Earth System Model. First, we can couple an atmosphere model to an ocean model. Stepwise, we may add a sea-ice model, a bio-geochemistry and a carbon cycle model etc. Each addition of complexity makes the model more and more computationally intensive.

**HPC for operational weather forecasting and services**

Timely dissemination of the forecast is the foremost requirement and requisite for enhanced computing power. It also depends on the number of forecast and the length of the forecast issued every day. NCMRWF acquired a 24-processor Cray SV1 system in 2001 and a Cray X1E with 64 processors in 2006. During 2009-10, the Ministry of Earth Sciences (MoES) augmented it computational power significantly with the acquisition of IBM POWER6 compute clusters and I/O clusters, integrated using a shared file system technology (multi-cluster GPFS) over an InfiniBand fabric connecting the compute nodes. Further in the year 2013, a 1 Peta Flop HPC and 9 Peta Byte storage system was acquired for weather and climate applications. In 2018, the computational power was augmented by 6.8 Peta flops with the acquisition of Cray-XC40 High-Performance Computing (HPC) system for operation of numerical weather/climate prediction systems and for improving modelling and assimilation processes. On 26$^{th}$ Sep 2024, Prime Minister of India, inaugurated the recently acquired HPC system with a total capacity 21.8 Peta Flops for the advancement of the weather and climate research in India. This system has ten percent of the peak compute dedicated on GPUs for Artificial intelligence and machine learning (AI/ML) applications. Further there is a dedicated AI/ML standalone system to experiment on AI/ML applications. This marks a significant surge in India’s computational capabilities, particularly for forecasting extreme weather events. This HPC system will enhance NWP capabilities, including data assimilation, global and regional weather models with higher resolutions. This will improve the weather prediction capabilities from short to S2S time-scales, including that of extreme weather events such as tropical cyclones, heavy precipitation, thunderstorms, heat waves, and droughts.

Artificial intelligence and machine learning (AI/ML) is bringing the next big revolution in weather and climate forecasting practices. Weather and Climate prediction centers across the world are now exploring ways to incorporate machine learning into various aspects of prediction. Few examples include data driven short range forecasting, developing hybrid-AI models where we use conventional dynamical models assisted by machine learning (for various parameterizations), use of machine learning in data assimilation, ensemble forecasting, and data pipelines and data management practices. The usefulness of AI/ML Large Language models is also being explored in making sense of climate data and in improving the reach of forecasts to stakeholders.

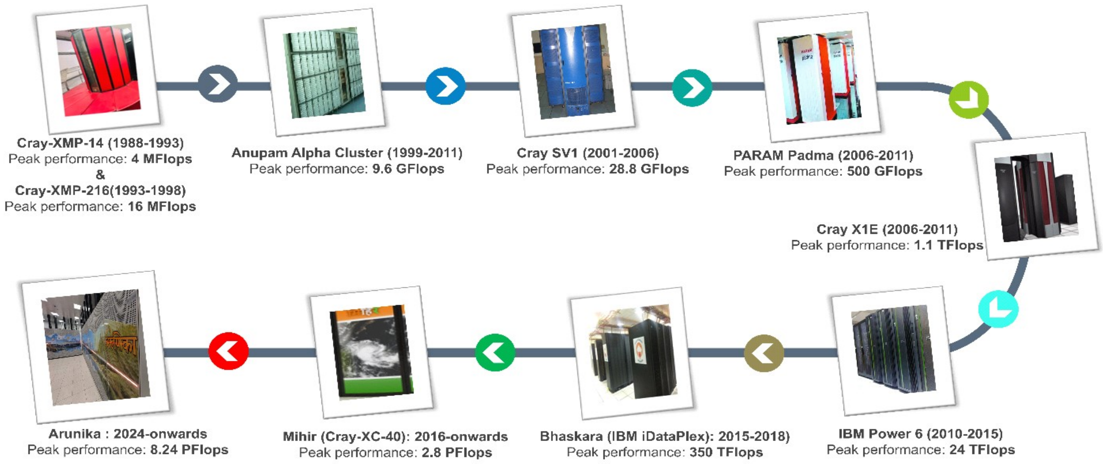


**Figure 1.** History of High-Performance computing at NCMRWF

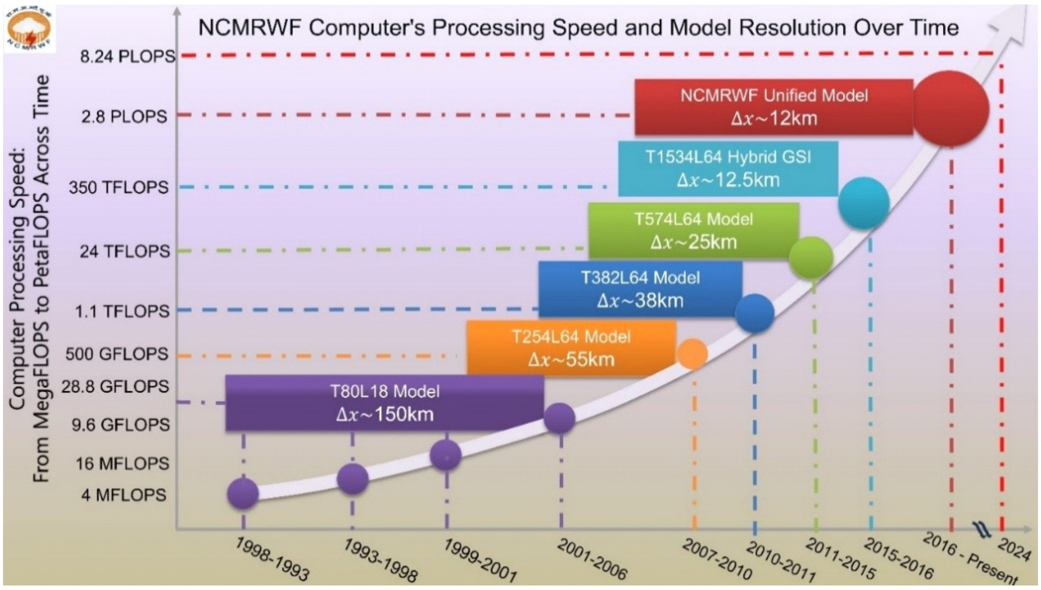


**Figure 2.** NCMRWF computer's processing speed and model resolution over time

# The Digital Agriculture Revolution: Transforming Ancient Traditions with Modern Innovation

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**"Balancing technology with tradition, India's agricultural renaissance promises a sustainable, resilient future, ensuring food security and safeguarding resources, positioning the nation as a global model for agricultural transformation."**

**Abstract**

India's agricultural sector, deeply rooted in tradition, is undergoing a transformative revolution as cutting-edge technologies merge with age-old practices. Employing 42% of the workforce and contributing 18% to GDP (FAO, 2023), the integration of artificial intelligence (AI) and ICT is reshaping the sector. From Assam's tea gardens to Punjab's rice fields, AI-driven solutions enhance productivity, sustainability, and resilience. The Indian Council of Agricultural Research (ICAR) notes AI-enabled practices can boost crop yields by 30% and reduce water usage by 25% (2023), while precision agriculture could save 2.3 trillion liters of water annually (World Economic Forum, 2023). Initiatives like the Digital Agriculture Mission have connected 5.5 million farmers to AI-powered advisory systems, enabling data-driven decisions (Ministry of Agriculture, 2023). This "Fourth Agricultural Revolution" is increasing productivity and attracting youth, with a 55% rise in participation (Tata Institute of Social Sciences, 2023). Innovations like AI and IoT sensors, and robotics are transforming practices while preserving cultural heritage. Balancing technology with tradition, India's agricultural renaissance promises a sustainable, resilient future, ensuring food security and safeguarding resources, positioning the nation as a global model for agricultural transformation.

**Keywords:** Agriculture, Artificial Intellegence, Internet of Things, Information and communications technology

**Introduction**

In the timeless landscapes of India, where agriculture has been the backbone of civilization for over 10,000 years, a remarkable transformation is unfolding. As the morning mist rises over terraced fields and sprawling plantations, it reveals a fascinating fusion of tradition and technology that would have seemed like science fiction just a generation ago. According to the Food and Agriculture Organization (FAO, 2023), India's agricultural sector employs nearly 42% of the country's workforce and contributes approximately 18% to its GDP, making it a crucial arena for technological innovation. Across the nation's diverse agricultural zones, from the rice bowls of Punjab to the spice gardens of Kerala, artificial intelligence and information technology are writing a new chapter in farming's ancient story. The Indian Council of Agricultural Research (ICAR) reports that AI-enabled farming practices have shown potential to increase crop yields by up to 30% while reducing water consumption by 25% (ICAR Agricultural Technology Application Research Institute, 2023). In the tea gardens of Assam, where traditional cultivation methods date back to the 1830s, modern sensors now monitor soil moisture levels with microscopic precision. The World Economic Forum's Agricultural Technology Impact Study (2023) estimates that such precision agriculture techniques could help India save approximately 2.3 trillion liters of water annually. Today's farmers are no longer solely guided by the position of the stars or the timing of monsoons; they have become digital agriculturists, partnering with artificial intelligence, sensors, and smart systems that are transforming farming into a precise science while preserving its artistic soul. The McKinsey Global Institute's report on "Digital Agriculture in India" (2023) reveals that AI and ICT adoption in Indian agriculture has grown at a compound annual growth rate of 22.5% since 2019, making it one of the fastest-growing sectors for technological integration. In remote villages, where farming practices have remained largely unchanged for centuries, smartphones now serve as portable agricultural advisors. The Ministry of Agriculture and Farmers Welfare reports that their Digital Agriculture Mission has connected over 5.5 million farmers to AI-powered advisory services (Digital Agriculture Mission Report, 2023). These systems analyze everything from weather patterns to market prices, helping farmers make informed decisions about planting, harvesting, and selling their crops. This technological renaissance isn't just about increasing productivity; it's about creating a more resilient and sustainable agricultural ecosystem. According to the National Institution for Transforming India (NITI Aayog), AI and ICT interventions in agriculture could help India achieve its sustainable development goals while potentially increasing farmers' income by 50-100% by 2025 (NITI Aayog Agricultural Transformation Report, 2023). As dawn breaks over India's vast agricultural landscape, we witness a unique moment in history where ancient wisdom meets cutting-edge innovation. In fields where farmers once relied solely on traditional knowledge passed down through generations, AI-powered drones now sweep across the sky, mapping crop health with unprecedented precision. The United Nations Development Programme (UNDP) has recognized India's agricultural digital transformation as a model for developing nations, noting how it successfully bridges the gap between traditional farming practices and modern technology (UNDP Agricultural Innovation Report, 2023). This is not just a story of technological advancement; it's a narrative of empowerment, sustainability, and hope. As we delve deeper into this agricultural revolution, we'll explore how specific innovations are reshaping various aspects of farming, from soil preparation to post-harvest management, creating a future where tradition and technology work hand in hand to feed a growing nation and world.

**Development: the evolution of agricultural technology**

The transformation of Indian agriculture represents a remarkable journey from traditional farming to digital innovation, marked by distinct evolutionary phases that have fundamentally reshaped the agricultural landscape. Beginning with the Green Revolution of the 1960s, led by Dr. M.S. Swaminathan, which saw wheat production surge from 12 million tonnes in 1965 to 20 million tonnes by 1970 (Indian Agricultural Research Institute, 2023), the sector has continuously embraced technological advancement. The 1990s introduced precision agriculture with GPS-guided tractors and basic soil sensors, reducing operational overlap by 85% (Journal of Agricultural Sciences, 2023). The early 2000s marked a pivotal shift with the integration of digital technologies, including the establishment of Kisan Call Centers in 2004, which have since handled over 37 million farmer queries (IFPRI, 2023). The current phase, termed the "Fourth Agricultural Revolution" by the World Economic Forum (2023), has ushered in sophisticated AI and IoT applications, with remarkable results: Microsoft's AI-SOWING app has increased yields by 30%, while IoT devices have enabled a 45% reduction in water usage through smart irrigation (Internet of Things Council of India, 2023). This technological evolution has culminated in significant economic impacts, with the Reserve Bank of India (2023) reporting a 40% increase in average farm income for technology-adopting farmers, while simultaneously achieving a 25% reduction in greenhouse gas emissions through precision farming techniques (ICAR Environmental Assessment Report, 2023). The integration of these technologies has not only improved agricultural productivity but has also attracted younger generations to farming, with the Tata Institute of Social Sciences (2023) noting a 55% increase in youth participation in agriculture, marking a significant shift in the sector's demographic profile and future prospects.

**Insights into various instruments**

Walking through India's agricultural landscape today reveals a fascinating array of technological marvels working in harmony with nature. In the misty tea gardens of Assam, ENOVISION works its magic like a master tea taster in digital form. Its E-Nose technology, inspired by the human olfactory system, detects the subtle aromatic compounds that determine tea quality. Nearby, in a modern control room, technicians monitor data streams that tell the story of each tea leaf's journey from garden to cup.

The story of innovation continues in the golden rice fields of Bengal, where AnnadarpanSMART has become the farmers' trusted companion. This system doesn't just see rice grains; it understands them. Using advanced image processing algorithms, it analyzes each grain's shape, size, and quality with a precision that human eyes could never achieve. Farmers who once relied on generations of experience now have scientific validation of their crop quality, opening doors to premium markets and better returns.

In the sprawling grain markets, GrainEX stands as a testament to how technology can enhance traditional quality control methods. Its AI-powered conveyor system processes thousands of grain samples per hour, identifying subtle defects and variations that might affect market value. The system has become so reliable that many traders now consider its assessment as authoritative as the judgment of veteran grain experts.

In the bustling spice markets, CT-VIEU, a digital inspector, ensures that red chilies meet the highest standards. With pixel-perfect accuracy, it examines chili pods, identifying defects and maintaining the integrity of the spice trade. Farmers and traders, empowered by this technology, know that only the best chilies will make their way to consumers, preserving the rich flavors of Indian cuisine.

In the silk-producing regions, Pebrine-O-Scope, a digital microscope, is a game-changer. It detects pebrine spores with unparalleled accuracy, safeguarding silkworms and ensuring the production of high-quality silk. Resham Darshan, another technological marvel, revolutionizes silk sorting by accurately grading silk yarns based on color. The silk industry flourishes, producing exquisite fabrics that adorn people around the world.

T-Netra, a vigilant tea inspector, ensures that finished tea is free from external contaminants. Its AI-powered vision identifies impurities, safeguarding the reputation of Indian tea. RIGE-SENSE, another innovative system, determines the age of rice by analyzing the color variations, using a chemical process that streamlines inventory management and ensures the quality of stored rice.

The revolution extends to livestock farming, where systems like Go-Paryavekshak and MAST-D have transformed animal husbandry. These AI-powered health monitoring systems track subtle changes in cattle behavior and vital signs, predicting potential health issues before they become serious problems. In poultry farms, GEMS has revolutionized operations by automating gender identification of day-old chicks and monitoring bird health parameters in real-time.

The integration of robotics brings another dimension to this technological transformation. TULIP, the automated tea leaf cutting machine, works with a precision that rivals human expertise. In apple orchards, automated harvesting systems gently pick fruit at the perfect moment of ripeness. These robotic systems don't just replace human labor; they enhance it, allowing farmers to focus on more strategic aspects of farm management.

Sama-Dhaan, an autonomous robotic platform, demonstrates the power of AI in precision farming. These robotic marvels promise to transform agriculture, making it more efficient and sustainable.

AquaSURAKSHA, a biosensor, stands guard against water pollution, detecting harmful endocrine-disrupting chemicals in fisheries. This technology is a crucial tool in safeguarding water resources and protecting public health.

**Conclusion**

As we look to the future, the integration of AI and ICT in agriculture promises even more revolutionary changes. The combination of machine learning, IoT sensors, and robotics is creating a new agricultural paradigm where data-driven decisions enhance rather than replace traditional farming wisdom. This technological evolution is not just about increasing productivity; it's about creating a more sustainable and resilient agricultural system that can feed a growing world while preserving our planet's resources.

Experts predict that by 2030, AI-driven agriculture will become the norm rather than the exception. The next wave of innovations will likely include more sophisticated predictive analytics for climate change adaptation, blockchain-based supply chain transparency, and even more advanced robotics for precision farming. However, the true success of this agricultural revolution will lie in its ability to maintain the delicate balance between technological efficiency and the timeless wisdom of traditional farming practices.

In this new era of digital agriculture, we're not just growing crops; we're cultivating a future where technology and tradition work together to create a more sustainable and prosperous agricultural sector. As these innovations continue to evolve, they promise to write new chapters in the ancient story of agriculture, ensuring that this vital profession remains both relevant and rewarding for generations to come. ●●

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# Revisiting Traditional Agriculture through Today's Innovation

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**"Traditional agriculture is a farming method that uses indigenous tools, knowledge, and natural resources. Traditional agriculture is also called "small-scale farming" which refers to agricultural practices followed from generation to generation."**

## Introduction

Agriculture has long been the basis of human civilization. The world has witnessed a long succession of agriculture to arrive at today's agriculture or farming evolving over thousands of years through experimentation, innovation, and adaptation. While modern farming techniques have led to significant increases in productivity, they have also contributed to the loss of traditional practices deeply rooted in the local culture and biodiversity. In India also, agriculture has witnessed several technological advancements and changes. With the introduction of 'Green Revolution' (GR) technologies, the entire country has witnessed a significant intensification of agriculture which has transformed India from food scarce country to a surplus one. However, this achievement has come with adverse effects like soil degradation, environmental pollution, human and animal health hazards, biodiversity losses, rising cost of cultivation, etc. The current agricultural research that has become the dominant form of producing knowledge for agriculture is still largely based on the notion that nature can be fully controlled and manipulated. It is oriented towards increasing the efficiency of production with the use of chemical inputs. This approach caters to the demands of large-scale production for the market but does not allow for a line of research that can address the priorities of sustainable improvement of agriculture of widely varying nature. A key implication of this productivity paradigm has been the diminishing resilience of farmers and rural communities and growing disparities between agricultural production characterized by intensification and standardization and 'diversity farming' practices. In this context, this has become a matter of concern whether the smallholders' highly heterogeneous agri-ecology-based 'diversity farming' practices innately rooted in the sustainability *mantra* can offer a viable alternative against both the market and scientific dominance of the current agri-industrial food paradigm. This has brought into the discourse the significance of revisiting traditional farming or local farming knowledge for use in today's modern agriculture and the importance of continuing research into traditional farming methods to ensure that they are passed down to future generations. An attempt has been made to highlight how traditional agriculture or farming knowledge is linked with the areas of modern methods and innovations for enhancing sustainability and resilience in crop production systems.

**Traditional agriculture**

Traditional agriculture is a farming method that uses indigenous tools, knowledge, and natural resources. Traditional agriculture is also called "small-scale farming" which refers to agricultural practices followed from generation to generation. Furthermore, they rely on old-age techniques and tools, and wisdom inherited from ancestors. It involves cultivating crops and raising livestock and doing allied activities. Traditional agricultural knowledge of local farming communities is a foundational component of modern agricultural practices. Traditional agriculture maintains crop genetic resources for the production process and sustains the livelihoods of the farmers. Traditional agriculture is holistic and embedded in the practice, experience, and experiments of farmers, evolving with changes that occur in environmental conditions. Traditional or indigenous agricultural practices adopted by locals largely depend on traditional knowledge and are common in agricultural systems to preserve ecosystem and biodiversity, and useful in maintaining sustainable food and human health. This tradition-based agriculture is followed in every locality in the world. Worldwide approximately 370 million indigenous peoples occupy nearly 22% of the land area.

Farmers possess a vast pool of indigenous knowledge in livestock and crop management which reduces external input dependency by utilizing various renewable farm resources as agricultural practices. These practices address the rural development and nature conservation; contribute to maintaining ecosystem of particular area which leads to sustainable use of biodiversity conservation.

**Characteristics of traditional agriculture**

Traditional agriculture involves growing multiple crops in one field, collecting rainwater for irrigation, and using organic fertilizers. It uses indigenous tools like axes, hoes, and sticks, organic fertilizers, and is well suited to smallholder farming systems and less expensive than modern farming. This is needless to mention that traditional agriculture is based on indigenous knowledge or local knowledge that is unique to a community, society, or system. As such, traditional agriculture is based on this indigenous knowledge. This knowledge is closely related to survival and subsistence and helpful in making decisions in food security, health, education, and resource management. The result of a continuous process of experimentation, innovation, and adaptation is always dynamic. Traditional agriculture can blend with knowledge based on science and technology and should therefore be considered complementary to scientific and technological efforts to solve problems in social and economic development. It is typical to capture and store systematically because it goes orally from one generation to another which is the main disadvantage. The main characteristics of this knowledge: generated within communities, location and culture-specific decision-making and survival strategies, not systematically documented, concerns critical issues of human and animal life, dynamic and based on innovation, adaptation, and experimentation, oral and rural in nature (Figure 1).

**Some traditional agricultural practices in NE states of India**

India has a rich biodiversity with many diversified agricultural systems which are being practiced since long. There are some common practices like agroforestry, crop rotations, mixed/inter-cropping, polyculture, and water harvesting performed by the people. In different states of the country, there is variation in agriculture and the native people have their own traditional agriculture system like seed processing, seed storing, field preparation, etc. A brief list of some traditional agricultural practices of North Eastern States of India is given in Table 1. These traditional agricultural practices have an impact on modern-day agriculture. To mention a few, we can take the example of irrigation practice in


**Figure 1.** Characteristics of traditional agriculture knowledge

Meghalaya. Various irrigation practices are done by the people of the state.

It follows better utilization of all production factors that ultimately increase the crop yield per unit of land. This practice generally provides suitable moisture for crops or lands. It is started at the beginning of rainfall and is helpful to manage cropping patterns in the soil. The most useful practices are bamboo drip irrigation and bench terrace irrigation. Both practices are predominant throughout the Northeast Region of India. Bamboo drip irrigation is an excellent example of the evolution of indigenous agriculture systems. In Nagaland, Zabo system is followed which is a traditional water management system in Nagaland, India that involves harvesting rainwater from the mountains and using it for agriculture. This system helps to manage water sources and soil fertility sustainably, check soil erosion, preserve soil fertility, and is eco-friendly. The Zabo system was developed in Kikruma village located in a rain shadow area that faced acute water scarcity. Similarly, the Apatani tribe in Arunachal Pradesh is most known for their unique practice of integrated rice-fish cultivation, where they grow rice and fish together in the same paddy fields, showcasing a highly sustainable and eco-friendly agricultural system. The Apatani practice is a highly sophisticated form of wetland rice cultivation without the use of any modern machinery or external inputs like fertilizers and pesticides. They terrace the fertile valley into small plots and create a complex irrigation system using bamboo pipes and canals to channel water from nearby streams. Such systems may be explored for upscaling as per location-specific suitability.

**Integration of traditional agriculture in modern agriculture: Key aspects of the concept**

One of the major features of traditional agriculture is that it allows for the integration of traditional and modern farming methods. While modern techniques have contributed to increased agricultural productivity, they are often resource-intensive and environmentally damaging. On the other hand, traditional methods, though sustainable, may not always meet the demands of large-scale agriculture.

**Table1. Indigenous agricultural practices in North Eastern states of India**

| State | Indigenous agricultural systems |
|---|---|
| Arunachal Pradesh | Panikheti system, Apatani system, Zabo farming, Alder based farming, Bun farming, Bamboo drip irrigation |
| Assam | Shifting cultivation, Double transplanting |
| Manipur | Shifting Cultivation, Bun cultivation, Rice-fish system, Trans-planting of crops |
| Meghalaya | Shifting cultivation, Terrace or Bun cultivation, Bamboo drip irrigation, Bench terrace irrigation, Alder based farming practice, Aquilaria based farming, Bamboo based farming practice, Bamboo—arecanut- betel based farming, Homestead farming, Khasi pine based farming, Tea based farming |
| Mizoram | Shifting Cultivation, Bun system, Rice- fish system, ZABO system |
| Nagaland | Shifting Cultivation, Terrace cultivation, Alder based cultivation |
| Tripura | Fish-cum-vegetable culture, Paddy-cum- fish culture, Fish- cum-duckery culture |
| Sikkim | Shifting cultivation, Dhankheti, Sukhabari, Mandarin-Intercrops |

Source: R. Goel et al., 2020

Integration in other words is the use of traditional agriculture in modern agriculture which refers to incorporating aspects of age-old farming practices, like crop rotation, intercropping, and natural pest control methods, into modern agricultural techniques, leveraging technology and advanced knowledge to create a more sustainable and environment-friendly farming system maintaining high yields; essentially, drawing on the wisdom of traditional practices to enhance modern farming methods. In modern agriculture, elements of traditional agriculture are being reintroduced, particularly practices that promote sustainability, often in response to growing concerns about environmental impact.

In this regard, the key aspects of the concept of reintroducing/ integrating through innovation, and experimentation show promises for modern agriculture, and the need of the farmers are mentioned below:

**Soil health management**

The traditional methods like composting and cover cropping can be utilized to improve soil fertility and structure, which is crucial for long-term crop productivity in modern agriculture.

**Biodiversity enhancement**

Biodiversity denotes the variety and variability of life on earth. Biodiversity and sustainable resource use are crucial for ecosystem stability and human survival. At present, biodiversity is under assault the world over due to rapid and accelerating anthropogenic activities causing a persistent decline in species diversity. Biodiversity is typically a measure of variation at the genetic, species, and ecosystem level while indigenous knowledge is the local knowledge that is exclusive to a given culture. Indigenous knowledge is most important to conserve the natural resources that are present in various geographical ranges throughout the world. Local people are very keen on conserving biodiversity for their survival, which ultimately conserves the whole environment. Traditional agriculture practices often promote diverse crop varieties and integrated farming systems, which can be incorporated into modern agriculture to improve biodiversity and ecosystem resilience.

**Water conservation:**

Traditional agriculture practices like water harvesting and efficient irrigation systems can be adapted to modern agriculture to optimize water usage. In modern agriculture, water conservation is crucial as it helps to preserve limited water resources, mitigate water scarcity, ensure sustainable food production, optimize water usage, and maintain the long-term possibility of agricultural systems by allowing farmers to maximize crop yields while using less water, especially in the face of increasing climate change and growing populations.

**Organic agriculture**

Organic agriculture delivers a broad set of practices to increase productivity in the farms. It is a holistic production management system that promotes and enhances the health of agro-ecosystems followed by the increasing biodiversity functions. Organic agriculture is managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment. It plays various vibrant roles in solving or reducing problems such as environmental degradation, biodiversity protection, rural development, and nature conservation.

**Multiple cropping**

Two or more crops are grown together on land to maintain soil conditions, control diseases and pests, etc. The crops together facilitate the condition of light and shade. This system also permits growing crops in different maturity periods. In traditional, the seeds are sown haphazardly by hand in the field; in mixed cropping, the seeds of all crops are sown simultaneously in the same field. Inter-planting allows cropping systems to reuse their own stored nutrients. In this way, productivity per unit area is higher than the mono-cropping systems

**Local knowledge integration**

Incorporating local farmers' understanding of their specific climate and soil conditions can lead to more tailored and effective modern farming practices. It provides valuable perceptions into a region's specific environmental conditions, allowing for more sustainable and resilient farming practices by leveraging traditional knowledge of crop adaptation, pest management, and resource utilization, which can be particularly beneficial in the face of climate change

**Research into traditional agriculture**

Research into traditional agriculture plays an important role in finding the scientific principles behind these age-old practices. While traditional knowledge is often rooted in practical experience and observation, scientific research can help explain why certain methods work and how they can be adapted or improved in light of current challenges. In addition to enhancing modern agriculture, research into traditional agriculture can help to address some of the major challenges agriculture is facing today. As climate change leads to more unpredictable weather patterns, traditional methods of water conservation, drought resistance, and pest management may offer solutions that modern techniques do not. By combining traditional practices with modern technology, researchers can develop new strategies for making agriculture more resilient to environmental changes. Moreover, authenticating and researching traditional agriculture can lead to the revival of crops and techniques that have fallen out of favour due to the dominance of modern agriculture. Many traditional crops are highly nutritious, drought-resistant, or pest-tolerant, making them valuable resources for food security in a changing climate scenario. This also includes the basis for the promotion of natural farming or regenerative agriculture.

**Benefits of integrating traditional practices in modern agriculture**:

There are some direct benefits of integrating traditional practices in modern agriculture viz., sustainability, resilience, economic viability, and community engagement. The integration of traditional practices with modern ones leads to reduced environmental impact by minimizing chemical use, promoting biodiversity, and conserving water resources. It improves resilience through improved ability to adapt to changing climate conditions and pest outbreaks. Moreover, the integration has the potential to make it cost-effective farming practices through reduced input costs indicating the economic viability of the system. Further, preserving and utilizing local knowledge of various traditional agriculture practices can empower farmers and strengthen rural communities for better community engagement:

To have sustainable development in respect of modern agriculture, various organizations involved in the research into traditional agriculture knowledge should come forward by making various government and non-government policies (Figure 2)

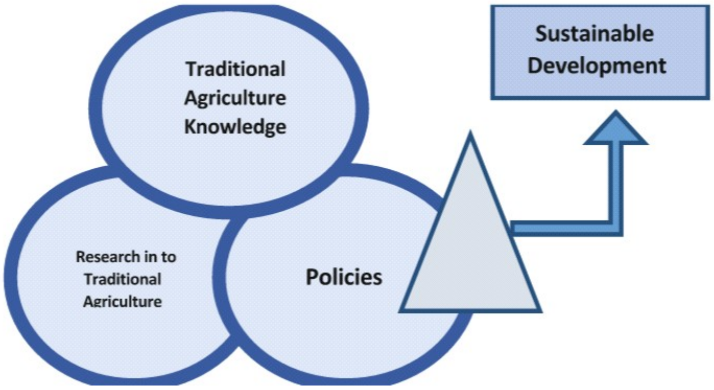


**Figure 2.** Relationship between traditional agriculture, research into traditional agriculture and policies for sustainable development

**Conclusion**

Traditional agriculture knowledge can be very well related to modern agriculture for suitable refinement of modern agriculture to take care of its ill effects and to render today's agriculture more sustainable, eco-friendly, cost-effective, and remunerative. Proper documentation of traditional agriculture knowledge/ practices is essential for preserving the agricultural heritage which has sustained communities for centuries. These practices or methods are passed down through generations. They offer valuable insights into sustainable farming, biodiversity conservation, and climate resilience. By engaging in research on traditional farming methods, we can better understand the scientific principles behind these practices and find ways to integrate them with modern agriculture and combine the best of both worlds. Hence, by revisiting and working with communities, researchers, and policymakers, it is very much possible to create a more sustainable and resilient agricultural system that honors the past while preparing for the future.

The maintenance of traditional agricultural practices is not just about saving history - it is about building a sustainable future for generations to come.

# Role of Agricultural Extension System in Assam's Agricultural Development


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**"Within the agricultural sector, agricultural extension may be interpreted narrowly or broadly. In a strict interpretation, the only purpose of agricultural extension is to disseminate information to raise the production and profitability of the farmers (agricultural production performance)"**

Agricultural extension is the application of scientific research and latest knowledge to agricultural practices through education of farmer. It operates within a broader knowledge system that includes research and agricultural education. Food and Agriculture Organization (FAO) and the World Bank refer to this larger system as AKIS/RD (Agricultural Knowledge and Information Systems for Rural Development). Agricultural information systems for rural development link people and institutions to promote learning and to generate, share and use agriculture- related technology, knowledge, and information. The system integrates farmers, agricultural educators, researchers and extensionists, enabling them to harness knowledge and information from various sources to improve farming and livelihoods. The primary responsibility of extension personnel is that of education of the farmers. Technology transfer is an educational process orchestrated by extension personnel through both formal and informal means. In principle, agricultural extension receives relevant information from the agricultural education system and feeds back field observations to this system. Extension is also professionally linked to the agricultural vocational and higher education systems in the sense that these systems also produce the agents (extension functionaries) who work in extension. The relationship between agricultural extension and agricultural research is even closer, because the knowledge that agricultural extension transfers is usually generated by agricultural research through applied and adaptive agricultural research development. Within the agricultural sector, however, agricultural extension may be interpreted narrowly or broadly. In a strict interpretation, the only purpose of agricultural extension is to disseminate information to raise the production and profitability of the farmers (agricultural production performance). In a broader interpretation, the purpose of agricultural extension is to advance not alone production knowledge but the whole range of agricultural development tasks, such as credit, supplies, marketing and markets (agricultural process development).

Agricultural development refers to the process of improving agricultural productivity and efficiency by implementing new technologies, practices, and policies, aiming to increase food production, enhance farmer incomes, and contribute to overall economic growth, often involving initiatives like research and development, infrastructure improvements, market access, and farmer education. Essentially, Agricultural development is about actively developing the agricultural sector to better meet the needs of a growing population. Key aspects of agricultural development include:

- **Increased crop yields:** Utilizing improved crop varieties, better irrigation systems, and efficient use of fertilizers to produce more food per unit of land.
- **Livestock improvement:** Enhancing animal breeds, nutrition, and disease management to maximize livestock productivity.
- **Technology adoption:** Integrating new farming techniques like precision agriculture, biotechnology, and sustainable practices.
- **Market access:** Facilitating better market linkages for farmers to sell their produce at fair prices.
- **Farmer education and training:** Providing knowledge and skills to farmers regarding new technologies and best practices.
- **Infrastructure development:** Investing in irrigation systems, rural roads, storage facilities, and cold chains to support agricultural activities.

**The key players of agricultural extension**

The field of 'extension' now encompasses a wider range of communication and learning activities organized for rural people by educators/ extension functionaries from diverse disciplines, including agriculture, agricultural marketing, health, business studies etc. Extension service providers play key role in disseminating the technologies developed in labs and improve the income of farmers and livelihoods. Since independence, extension services in India were being provided mainly by the public sector. Even in the present times the public sector is the major extension service providers through a two-tier system. At the central level, Indian Council of Agriculture Research (ICAR) is the nodal establishment for agriculture research and extension in India while at the state level, the State Agricultural Universities (SAU) via the Krishi Vigyan Kendra (KVKs), the departments of Agriculture, Veterinary & Animal Husbandry and Fisheries and Agriculture Technology Management Agency (ATMA) at the district level facilitate agriculture extension. However, the public extension is highly skewed towards crop husbandry ignoring the allied sectors. Besides there are several private players, civil-society organizations including farmer-based organizations and NGOs in the existing public extension service system, that play a major role in providing extension services. Amongst the non-public players, the input dealers are engaged with marketing of seeds, pesticides, fertilizers and farm machinery and a considerable section of farmers get their primary agricultural information from the input dealers in their vicinity. However, a major issue with these input dealers is that they usually engage themselves in promotion of different products instead of extending technical advice to the farmers. To address this issue, the government of India, recognizing the importance of this category of extension support to farmers, has started offering a course by MANAGE and other recognized institutes on input use efficiently. This is expected to help the input dealers to brush up on the latest technical now-hows in various sub-sectors of agriculture and to certify them as qualified Input Dealers.

Private sector agribusiness and input manufacturing companies also undertake direct extension activities. These extension activities are however in support of their products and seek to help the farmers to realize higher production (and thus returns) through necessary pre-sowing preparation, optimum seed rate, correct agronomic practices, application of nutrients and harvesting techniques. Several NGOs are actively involved in the development of rural areas and naturally oriented themselves towards land-based livelihoods. Hence, they accommodate a fundamental component of extension in their routine interventions. Being connected to the grassroot level, NGOs can complement the Government agencies in extension services. They can easily indulge in technology transfer by conducting training programmes by themselves or in collaboration with the experts from universities and KVKs, etc. Additionally, NGOs can readily associate themselves with the common modes of extension including demonstrations, exhibitions, awareness campaigns, mass media and publications. NGOs can also ensure community participation through Self-Help Groups (SHGs), Farmer Producer Organizations (FPOs), etc. They can also support the private sector by communicating the farmers' needs and may contribute to the research and development plans. They can also facilitate marketing and establishing linkages between producers and market service providers.

Organized user groups like Farmer Producer Groups, Commodity Interest Groups, Farmers Clubs, Farmer's Cooperatives etc. roles in extension in niche regions and areas. Generally, farmers groups play an important role in reducing the cost of cultivation, increased profitability, information access and reduce the transaction cost there by facilitating farmers to achieve higher price realization. The consumers also get benefitted as they get good quality products at lesser costs. To address the issues related to the small and marginal landholdings, Government of India announced the formation of 10,000 Farmer Producer Organizations (FPOs) by 2024-25 in India. FPOs are considered capable of creating both forward and backward linkages in agricultural produce supply chains. FPOs are considered one of the best recognized aggregation models in India. Government of India and many states including Assam are promoting Farmers Producers' Organizations (FPOs) as they also play important role in strengthening the extension activities.

ICT is an imperative tool to link value chains in agriculture. Due to the increasing number of ICTs tools such as mobile phones, internet, TV etc. has shown tremendous potential to disseminate information to the farming fraternity. However, a scalable intervention leveraging ICT is yet to be realized. Kissan Call Centres have also proved to be an important and reliable arm disseminating information and addressing farmer's queries. Kisan Call Center agents are known as Farm Tele Advisors (FTAs), who are graduates or above in agriculture or allied areas and possess excellent communication skills in their respective local languages. Queries which cannot be answered by FTAs are transferred to higher-level experts in call conferencing mode. These experts are subject matter specialists of State Agricultural Departments, ICAR & State Agricultural Universities.

**Challenges in Assam's agricultural development**

Agricultural development problems and economic development problems runs parallelly in Assam. Agricultural development in Assam is impeded by a range of challenges, including socio-cultural traditions, infrastructural gaps, and limited access to modern farming methods and technologies. Traditional agricultural practices, such as releasing livestock for free grazing outside the rice cultivation period, unintentionally lead to crop damage and reduced yields. Isolated rice cultivation by individual farmers within fenced areas increases vulnerability to wildlife attacks and discourages collective farming initiatives. Social resistance to crop diversification often results in non-cooperation and isolation for farmers attempting innovation. A lack of knowledge about scientific agricultural practices further exacerbates the situation. Inadequate availability and high costs of quality seeds, fertilizers, and crop protection methods combined with insufficient knowledge on proper utilization methods of these valuable inputs prevents farmers from improving their agricultural operations and in turn the productivity of the crops being cultivated. The lack of essential post-harvest infrastructure, including dryers, cold storage, and food processing facilities, limits the preservation and value addition of the produce. Furthermore, restricted market access forces dependence on intermediaries, which in turn reduces the farmers' overall income. Geographical constraints, inadequate transportation, lack of irrigation facilities and renewable energy systems, and unreliable electricity in remote areas further impede agricultural productivity. Additionally, Assam's recurring floods exacerbate these challenges, leading to extensive crop losses and soil degradation.

The major challenges that impede agricultural development in Assam includes:

**(a) Small land holdings:** Small and marginal farmers dominate the landholding pattern in Assam. A large proportion of farmers in Assam have small landholdings, limiting their ability to adopt advanced farming methods. More than 60 per cent of the farmers hold below 1 hectare of land, and more 80 per cent of them hold below 2 hectares. The average size of operational holding is 1.10 hectares only and more than 85% of farmer family are either small or marginal with an average holding of only 0.36 hectares (Economic Survey, Assam, 2023-24). With the rapid increase of population on one hand and lack of economic diversification on the other, the agricultural plots in Assam have undergone subdivision in every generation and hence, the agricultural land now has been turned into uneconomical and fragmented small plots. Such fragmented plots are usually unsuitable for application of modern machinery. These landholdings are often considered too small to provide a sustainable income for a farmer due to factors like land fragmentation, poor soil quality, unreliable water access, and limited access to modern farming techniques, which are prevalent issues in the state's agricultural sector, significantly impacting the livelihoods of many farmers in Assam.

**(b) Inadequate irrigation facilities:** A significant challenge faced by the agriculture sector in Assam is the severe lack of proper irrigation facilities, despite the state receiving substantial rainfall, due to its uneven distribution throughout the year, leading to crop failures during dry spells and significantly impacting the livelihoods of farmers and overall agricultural productivity. The State of Assam is endowed with abundant water resources. The two major river systems - the Brahmaputra and the Barak along with numerous tributaries constitute the rich surface water resources of the State. The ground water availability in the State is falling under safe category. Despite the rich resources of water in the State, irrigation has become highly essential because of adverse and unpredictable weather condition including flood, erosion and drought like situation etc. The state is characterized by a low proportion of irrigated area as gross irrigated area (to the gross cropped area) under all crops is about 5.50% in Assam which is below than the national average of 22%. This leaves a large portion of agricultural land vulnerable to drought conditions. Lack of irrigation during critical stages often results in significant crop losses, impacting farmers' income and food security. Farmers are often restricted to growing only monsoon-dependent crops due to unreliable water availability Efforts for adopting Comprehensive irrigation projects, promotion of water conservation methods, and empowerment of farmers through modern technologies are essential to mitigate the impacts of drought and enhance agricultural productivity in Assam.

**(c) Inadequate mechanization of agricultural operations:** Though there has been large scale mechanization of agriculture in some developed states in India, most of the agricultural activities in Assam is performed by human hand using simple and conventional tools and implements like wooden plough, sickle, etc. Little or no use of machines is made in ploughing sowing, irrigating, thinning and pruning, weeding harvesting threshing and transporting the crops. This is specially the case with small and marginal farmers which results in massive wastage of human labour and low yields per capita of labour force.

**(d) Lack of adequate storage and processing facility:** A substantial quantity of products harvested in Assam perishes due to lack of storage and processing facilities. Simple, efficient, and cost effective technologies for perishables, such as roots, tubers, fruits and vegetables, are not as highly developed in the country compared to the storage technologies for cereal grains and legumes. As a result, post-harvest food storage losses are very high. Storage facilities in the rural areas are either totally lacking or grossly inadequate. Traditional storage facilities have certain deficiencies, including a low elevated base giving easy access to rodents, wooden floors that termite could attack, weak supporting structures that are not moisture-proof and inadequate loading and unloading facilities. Thus, heavy post harvest losses happen due to insufficient storage facilities, especially in times of bumper harvests. Under such circumstances, the farmers are bound to sell their produce immediately after the harvest at the prevailing market prices which are bound to be low and deprive the farmers of their legitimate income.

**(e) Traditional farming practices:** Traditional agricultural practices in Assam, like relying heavily on rain-fed cultivation, frequent crop rotation with low-yielding varieties, and free-grazing livestock, contribute significantly to low crop productivity, often resulting in poor yields and hindering the overall agricultural output of the state. Rice is the staple crop of Assam and forms the backbone of the state's farming practices that are often intertwined with socio-cultural traditions. These socio-cultural traditions have been passed down through generations. While these traditions play an important role in the social fabric of Assam's rural communities, they also pose significant challenges to agricultural advancement and productivity. One notable socio-cultural practice involving livestock management is to tie their livestock only during the rice cultivation season. For the remainder of the year, these animals are allowed to graze freely in open areas. While this practice is cost-effective and culturally significant, it often results in unintentional crop destruction when the livestock stray into cultivated fields. This not only affects the yields of individual farmers but also discourages the adoption of more intensive and planned agricultural methods. Another significant challenge is the practice of isolated rice cultivation. In many parts of Assam, individual farmers cultivate rice within fenced areas, which makes their crops highly vulnerable to wildlife and bird attacks. These localized losses can be devastating, particularly for small-scale farmers who lack the resources to recover from such setbacks. The absence of collective farming efforts exacerbates this problem, as farmers miss opportunities to pool resources, share risks, and implement coordinated strategies to protect their crops. Social resistance to crop diversification often compel the farmers to remain dependent on traditional, low-yield crops and hence are unable to experiment with potentially more profitable or sustainable farming practices. This further limit agricultural progress in Assam.

**(f) Marketing problems**: Agricultural markets in Assam are under-developed. Farmers sell their produce to the nearest buyers, mostly immediately after harvesting when the price is at the lowest, instead of trying to find the best market for their products. Geographical isolation, weak transportation and communication systems, poor marketing facilities, poor or non-existent market intelligence (e.g., information on price and place to sell) are some of the principal marketing-related problems.

**(g) Natural calamities:** Floods and dry spells are the principal natural disasters faced by farmers in Assam every year. The principal source of floods is the Brahmaputra River and its tributaries. Although it has been decades since the proposal to dredge the Brahmaputra came out, its progress and impacts are unknown. The loss of crop, livestock, house, cultivable land, and human lives are common during the yearly flood, which also takes a toll on human spirit.

**(g) Non-economic factors:** Lack of education, ignorance about the changing economic conditions, out-dated thinking, prejudiced cultural values, and lack of scrupulous legislative and administrative machinery are some of the principal non-economic factors that hinder agricultural development in Assam. All these factors adversely affect agricultural as well as economic development of the state.

**(h) Insufficient service delivery system:** Notwithstanding the existence of unified agricultural extension system, there is still poor coordination between researchers, extension agents and farmers in Assam. This situation is worsened by the low extension-farmer ratio and consequently farmers are unable to take up new innovations aimed at boosting their productivity.

## Role of extension functionaries in Assam's agricultural development

Agriculture sector of Assam is confronting issues such as a huge yield gap, a multitude of smallholders, imbalances with respect to input use and declining natural-resource productivity. Extension systems within the state that have an important role to play in addressing these concerns, are constrained by financial, infrastructural, and human resource limitations. The inclusiveness of extension services remains a major concern. Considering the prevalence of smallholders in the agriculture sector and the complexity of the problems confronting them, suitable extension strategies need to be formulated by extension experts. Extension functionaries play a crucial role in the agricultural sector in Assam, as they are responsible for transfer of latest agricultural technologies to the farmers. They work for empowering farmers with knowledge, skills, and resources, thereby contributing significantly to the sustainable development of the agricultural sector in Assam. The following core areas have been considered and stressed upon by extension workers with a vision of augmenting development in the agriculture sector of Assam.

### Capacity enhancement of farmers

Enhancement of capacity especially of marginal and small farmers is crucial for Agricultural development in Assam. Farmers' capacity building is a continuous process that allows access to information, facilitation, and empowerment, and fosters technical advancement. The objective is to empower farmers to effectively address their daily challenges and seize opportunities that come their way. Capacity enhancement of farmers places community engagement at the core of interventions, promoting the self-reliance of farmers. Capacity building brings several benefits to farmers, the agricultural development of the country, and society as a whole. These include improved food safety, diversified income sources, community development, rural-urban migration mitigation, resilience to climate change, market access and trade opportunities, poverty alleviation, women's empowerment, preservation of indigenous knowledge, incentives for youth etc. The extension functionaries, more particularly of the KVKs of Assam, are conducting training programmes regularly to enhance the skills of farmers, educating them about improved farming techniques, pest control, soil management, and other aspects of agriculture and allied sectors. Similar capacity building programmes are also conducted from time to time by the line departments and other private extension agencies of Assam for upliftment of the farmers.

### Selection of site- specific technologies

Technology adoption by smallholder farmers in Assam has remained persistently low over recent decades, even where such technologies are ostensibly profitable for farmers to use. The prime reasons for such low adoption rates include lack of information and difficulties in learning, availability of technologies that are ill-suited to local conditions, absence of crop insurance facilities, liquidity constraints, high transaction costs due to poor infrastructure, and procrastination and time-inconsistent preferences. However, during the recent times different extension agencies including the KVKs have been instrumental in transferring location-specific agricultural technologies to the farming community of the state. Under the milieu, technologies which are feasible, sustainable, and profitable to a particular location are now selected well ahead by the extension functionaries and demonstrated on a large scale for popularization among farmers/ entrepreneurs. They facilitate the adoption of new technologies and innovations such as advanced irrigation methods, advanced management practices, newly released varieties of crop and livestock, organic farming practices, and the use of efficient farm machinery especially in the context to modern agriculture. Embracing innovative technologies can significantly enhance agricultural productivity, reduce costs, and improve overall sustainability. A boost in the agricultural productivity will aid in fostering agri-business which in turn will contribute towards the overall agricultural development of the state. Improving the agricultural productivity is important for diverse reasons. Apart from providing more food, increasing the productivity of agricultural farms affects the region's prospects for growth and competitiveness on the agricultural market, income distribution and savings, and labour migration. Besides, an increase in agricultural productivity implies a more efficient distribution of scarce resources. Increases in crop production are key to ending hunger, as well as economic and social development.

**Timely supply of quality seeds and planting materials**

As climate change intensifies farmers face escalating challenges in managing pests, diseases, and calamities like flood and drought. Access to quality planting materials and the use of organic methods becomes critical in mitigating these threats and building agricultural resilience. Planting materials that exhibit resistance or tolerance to environmental stresses and pests can help farmers to endure the impact of these challenges and safeguard their livelihoods. By investing in superior planting materials and using organic methods, farmers can boost their productivity, improve food security, and elevate their economic standing. It is established that use of improved quality seed alone can increase yield up to 18%. Thus, timely availability of quality seeds suitable for different agro -climatic conditions in adequate quantities and at affordable price is vital for augmenting production and productivity. Extension functionaries facilitate this process and give emphasis on seed production of various field crops like paddy, rapeseed and pulses so that the demand for quality seeds can be met along with income enhancement of the farmer.

**Mechanization of agriculture**

In recent times where time is considered as money, shifting of agriculture toward mechanisation becomes utmost importance as it will reduce cost and drudgery. Mechanization of agricultural operations implies the use of diverse power sources and improved farm implements and equipments, with a view to reduce the drudgery of the farmers and draught animals, enhance the cropping intensity, precision in metering and placement of inputs and timelines of efficiency of utilization of various crop inputs (seed, chemical, fertilizer, irrigation, water etc.) and minimize the losses at different stages of crop production. The ultimate goal of farm mechanization is to enhance the overall productivity and production with the lowest cost of production. It also helps in the conservation of the produce and byproducts from qualitative and quantitative damages, enables value addition and establishment of agro processing enterprises for additional income and employment generation from farm produce. Extension personnel in Assam have been influential in this pretext and a considerable fraction of the farming community has taken initiatives to mechanize their agricultural operations. Farmers now use different types of farm machineries and implements which are made available to them under various government schemes and missions like SMAM, Mukhya Mantri Krishi Sa Sajuli Yojana (MMKSSY), Assam Agribusiness and Rural Transformation Project (APART) etc.

**Crop diversification and intensification**

Assam has high prospect for agricultural intensification and diversification, mainly towards high value crops. In case of rice, mono cropping has allowed the field to remain fallow for a considerable period, wherein more than one crop can be cultivated in a year. As the climate is favourable, farmers can opt for Rabi crops such as vegetable crops such as chili, capsicum, cabbage, cauliflower, knolkhol, potato, fodder crops (oat) etc. Alternatively, inclusion of summer leguminous crops such as green gram, black gram etc. can improve and sustain the fertility and productivity status of soil. Depending on the land situation, multiple cropping options such as inter-cropping, relay cropping, cultivation of crops through raised & sunken bed techniques etc. can play an important role in augmenting agricultural production in Assam. Agricultural crop diversification is crucial for sustainable agriculture as it can enhance biodiversity, reduce the risk of crop failure, improve resilience to pests and diseases, and promote overall farm productivity. Crop diversification enables farmers to gain access to national and international markets with new products. Diversifying from the monoculture of traditional staples can have important nutritional benefits for farmers and can support the state in becoming more self-reliant in terms of food production. Thus, extension workers have been emphasized on intensification and diversification of crops thereby promoting the cultivation of high-value crops and introducing farmers with new crop varieties. Introduction of high value exotic species of crops are essential at times for income enhancement of the farmers, but one should also consider factors viz. availability of natural enemies to control pest/disease outbreak associated with it, competitive interactions, ease of propagation etc. Crop diversification provides better conditions for food security and enables farmers to grow surplus products for sale at market and thus help to obtain increased income to meet other needs related to household well-being.

**Market information and linkages**

The role of extension functionaries in facilitating marketing is now being emphasized in a big way, be it through FPO/FPCs (Farmers' Producer Organizations/Farmer Producer Company), start-ups, agri-business ventures, Agripreneurship, etc. They assist farmers in accessing markets by providing information about market demand, prices, and connecting them with potential buyers, both local and beyond Assam. They provide farmers with information on market prices and arrivals of different commodities. Extension functionaries have helped in the promotion and formation of Farmer Producer Organisations (FPO) in Assam which plays an intrinsic role in various aspects of farming. Under various schemes of the government, extension functionaries educate the farmers about value addition techniques such as processing, packaging, and grading. By adding value to their products, farmers can access higher-value markets, including local supermarkets, restaurants, and export markets. Extension functionaries play a role in the export of agricultural commodities in Assam by providing market information and training farmers on quality, price, and consumer preferences.

**Conclusion**

Assam is blessed with diversified agro-ecological system and in order to make agriculture as lucrative as other businesses it is necessary to harness this diversification. The development of the agriculture sector in the state is impeded by factors such as regular floods, drought, and ever-increasing population pressure on land leading to fragmented land holdings. Small-holder farming is the key to livelihoods of many rural households in the state. Amidst continued problems, there lies a silver lining which depend on identification and commercialization of agricultural and allied sectors with a blended approach, i.e. incorporation of the efficiency of modern technology and the sustainability of traditional farming methods. Productivity of various commercially potential crops, livestock and fishes can be increased through use of better technology, management, and provision of quality planting materials/ germplasm for the farmers so that the produce can be sold in distant markets in addition to self-consumption and sale in the local markets. Thus, commercialization of the small holders of the state is expected to increase the export potential of agricultural products of Assam. Emphasis has also been given on pre- and post-harvest treatment, proper harvesting techniques, setting-up of collection centres with grading facilities, transport facilities and marketing facilities. For realising these goals of the state machinery, extension functionaries have been playing a pivotal role and have made a commendable contribution to the economy of the state. ●●

# Harnessing Frontier Technologies for Climate-Resilient Animal Husbandry: Enhancing Productivity and Animal Health

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**"Climate change is increasingly impacting animal husbandry, necessitating the adoption of innovative technologies for informed decision-making."**

**Introduction**

Animal husbandry is vulnerable to climate variability and extremes. Extreme weather events, such as heat waves, droughts, and floods, can lead to significant economic losses, animal mortality, and reduced productivity. To mitigate these risks, farmers and policymakers need access to accurate and timely weather and climate information. Frontier technologies are revolutionizing how this information is collected, analyzed, and utilized in decision-making. Climate change is increasingly impacting animal husbandry, necessitating the adoption of innovative technologies for informed decision-making. This write-up explores frontier technologies that leverage weather and climate data to enhance animal health, productivity, and resilience. Now, let us see different frontier technologies which can enhance the production, good health in animal husbandry.

**Frontier technologies in animal husbandry**

- **High-resolution weather forecasting:** Advanced numerical weather prediction models, coupled with dense observational networks, provide hyper local forecasts with unprecedented accuracy. This enables farmers to anticipate extreme weather events and take proactive measures to protect their livestock especially for the farmers in the extensive and semi intensive farming.
- **Remote sensing and satellite imagery:** Satellites equipped with advanced sensors monitor vegetation health, soil moisture, and other key indicators of ecosystem health. This information is crucial for assessing feed availability, predicting drought risks, and optimizing grazing management.
- **Artificial intelligence and machine learning:** AI and ML algorithms analyze vast datasets of weather, climate, and animal health data to identify patterns, predict outcomes, and optimize

decision-making. For example, these technologies can be used to forecast disease outbreaks, optimize feed rations, and predict milk yield.

- **Internet of Things (IoT) and sensor networks:** IoT devices and sensor networks collect real-time data on environmental conditions, animal behavior, and physiological parameters. This data can be used to monitor animal welfare, detect early signs of stress, and optimize resource allocation.
- **Blockchain technology:** Blockchain can enhance the traceability and authenticity of weather and climate data, ensuring its integrity and reliability. It can also facilitate secure and transparent transactions related to climate risk management and insurance products.
- **Precision livestock farming (PLF)**: It involves using sensors, data analysis, and automation to monitor and manage individual animals or groups more effectively.

Modern livestock farming leverages advanced technologies to enhance resilience and productivity. High-resolution weather forecasting provides accurate predictions of extreme events, allowing farmers to proactively protect their animals. Remote sensing and satellite imagery monitor vegetation health and soil moisture, crucial for assessing feed availability and mitigating drought risks. Artificial intelligence and machine learning analyze vast datasets to predict disease outbreaks, optimize feed rations, and forecast milk yield. The Internet of Things collects real-time data on environmental conditions and animal behavior, enabling improved animal welfare and resource management. Finally, block chain technology ensures the integrity and reliability of weather and climate data, facilitating secure and transparent transactions related to climate risk management. Now, we will describe the Precision Livestock Farming (PLF) in detail as it addresses several challenges and opportunities in modern livestock farming, contributing to improved efficiency, sustainability, animal welfare, and profitability.

**Precision livestock farming (PLF)**

It is a transformative approach to animal husbandry that leverages advanced technologies to monitor and manage livestock with unprecedented accuracy and efficiency. By collecting and analyzing vast amounts of data, PLF empowers farmers to make informed decisions that optimize animal health, productivity, and welfare while minimizing environmental impact. It is part of the broader concept of precision agriculture, where specific interventions are tailored to individual animals or groups within a herd, rather than treating all animals the same way. By automating tasks and optimizing resource use, PLF ensures sustainable, efficient, and ethical livestock farming while improving productivity and profitability.

**Key Components of PLF**

Precision Livestock Farming (PLF) encompasses several key components (Fig. 1). The integration of these elements enables a level of precision in animal husbandry previously unattainable, significantly enhancing accuracy and efficiency. The following are some of the key components of PLF:

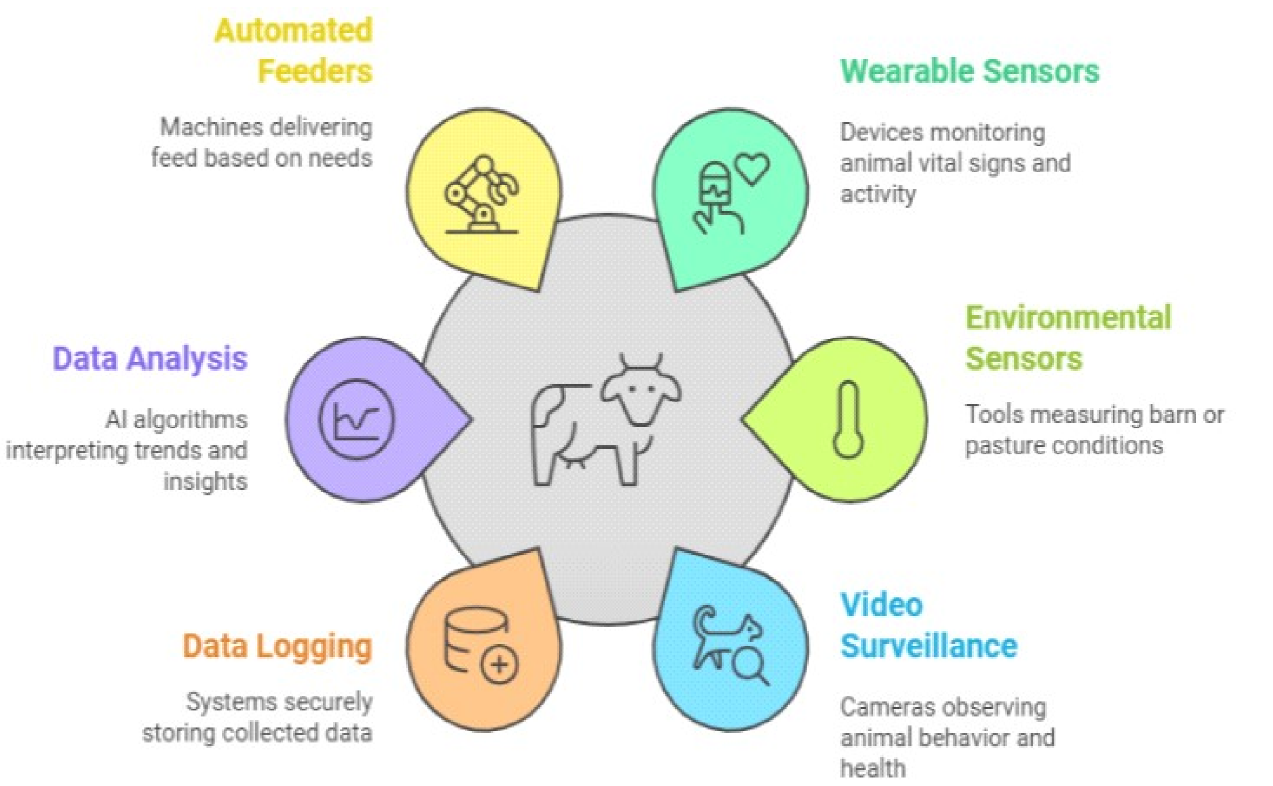
1. **Sensors and monitoring technologies**
   - **Wearable Sensors:** These devices, such as collars, ear tags, and leg bands, monitor individual animals' vital signs (e.g., temperature, heart rate, respiration), activity levels, and even rumination patterns.
   - **Environmental Sensors:** These monitor environmental conditions like temperature, humidity, air quality, and light intensity within the barn or pasture.
   - **Video Surveillance:** Cameras can monitor animal behavior, detect anomalies, and assess overall herd health.
2. **Data acquisition and management:**

- **Data logging and storage:** Collected data is stored securely and efficiently in databases.
- **Data analysis and interpretation:** Sophisticated algorithms and artificial intelligence (AI) are employed to analyze data, identify trends, and generate insights

3. **Automated systems:**

- **Automated feeders:** Precisely deliver feed based on individual animal needs and optimize feed efficiency.
- **Automated milking systems:** Enhance milk production and quality while reducing labor costs.

**Automated environmental controls:** Maintain optimal environmental conditions for animal comfort and productivity.




**Fiigure 1.** Components of precision livestock

**Benefits of precision livestock farming**

- **Improved animal health and welfare**
    - Early detection of diseases through continuous monitoring.
    - Reduced stress and improved comfort through optimized environmental conditions.

- Tailored nutrition and management strategies for individual animals.

- **Enhanced productivity**
    - Increased milk production, faster growth rates, and improved feed conversion.
    - Optimized breeding programs for improved genetic potential.
- **Reduced costs**
    - Efficient resource utilization, including feed, water, and energy.
    - Minimized labor requirements through automation.
- **Environmental sustainability**
    - Reduced greenhouse gas emissions through optimized feed utilization and manure management.
    - Minimized environmental impact through precise resource allocation.

**Applications of PLF in animal husbandry**

Applications of weather and climate data in animal husbandry are pivotal in enhancing productivity, ensuring animal welfare, and building resilience against climate challenges.

- Feed Management involves leveraging weather and climate data to optimize critical aspects such as feed allocation and crop management. For example, accurate forecasts can inform the timing of planting and harvesting feed crops, reducing wastage and ensuring consistent supply. Additionally, selecting drought-resistant crop varieties based on climate projections helps mitigate the impact of adverse weather conditions on feed availability.
- Disease Control benefits significantly from real-time environmental monitoring. Early detection of changes in temperature, humidity, and other conditions can help predict potential disease outbreaks, enabling proactive measures to protect animal health. This approach minimizes losses and ensures a healthier livestock population.
- Animal Welfare is enhanced through the integration of IoT sensors and other monitoring technologies. These tools provide continuous tracking of animal behavior and physiological parameters, such as temperature, activity levels, and stress indicators. By identifying and addressing issues promptly, farmers can maintain optimal welfare conditions and improve overall productivity.
- Risk Management is another critical area where climate information plays a role. By using detailed climate data, insurers and financial institutions can design climate-smart insurance products and other instruments tailored to protect farmers against weather-related risks. This financial safety net allows farmers to recover more quickly from adverse events, ensuring the sustainability of their operations.

**Challenges and considerations**

Precision Livestock Farming (PLF) technologies face several key challenges (Fig. 2) that must be addressed for effective implementation. A primary concern is the high initial investment required, as these systems often demand substantial financial resources for installation and setup. Data security and privacy also pose significant issues, as ensuring the secure storage and ethical use of sensitive animal data is paramount. Furthermore, the operation and maintenance of PLF systems require skilled personnel, highlighting the need for technical expertise in the workforce. Lastly, seamless integration of PLF technologies with existing farm management practices is essential to ensure their practicality and efficiency in real-world agricultural operations.


**Figure 2.** Challenges in precision livestock farming

**Conclusion**

Frontier technologies offer unprecedented opportunities to enhance animal husbandry in a changing climate. By leveraging these technologies, farmers and policymakers can make more informed decisions, improve animal health and productivity, and build resilience to climate variability and extremes. Continued research and development, coupled with effective capacity building and policy support, will be essential to realize the full potential of these technologies. Lastly, Policy and Decision-Making are driven by accurate and timely weather and climate data. Policymakers can use this information to develop strategies and regulations that support climate-resilient animal husbandry. These measures ensure long-term sustainability and help farmers adapt to the evolving challenges posed by climate change.

# Technology Commercialization Drive of Assam Agricultural University

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**Assam Agricultural University has developed a number of technologies which are commercialized from time to time. All these technologies are sold to some commercial firms that helped the university to earn handsome revenue.**

Technology commercialization refers to the process of turning innovative technological ideas, research, or inventions into commercially viable products or services that can be sold or licensed for use in the market. It plays a crucial role in bridging the gap between innovation and the marketplace, ensuring that new technologies reach their potential and contribute to economic growth, competitiveness, and societal development. Technology Commercialization Drive is an organized initiative or strategy aimed at accelerating the transition of technologies from research and development (R&D) stages to the marketplace. It involves a series of steps designed to ensure that the research outcomes are effectively transformed into products, services, or processes that can provide real-world benefits and economic returns. The key components of the Technology Commercialization Drive are Innovation Identification, Market Analysis, Intellectual Property (IP) Protection, Technology Development and Prototyping, Funding and Investment, Regulatory Approvals, Business Strategy and Go-to-Market Plan, Commercialization Execution, Partnerships and Collaboration and Scale-up and Growth.

**The importance of technology commercialization**

By translating innovations into market-ready products, commercialization drives economic growth, creates jobs, and boosts national and global economies. Commercializing technology fosters the creation of new industries, companies, and services, which in turn leads to job opportunities in R&D, manufacturing, marketing, and sales. Successful commercialization allows companies and countries to stay competitive in the global marketplace by providing access to cutting-edge technologies and innovations. Many technological innovations, especially in sectors like healthcare, agriculture, and energy, can have transformative effects on society by improving living standards, solving societal challenges, and addressing global issues such as climate change or public health crises. Successful commercialization of technologies can attract significant investment, both in terms of venture capital and government funding, further driving innovation and growth.

However, there are some challenges in Technology Commercialization such as market uncertainty, High Costs, Regulatory Hurdles, Intellectual Property Issues, Access to Capital, time to Market etc which could be overcome by strategic planning and execution.

Assam Agricultural University has developed a number of technologies which are commercialized from time to time. Some of the technology commercialized during last few years are Assam Mix (2011) , Biofor-Pf-2, Biogreen-5 (2017), Nanobiopesticide (2017) , Biofertilizers and Biopesticides (2018), Outenga Spicy Drink, Outenga Chutney Mix (2018), Rice Based Alcoholic Beverage "Sai Apong" (2019), Rice Based Alcoholic Beverage "Xaajpani (2021), Purple Rice "Labanya (2022), Elephant Apple Powder (2024) . All these technologies are sold to some commercial firms that helped the university to earn handsome revenue. (Table 1).

The university has been selling some of its produce such as different varieties of rice seeds, planting material of several horticultural crops, tea leaves, biofertilizers , biopesticides, mushrooms, fish seeds, fishes, vermicompost, weaved products, bakery products etc to individual customers from the sale counter of the university and through different agricultural fairs as well. Of late the university has started selling its products under brand name AAU Select through online platforms such as ONDC (Open Network for Digital Commerce, which is a non-profit initiative by the Government of India's Department for Promotion of Industry and Internal Trade i.e., DPIIT) and AMAZON making the presence of Assam Agricultural University in the E Commerce platform.

The initiative of Assam Agricultural University in the area of E Commerce started with selling its premium product, *"Labanya"* purple rice, developed at ARRI, Titabor during September 2022 through AMAZON. Labanya has made its presence very visible with capturing consumers from whole nation. With the experience of the success of Labanya at E Commerce platform, the Assam Agricultural University E Commerce (AAU-E Com) was set up during 22nd March 2024 with aim to offer the university produced quality products under the brand name AAU-Select to the worldwide and nationwide consumers. Assam Agricultural University-Agricultural Market Intelligence Unit (AAU-AMIU) has been entrusted with th The E Commerce unit of the university is a business-to-consumer (B2C) type of E Commerce, where the unit sells the products directly to the consumer. The unit has started selling 8 numbers of AAU Select products (Labanya - Purple rice, four variants of tea leaves, organic **Natural Fabric Dye, natural** Lemongrass Oil, Citronella Oil, Bioguard Crop Booster and Bioprotectants, Zeugo Lure- for controlling fruit fly, Zivakrit-NPK Biofertilizer) in the beginning including variants at present.

**Business so far**

Up till now the business has successfully made sales exceeding ¹ 3,00,000 through both online and offline mode. This highlights the growing popularity and customer trust in our products. 'Labanya' and university produced tea have been the best-selling items, consistently leading in terms of popularity and sales across all platforms. Their success demonstrates their appeal to a wide range of customers. It may be worth mentioning that the customer base for AAU Select products rages from different parts of India covering Kolkata, West Bengal, Kolkata, West Bengal, New Delhi, National Capital Region, Bangalore, Karnataka, Tamil Nadu, Maharashtra, Manipur and various districts of Assam. Till now, no single product has been returned back by any of the customers. It may be worth mentioning that at the recently held Regional Agricultural Fair 2025 during 4-6 January, 2025 at the Jorhat campus of the university, many products were sold to customers that resulted in gross return of Rs. 2,70,000 within two days.

**Upcoming product**

A number of products produced under different colleges and establishments are ready for sale through the AAU E Commerce platform which is already have been sold off line successfully. Some of those includes, hand woven various materials, millet based bakery products, bao rice, seeds of different types of crops, molasses, honey, mushrooms, mustard oil, various tea variants, Panchagavya, Soap, Soup Mix, Curry Mix, and others. However, for ready to consume food products FSSAI licence has to be procured appropriately. These products complement the current offerings and cater to a broader audience, providing customers with more choices while maintaining the same high standards of quality and customer satisfaction

**Plan for further scaling up/expand the business**

The unit is planning to launch several numbers of products after acquiring the FSSAI licence for ready to eat products. While doing the business, it was felt that the packaging of some of the products needs to be improvised to attract different strata of consumers. Hence, a packaging unit has to be developed to support the AAU-E Com. Delivery of online and off line ordered products may be handled by the unit to cater the need of the Jorhat and nearby areas that would reduce the handling charges to be given to AMAZON. The return policy may be introduced for some of the commodities to capture the potential consumers. The product of FPC's/FPO's may be considered for selling under AAU E Com if their products are found to be of the standard of AAU Select brand. Once the unit runs in huge profit, permanent accountant may be recruited.

The Technology Commercialization Drive is essential for turning scientific discoveries and technological innovations into valuable products and services that can benefit society and the economy. By fostering innovation, ensuring proper protection of intellectual property, securing funding, and strategically bringing products to market, the commercialization process helps technologies realize their full potential. Successful commercialization requires collaboration across various sectors, careful planning, and adaptability in a rapidly evolving technological landscape. The university is committed to serve the agricultural sector of the state in particular and the region in general through commercializing the technologies developed in collaboration with appropriate partners.

To know in details about the E Commerce unit of the university, interested persons may please contact in the following numbers and email.

**Contact details**

**Email**: amiu.ecom@aau.ac.in; **Phone**: 88120 46413 ●●

**Table 1.** List of technology transferred

| Sl. No. | Name Of The Technology | Name & Address of the Licensee | Year of Commercialization | Concerned Establishment |
|---|---|---|---|---|
| 1. | Assam Mix | Aasray Concept Food, Amingaon, Guwahati | 30th December, 2011 | Department of Food Science & Nutrition, College Of Community Science, AAU , Jorhat |
| 2. | Bioinputs And Training Manpower For Multiplication Of Bio-Inputs | School of Livelihood & Rural Development, Valley View, Shillong, Meghalaya | 29th September, 2016 | Dr (Agri.) on Behalf of AAU |
| 3. | Biofor-Pf-2<br>Biogreen-5 | Orgaman R & D Division, Jorhat, Assam | 16th June, 2017 | Dr (Agri.), AAU, Jorhat |
| 4. | Development Of Nanobiopesticide. (Project) | Cng Agrocare Pvt Ltd, West Bengal Subsidiary of, Peak Chemical Industries Ltd, West Bengal (Pcil) | 11th July, 2017 | Department of Plant Pathology, AAU, Jorhat |
| 5. | Wound Healing Vide Patent No 270519 | Herbal Medicinal Research Centre (Ngo), Bahona, Jorhat, Assam | 29th December, 2017 | Dr (Agri.), AAU, Jorhat |
| 6. | Biofertilizers<br>Biopesticides | Green Biotech Ecosolutions Pvt. Ltd, Imphal, Manipur | 25th January, 2018 | Department of Plant Pathology, AAU, Jorhat |
| 7. | Safecrop & Glv (Biofertilizer & Biopesticides) | M/S Varsha Bioscience & Technology Pvt. Ltd, Hyderabad | 27th January, 2018 | Department of Plant Pathology, AAU, Jorhat |
| 8. | Ethnic Rice Based Alcoholic Beverage“Xaajpani” | Maverick Technologies,<br>R & D Division, Jorhat, Assam | 29th January, 2018 | Department of Agricultural Bio Technology, AAU, Jorhat |
| 9. | Food Processing Unit:<br>Outenga Spicy Drink<br>Outenga Chutney Mix | Mr. Pranab Jyoti Bhuyan, Lotus Villa 28, Anu Baruah Path, Gandhibasti Road, P.O. Silpukhuri, Guwahati - 781003 | 30th January, 2018 | Dr (Agri.) , AAU, Jorhat |
| 10. | Ethnic Rice Based Alcoholic Beverage “Sai Apong” | Assam Heritage Brewery (Ahb), Jorhat, Assam New Subsidiary Of, M/S Punjab Engineering Company (Peco) Rajabari Jorhat | 6th March, 2019 | Dr (Agri.) AAU, Jorhat |
| 11. | Ethnic Rice Based Alcoholic Beverage,“Xaajpani” | Shri Deepjyoti Dowari S/O Late Khogeswar Dowari, R/O Laguwabari, Nahoronihabi Gaon, Rajmai, Demow, Sivasagar, Assam | 05th March, 2021 | Department of Agricultural Bio Technology, AAU, Jorhat |
| 12. | Ethnic Rice Based Alcoholic Beverage,“Xaajpani” | One Horn Brewery Pvt. Ltd, Bengtol Gate, Chepaguri No. 1, Chirang, Assam | 20th September, 2022 | Department of Agricultural Bio Technology, AAU, Jorhat |
| 13. | Purple Rice “Labanya” | Nilanchal Agriscience Llp, Guwahati | 19th October, 2022 | ARRI, Titabar, AAU, Jorhat |
| 14. | Ethnic Rice Based Alcoholic Beverage,“Xaajpani” | Mr. Bhargav Jyoti Roy<br>S/O Late Dilip Roy<br>C/O Dipali Gas Agency, W-No-3, Bazaar Road, Sorbhog, Barpeta, Assam | 7th November, 2023 | Department of Agricultural Bio Technology, AAU, Jorhat |
| 15. | Ethnic Rice Based Alcoholic Beverage,“Xaajpani” | Phukan Heritage Breweries Pvt. Ltd, House No 4, Bidyanagar, Byelane 1, Namghar Path, Panajabari, Guwahati, Assam | 10th May, 2024 | Department of Agricultural Bio Technology, AAU, Jorhat |
| 16. | Elephant Apple Powder | R2w Bio Solutions And Engineering Pvt. Ltd, Sbi Atm Complex, Lahapara, Panikhaity, Guwahati, Assam | 6th June, 2024 | Food Science and Technology, AAU, Jorhat |

# Biotechnological Interventions in Agriculture in the Era of Climate Change

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**"The field of biotechnology has made major contributions to agricultural practices in recent decades, facilitating the creation of genetically modified (GM) crops that exhibit characteristics such as tolerance to drought, herbicides, resistance to insects, and enhanced nutritional profiles."**

## Introduction

Agriculture serves as a fundamental component of global food security and is currently confronting unparalleled challenges in the 21st century as a result of the intensifying effects of climate change. Rising temperatures, erratic rainfall patterns, extended periods of drought, and heightened occurrences of pest and disease outbreaks pose significant risks to agricultural productivity and sustainability. The Intergovernmental Panel on Climate Change (IPCC) projects that global crop yields may decrease by 10-25% by the year 2050 if existing trends persist, which would worsen food insecurity in vulnerable areas (IPCC, 2023). In this scenario, biotechnological interventions are becoming significant methodologies to tackle the complex challenges presented by climate change. Through the application of genome engineering techniques, including CRISPR-based genome editing system, bioinformatics, synthetic biology, and microbial applications, researchers are developing crop varieties that exhibit resilience to climate-related challenges. These breakthroughs aim to enhance yield potential while minimizing the ecological impact of agricultural practices.

The field of biotechnology has made major contributions to agricultural practices in recent decades, facilitating the creation of genetically modified (GM) crops that exhibit characteristics such as tolerance to drought, herbicides, resistance to insects, and enhanced nutritional profiles. Nonetheless, the range of biotechnological applications has notably widened in recent years due to the emergence of advanced methodologies like CRISPR-Cas systems and synthetic biology techniques. These technologies provide remarkable accuracy and effectiveness in modifying plant genomes, facilitating the incorporation of traits that bolster resilience to severe weather events, enhance water and nutrient utilization, and increase photosynthetic efficiency. Moreover, the application of microbial interventions, including plant-growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, are increasingly recognized as sustainable strategies to enhance crop productivity in challenging environmental circumstances. This article examines significant biotechnological innovations that tackle the challenges posed by climate change in agriculture, highlighting their capacity to transform food systems and encourage sustainable farming practices.

## Biotechnological tools addressing climate change challenges in agriculture

Climate change poses significant threats to global agriculture, including extreme weather events, water scarcity, and the spread of pests and diseases. To combat these challenges, biotechnological tools have emerged as powerful solutions to enhance crop resilience and productivity. Genetic engineering, CRISPR-Cas9 gene editing, RNA interference (RNAi), and marker-assisted selection (MAS) are among the key technologies being employed to develop climate-resilient crops. These tools enable the precise modification of genes to improve traits such as drought tolerance, disease resistance, and yield stability under stress conditions. By leveraging these advancements, scientists are creating crops that can withstand environmental stresses, ensuring food security in the face of a changing climate. A comprehensive list of biotechnological interventions for developing various climate-resilient crops is presented in Table 1.

**Genetic engineering for climate-resilient crops**

Genetic engineering has played a crucial role in the advancement of crops that exhibit resilience to the detrimental impacts of climate change. Through the introduction of targeted genes into the genomes of crops, researchers have developed varieties that demonstrate improved tolerance to conditions such as drought, salinity, and elevated temperatures. Transgenic rice varieties that express the DREB (Dehydration-Responsive Element-Binding) transcription factor have shown enhanced drought tolerance through the regulation of stress-responsive genes (Dubouzet et al. 2003). In a similar vein, cotton that has been genetically modified to exhibit improved salinity tolerance has been created through the overexpression of the NHX1 gene, responsible for encoding a vacuolar sodium/proton antiporter (Wu et al. 2004).

A further area of interest is the advancement of crops exhibiting enhanced photosynthetic efficiency. The objective of the study was to improve carbon fixation and water-use efficiency in the context of elevated $CO_2$ levels by incorporating genes linked to the $C_4$ photosynthetic pathway into $C_3$ crops, including rice and wheat (Hibberd et al. 2010; Kajala et al. 2011; von Caemmerer et al. 2012). These advancements have the potential to mitigate yield losses caused by thermal and water stress, thereby enhancing food security in an increasingly warm environment (Long et al. 2022).

**CRISPR-based genome editing**

The CRISPR-Cas system has transformed agricultural biotechnology by offering a precise and efficient approach to genome editing. This technology facilitates precise alterations in plant genomes, leading to the creation of crops that exhibit improved resistance to both abiotic and biotic stresses. For example, the CRISPR-mediated knockout of the *OsSWEET14* gene in rice has resulted in enhanced resistance to bacterial blight, a severe disease worsened by shifting climatic conditions (Li et al., 2024).

CRISPR technology has been utilized to enhance drought tolerance in agricultural species by focusing on genes that play a role in abscisic acid (ABA) signaling pathways. Editing the PYL genes in wheat (*Triticum aestivum* L.) has led to a decrease in stomatal closure, thereby improving water-use efficiency in drought conditions (Mao et al., 2022). Furthermore, CRISPR-based methodologies are being employed to engineer crops with modified flowering times and maturation periods, facilitating their adaptation to altered growing seasons induced by climate change.

**Leveraging OMICS approaches for developing climate-smart crops:**

The practice of sustainable agriculture amidst climate change presents a major obstacle that necessitates creative strategies to maintain food security, promote environmental health, and ensure economic viability. Omics technologies, including genomics, transcriptomics, proteomics, metabolomics, and phenomics, serve as robust methodologies to tackle these challenges by delivering comprehensive understanding into the molecular mechanisms that govern plant and microbial responses to environmental stressors.

**Genomics for crop improvement**

The field of genomics, which focusses on the comprehensive analysis of an organism's entire DNA sequence, has transformed crop breeding practices by facilitating the discovery of genes linked to stress resilience, productivity, and nutritional value. Genome-wide association studies (GWAS) and quantitative trait loci (QTL) mapping have been employed to identify genetic markers associated with drought and heat tolerance in crops such as wheat and rice (Varshney et al., 2019). Furthermore, the application of CRISPR-Cas9 technology in genome editing has enabled the accurate alteration of genes to improve stress resilience while avoiding the incorporation of exogenous DNA (Zhang et al. 2014).

**Table 1**: Biotechnological advancements in climate-smart crop development: a two-decade overview (1991-2022)

| Crop | Gene and genetic engineering methods used | Target trait | Trait improvement | References |
|---|---|---|---|---|
| Rice | Silencing the ERF transcription factor gene *OsERF922* y CRISPR editing | Disease resistance | Resistant to rice blast in both seedling and tillering stages | Perlak et al. 1991 |
| Rice | Marker assisted selection (MAS) for *Sub1* gene | Submergence tolerance | Improved survival under submergence | Xu et al. 2006 |
| Rice | RNAi silencing of *RACK1* gene expression | Drought resistance | Higher growth even at water stress | Li et al. 2009 |
| Rice | Transgenic rice expressing Capsicum annum methionine sulfoxide reductase B2 (*CaMsrB2*) gene | Drought resistance | Drought tolerance at reproductive stage | Dhungana et al. 2015 |
| Rice | Knockdown of *gna1a*, *dep1,* and *gs3* gene | Abiotic stress resistance—Climate-ready crop | High yield, large grain size, grain number, improved grain weight | Li et al. 2016 |
| Rice | CRISPR edition of 3' end of OsLOGL5 coding sequence | Drought resistance | Increase in grain yield | Li et al. 2016 |
| Rice | CRISPR of *gs3* and *dep1* genes | Salinity tolerance | | Li et al. 2016 |
| ASD India Rice | Transgenic of gene DNA helicase-47 (*PDH47*) from *Pisum sativum* | Drought resistance | Regulate several stress response genes | Singha et al. 2017 |
| Rice | Cytokinin homeostasis | Stress resistance | Increase in grain yield | Cui et al. 2020 |
| Rice | CRISPR editing on MADS-box transcription factors for gene *MADS78* and *MADS79* | Seed germination | Endosperm cellularization and early seed development | Paul et al. 2020 |
| Maize | Transgenic maize with homologous *ZmNF-YB2* | Drought resistance | 50% increase in grain yield | Nelson et al. 2007 |
| Maize | Marker-assisted selection (MAS) for drought-tolerant traits (e.g., *Vgt1*, *ZmDREB1*) | Drought resistance | Improved drought tolerance and yield stability | Ribaut et al., 2007 |
| Maize | Transgenic maize preserving RNA stability and translation of Cold shock protein B | Drought resistance | Maintain the cellular functions under water stress conditions | Sammons et al. 2014 |

**Transcriptomics to understand stress responses**

Transcriptomics, a method for analyzing gene expression patterns, offers valuable perspectives into the mechanisms by which plants react to environmental stressors including drought, salinity, and high temperatures. RNA sequencing (RNAseq) has been utilized to discern differentially expressed genes (DEGs) in response to stress conditions, uncovering essential molecular pathways that play a role in stress adaptation (Wang et al. 2003). This information can be utilized to enhance crop resilience to stress through precise breeding techniques or genetic modification.

**Proteomics for functional insights**

The large-scale study of proteins—the functional molecules found in cells—is the main focus of proteomics. Researchers are able to discover proteins that are essential for stress adaption by examining changes in protein abundance and post-translational modifications under stress. For instance, proteomic research has shown the function of antioxidant enzymes and heat shock proteins (HSPs) in reducing oxidative stress and heat in crops (Kosová et al., 2011). The creation of crops with improved stress resistance may be guided by these results.

**Metabolomics for metabolic profiling**

Metabolomics encompasses the thorough examination of metabolites, which are the final products resulting from cellular activities. This methodology clarifies the metabolic pathways that are engaged in stress responses and the utilization of nutrients. Metabolomic investigations have revealed significant metabolites, including proline and sugars, that accumulate in plants experiencing drought stress, aiding in osmotic adjustment and enhancing stress tolerance (Obata & Fernie, 2012). These insights can be utilized to develop crops that exhibit enhanced resilience to stress and improved efficiency in nutrient utilization.

**Phenomics for high-throughput trait analysis**

Phenomics, characterized by the high-throughput assessment of plant traits, serves to enhance other omics methodologies by delivering comprehensive phenotypic data. Cutting-edge imaging technologies and machine learning algorithms facilitate the swift assessment of extensive populations for characteristics including growth rate, biomass, and stress responses (Yang et al., 2020). This enables the recognition of optimal genotypes for breeding initiatives focused on the creation of climate-resilient crops.

**Integration of omics approaches**

The amalgamation of multi-omics data via systems biology methodologies facilitates a comprehensive comprehension of plant reactions to climate change. The integration of genomics, transcriptomics, and metabolomics data has elucidated intricate regulatory networks that govern drought tolerance in maize (Zhang et al., 2021; Li et al. 2024). Integrated methodologies facilitate the creation of predictive models that enhance the efficiency of crop improvement processes.

**Bioinformatics and big data in agriculture**

Through the use of big data analytics and bioinformatics to agriculture, scientists are now able to pinpoint genetic characteristics linked to climate resistance. GWAS and high-throughput sequencing technology have made it easier to identify quantitative trait loci (QTLs) associated with insect resilience, heat resistance, and drought tolerance in important crops (Devate et al. 2022; Zhang et al. 2024; Sukumaran et al. 2018). Bioinformatics technologies provide insights into intricate stress-response systems by forecasting gene functions and regulatory networks via the analysis of massive datasets.

To help create climate-smart crop types, machine learning algorithms are also being used to forecast crop performance in a range of climatic circumstances. One example is the use of predictive modelling to find potential genes to increase maize's nitrogen-use efficiency, a feature that is essential for climate change-resilient agriculture (Ertiro et al., 2020).

**Synthetic biology for sustainable agriculture**

Advances in agricultural biotechnology are being driven by the discipline of synthetic biology, which blends biology, engineering, and computer sciences. Researchers are growing crops with enhanced nutritional content and increased tolerance to environmental challenges by using synthetic gene circuits and metabolic pathways. Stress-responsive gene expression is made possible by engineered synthetic promoters, which aid in crop adaptation to shifting environmental circumstances (Zhang et al., 2024).

Furthermore, crops that normally lack the capacity to fix nitrogen are being improved via synthetic biology, which lessens the requirement for synthetic fertilizers. In order to promote sustainable nitrogen utilization in farming, researchers have successfully incorporated symbiotic bacterial nitrogen-fixation routes into crops including wheat and rice (Rosenblueth et al. 2018).

**Microbial interventions**

Applying microbial treatments, including endophytic fungi and plant-growth-promoting rhizobacteria (PGPR), is becoming more popular as an environmentally acceptable way to increase crop resilience to climate change. By altering root structure and boosting water intake, PGPR strains—such as *Bacillus subtilis* and *Pseudomonas fluorescens*—have been shown to increase crop resistance to drought (Shah et al., 2024). Likewise, mycorrhizal fungi form symbiotic associations with plant roots to improve stress tolerance and nutrient uptake.

The possibilities of microbial interventions are being further expanded by developments in metagenomics and microbial genome editing. Scientists want to develop bioinoculants that may improve plant development in response to certain stressors, like heat or salt, by designing microbial consortia with specialized roles. In the context of climate change, for instance, modified strains of *Azospirillum brasilense* have shown increased nitrogen-fixing efficiency, supporting sustainable agriculture (Bashan et al. 2014).

**Challenges and future prospects**

Notwithstanding the promise of biotechnology, several problems persist. Regulatory obstacles, societal acceptability, and ethical issues of genetic changes must be resolved. Moreover, equal access to biotechnological breakthroughs must be guaranteed, especially for smallholder farmers in developing nations. Future study needs to concentrate on the integration of several biotechnological methodologies to establish resilient agricultural systems. The integration of CRISPR, synthetic biology, and microbiome engineering has significant potential for developing advanced crops suited to various agroecological environments. Moreover, cross-disciplinary collaboration and global alliances are crucial for expediting the implementation of biotechnological advances.

**Conclusion**

The escalating challenges posed by climate change necessitate the integration of advanced biotechnological approaches to enhance the resilience, sustainability, and productivity of agriculture. Techniques such as genetic engineering, CRISPR-Cas genome editing, bioinformatics, synthetic biology, and microbial applications are increasingly being employed by scientists to address critical issues, including declining crop productivity, abiotic and biotic stress tolerance, and global food security in the face of a rapidly growing population. However, the effective implementation of these technologies requires a multidisciplinary approach that incorporates scientific innovation, policy frameworks, public perception, and social equity. It is imperative to critically evaluate the legal and economic implications associated with these advancements to ensure their equitable distribution and accessibility, particularly for smallholder farmers and marginalized communities that are disproportionately vulnerable to climate-induced agricultural disruptions. Consequently, dedicated funding for agricultural biotechnology must be prioritized, alongside fostering collaboration among stakeholders, policymakers, and scientists to develop and implement a climate-resilient agricultural system that is both technologically advanced and socially inclusive.

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# Improved Breeding Strategies for Climate-Smart Crops

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**"Traditional breeding methods have been instrumental in improving crop varieties, but their pace is often slow and limited by the availability of genetic diversity. Advancements in molecular biology and genomics have revolutionized plant breeding."**

Climate change poses significant challenges to global food security, impacting crop yields and quality. To address these challenges, innovative breeding strategies are essential to develop climate-smart crops that can withstand extreme weather events, adapt to changing environmental conditions, and enhance agricultural sustainability.

Traditional breeding methods have been instrumental in improving crop varieties, but their pace is often slow and limited by the availability of genetic diversity. However, advancements in molecular biology and genomics have revolutionized plant breeding, enabling scientists to develop climate-resilient crops more efficiently.

**Key Improved Breeding Strategies**

**Marker-Assisted Selection (MAS)**

This technique utilizes molecular markers linked to specific traits of interest, such as drought tolerance or disease/insect-pest resistance. By identifying and selecting plants with the markers, breeders can accelerate the breeding process and increase the accuracy of selection. MAS has been successfully used in rice breeding to improve drought tolerance, salinity tolerance, and resistance to several diseases including blast and bacterial leaf blight (BLB). For example, the *DRO1* gene, associated with drought tolerance, has been introgressed into various rice cultivars using MAS (Mackill and McNally 2009). Similarly, the breeders have employed MAS to develop wheat varieties with enhanced resistance to diseases like rust and powdery mildew, which are exacerbated by climate change. MAS has also been used to introgress the *Lr34* gene, which confers resistance to multiple rust diseases, into different wheat cultivars (Ellis and Park, 2014).

**Genome-Wide Association Studies (GWAS)**

GWAS involves scanning the entire genome of a population to identify genetic variations associated with specific traits. This approach can help identify novel genes and alleles that contribute to climate resilience. GWAS has been instrumental in identifying genetic loci associated with drought tolerance, heat stress tolerance, and nitrogen use efficiency in soybean. Song et. al. (2013) used GWAS and identified QTLs associated with drought tolerance on chromosomes 11 and 20 in soybean. GWAS in maize has led to the identification of genes related to drought tolerance, heat stress tolerance, and resistance to insect pests. Romay et.al. (2013) used GWAS and identified QTLs associated with drought tolerance on chromosomes 1, 5, and 9 in maize.

**Genomic Selection (GS)**

GS predicts the breeding value of an individual based on its entire genome sequence, rather than just a few markers. This approach can significantly increase the accuracy of selection, especially for complex traits. In wheat, the GS has been successfully applied in improving yield, disease resistance, and quality traits. Further, the GS has been used to predict the breeding value of wheat (Heffner et al. 2010) and maize (Riedelsheimer et.al. 2013) lines for yield and disease resistance, leading to more efficient selection and faster development of new varieties.

**Speed Breeding**

This technique involves manipulating environmental conditions, such as light and temperature, to accelerate the plant growth cycle. By shortening the breeding cycle, speed breeding can significantly reduce the time required to develop new varieties and thus enhance the genetic gain. For example, speed breeding has been used to shorten the breeding cycle of wheat and barley from 6-8 months to 3-4 months, leading to faster development of new varieties (Mickelson et.al. 2016).

**Genome Editing**

CRISPR-Cas9 is a powerful tool that allows scientists to precisely edit the genome of plants/ animals. This technology can be used to introduce new traits, modify existing genes, or correct genetic defects, enabling the development of climate-resilient crops with enhanced agronomic performance. CRISPR-Cas9 has been used to edit the *OsMYB3R-2* gene in rice, which regulates root development and drought tolerance (Wang et.al. 2018). Similarly, CRISPR-Cas9 has been used to edit the *TaGW2* gene in wheat, which controls grain weight and yield (Wang et.al. 2014).

**Emerging Trends and Technologies**

**Synthetic Biology**

This interdisciplinary field combines engineering principles with biology to design and construct novel biological systems. Synthetic biology can be used to engineer crops with enhanced stress tolerance, improved nutrient use efficiency, and other desirable traits.

Synthetic biology approaches are being explored to engineer soybeans with improved nitrogen fixation, enhanced oil content, and increased resistance to biotic and abiotic stresses. For example, synthetic biology is being used to engineer soybeans with improved nitrogen fixation by introducing genes from nitrogen-fixing bacteria (Liu et.al. 2021).

**Artificial Intelligence (AI) and Machine Learning**

AI and machine learning algorithms can be used to analyze large datasets, predict crop performance, and optimize breeding decisions. These technologies can help breeders make more informed decisions and accelerate the development of climate-smart crops.

AI and machine learning algorithms are being used to analyze large datasets of maize breeding data to predict crop performance, optimize breeding decisions, and accelerate the development of new varieties. Similarly, AI and machine learning are being used to predict the breeding value of maize lines for drought tolerance and grain yield, leading to more accurate selection and faster genetic gain (Crossa et al. 2017).

**Big Data Analytics**

The integration of big data analytics with breeding programs can provide valuable insights into crop performance, environmental factors, and genetic diversity. This information can be used to develop more effective breeding strategies and improve the overall efficiency of breeding programs.

As an example, the big data analytics is being used to integrate data from various sources, such as weather data, soil data, and breeding data, to develop more effective rice breeding strategies and improve the overall efficiency of breeding programs. It has been used to predict the optimal planting date for rice based on weather data and soil data, leading to improved yields and reduced water use (Atlin et.al. 2016).

**Conclusion**

By embracing the innovative breeding strategies and technologies, scientists can develop climate-smart crops that are better adapted to the challenges of a changing climate. These efforts are crucial for ensuring global food security and promoting sustainable agriculture in the face of increasing environmental pressures. ●●

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# Impact of Climate Change on Sericulture Industry

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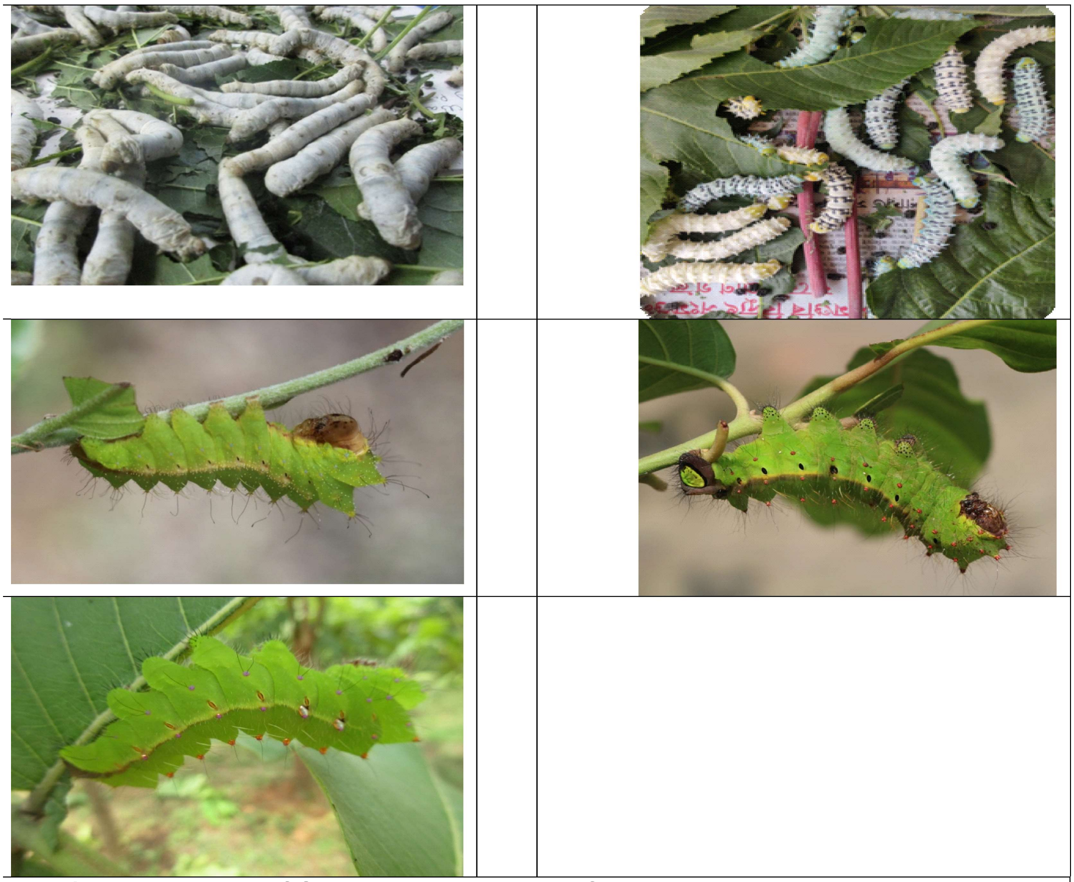
**"Silkworms belong to the order Lepidoptera and by nature they are herbivorous. Life cycle of silkworms comprised of egg, larva, pupa and adult. In each stage of their life they need specific environmental condition as they are very delicate and needs special care to grow properly."**



**gure 1.** Various types of Commercial silkworms of India. A. Mulberry silkworm, B. Eri lkworm, C. Temperate tasar silkworm, D. Muga silkworm, E. Tropical tasar silkworm

## Introduction

Sericulture industry comprised of commercial cultivation of five different types of silkworms *viz*., mulberry (*Bombyx mori* L,), eri (*Samia ricini* Donovan), muga (*Antheraea assamensis* Helfer) and tropical tasar (*Antheraea mylitta* Drury) and temperate tasar (*Antheraea pernyi* Guer.Mene. and *Antheraea proylei* Jolly) (Figure 1). It is a farm based ancient industry where food plants are grown for feeding the silkworms, silkworms eggs are produced to rear the silkworm from which the cocoons are obtained to get the silk.

The average annual production of silk around the world is 91,319 MT. The top five countries in silk production are: China, India, Uzbekistan, Vietnam and Thailand. According to International Sericulture Commission, China and India are the leading countries in silk production with 50,000 MT and 36,682 MT, respectively during the year 2022. Global Sericulture Market reached US$ 251.2 billion in 2022 and is expected to reach US$ 468.4 billion by 2030, growing with a CAGR of 8.1% during the forecast period 2023-2030. The Indian sericulture market size reached INR 531.1 billion in 2023. IMARC group expects that the market to reach INR 1,994.6 billion by 2032, exhibiting a growth rate (CAGR) of 15.4% during 2024-2032. Indian sericulture industry generated employment for 9.2 million persons in 2022-23. Production trend of mulberry, eri, muga and tasar raw silk of India in last thirteen years is presented in the table 1.

**Table 1. Trend of raw silk production in India from 2011 to 2023**

| Year | Mulberry (MT) | Eri (MT) | Muga (MT) | Tasar (MT) | Total (MT) |
|---|---|---|---|---|---|
| **2010-2011** | 16360 | 2760 | 124 | 1166 | 20410 |
| **2011-2012** | 18272 | 3072 | 126 | 1589 | 23060 |
| **2012-2013** | 18715 | 3116 | 119 | 1729 | 23679 |
| **2013-2014** | 19476 | 4237 | 148 | 2619 | 26480 |
| **2014-2015** | 21389 | 4726 | 158 | 2434 | 28708 |
| **2015-2016** | 20478 | 5060 | 166 | 2819 | 28523 |
| **2016-2017** | 21273 | 5637 | 170 | 3268 | 30348 |
| **2017-2018** | 22066 | 661 | 192 | 2988 | 31906 |
| **2018-2019** | 25345 | 6910 | 233 | 2981 | 35468 |
| **2019-2020** | 25238.6 | 7204.0 | 240.5 | 3136.4 | 35819.6 |
| **2020-2021** | 23896 | 6947 | 239 | 2689 | 33770 |
| **2021-2022** | 25818 | 7364 | 255 | 1466 | 34903 |
| **2022-2023** | 27654 | 7349 | 261 | 1318 | 36582 |

(Source: Annual report, Central Silk Board**)**

The changing climate of the world is presumed to influence the global sericulture industry also which is discussed below.

**Favourable environmental condition for silkworm**

Silkworms belong to the order Lepidoptera and by nature they are herbivorous. Life cycle of silkworms comprised of egg, larva, pupa and adult. In each stage of their life they need specific environmental condition as they are very delicate and needs special care to grow properly. Mulberry and eri silkworms are reared indoor, that is why optimum environmental condition required by them can be to some extent manageable. As muga and tasar silkworms are reared outdoor it is difficult to control the environment. The chief ecological factors temperature, humidity, light and air during the incubation of egg and larval life has pronounced effect on the health and growth of larvae. During the time of cocoon spinning also they need specific environment. However, other factors like nutrition, rearing method, moulting care, bed cleaning, spacing has also plays significant role in the cocoon production both in quantity and quality.

Silkworms are poikilothermic/cold blooded animals and therefore, according to the environmental condition their body temperature also changes. Their body temperature is $1^0$C higher than the atmospheric temperature. Bardoloi and Hazarika (1994) elaborated thermoregulatory mechanisms adapted by muga silkworm in the nature. Direct effect of temperature has been noticed on the various physiological functions of silkworm. Metabolic rate, enzyme activity, nutrient conversion, digestion, assimilation, excretion, nervous stimulations, hormonal actions are influenced by environmental temperature. The silkworms are capable of survive in temperature in between $15^0$C to $40^0$C. But optimum temperature range for the performance of physiological activity in the right manner is $20^0$C to $28^0$C. Again, for the production of good quality cocoons, ideal and desirable temperature ranges from $23^0$C to $28^0$C. When the temperature increases metabolic activity of the silkworms becomes faster consequently growth of the larva also enhances resulting in the shorter larval period and life cycle and reverse in the case of low temperature, resulting in longer larval period and life cycle. Temperature above $30^0$C and below $20^0$C both are considered to be harmful to the silkworms.

Optimum humidity range for growth of silkworm is 70% to 85%. The role played by humidity on the growth and health of silkworm is similar with that of temperature. The compound effect of both temperature and humidity decides the growth of the silkworm larva and production of quality cocoons. Humidity directly affects the physiological activity of silkworm. Low humidity reduces the moisture content of the leaves affecting the larvae by lowering the growth and wastage of leaves. Again, high humidity invites the pathogens to cause diseases of silkworm.

Air current of 0.3 meters per second helps to keep the silkworms healthy. The growth of the silkworms is uniform at 16 hours light and 8 hours dark condition in a day.

Incubation is a crucial phase of the silkworm life. Optimum humidity and temperature required for the growth of the embryo is $24^0$-$25^0$ C and 80-85%.

Silkworms require relatively dry atmosphere during the time of cocoon spinning. Ideal temperature for good cocoon spinning should not exceed $26^0$ C and relative humidity should be in the range of 60-70%. Temperature beyond the optimum range affects the quality of cocoon.

**Likely effect of climate change on sericulture industry**

Climate is the long term change of weather, generally for a period of 30 years. The climate is changing rapidly and its effect is manifold. According to the Synthesis Report on Climate change, 2023 of Intergovernmental Panel on Climate Change, due to emissions of greenhouse gases caused global warming, which has led to reach the global surface temperature 1.1°C above 1850-1900 in 2011-2020.The climate is changing rapidly with continuous increase of greenhouse gas emissions resulting in melting of polar ice reserves and rising of sea water level, it is expected that the effect will be manifold on biodiversity. On the basis of the increase of greenhouse gases, the climatic model predicts an average increase of 1.4 to 5.8 °C in global temperature from 1990 to 2100, probably leading to a more rapid increase in temperature at the surface of terrestrial zones and more extreme local variations (Karl and Trenbeth, 2003).

Considering the above, like all the agro-based industries, the sericulture industry may face many challenges. In order to mitigate those, R&D approaches may also be attuned towards discovering climate-resilient sericulture practices and tools. Some of the effects are discussed below:

- The wild tasar eco-races and wild muga population is facing the threat of extinction in their natural habitat due to environmental degradation, deforestation and other factors associated with it. Other wild silkworm species like *Antheraea frithi, A. roylei, Attacus atlas, Actias luna etc.* is also facing the same problem. This will lead to genetic erosion and variability.
- Different type of voltinism is found in different silkworm species. Mulberry silkworm by nature shows uni, bi and mulvoltinism. Tropical tasar is uni, bi and trivoltine whereas temperate tasar is weak bivoltine in nature. Muga and eri silkworms are multivoltine. This voltinism nature of silkworm may change due to rise in global temperature and there may be more number of generations in a year as the life cycle may be shortened. This may lead to scarcity of the leaves to feed the silkworms.
- A sharp change in the air temperature of the worm relative to the norm (25-26$^{o}$C) weakens the activity of the silk gland due to disruption of the growth and development process of worm As a result, the viability of worms has been scientifically proven to decrease by 6.5%, cocoon weight by 61.5-64.4%, silkworm weight by 73.7- 74.5%, productivity by 8-10 kg (Bekkamov and Samatova, 2023).
- Hussain *et al*. (2011) while investigating the effect of temperature and humidity fluctuations on fecundity and fertility of the eleven inbred silkworm lines of mulberry silkworm by exposing 4$^{th}$ and 5$^{th}$ instar larvae to 25±1°C, 30±1°C and 35±1°C in combination with 55, 65 and 75% relative humidity (RH) for 3hr daily found that temperature and relative humidity during larval rearing affected the fecundity and fertility of inbred silkworm lines adversely with low fecundity and high incidence of unfertilized eggs. Best results were obtained in the 25±1°C with 75% RH combination. They also observed the gradual decrease in the egg number with the increase in temperature and gradual decrease in fertility with decrease in relative humidity at a given temperature. The performance of silkworm lines was affected significantly at 25, 30 and 35ÚC with all three combinations of humidity (55, 65 and 75%). According to their research the fluctuation in the temperature up to 30°C is within the tolerable limits of the silkworm lines provided that the relative humidity may remain between 70-80%.
- Das *et al*., 2023 studied the temperature trend and its effect on eri and muga sericulture in four districts Assam. They observed that the temperature of the four districts namely; (for the months of April, May, October and November) KarbiAnglong, Golaghat, (for eri cultivation) and Lakhimpur, Sivsagar (for muga cultivation) during 1991 to 2002 is rising. They revealed that cultivation of muga will be affected a lot as host plants will suffer from diseases like grey blight and gall insects, as both expand in a favorable way in hot temperature. The temperature of Golaghat was increasing at an increasing rate which might lead to rise in some insects like red hairy caterpillar and semi looper and tobacco caterpillar (in castor plants) as they occur mostly in hot temperature (as June, July and August has very hot temperature in Assam) which will affect the eri cultivation resulting in fall in eri production.

- *Aherua* and *Bhadia*, these two muga crops fall during unfavorable climatic conditions characterized by high temperature, high humidity and high rainfall. High temperature prevailing during this period has adverse effect on gonad development in the larvae causing inadequate fertilization of the female embryos during coupling. This leads to low hatching of eggs, (Neog *et al*., 2015)
- Exposure of seed cocoons to high temperature of 35ÚC in combination with low relative humidity results in decreased egg recovery and increased incidence of unfertilized eggs (Ayuzawa *et al*., 1972).
- Climate change may affect the physical, chemical and biological properties of soil. It will affect organic matter status, C and nutrient cycling, plant available water and hence plant productivity, which in turn will affect soil pH. (Reth *et al*. 2005)
- Mulberry is a C3 plant and C3 plants are relatively inefficient in using $CO_2$ and have their photosynthetic apparatus in the outer mesophyll cells. To compensate for this inefficiency stomata must remain open longer exposing them to potentially increased evapotranspiration and respiration rates. As a result these plants grow better in cooler moist environments with elevated $CO_2$ concentrations (Ram *et al*. 1999).
- Long *et al.* (2006) and Polley (2002) reported the effect of rising $CO_2$ on plants yield through photosynthesis and stomatal conductance whereas the growing evidence suggesting that C3 crops may respond positively to increased atmospheric $CO_2$ in the absence of other stressful conditions (Long *et al*., 2004).But the beneficial direct impact of elevated $CO_2$ can be nullified by other effects of climate change, such as elevated temperatures, higher tropospheric ozone concentrations and altered patterns of precipitation.
- The pest population of a crop or plant species is the result of the combined effect of temperature, precipitation, humidity, soil moisture, atmospheric $CO_2$ and $O_3$ etc. An increase in temperature may change in geographical distribution, increased over wintering, changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop-pest synchrony of phenology, changes in interspecific interactions and increased risk of invasion by migrant pests (Memmott *et al*., 2007; Parmesan, 2007). Eg. The leaf webber, *Diaphania pulverulentalis* has been noticed as a serious pest in Karnataka since 1995 which has also spread to Tamil Nadu and Andhra Pradesh on local, M5, MR2, S36 and V1 mulberry varieties (Ram *et al*., 2016).
- Coakley *et al.* (1999) stated that plants are more susceptible to rust diseases with increased temperature.
- Elevated $CO_2$ may modify pathogen aggressiveness and/or host susceptibility and affect the initial establishment of the pathogen, especially fungi, on the host (Plessl *et al*., 2005; Matros *et al*., 1996;), increased fecundity and growth of some fungal pathogens under elevated $CO_2$ (Hibberd *et al*., 2006, Chakraborty *et al*., 2000) and greater plant canopy size, especially in combination with humidity and increased host abundance, can increase pathogen load (Chakraborty and Datta, 2003, Pangga *et al*., 2004).Almost all the host plants of silkworms are infected with rust pathogen. Due to global warming and elevated $CO_2$ there may be more fungal diseases in the food plants of silkworm as stated by many researchers in other crops.

**Measures to mitigate the effect of climate change on sericulture**

- Conservation of silkworm and its host plant germplasm through *in-situ*, *ex-situ* and cryo-preservation method.
- To identify novel genes of both silkworm and host plants to increase adaptability.

- Induction of pupal diapause in muga silkworm to skip the rearing in unfavourable seasons.
- Development of thermo-tolerant and humidity-tolerant silkworm lines to increase productivity during the hot summer months. A few mulberry silkworm races developed for the purpose are mentioned below:

(a) Bivoltine mulberry silkworm races tolerant to high temperature/humidity: SK7. B. Con4, N5. HTH10, WB1.
(b) New hybrid mulberry silkworm races tolerant to high temperature/humidity: HTH 3 x HTH 6, HTH 4 xHTH 9.
(c) Multivoltine mulberry silkworm breeds tolerant to high temperature: Nistari, Cambodge.
(d) Bivoltine mulberry breeds tolerant to high temperature: SK4C, BHR3.
(e) Bivoltine mulberry silkworm breeds suitable for adverse season: WB7.5 x WB1.3

- Development of productive hybrids by using different morphotypes of muga, eri and tasar silkworm.
- Research study should be conducted to know the male sterility of muga silkworm to solve the seed problem for rearing '*katia*' (autumn) commercial crop.
- To develop new climate resilient mulberry and other silkworm host plant varieties suitable for drought tolerance, flood tolerance, alkalinity tolerance, disease tolerance etc. In mulberry some mulberry variety has already been developed. Examples:

(a) Mulberry varieties tolerant to drought : S 13, S 34,AR 11.
(b) Mulberry varieties resistant to salinity: V1, AR 10, TR4,TR10.
(c) Mulberry varieties resistant to alkalinity: S 34, AR 12.
(d) Mulberry variety tolerant to flood: C-2028.
(e) Mulberry varieties resistant to powdery mildew: MR1, MR2

- Study should be conducted to understand the host-plant-pathogen-insect interaction in the changing scenario of climate.
- Development of disease and pest diagnostic tool for early detection and prediction of disease and pest and formulation of management strategies.
- Biotechnogical approaches mainly genetic engineering must be involved in developing resilient breeds and feeds for sustaining the industry.

## Conclusion

It is presumed that climate change may affect the sericulture industry in the long run, which may ultimately cause serious problem to the livelihood security of millions of people involved with this industry directly or indirectly. Recent data on silk production has not indicated any negative impact, which is of course a positive sign. However, it is the time to take necessary steps to combat the possible ill effects of the climate change.

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# Technological Breakthrough in Irrigation and Water Management

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**"In India, important surface water resources are rivers, lakes, ponds, and tanks. There are around 10,360 rivers and their tributaries having a length of more than 1.6 kilometres."**

India covers around 2.45% of the world's surface area, accounts for 18% of the world's population and has 4% of the world's water resources. Rainfall is the primary source of freshwater and India receives an average of 1170 mm of rain per year, which equates to around 4,000 cubic kilometres (960 cu miles) of rain per year or about 1720 cubic meters (61,000 cu feet) of freshwater per person. Rainfall is dependent on South-west monsoon, North-east monsoon, shallow cyclonic depressions and disturbances and on violent local storms. Most of the rain occurs during its monsoon seasons (June to September), with the northeast and north receiving far more rains than India's west and south. Other than rains the melting of snow over the Himalayas after the winter season feeds the northern rivers to varying degrees. However, the southern rivers, experience more flow variability over the year. Owing to spatial and temporal variability in the rainfall, distribution of water resources in India is highly tilted in space and time. Surface and groundwater resources play important role in the socio-economic development of the country. Despite extensive river system, safe and clean drinking water as well as supply of irrigation water for sustainable agriculture is always in shortage across India, in part because it has harnessed a small fraction of its available and recoverable surface water resource. Of the water it withdrew from its rivers and groundwater wells, India dedicated about 688 cubic kilometres to irrigation, 56 cubic kilometres to municipal and drinking water applications and 17 cubic kilometres to industry.

In India, important surface water resources are rivers, lakes, ponds, and tanks. There are around 10,360 rivers and their tributaries having a length of more than 1.6 kilometres. India's average annual water availability between 1985 and 2023 is estimated at 2,115.95 billion cubic meters (BCM) as per the estimate of Central Water Commission (CWC) in 2024 which is higher than the 1999.2 BCM estimated in 2019. The increase is due to the inclusion of Bhutan's contribution to the Brahmaputra basin and Nepal's contribution to the Ganga basin. The CWC estimates utilizable surface water at 690 BCM out of the total 1,999.2 BCM. This is because, roughly 90 per cent of the annual flow of Himalayan Rivers occurs during a period of four months and capturing such resources is difficult because of the unavailability of adequate storage reservoir sites (Central Water Commission, 2015). Based on the 2019 study, per capita availability of water per year was 1486 cubic meters for the year 2021.For 2024, with the new data, the per capita availability is projected to be 1513 cubic meters (based on a population of 1.398 billion). Despite the increase, India remains under **water stress** (less than 1,700 cubic meters per capita).

Groundwater is an important source of irrigation. The static fresh groundwater reserves of the country have been estimated as 1,082 BCM. The dynamic component which is replenished annually has been assessed as 437.60 BCM. The main source of replenishable ground water resources is recharge from rainfall, which contributes to nearly 61 % of the total annual ground water recharge. Annual extractable ground water resource is 398.08 BCM and annual ground water extraction has been assessed as 239.16 BCM (Central Ground Water Board 2022). The average stage of ground water extraction for the country as a whole works out to be about 60.08 %. Contribution of ground water in irrigation sector is nearly 62 % while in rural water supply and urban water supply, contribution is 85 % and 50 %, respectively. Although, ground water plays an important role in the agricultural sector, however, there has been depletion of ground water level in many parts of the country due to overexploitation of ground water, mainly in areas where intensive agriculture is followed under irrigated condition, indicating unsustainable use of ground water. Globally, the rate of groundwater utilization is increasing by 1% to 2% per year and as per the estimate, at the current rate of ground water utilization, demand may surpass supply by nearly 40% by 2030 putting both water and food security at risk.

Water is considered as a powerful indicator of ecological sustainability and economic prosperity. Efficient use of water resources in agriculture is very much essential for sustaining agricultural productivity, ensuring food security, and promoting socio-economic development. However, water management in agricultural sector is facing numerous challenges. Demands on agricultural water are likely to increase in future as domestic, industry and environmental uses of water continue to grow. Besides, inefficient irrigation practices like flood irrigation and furrow irrigation contribute to wastage of water, soil erosion, and salinization, undermining the sustainability of agricultural production systems (Cerdà et al., 2021). Climate change has emerged as the significant challenge which influence the regional hydrological cycle that affects water resources and reduce the availability and reliability of water supplies in many places which are already subject to water scarcity. The effect of variation in rainfall patterns may affect the natural recharge process, and increased temperatures may enhance crop evapotranspiration and irrigation demand in a different part of the world. Therefore, judicious utilisation of available water resources in agriculture, given the due concern for water storage, conveyance and distribution, needs to be planned for the sustainability of agriculture throughout the water-scarce countries. A comprehensive approach is required that integrates technological innovation, policy interventions, and community participation to promote sustainable water management.

Efficient water management practices in agriculture are vital for maximizing crop productivity and minimizing water wastage. Conventional irrigation methods like flooding furrow irrigation etc. face several challenges which not only affect agricultural productivity but also contribute to water scarcity, energy consumption, and soil degradation. Conventional irrigation methods are associated with wastage of water and therefore, often require significant energy inputs for water conveyance, pumping, and distribution. In flood irrigation, there is substantial loss of water through surface runoff, evaporation and deep percolation beyond the root zone. Similarly, in furrow irrigation also, there is wastage of water due to inefficient water distribution, evaporation, and runoff. Soil degradation through various mechanisms, including soil erosion, salinization, and waterlogging are also associated with conventional irrigation methods. Flood irrigation and furrow irrigation systems lead to soil erosion, especially on sloppy terrain, where water runoff can carry away valuable topsoil, nutrients, and organic matter. In flood and furrow irrigation systems, pumping water over long distances or elevations can consume substantial amounts of energy, contributing to greenhouse gas emissions and environmental pollution (Kahil, et al., 2015). To address these challenges, a transition is necessary towards more efficient, sustainable and climate smart irrigation practices. There has been considerable advancement in irrigation technologies which aim to enhance water use efficiency, minimize wastage and optimize crop yields while reducing the environmental footprint of irrigation practices. A few of the recent advancement in the field of irrigation water management is discussed below.

**Precision Irrigation**

Precision irrigation is an advanced approach to water management in agriculture that utilizes the technology to apply need-based and accurate amount of water to a plant at an appropriate time and location. In precision irrigation, water is applied in variable rate; generally regulated by the inputs of sensors which help in reducing water losses and thereby conserving water resources and minimizing environmental impact. Precision irrigation can also improve nutrient uptake by delivering nutrients directly to the root zone of plants, reducing leaching and runoff. There are generally two major components in precision irrigation system i.e. physical set up which apply water to crops and the control system that operates and manages the irrigation system. The main steps involved in the control and management system are data collection, interpretation, control and assessment. A precision irrigation system needs accurate in situ spatial and temporal real -time information on soil, crop, and weather conditions. Currently, several soil and plant-based sensors and automatic weather stations are available which can provide reliable information of required soil, crop, and weather parameters. After collection of data, it is required to analyse and interpret the data and there are several multidimensional model / simulation software / tools are available that can forecast crop response to different applications. In a precision irrigation system, rationalization of inputs such as water and nutrients and irrigation scheduling (based on the in situ soil and weather conditions) at suitable temporal and spatial scales is very much important. The most reliable and highly accurate method of managing irrigation water is to integrate real-time data from the in situ sensors with automatic controllers. Precision irrigation system can be integrated with advanced irrigation planning and application systems with sensing, simulation and control systems. This involves the use of real-time automation and control of the system. Precision irrigation has the potential to revolutionize water management in agriculture, offering a sustainable solution to the challenges of water scarcity, climate change, and food security.

**Automation in irrigation**

Automation in irrigation systems plays a crucial role in updating irrigation practices and can replace manual irrigation. With the help of technology, an automated system monitors and regulates various aspects of operation like irrigation scheduling, delivery and distribution which enable farmers to achieve precise and targeted water application, resulting in improved crop yields, water savings, and resource management. An important component of automated irrigation system is the use of sensors to monitor soil moisture status, weather condition and crop water requirement in real time which provide data for irrigation decision and management strategies based on the environmental conditions. Flow and distribution of water within irrigation systems is controlled with the help of automated valves and pumps for scheduling and adjusting water delivery rates to match crop water demand and minimize losses. Recent advancement in automation in irrigation enables remote monitoring and control of irrigation operation, predictive analytic and automated decision-making processes. This system focuses on system integration, connectivity and intelligence through the use of Internet of Thing (IoT) technologies, cloud computing, and artificial intelligence (AI) algorithms which solve the problems of over- and under-irrigation based on crops and weather scenarios. One of the key advantages of IoT-based irrigation systems is their ability to collect and analyse large volumes of data from multiple sources, including soil moisture sensors, weather stations, crop sensors, and satellite imagery.

**Weather-based Irrigation Scheduling**

Weather-based irrigation scheduling relies on weather data such as solar radiation, temperature, humidity and wind speed to estimate crop water demand and calculate the amount of water needed to replenish soil moisture levels. In this approach, estimation of reference evapo-transpiration which is the evapotranspiration from a reference surface (ETo) under standard weather condition is required. The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m-1 and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground (FAO Irrigation and Drainage Paper No. 56). The FAO Penman-Monteith method is recommended as the sole standard method for computation of the reference evapotranspiration. This method relies on weather data such as solar radiation, temperature, humidity and wind speed to estimate crop water demand and calculate the amount of water needed to replenish soil moisture levels. By combining ETo with crop coefficients (Kc ) that reflect crop-specific water requirements, farmers can estimate evapo-transpiration of crop (ETc) and determine irrigation needs based on the difference between ETc and rainfall. Different tools and techniques can be used to get real time weather information, calculation of evapo-transpiration and irrigation recommendations for optimizing irrigation water management strategies. Irrigation scheduling based on the weather information can also be integrated with soil moisture sensor, remote monitoring system and automated irrigation system for higher efficiency and precision in irrigation. Recently, weather forecasting models and machine learning algorithms are also utilized to anticipate weather pattern, predict water demand of the crop and regulate scheduling of irrigation accordingly.

**Re-use of wastewater in agriculture**

Due to water scarcity in the agriculture sector, recycling of wastewater is becoming more popular to supplement water demand for agriculture. Water recycling and reuse is the process of treating wastewater, drainage water, or other non-potable water sources and reuse it for irrigation and agricultural purposes. Reclamation and reuse of makes non-potable wastewater useful instead of it being discharged into the environment and potentially polluting the ecosystems. The recycled water can be used for irrigation or industrial purposes as well as domestic purposes, if properly treated. Recycling of wastewater has a positive impact on the environment as it reduces dependence on freshwater resources and reduces the quantity of wastewater released into the environment. It can be an important adaptation response to climate change as the increasingly erratic weather conditions are likely to have negative impact on freshwater resource. Moreover, reclaimed wastewater can enhance soil fertility and improve crop productivity when applied judiciously as it contains several nutrients and organic matter. There are several methods to treat waste water from municipal, industrial, or agricultural sources such as sedimentation, filtration, and disinfection to remove contaminants and pathogens before reuse in irrigation.

**Micro-irrigation**

Drip irrigation is an innovative methods of irrigation by which water can be supplied directly into the root zone. Drip irrigation system is more efficient than other surface irrigation method which helps in increasing crop yield and water use efficiency and also helps in water saving. Unlike traditional surface irrigation methods, drip irrigation delivers water precisely where it is needed, minimizing evaporation, runoff, and soil erosion (Santosh *et al*., 2022). There is an increase in crop yields and reduction in the cost of fertilisers, pesticides and power for irrigation when using this method of irrigation. Drip irrigation systems consist of a water source, a distribution network, and emitters or drippers that release water near the plant roots. In case of subsurface drip irrigation (SDI), emitters are buried below the soil surface and water is delivered directly to the root zone of plants. As the emitters are placed underground, sub surface drip irrigation system minimizes water losses due to evaporation and surface runoff and also reduces the risk of weed growth and damage to irrigation equipment.

**Conclusion**

Advanced irrigation technologies are no longer a choice but a necessity for sustainable agricultural development. Precision irrigation is an advanced approach to apply need-based and accurate amount of water at right time and location. It integrates advanced irrigation planning and application systems which involves the use of real-time automation and control of the system. Irrigation scheduling based on the weather information can be integrated with soil moisture sensor and automated irrigation system for higher efficiency and precision in irrigation. By embracing these advances, we can achieve a balance between agricultural productivity and environmental sustainability.

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# Machine Learning Methods for Crop Yield Estimation and Applications in Crop Insurance

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**"In the past decade, there have been rapid advances in the use of remote sensing (high-resolution satellite images/ drone images), cloud computing, statistical analysis, crop models, Machine Learning (ML) and Artificial Intelligence (AI) based analytics which are increasingly used for yield assessment."**

## Introduction

Agriculture is the foundation for global food security and economic sustainability, particularly in primarily agricultural economies like India [1]. Crop yield is a major indicator of agricultural productivity and helps decision makers to make informed decisions for optimizing productivity and income. Estimation of crop yield is crucial for agricultural planning, food security and market stability [2]. Historical yields are also the primary input for framing policies related to crops such as crop insurance policies. High accuracy of crop yield estimates is essential for effective decision making [3]. Traditional methods of yield estimation were heavily reliant on farmers' interactions, Patwaris, historical trends and field surveys. These methods have inherent disadvantages in capturing the actual field heterogeneity and crop dynamics as it is influenced by the complex interactions of a crop with the weather, soil, and management practices [4].

Statistical models like regression analysis which relied on historical and environmental parameters for predicting crop yield were initially used for crop yield estimation. With the advancement in technology, yield estimation has become more accurate and reliable owing to better computing abilities and data availability. It has now become possible to automate processes, decreasing the time required for estimating crop yields, which is very crucial for agricultural planning and deploying efficient management practices for increasing production and minimizing post-harvest losses. In the past decade, there have been rapid advances in the use of remote sensing (high-resolution satellite images/ drone images), cloud computing, statistical analysis, crop models, Machine Learning (ML) and Artificial Intelligence (AI) based analytics which are increasingly used for yield assessment [5], [6], [7], [8], [9]. ML has revolutionized computational domain, offering tools to analyze vast datasets, predict outcomes with higher accuracy, and provide actionable insights [10], [11].

This article explores the different machine learning approaches for crop yield estimation and highlights its practical implementations for crop insurance globally and in the Indian context.

**Machine learning methods for crop yield estimation**

Machine learning (ML) is a branch of Artificial Intelligence (AI) that focuses on building systems capable of learning from data and improving their performance over time without being explicitly programmed [12]. Machine learning algorithms use information derived by analyzing input data such as patterns to make predictions, decisions, or perform tasks [[13]. ML can be used to predict crop yields with increased precision by analyzing the multiple interrelated factors that influence agricultural productivity, such as weather conditions, soil properties, crop management practices, along with historical yield data. ML models have the capability to handle large datasets and utilize them to identify patterns, trends, and correlations while processing non-linear tasks that traditional methods cannot [14].

The use of ML methods for crop yield estimation has increased rapidly which is evident from the number of original articles published in peer-reviewed journals over the years (Fig.1). Publications remained one each year globally between 2008 and 2012 while it increased to 12 in 2018 based on a review by Klompenburg *et al* (Fig. 1) [15]. The number has increased to about 37 in 2022 [4].

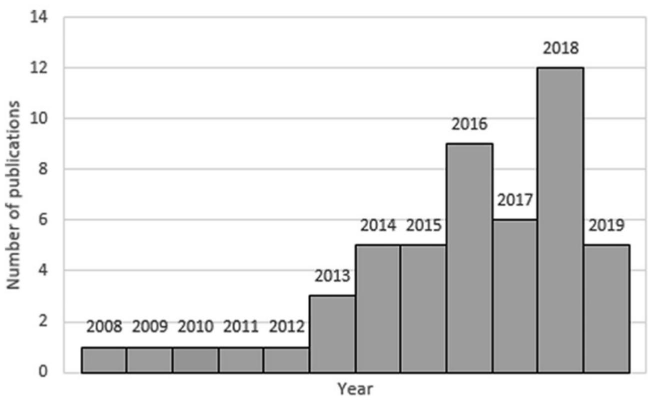


**Figure 1.** Number of publications in peer-reviewed journals on use of ML techniques for crop yield estimation [15]

ML methods in the late 1990s and early 2000s for crop yield prediction included linear models, decision trees, and clustering techniques [16] The introduction of deep learning in the 2010s marked a paradigm shift, enabling the integration of complex data types such as satellite imagery and time-series data. In recent years, with better computational powers, ML methods like Random Forests and Artificial Neural Network have gained popularity, enhancing model accuracy and reliability [[4].

Remote sensing has enabled access to high-resolution spatial data, enhancing predictions of crop health and productivity. Techniques like spectral analysis and temporal image classification are integrated with ML for real-time insights [17], [18]. Several types of ML methods are used for crop yield estimation, each suited to specific data types, complexity levels, and prediction goals. These methods can be broadly categorized as supervised, unsupervised, and hybrid approaches.

**(a) Supervised methods**

In the supervised learning approach, the model is trained on labeled data, meaning that the input features (e.g., weather, soil, and management data) are paired with corresponding outputs (crop yields). This method is widely used in crop yield estimation due to its ability to provide precise and interpretable predictions. Key supervised methods include regression models, tree-based methods and neural networks.

***Regression models***

Regression models for crop yield estimation include linear regression, polynomial regression and support vector regression. Linear regression assumes a linear relationship between input features and crop yield and is used for estimating crop yield based on a few dominant factors like temperature and rainfall. Polynomial regression extends linear regression by incorporating polynomial terms to capture non-linear relationships, such as the effect of increasing fertilizer levels on crop yield. Support vector regression uses kernel functions to map inputs into higher-dimensional spaces and is useful for handling complex, non-linear relationships between environmental factors and crop productivity.

***Tree-based methods***

Tree-based methods rely on decision tree structures to predict crop yields and are particularly effective for handling non-linear relationships, heterogeneous datasets, and complex interactions between variables such as weather, soil, and management practices. A decision tree divides data into subsets by repeatedly splitting it based on feature thresholds. Each split minimizes a loss function (e.g., mean squared error for regression) and predictions are made by averaging the output of the samples in each terminal node. Tree-based methods include decision tree regression, random forests and Gradient Boosting Machines (GBM). Random forest work as an ensemble of multiple decision trees trained on bootstrapped samples of the dataset. Each tree makes a prediction, and the final output is the average (for regression) or majority vote (for classification). Random forest reduces overfitting compared to single decision trees and handles missing data and outliers well. GBM builds trees sequentially, where each new tree corrects the errors made by previous trees. It focuses on the hardest-to-predict samples in each iteration by assigning higher weights. Popular variants of GBM are XGBoost, LightGBM, and CatBoost.

***Neural networks***

Neural networks are inspired by the structure and functioning of the human brain. They consist of interconnected layers of nodes (also called neurons) that process and analyze complex patterns in data. Neurons are the basic computational unit in a neural network, performing operations like weighted summation and activation. Data flows through layers (input - intermediate hidden layers - output), and each neuron computes a weighted sum of inputs, applies an activation function, and passes the result to the next layer. The difference between the predicted output and the actual value is measured using a loss function. The network updates its weights to minimize the loss using a method called gradient descent and the process is repeated for multiple iterations until the loss converges to a minimum or a stopping criterion is met. Types of neural networks for crop yield estimation include Feedforward Neural Networks (FNNs), Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), Long Short-Term Memory Networks (LSTMs), and Deep Neural Networks (DNNs).

**(b) Unsupervised methods**

Unsupervised approach identifies hidden patterns or clusters in data with no labels. It groups data points with similar features using clustering approach or simplifies complex datasets while retaining essential information through dimensionality reduction. These methods identify patterns, structures, or groupings within the data, making them useful for exploratory analysis, dimensionality reduction, and feature extraction in crop yield estimation and can be used when historical yield data is unavailable.

***Clustering methods***

Data points (e.g., regions, farms, or crops) are grouped into clusters based on similarity metrics such as Euclidean distance or cosine similarity and each cluster represents a set of similar conditions or patterns affecting yield. Common algorithms include k-means clustering, which divides data into clusters by minimizing intra-cluster variance; hierarchical clustering, which builds a tree of clusters based on nested groupings; and DBSCAN (Density-Based Spatial Clustering of Applications with Noise), which groups dense regions while treating sparse regions as outliers.

***Dimensionality reduction***

These methods compress high-dimensional data into fewer dimensions for easier visualization and processing and are useful for datasets with numerous features such as remote sensing images. Common techniques include Principal Component Analysis (PCA), t-Distributed Stochastic Neighbor Embedding (t-SNE) and Autoencoders. PCA projects data onto components that capture the maximum variance and is useful for extracting the relevant data. T-SNE is a non-linear technique for visualizing high-dimensional data in 2D or 3D [19]. Autoencoders are neural networks designed for data compression and reconstruction.

**(c) Hybrid methods**

Hybrid machine learning methods combine multiple approaches or algorithms to improve prediction accuracy, robustness, and generalizability. These methods integrate the strengths of different models, such as supervised, unsupervised, and deep learning techniques, to handle the complexities of crop yield estimation, which involves diverse datasets, non-linear relationships, and multi-source data. It combines the strengths of different algorithms to reduce errors while increasing computational time due to use of multiple models. Examples of hybrid methods include ensemble approach which combines multiple models to develop a single, more accurate prediction. Deep hybrid models integrate deep learning models like CNNs or LSTM networks with traditional machine learning techniques. A combination of unsupervised and supervised learning is also used to preprocess data or extract features using unsupervised method, followed by supervised learning for yield prediction. Traditional statistical methods are also combined with machine learning to improve interpretation capability and accuracy of prediction.

In recent years, ML techniques have been widely used to achieve accurate yield prediction for different crops [17], [20], [21], [22], [23]. The most popular ML method utilized in agricultural yield prediction is Random Forest followed by ANN (Fig. 2). Deep learning algorithms like CNN, LSTM, and DNN are also increasingly utilized for crop yield prediction and are often combined, particularly when utilizing remote sensing data [4].

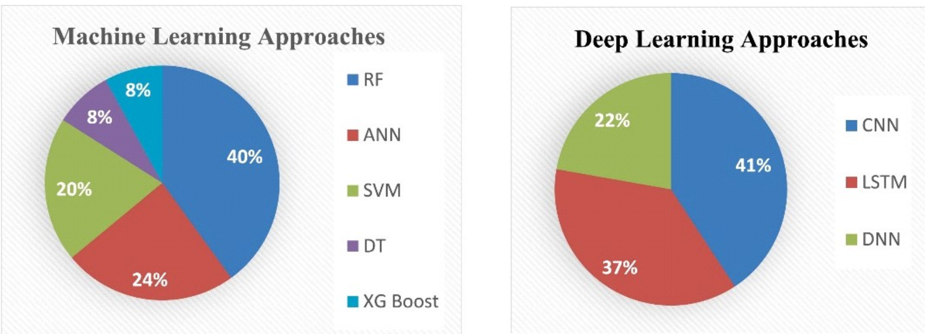


**Figure 2.** Use of ML techniques for crop yield estimation based on review of literature by Jabed & Murad [4]

**Applications in crop insurance**

Agriculture is prone to multiple risks due to unforeseen circumstances and globally, crop insurance has become an indispensable risk management tool to minimize losses. In Europe, the European Commission's Joint Research Centre (JRC) utilizes the MARS (Monitoring Agricultural Resources) Crop Yield Forecasting System (MCYFS) to provide timely forecasts of crop yields for the European Union. For the sustainable management of the agricultural market of the EU, the JRC has been making in-season forecasts of expected crop yield for the major crops in the European Union (EU) Member States (MS) since 1993 [24].

In the United States, the Federal Crop Insurance Program (FCIP) under the U.S. Department of Agriculture (USDA), provides subsidized insurance to farmers, covering both yield losses and revenue shortfalls [25]. It uses historical weather data to assess risk and premiums, Remote Sensing imagery for monitoring crop health and detecting adverse conditions, and yield modeling using Regression models for predicting average yields. Machine learning techniques for integrating soil, weather, and management data coupled with bid data analytics for aggregation of historical claims, yield data and market trends for risk assessment are also utilized.

In Canada, a government-supported insurance program (AgriInsurance) covering yield reductions, quality losses, and specific perils like drought and frost is implemented utilizing high-resolution satellite images to monitor crop growth stages and detect anomalies and risk assessment models to calculate premiums [26]. Geospatial analysis is used for regional risk profiling.

China's National Agricultural Insurance Program focuses on providing risk coverage to farmers, with heavy subsidies from the government [27]. Satellite Data and AI is used for monitoring crop growth and detecting adverse events. Weather and vegetation indices are used for estimating losses and insurance payouts.

GEOGLAM is the Group on Earth Observations Global Agricultural Monitoring Initiative. It is an international G20-endorsed program geared toward enhancing the use of Earth observations (EO) to strengthen decision-making, action-making, and policy in terms of food security and sustainable agriculture. The main objective of this initiative is to leverage and build upon existing models, programs using Earth observation technologies, capacity development, monitoring, and development activities. The EO data is effectively helpful for monitoring agricultural conditions globally [28]

**Crop insurance in India: Pradhan Mantri Fasal Bima Yojana (PMFBY)**

Indian agriculture is highly unpredictable due to the large dependence on weather for harvesting good yields. Most of the farmers in India are small and marginal farmers who are prone to greater risk due to adversities in weather. Better management of agricultural risks is the need of the hour to address the challenges involved with food and income security. The Pradhan Mantri Fasal Bima Yojana (PMFBY) is an area yield index insurance scheme implemented in the country since kharif 2016 that has many features to compensate farmers for multiple risks within the crop season. The Department of Agriculture and Farmer's Welfare (DA&FW), Government of India is the nodal agency for implementation of the scheme in the country with the mandate of utilizing technological solutions. Remote sensing, mobile applications and data analytics are used for implementing the scheme effectively in all states of the country.

The scheme adopts an area approach, identifying an Insurance Unit (IU) as the basic unit for crop yield estimates. Crop yields for the current and past years are the basis for crop loss assessment and associated indemnity pay-outs. Crop yield estimation was estimated through Crop Cutting Experiments (CCEs) conducted at the IU level by manually measuring yields at random points within the IU. This method is prone to subjectiveness and leads to higher standard error of estimates. This challenge is sought to be overcome using technology for estimation of crop yields. Satellite data, long-term weather datasets and scientific collection of CCEs through mobile apps is recognized and promoted under the PMFBY.

During 2016-2022, DA&FW with the collaboration of Mahalonobis National Crop Forecast Centre (MNCFC) engaged various technical agencies/experts/research institutes conducted various pilot studies in different parts of the country to check the feasibility and accuracy of utilizing innovative technology-based methods for crop yield estimation. These pilot studies helped to assess the best available methodology/strategy for implementing technology-based yield estimation at the IU level with the best accuracy. Pilot studies were conducted during the kharif and rabi seasons in 2019-20 and after detailed analysis and comparison of results, the expert committee recommended technology-based yield estimation for two crops – paddy and wheat at the national level. Pilots for other crops were conducted in kharif 2022 and rabi 2022-23. Extended pilots for selected crops will be initiated in the upcoming seasons to bring in more crops for technology-based yield estimation under PMFBY.

Since kharif 2023, to promote the large-scale adoption of technology in insurance sector and decrease biasness due to subjectiveness, the Government of India has initiated the Yield Estimation System based on TECHnology (YES-TECH) under PMFBY. YES-TECH advocates the blended use of modelled yield estimates and CCE data for insurance claim assessment. Five models have been suggested under the YES-TECH framework and states are free to choose their model based on consultation with their mentoring institutions. The models under YES-TECH are:

- Semi-Physical Model
- AI/ML Model
- Crop Simulation Model
- Ensemble Model
- Parametric Index of crop performance

All models require the use of datasets relevant to the approach adopted from remote sensing data or ground based sensors. The semi-physical model is based on the Radiation Use Efficiency (RUE) Model of Monteith. Parameters required include crop planting/harvest dates, water and temperature stress. Satellite derived vegetation indices, meteorological data, hydrological variables and edaphic factors are used in the AI/ML models. Crop Simulation models need intensive parameterization from genetic characteristics of the crop, crop management practices, pest/disease occurrences besides meteorological and edaphic data. The ensemble approach can be done through various techniques to estimate yields. The parametric index is a compositive index of crop health incorporating multiple physical and biophysical parameters estimated from satellite and weather datasets. The ensemble method is preferred owing to its increased accuracy, reduced variance for predictions and improved generalization.

Currently, 14 states in the country have implemented or are in the process of implementing YES-TECH under PMFBY. The states select a Technology Implementation Partner (TIP) for implementing the program and a mentor Agency (MITR) for monitoring and evaluation of results of the models. The YES-ECH Committee is responsible for overall execution and monitoring of the program as MNCFC functions as the secretariat of the YES-TECH Committee for all related activities.

**Conclusion**

Machine learning has transformed crop yield estimation, offering tools to enhance productivity, optimize resource use, and mitigate climate risks. By aligning global advancements with local needs, countries like India can harness the full potential of ML, ensuring sustainable agricultural practices and food security for future generations. These advancements have significantly enhanced the reliability of crop insurance systems, offering data-driven solutions for risk assessment and claim settlement. By leveraging diverse data sources, including satellite imagery, weather patterns, and historical yields, ML models provide insights that support both farmers and insurers in mitigating risks associated with climate variability and crop failures. As these technologies continue to evolve, hybrid models, combining domain knowledge and data-driven techniques, hold promise for further improving prediction accuracy and adaptability. ●●

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# Frontier Geospatial Technologies for Climate-Responsive Agriculture

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**"This evolution in agricultural technology represents a significant departure from traditional farming methods, offering new possibilities for enhancing agricultural resilience while optimizing resource use efficiency."**

In the era of escalated environmental challenges and technological advancement, the integration of space technology with agrometeorology has emerged as a transformative force in modern agriculture. As global food systems face mounting pressures from climate change, population growth, and resource constraints, the need for precise, data-driven agricultural practices has never been more critical. Geospatial technology, encompassing satellite remote sensing, geographic information systems (GIS), and global positioning systems (GPS), has enhanced our ability to monitor, analyse, and manage agricultural systems with unprecedented accuracy and scope. This technological integration has fundamentally altered how we understand and respond to weather patterns, climate variability, and their impacts on agricultural productivity. The advent of high-resolution satellite imagery, coupled with advanced data analytics and artificial intelligence, has enabled farmers and researchers to gain deep insights into crop conditions, soil health, and meteorological patterns at multiple spatial and temporal scales. This evolution in agricultural technology represents a significant departure from traditional farming methods, offering new possibilities for enhancing agricultural resilience while optimizing resource use efficiency. The convergence of geospatial tools with agrometeorology has created a robust framework for precision agriculture, enabling site-specific management practices that account for spatial and temporal variability in environmental conditions. These advances are particularly significant in the context of climate change adaptation, where the ability to predict and respond to weather extremes can mean the difference between crop success and failure. Furthermore, the adaptability of space technology through mobile applications and web-based platforms has made sophisticated agricultural decision support tools accessible to farmers across different scales of operation, from smallholder farmers in developing regions to large-scale commercial operations in industrialized nations. This technological revolution in agriculture not only enhances productivity and resource efficiency but also contributes to the broader goals of sustainable agriculture and food security. As we continue to face increasingly complex agricultural challenges, the role of geospatial technology in agrometeorology becomes ever more crucial in building resilient and sustainable food systems for future generations.

**Weather monitoring and forecasting**

Satellite technology has improved the accuracy of weather monitoring and forecasting capabilities through an extensive network of advanced space-based observation systems. These satellites, equipped with advanced sensors, continuously track atmospheric conditions, greenhouse gas (GHG) accumulation, and other vital parameters, providing real-time information on temperature variations, precipitation patterns, soil moisture distributions and GHG concentrations that directly impact agricultural productivity. The integration of data from multiple satellite platforms has significantly enhanced the accuracy of weather forecasting models, which are essential for crop management and risk mitigation strategies. This technological advancement is key in identifying regions vulnerable to droughts or flooding, allowing governments and farmers to take proactive measures.

The global network of meteorological satellites has created an intricate web of environmental surveillance, with platforms like INSAT-3D, NASA's Atmospheric Infrared Sounder (AIRS), and NOAA's AMSU-A delivering detailed temperature mapping across diverse geographical regions. Precipitation monitoring has witnessed a remarkable evolution with the deployment of specialized satellite missions like the Global Precipitation Measurement (GPM) and the Tropical Rainfall Measuring Mission (TRMM), developed through collaboration between NASA and JAXA. These missions have increased our ability to track global precipitation patterns in near-real-time, providing crucial insights for agricultural planning and water resource management. The GPM mission, with its innovative dual-frequency radar system, represents a significant leap forward in precipitation monitoring technology, offering unprecedented accuracy in rainfall predictions and enabling more effective drought monitoring and irrigation planning,as highlighted in Figure 1.

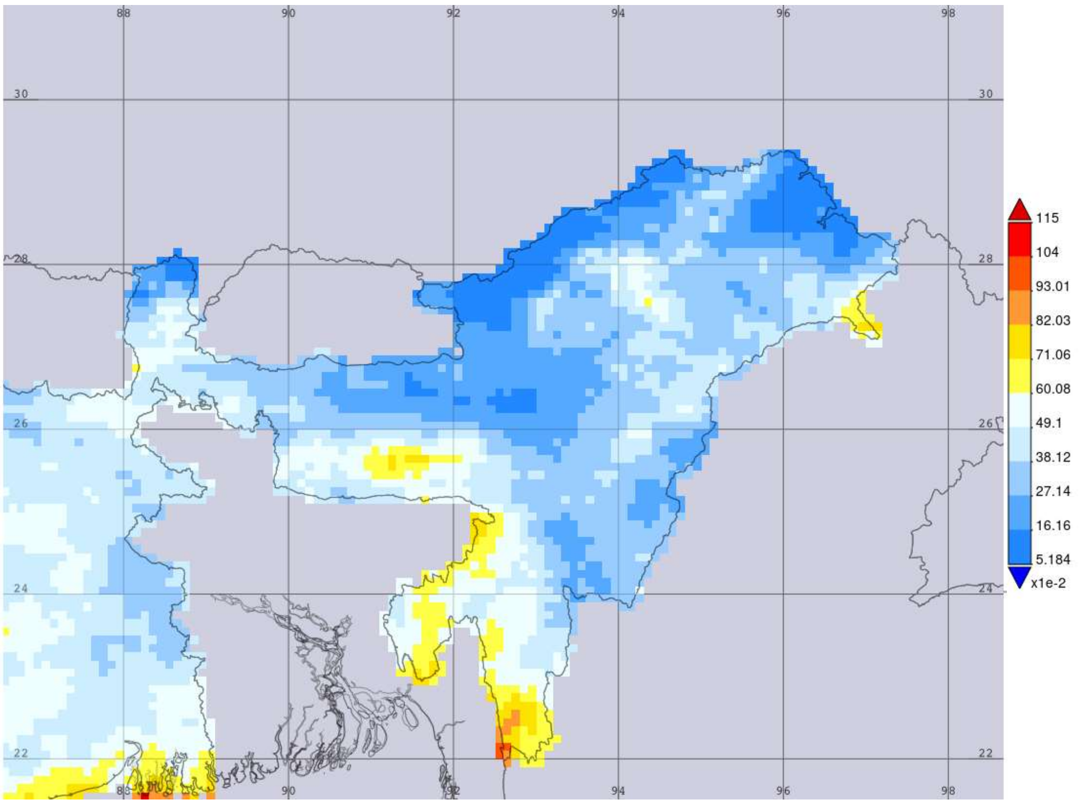

**Figure 1.** Time-averagedmap of precipitation estimate (inch/day) over North East Indiafrom 01-09-2024 to 01-10-2024 (Source: Global Precipitation measurememt, NASA Earthdata)

The accumulation of GHG in the atmosphere is one of the main drivers of climate change, affecting both natural ecosystems and agricultural productivity. Carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) contribute to rising global temperatures, altering weather patterns and increasing the frequency of extreme climate events. The role of satellites in monitoring greenhouse gas concentrations has become increasingly critical as agriculture grapples with the challenges of climate change. Advanced platforms such as NASA's Orbiting Carbon Observatory-2 (OCO-2) (Figure 2) and the European Space Agency's Sentinel-5P provide detailed measurements of these GHGs. These observations are instrumental in understanding the complex relationships between GHG accumulation, changing weather patterns, and crop productivity that help in developing strategies to mitigate the impact of climate change on farming systems while adapting agricultural practices to evolving environmental conditions.

**Figure 2.** Global daily average map of assimilated Carbon Dioxide from Orbiting Carbon Observatory -2 (OCO-2) satellite (Source: NASA Earthdata)

Soil moisture monitoring through satellite technology has emerged as a game-changer in agricultural water management. Specialized missions like NASA's Soil Moisture Active Passive (SMAP), Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) etc. provide high-resolution data that enables precise tracking of soil moisture levels across vast agricultural regions. This information has proven invaluable in optimizing irrigation practices, conserving water resources, and enhancing crop resilience in water-stressed areas. Integrating soil moisture data with other meteorological parameters has led to more sophisticated drought prediction models and improved agricultural planning capabilities. The global monthly volumetric soil moisture map generated from AMSR2 satellite is illustrated in Figure 3.

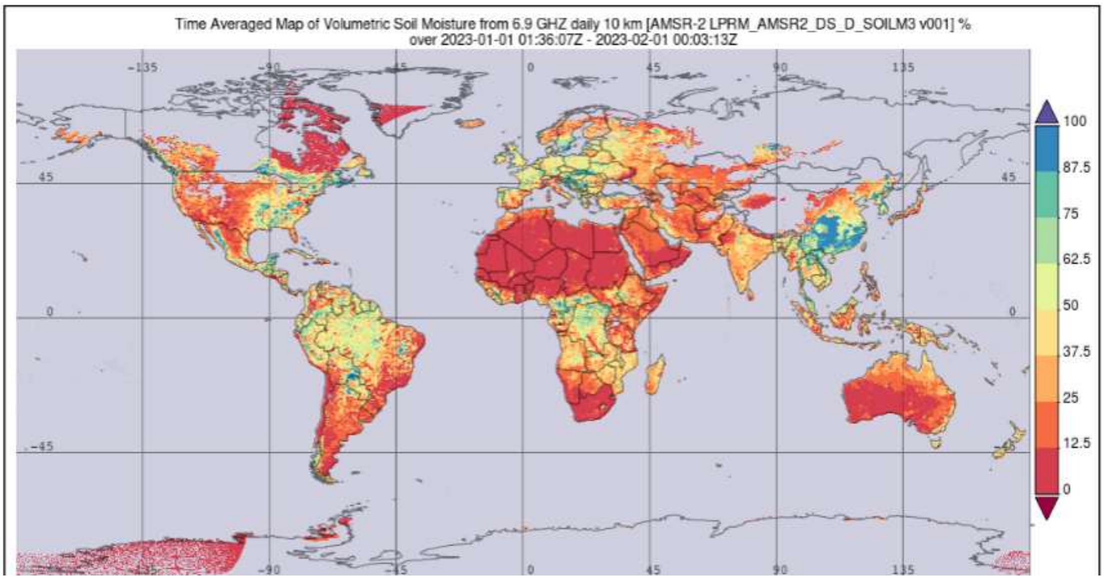


**Figure 3.** Global monthly volumetric soil moisture (in %) map from AMSR2 Satellite (Source: NASA Earthdata)

The advent of LiDAR (Light Detection and Ranging) technology has added another dimension to atmospheric monitoring capabilities. Missions like NASA's CALIPSO provide detailed vertical profiles of atmospheric parameters, including aerosol distribution, temperature gradients, and wind patterns. This technology has enhanced our understanding of air quality impacts on agriculture and improved our ability to predict weather patterns that affect farming operations. Moreover, the accessibility of these satellite data through platforms like NASA Earthdata, India's Bhuvan, and MOSDAC has democratized access to critical climate information, enabling researchers and policymakers to develop more effective farming strategies.

India's contributions to space-based weather monitoring through its Earth Observation Satellite (EOS) series have significantly enhanced regional meteorological capabilities. Satellites like Oceansat-2, Megha-Tropiques, SCATSAT-1, and INSAT-3D form a comprehensive network for monitoring ocean-atmosphere interactions and regional weather patterns. These missions have strengthened India's competences for weather forecasting and provided valuable support to the agricultural sector in adapting to changing climatic conditions. The integration of data from these satellites with global observation networks has created a robust system for weather monitoring and agricultural planning, demonstrating the power of international collaboration in advancing agrometeorology.

**Crop monitoring and yield prediction**

Now-a-days effective crop monitoring and yield prediction are strengthened by utilizing satellite-derived weather variables, which provide real-time, high-resolution information on various environmental factors. These variables, including temperature, precipitation, humidity, solar radiation, and wind patterns, significantly influence crop growth and productivity. By continuously monitoring these weather parameters, early detection of potential stress factors such as drought, excessive rainfall, or temperature fluctuations, timely interventions can be implemented to protect crop health and maximize yield potential.

Remote sensing technology, with near real-time weather data, enhances the accuracy of crop health assessments. Multispectral and hyperspectral imaging techniques detect subtle variations in vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), which reflect changes in photosynthetic activity, biomass accumulation, and stress conditions (Figure 4). These insights help identify early signs of water stress, nutrient deficiencies, and disease outbreaks, enabling precise and timely responses to mitigate potential yield losses. The ability to monitor crop conditions across vast agricultural landscapes ensures a proactive approach to farm management, reducing risks and optimizing resource utilization.

Artificial intelligence and machine learning algorithms further improve the processing and interpretation of the satellite-derived weather data for crop monitoring. By analyzing historical climate patterns alongside real-time satellite observations, these advanced computational tools identify trends, predict weather impacts on crop growth, and generate reliable yield forecasts. This predictive capability supports decision-making in agricultural planning, helping farmers adjust sowing schedules, irrigation management, and fertilizer applications based on anticipated weather conditions.

The integration of GPS technology with daily weather analysis has strengthened precision agriculture by providing detail insights into spatial variations in soil moisture, temperature fluctuations, and nutrient distribution. This information supports site-specific management practices, ensuring that water and fertilizers are applied efficiently, reducing wastage, and improving overall crop productivity. Moreover, real-time weather tracking enables adaptive responses to changing climatic conditions, minimizing the impact of adverse weather events on agricultural output. Monitoring of the long-term impacts of changing weather patterns on crop productivity, helps in developing resilient farming practices. The ability to track extreme weather events, such as heatwaves, storms, and droughts, allows for proactive risk management, ensuring that crops receive adequate protection through timely interventions. Additionally, integrating climate models with crop monitoring systems improves the accuracy of yield predictions, supporting food security planning and market analysis at regional and global levels.

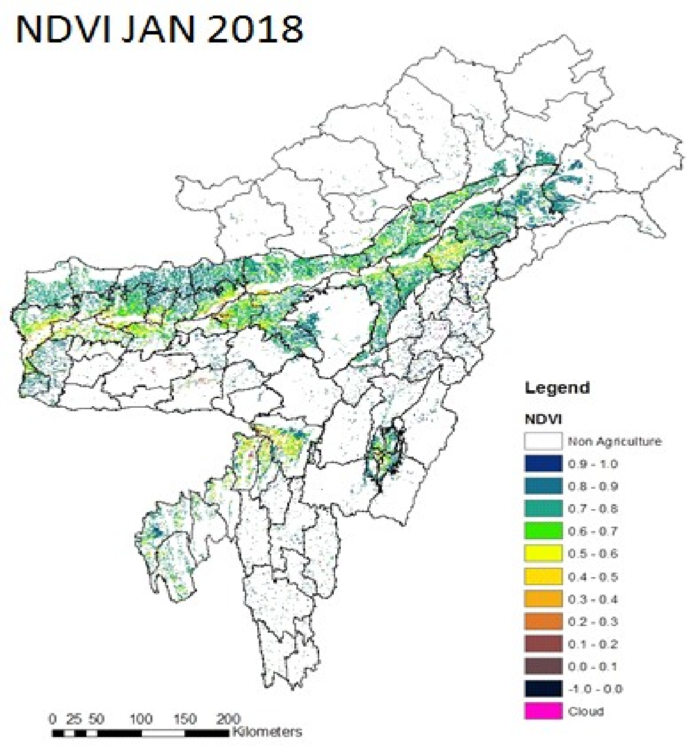


**Figure 4.** NDVI map in agricultural area of North Eastern Region of India

## Agro-advisory services

Recently, various weather parameters are effectively retrieved using data from optical, thermal-infrared (IR), and microwave remote sensing technologies. The integration of multispectral remote sensing with narrow-band spectral reflectances has proven valuable in providing accurate land surface albedo measurements, which plays a crucial role in understanding energy balance and climatic interactions at the Earth's surface.Agro-Ecological Zoning (AEZ) is a fundamental approach to agricultural development planning, as the viability and success of specific land use systems are directly dependent it. Remote sensing technologies play a pivotal role in implementing AEZ by providing essential data required for mapping and analyzing the biophysical and ecological characteristics of agricultural landscapes.Physiographic, soil, climate, and agroclimatic indices maps are critical information to define the agroclimatic zone. Each zone illustrates the land use and land cover at different elevations, soil types with important climatic information for any developmental planning by careful assessment of agro-climatic resources.By integrating satellite-based observations with agro-climatic data, soil properties, land suitability, and climatic variationscan be assessed, which are crucial for determining the best land-use practices.

The accurate estimation of evapotranspiration (ET) is critical for understanding the regional water balance and managing water resources effectively for agricultural, hydrological, and environmental applications. Temperature significantly influences ET, and its spatial variation must be thoroughly analysed for precise calculations. The empirical relationship between long-term temperature trends and the digital elevation model (DEM) within a Geographic Information System (GIS) framework facilitates the depiction of spatial variations in both monthly and annual mean temperatures. These temperature variations are then used to compute spatial Potential Evapotranspiration (PET) and Available Soil Water Capacity (ASWC). Combined with information on soil properties and prevailing land-use practices, these datasets contribute to characterizing regional climates and improving water resource management strategies.Remote sensing based agroclimatic characterization for Champhai district of Mizoram is shown below in Figure 5 and Table 1.

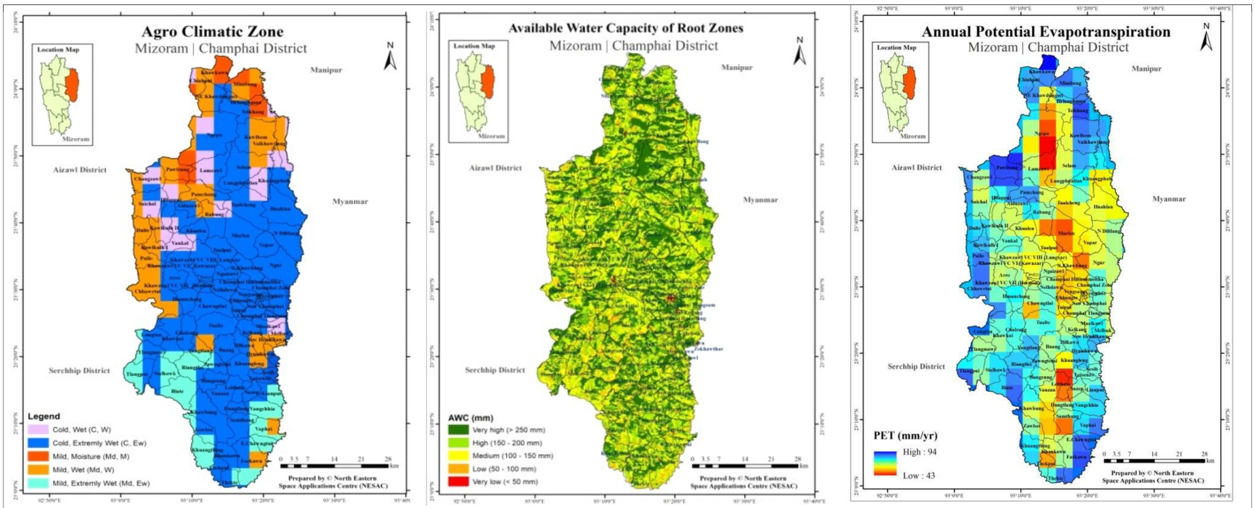


**Figure 5.** Agroclimatic zone (a), Available Water capacity (b) and Annual Potential Evapotranspiration Map of Champhai district of Mizoram

The detection of plant stress due to abiotic factors such as extreme temperatures, drought, frost, flooding, salinity, and heavy metal contamination, as well as biotic factors including diseases and pest infestations, is essential for ensuring sustainable crop production. Plants exhibit distinct physiological and biochemical responses under stress conditions, often leading to disruptions in their ability to convert photosynthetically active radiation (PAR) into biomass. This reduction in efficiency can be attributed to diminished chlorophyll levels and alterations in the plant's internal structure. Healthy vegetation typically exhibits higher reflectance in the near-infrared spectrum and lower reflectance in the visible spectrum, whereas stressed crops show the opposite pattern. These spectral characteristics enable the identification of healthy and stressed crops using remote sensing techniques. Various satellite-derived products, including the NDVI, land surface temperature (LST), and ET, play an instrumental role in assessing water and vegetation stress. These tools are particularly beneficial for effective irrigation scheduling and optimizing crop management practices. By continuously monitoring these parameters, farmers and agricultural planners can take required interventions, ensuring that crops receive adequate moisture at critical growth stages while minimizing water wastage. The ability to detect early signs of plant stress through satellite remote sensing allows for timely interventions, thereby mitigating potential yield losses and improving overall agricultural sustainability.

**Table 1.** Agro- climatic characterizationof Champhai district of Mizoram

| Zone | LULC | Texture | AWC (mm) | LGP (Days) | Elevation (m) |
|---|---|---|---|---|---|
| Cold, Wet (C,W) | Forest (72.37%), Shifting cultivation (12.72%), Scrub land (11.84%), Agriculture (2.43%), Builtup and other areas (0.63%) | Sandy Clay Loam (38.7%), Light Clay (27.38%), Clay Loam (25.94%) | VH (37.72%), M (33.89%), H (23.26%) | 300 (62.8%), 270 (37.19 %) | 800-1600 (51.64%), 400-800 (37.1%) |
| Cold, Extremely Wet (C, Ew) | Forest (77.08%), Shifting cultivation (11.587%), Scrub land (6.76%), Agriculture (3.45%), Builtup and other areas (1.12%) | Sandy Clay Loam (40.74%), Light Clay (33.19%), Clay Loam (21.53%) | VH (40.34%), M (31.63%), H (22.15%), | 300 (86.84 %) | 800-1600 (49.19%), 2000-2094 (32.54%), 400-800 (13.71%) |
| Mild, Moist (Md, M) | Forest (68.16%), Shifting cultivation (19.45%), Scrub land (10.29%), Agriculture (1.31%), Builtup and other areas (0.79%) | Sandy Clay Loam (37.21%), Clay Loam (31.07%), Light Clay (23.74%) | VH (45.48%), M (28.01%), H (20.77%), | 270 (100%) | 400-800 (57.51%), 800-1600 (31.06%) |
| Mild, Wet (Md, W) | Forest (77.17%), Shifting cultivation (13.28%), Scrub land (6.8%), Agriculture (1.85%), Builtup and other areas (0.9%) | Sandy Clay Loam (36.84%), Clay Loam (31.54%), Light Clay (25.92%) | VH (38.23%), M (34.81%), H (20.95%), | 270 (46.18 %), 300 (44.36 %) | 800-1600 (43.92%), 400-800 (43.43%) |
| Mild, Extremely Wet (Md, Ew) | Forest (72.64%), Shifting cultivation (16.27%), Scrub land (7.66%), Agriculture (2.18%), Builtup and other areas (1.23%) | Sandy Clay Loam (35%), Clay Loam (32.43%), Light Clay (25.27%) | M (35.87%), VH (30.03%), H (23.38%), | 300 (55.23 %), 240 (25.04 %), 270 (19.72 %) | 800-1600 (49.01%), 400-800 (34.87%), 1600-2094 (13.68%) |

The applications ofthe mobile app-based approach have further enhanced the accessibility and utility of agrometeorological data for farmers. These applications facilitate the archiving of spatial and temporal information on prevailing crop conditions and location-specific disease and pest infestations. The detection of crop growth stages and the provision of crop-specific agrometeorological advisories are crucial in minimizing the adverse impacts of weather anomalies and pest outbreaks on agricultural productivity. By this mobile technology, farmers can receive real-time guidance on best management practices,enabling them to take preventive measures and optimize resource allocation.One notable advancement is the development of "AASMAN" (Agromet Advisory Services and Management of Farm Resources) mobile application. This app has been designed to provide farmers with seamless and timely access to agrometeorological services directly on their mobile devices (Figure 6). AASMAN integrates weather forecasts from the India Meteorological Department (IMD), along with weather and pest warnings, a fertilizer calculator, a pesticide calculator, and crop-specific advisories tailored to different agricultural zones.


**Figure 6.** AASMAN mobile app for agro-advisory services

**Precision agriculture**

Significance of satellite-based precision agriculture lies in the sophisticated network of Earth observation satellites that continuously monitor our planet. This constant stream of data has become the cornerstone of modern precision farming techniques.Weather patterns and their impact on agriculture have always been at the forefront of farmers' concerns. Satellite meteorology addresses these concerns by providing accurate, timely weather forecasts and monitoring capabilities. Through the analysis of atmospheric conditions, cloud formations, and precipitation patterns, prediction of weather events with greater accuracy are now possible. This predictive capability allows for better planning of crucial farming operations such as planting, irrigation, fertilizer application, and harvesting. Detail maps showing the variations in soil moisture, crop health, and field conditions across the agricultural land are now generated through the analysis of time-series satellite imagery, reveal patterns and anomalies that might be invisible to the naked eye. One of the most significant advantages of satellite meteorology in precision agriculture is its ability to support agro-input management. By combining weather forecasts with soil measurements, such as nutrient availability, moisture content etc. derived from satellite data, scheduling of irrigation, fertigation, plant protection measures canbe optimized.

Climate change has introduced new challenges to agriculture, making the role of satellite meteorology even more critical. Long-term satellite observations help track changing weather patterns, shifting growing seasons, and evolving pest pressures. This information enables to adapt cultural practices to changing conditions, selecting appropriate crop varieties and adjusting management strategies to maintain productivity in the face of environmental changes.The integration of satellite meteorology with other precision agriculture technologies is creating powerful synergies. Ground sensors, drones, and GPS-guided equipment work in concert with satellite data to provide a complete picture of agricultural operations. This multi-layered approach to precision agriculture is particularly effective in large-scale farming operations, where managing spatial variability is crucial for optimal productivity.

## Unmanned Aerial Vehicles (UAVs)

Aerial platforms, commonly known asUnmanned Aerial Vehicles (UAVs) or drones, serve as a vital bridge between satellite observations and ground-level measurements, offering unprecedented flexibility and detail in agricultural data collection. Their ability to operate at low altitudes while carrying sophisticated sensors has transformed how we validate and complement satellite-based observations. While satellites provide broad coverage of agricultural landscapes, their measurements often need verification at the field level. UAVs excel in this role, capable of collecting high-resolution data that can validate satellite observations of crop health, soil moisture, and other critical agricultural parameters as depicted in Figure 7 & 8. This validation process enhances the accuracy and reliability of satellite-based agricultural monitoring systems, making them more valuable for practical farming applications.

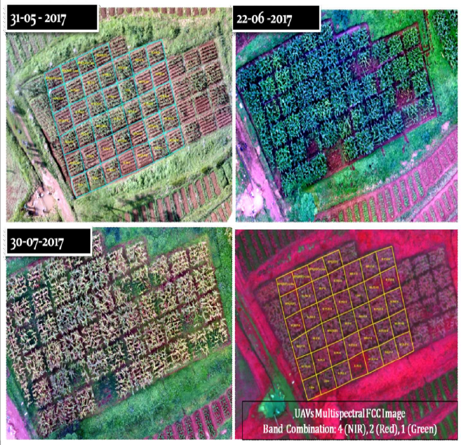


**Figure 7.** Temporal images of UAV for abiotic Stress Detection in *in-field* Maize

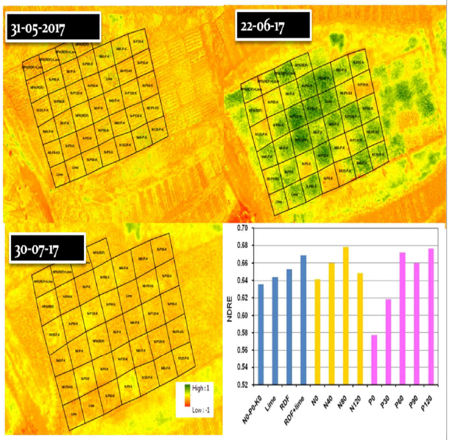


**Figure 8.** Normalized Difference RedEdge (NDRE) index-based crop health assessment using UAV data

The temporal and spatial flexibility of UAVs adds a new dimension to agro-meteorological observations. Unlike satellites that pass over an area at fixed intervals, drones can be deployed on-demand, and gather data whenever needed. This capability is particularly valuable during critical growth stages or when unexpected issues arise. The ability to quickly deploy UAVs complements satellite monitoring by providing immediate, detailed information that can guide time-sensitive farming decisions.One of the most significant contributions of UAVs lies in their capacity for detailed microclimate monitoring. Drones equipped with temperature, humidity, and wind sensors can map atmospheric conditions at various heights above crop canopies. This vertical profiling of the atmosphere provides crucial data for understanding local weather patterns and their effects on crop development. The evolution of sensor technology has greatly enhanced the capabilities of UAVs in agricultural applications. Modern drones can carry multispectral and hyperspectral cameras, thermal sensors, and LiDAR systems, enabling them to collect data that complements satellite measurements. These sensors can detect subtle variations in crop health, water stress, and nutrient deficiencies at resolutions far exceeding those possible with satellite imagery alone. When combined with satellite observations, this information creates a more comprehensive picture of the agricultural environment from ground level to the upper atmosphere.

## Climate resilient agriculture

Long-term geospatial datasets help analyse the impacts of climate change on agriculture and has emerged as a cornerstone technology in developing and maintaining climate resilient agriculture. Through continuous Earth observation and sophisticated data collection, these space-based systems provide crucial insights into changing weather patterns, temperature variations, and precipitation distributions that directly impact agricultural productivity. The technology's ability to monitor and analyse long-term climate trends, combined with real-time observations, helps in developing effective adaptation strategies for sustainable food production. These systems excel in multiple critical areas: precise temperature monitoring across vast agricultural landscapes, detailed tracking of precipitation patterns, early warning systems for extreme weather events, and comprehensive soil health assessment. The integration of this technology has transformed crop diversification strategies by helping in identification of suitable crops for different regions based on changing environmental conditions. Additionally, satellite data plays a vital role in agricultural expansion and site selection, particularly for horticultural crops, by analysing long-term climate trends and soil conditions to identify viable locations for farming ventures. The technology's capability to support climate-smart agriculture extends beyond adaptation to include mitigation strategies, helping farmers implement practices that enhance carbon sequestration while maintaining productivity. Cultivation of single, double and multiple crops in Assam was mapped using geospatial technology and illustrated in Figure 9. The integration of satellite data with climate modelling has significantly improved our ability to project future agricultural scenarios, enabling better planning and preparation for climate-related challenges. This comprehensive approach to agricultural monitoring and management, supported by continuous technological advancements in sensor technology and data processing capabilities, has become indispensable in building resilient agricultural systems capable of withstanding climate change impacts. As global agriculture faces increasing pressure from climate change, satellite-based agro-meteorology continues to evolve, offering more sophisticated tools and solutions for ensuring food security through climate-resilient farming practices.

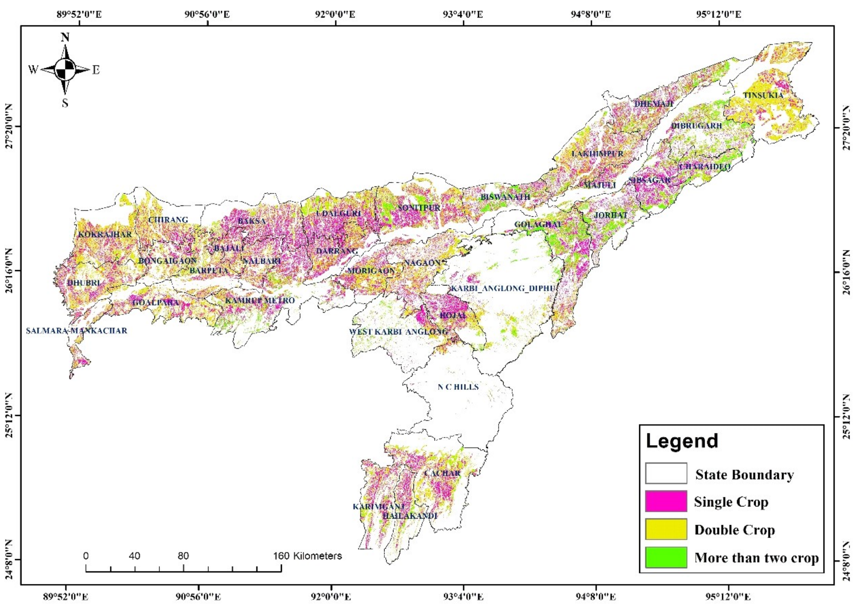


**Figure 9.** Cultivation of single, double and multiple crops in Assam during the year 2021-22

## Conclusion

Space technology-based agrometeorology represents a transformative advancement in modern agricultural practicesfor sustainable food production and climate resilience. This technological revolution has fundamentally altered how we monitor, analyze, and manage agricultural systems across multiple scales. Through the Earth observation systems, advanced sensor technologies, and integrated data analytics, we now possess unprecedented capabilities to address the complex challenges facing global agriculture in the 21st century.The synergy between various technological components - from satellite remote sensing and GPS to UAVs and mobile applications - has created a comprehensive framework for precision agriculture and climate-smart farming practices. This integration has proven particularly valuable in weather monitoring and forecasting, crop health assessment, yield prediction, and the delivery of targeted agro-advisory services. The ability to collect and analyse data at multiple spatial and temporal scales, combined with artificial intelligence and machine learning algorithms, has enhanced our capacity to make informed decisions about agricultural management and resource allocation.

Looking ahead, the continued advancement of satellite-based agro-meteorology, coupled with emerging technologies like UAVs and artificial intelligence, promises even greater possibilities for agricultural innovation and sustainability. As we face increasingly complex challenges from climate change and growing food demand, these supreme technology will become even more crucial in building resilient food systems. The success of this technological integration in agriculture demonstrates the potential for space-based technologies to contribute meaningfully to global food security while promoting environmental sustainability and climate resilience.

# Harnessing Frontier Technologies to Transform the Fisheries Industry in North East India

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**The fisheries industry in North East India is characterized by a large number of small-scale fishers and farmers, who face significant challenges in terms of low productivity, limited access to markets, and environmental degradation.**

**Abstract**

The fisheries industry in North East India is a vital sector that contributes significantly to the region's economy and food security. However, the industry faces numerous challenges, including low productivity, inefficient supply chains, and environmental degradation. This article explores the potential of frontier technologies, such as artificial intelligence, blockchain, and the Internet of Things (IoT), to transform the fisheries industry in North East India. We discuss the applications, benefits, and challenges of these technologies and propose a roadmap for their adoption in the region.

**Introduction**

It is projected that the global population will reach approximately 9.6 billion by the year 2050, and over 75% is expected to reside in urban areas. Consequently, there will be a growing need for food, particularly for animal protein. In this regard, aquaculture play a crucial role in satisfying the protein demand for the growing population. The fisheries industry in North East India is characterized by a large number of small-scale fishers and farmers, who face significant challenges in terms of low productivity, limited access to markets, and environmental degradation. The industry is also plagued by issues such as overfishing, bycatch, and discarding, which can have devastating impacts on the environment and the livelihoods of fishing communities. Nevertheless, traditional aquaculture, which includes extensive and intensive farming faces difficulties in meeting this demand due to increasing expenses, climate change and environmental pollution. This obstacles are further added with resource limitations, encompassing diminishing culturable land, restricted freshwater resources, soil deterioration and soil acidity. However, for sustainable, an aquaculture system must have ideally a positive impact on the environment while maintaining economic viability. Additionally, social acceptability is a crucial factor in sustainability, meaning that consumer acceptability should be greater for the produced product. Therefore, this arises the need to find, promote and use more sustainable aquaculture production models, including Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture System (RAS), Biofloc technology and Aquaponics, which could reduce pressure on natural resources and improve food supply (increased diversification in terms of species and trophic levels) adhering to circular economy principles. Adoptability to such sustainable aquaculture technology could harness the productivity at its best potential subjected to environmental concerns.

Frontier technologies, such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT), have the potential to transform the fisheries industry in North East India by improving efficiency, reducing waste, and promoting sustainability. In this article, we explore the applications, benefits, and challenges of these technologies and propose a roadmap for their adoption in the region. Other than the above mentioned technologies; considering species diversification, providing nutritionally balanced formulated feeds, disease management, ornamental fisheries, promoting wetland fisheries, polyploidy production and marker-assisted selective breeding could also help in enhancing the aquaculture production particularly in the Northeast India. Nevertheless, adopting and integrating the cut-out advanced technologies along with the traditional or intensive fish farming will imperatively increase the fisheries potential from the vast biological resources of Northeast India. Some of the frontier technologies suitable to harness productivity were discussed in this article:

**(A) Artificial Intelligence (AI):** AI has numerous applications in the fisheries industry, including:

- **Predictive analytics:** AI can be used to analyze data on fish populations, weather patterns, and ocean currents to predict the best fishing locations and times.
- **Image recognition:** AI-powered image recognition systems can be used to identify fish species, detect diseases, and monitor water quality.
- **Automated decision-making:** AI can be used to automate decision-making processes, such as determining the optimal fishing gear and techniques. The adoption of AI in the fisheries industry can bring numerous benefits, including:
- **Improved efficiency:** AI can help fishers and farmers to optimize their operations, reducing waste and improving productivity.
- **Enhanced sustainability:** AI can help to identify areas of high conservation value, allowing fishers and farmers to avoid damaging these areas.
- **Increased profitability:** AI can help fishers and farmers to improve their profitability by optimizing their operations and reducing costs.

**(B) Blockchain:** Blockchain technology has the potential to transform the fisheries industry by improving transparency, traceability, and accountability. Some potential applications of blockchain in the fisheries industry include:

- **Catch documentation:** Blockchain can be used to create a secure and transparent record of catch data, including the location, time, and species of fish caught.
- **Supply chain management:** Blockchain can be used to track the movement of fish and seafood products through the supply chain, improving transparency and accountability.
- **Certification and labelling:** Blockchain can be used to create secure and transparent certification and labelling schemes, allowing consumers to make informed choices about the seafood they buy.

The adoption of blockchain in the fisheries industry can bring numerous benefits, including:

- **Improved transparency:** Blockchain can help to improve transparency in the fisheries industry, allowing consumers to make informed choices about the seafood they buy.

- **Enhanced accountability:** Blockchain can help to improve accountability in the fisheries industry, allowing regulators and industry stakeholders to track the movement of fish and seafood products through the supply chain.
- **Increased profitability:** Blockchain can help to improve profitability in the fisheries industry by reducing costs and improving efficiency.

**(C) Internet of Things (IoT):** It refers to an internet-connected network of multiple physical devices that can collect and share data with minimal human intervention. IoT data analytics detects trends in data, extracts new insights on crop growth, livestock health, and potential process improvements, thereby facilitating effective problem solving and decision making with reduced human error. Some potential applications of IoT in the fisheries industry include:

- **Fisheries monitoring:** IoT sensors can be used to monitor fish populations, water quality, and weather patterns, providing valuable insights for fishers and farmers.
- **Aquaculture management:** IoT sensors can be used to monitor water quality, temperature, and other parameters in aquaculture systems, allowing farmers to optimize their operations.
- **Fishing gear management:** IoT sensors can be used to monitor the performance of fishing gear, allowing fishers to optimize their operations and reduce waste.

The adoption of IoT in the fisheries industry can bring numerous benefits, including:

- **Improved efficiency:** IoT can help to improve efficiency in the fisheries industry by optimizing operations and reducing waste.
- **Enhanced sustainability:** IoT can help to promote sustainability in the fisheries industry by monitoring fish populations, water quality, and weather patterns.
- **Increased profitability:** IoT can help to improve profitability in the fisheries industry by reducing costs and improving efficiency.

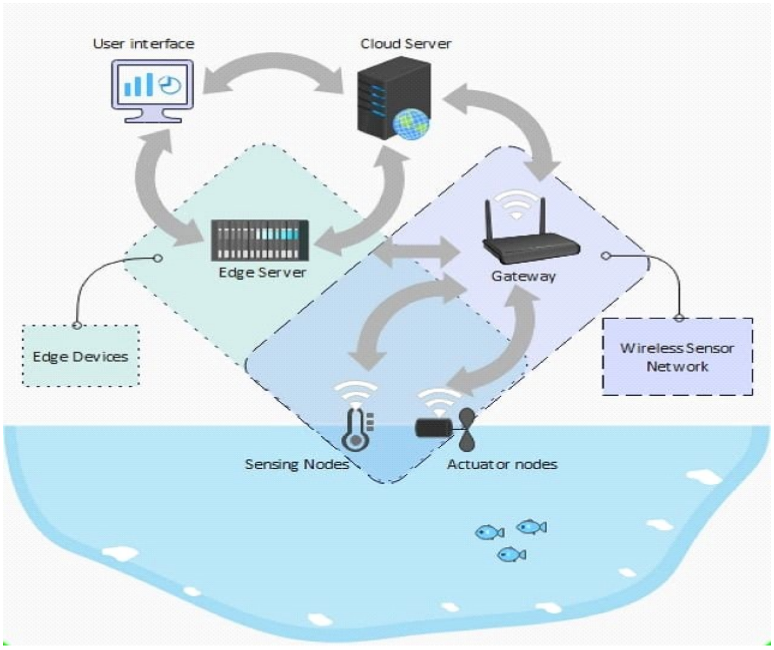



**Figure 1.** Artificial intelligence and IoT application for advanced aquaculture

(D) **Recirculatory aquaculture system (RAS):** RAS are tank-based aquaculture systems, where fish are farmed under controlled conditions. The major advantages of RAS include the usage of less water, biosecurity and high yield. Few major challenges, including insufficient knowledge about RAS technology, high energy requirement, high initial investment and difficulties in removing pathogens once entered the RAS. However, with the current knowledge and technologies of RAS, it is highly possible that on RAS farms, only the culture of high value fish species could make profit. To reduce the cost of RAS, it is essential for fish farmers, fish scientists and engineers to work together to design every part of the RAS stems effectively. RAS will revolutionize the aquaculture industry, especially for big cities and countries with limited water space for traditional aquaculture.

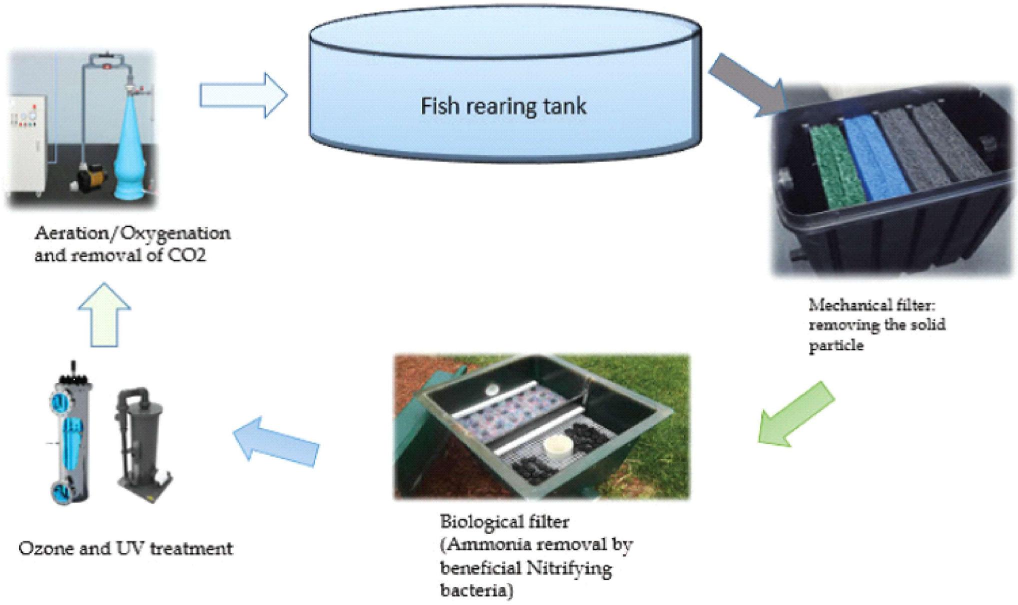



**Figure 2.** Recirculatory aquaculture system (RAS) for advanced aquaculture

(E) **Integrated multitrophic aquaculture system (IMTA):** Integrated multi-trophic aquaculture (IMTA) system based on a balanced ecosystem concept where waste from one system is input for other system within the same trophic structure. This farming method is different from finfish "polyculture", where the fishes share the same biological and chemical processes. Multi-trophic refers to the combination of species from different trophic levels in the same system. The multi-trophic sub-systems are integrated in IMTA that refers to the more intensive cultivation of the different species in proximity of each other, linked by nutrient and energy transfer through water. In IMTA systems, fed aquaculture species (e.g. shrimp or finfish) are cultured along with organic extractive species (e.g. suspension and/or deposit feeders) and/or inorganic extractive species (e.g. seaweeds or microalgae) with commercial value. Being cultured in the right proportions, the extractive species recycle nutrients that are being excreted by other species that otherwise would be lost in the system. Thus, multi-species models are being developed to predict optimized stocking densities and, at the same time, to allow an optimized nutrient removal from the water column, and to describe the ability of the system or the culture site to process excrement. This way, it is possible to maximize resource utilization while minimizing environmental impacts both increasing production and satisfying sustainability.

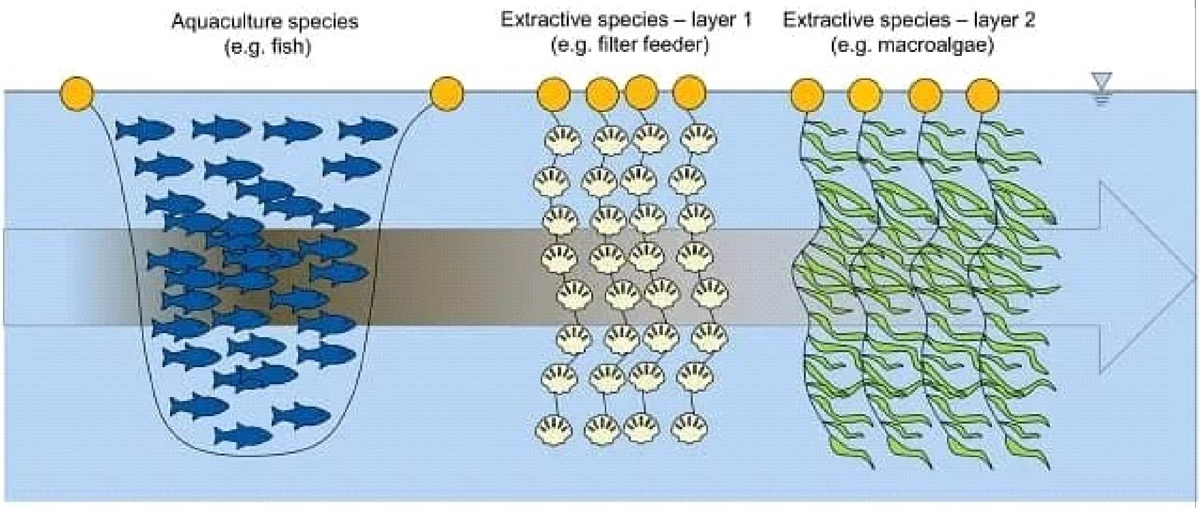



**Figure 3.** Integrated multi-trophic aquaculture (IMTA) aquaculture system

**(F) Aquaponics:** Potentializing the 'circular bio-based economy' concept, aquaponics has exhibited immense potential for reduced resource utilization, discharge mitigation, nutrient, energy, wastewater recycling, and production of highly nutritious food within the system. Aquaponics is a near zero discharge system where 90-95% of wastewater is reuse within the system thus facilitating better water management. Aquaponics integrates the recirculating aquaculture system (RAS) and the hydroponics (growing plants without soil), where the nutrient-rich effluent from the fish tank containing waste products of fish and uneaten feed serves as the main nutrient source for plants in the hydroponic bed and clear water is recirculated back to the culture tank with the help of tanks after oxygenated. Thus aquaponics led to production of both animal and agricultural commodities to harness maximum profit for the farmers. However, due to high increment of cost effectiveness and technical gap, adaptability to aquaponics in Northeast India is particularly limited and needs immediate technological intervention and awareness among the farmers.

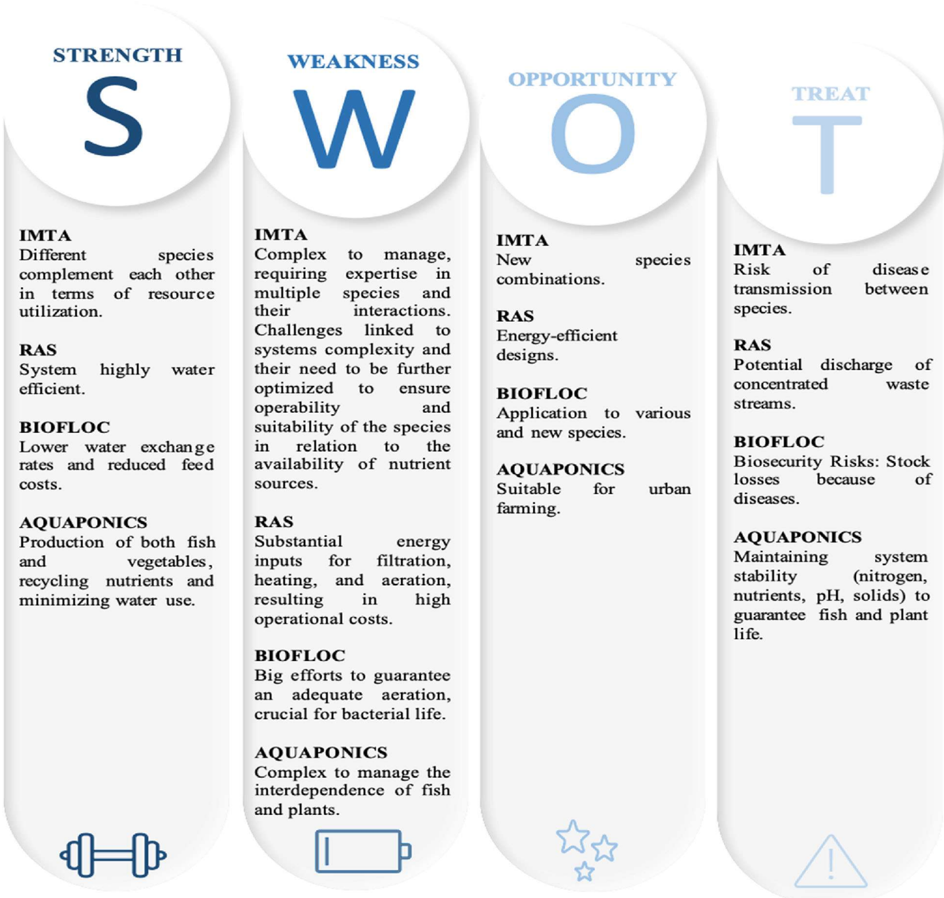
**(G) Biofloc (BFT):** BFT is an environment friendly aquaculture technique based on in-situ microorganism production. Biofloc is the suspended growth in ponds/tanks which is the aggregates of living and dead particulate organic matter, phytoplankton, bacteria and grazers of the bacteria. It is the utilization of microbial processes (nitrification) within the pond/tank itself to provide food resources for cultured organism while at the same time acts as a water treatment remedy.

This system is also called as active suspension ponds or heterotrophic ponds or even green soup ponds. The principle of the technique is to maintain the higher C-N ratio by adding carbohydrate source and the water quality is improved through the production of high quality single cell microbial protein. Biofloc system is most suitable for species that can tolerate high solids concentration in water and are generally tolerant of poor water quality.

**Figure 4.** Biofloc unit with high stocking density culture of fish

## Conclusion

Considering the immense potential to harness productivity from the vast water resources having significant faunal diversity of Northeast India; strategic implementation and adaptation of frontier aquaculture technologies will aid to enhance fisheries production at its potential. Further, adopting advanced technologies will led to the economic and social upliftment of the small and marginal fish farmers of Northeastern states of India and simultaneously promoting sustainable aquaculture production. However, providing appropriate technical guidance or assistance and front line demonstrations of these recent technologies will be a prerequisite for better acceptability and utility among farmers of Northeast India.●●



# Tech-Enabled Crop Protection: Role of Frontier Innovations in Insect Pest Management

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**"Digitization is the process of converting information into a computer-readable format; these technologies are the electronic tools, systems, devices, and resources that generate, store or process data, such as mobiles, social media, etc."**

**Introduction**

With the global population expected to cross 9 billion by 2050, 70% more food needs to be produced. Regrettably, India ranks 107th out of 121 countries on the Global Hunger Index 2022 (Index, 2022). With 2.4% of the world's total land area, India has to support 14% of the world's total population. The number of Indians at risk from hunger in 2030 is expected to be 73.9 million. Needless to cite, digital transformation in Indian agriculture is essential to enhance efficiency, productivity, and sustainability.

**Digital agriculture**

Digitization is the process of converting information into a computer-readable format; these technologies are the electronic tools, systems, devices, and resources that generate, store or process data, such as mobiles, social media, etc (Senaras and Sezen, 2020).

| | | | |
|---|---|---|---|
| Total Population: 1.42 billion | Total Telecom Subscribers: 1.19 billion | Total Internet Subscribers: 0.95 billion | Active Social Media Users: 0.46 billion |
| E-commerce Penetration: 18.90% | M-commerce penetration: 30.00% | M-wallet Transaction Volume: 25.00 billion | Mobile Banking Transaction Volume: 14.49 billion |

**Figure 1.** Key enablers of digital transformation in India (As of 2024-Google)

**Artificial intelligence (AI)**

The term "artificial intelligence" was first introduced in 1955 by John McCarthy (McCarthy *et al.*, 2006). It is a branch of computer science that deals with the simulation of human intelligence processes by computer systems, such as problem-solving, learning, and decision-making. Machine learning (ML) is the application of AI that allows a system to automatically learn and improve from experience. Deep learning (DL) uses complex algorithms and deep neural networks to train a model.ML is a subset of AI. In turn, DLis a subset of ML. Modern AI Deep learning emerged as a dominant model within AI, driven by advances in neural networks. Convolutional neural networks revolutionised image recognition, and recurrent neural networks improved sequential data processing. For more details visit: https://towardsdatascience.com/traditional-ai-vs-modern-ai-5117b469a0c9

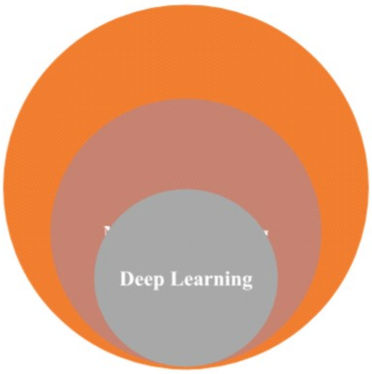


**Figure 2.** Domains of Artificial Intelligence (Latif *et al.*, 2019)

**Artificial intelligence techniques in plant protection**

**Machine learning (learning from experience or predictive analytics):** It is a subset of AI that is concerned with the design and development of algorithms and statistical models that enable computers to evolve behaviour based on empirical data. ML analyses data from sensors, satellites, and drones to detect patterns related to pests, diseases, and crop health. They can predict potential issues and recommend appropriate actions (Behmann *et al*., 2015).

**Deep learning (DL):** It is a subset of machine learning that employs artificial neural networks that learn by processing data. DL models can analyse images of crops to detect diseases and pests based on their logical functioning. It provides a hierarchical representation of the data by means of various convolutions. To improve feature extraction, neural networks are integrated with various image pre-processing algorithms (Alqethami*et al*., 2022).

A convolutional neural network (CNN) is a type of deep learning neural network architecture commonly used in computer vision. Examples of CNN used in plant protection are AlexNet: This breakthrough came in 2012 and was invented by Krizhevsky *et al*. It involves 1.3 million images divided into 1,000 categories, and it is known for its deep layers and efficient feature extraction. YOLO (You Only Look Once): YOLO is a real-time object detection system often used for identifying pests or anomalies in crop fields (Takayama *et al*., 2021).

**Image processing techniques:** There are 5 types.

**(a) Visualisation:** Find objects that are not visible in the image.

**(b) Recognition:** Distinguish or detect objects in the image.

**(c) Sharpening and restoration:** Create an enhanced image from the original image.

**(d) Pattern recognition:** measure the various patterns around the objects in the image.

**(e) Retrieval:** Browse and search images from a large database of digital images that are similar to the original image.

**Natural Language Processing (NLP):** It focuses on enabling computers to understand, interpret, and generate human language. NLP can be used to analyse text data from agricultural reports, weather data, scientific papers, or social media to identify trends and outbreaks of pests and diseases. It can be used in chatbots or virtual assistants to answer farmers' queries and provide information on crop protection measures. Examples of NLP data sets Wikipedia Dump, GPT-2 Dataset, Quora Question Pairs (Hegde and Patil, 2020).

**Data sets for training artificial intelligence:** This is the collection of data that is needed to train the model and make predictions. Examples: For computer vision: ImageNet, COCO, and MNIST. For autonomous vehicles, nuScenes and the KITTI Vision Benchmark Suite (Meyer and Kuschk, 2019).

**Applications of artificial intelligence in plant protection**

- **Pest and Disease Detection:** AI can analyze images of crops to detect early signs of diseases or pest infestations, enabling timely intervention (Selvaraj *et al*., 2019). It can process data from satellites and drones to monitor large areas of farmland for signs of stress or infestations (Rajagopal *et al*., 2023).
- **Predictive analytics:** AI can integrate weather data to predict disease and pest outbreaks, allowing farmers to take preventive measures. AI can simulate the growth of crops under different conditions to predict disease and pest susceptibility (Ampatzidis, 2018).
- **Precision agriculture:** AI-driven systems can adjust the application of pesticides or herbicides based on real-time data, optimizing resource use and minimizing environmental impact.
- **Autonomous farm equipment:** AI-powered robots and autonomous machinery can patrol fields for pests and diseases, applying treatments as needed with precision.
- **Integrated pest management (IPM):** AI can help create IPM plans by analyzing data on pest populations, crop health, and environmental conditions.
- **Data analysis:** AI can process and analyze vast amounts of agricultural data to identify patterns and correlations that help in making informed decisions about crop protection.
- **Smart irrigation:** AI can optimize irrigation schedules based on crop needs, helping to prevent waterlogged conditions that can promote disease.
- **Early warning systems:** AI can provide early warnings to farmers when environmental conditions become conducive to disease or pest outbreaks.
- **Pest and disease resistance breeding:** AI can analyze genetic data to identify genes associated with pest and disease resistance in crops, aiding in the development of more resilient plant varieties.
- **Crop monitoring apps:** AI-powered mobile apps can allow farmers to take pictures of their crops and receive instant analysis and recommendations for pest or disease management.
- **Market and supply chain analysis:** AI can analyze market data and predict demand, helping farmers make decisions about crop protection and production.
- **Collaborative platforms:** AI-powered platforms can connect farmers, researchers, and experts to share information and best practices in crop protection.

**Global positioning system (gps) and geographic information system (gis)**

It provides information related to the location of an object or area to the users using a ground-based antenna and receiver, with the help of signals collected from the satellites. GPS is widely used in many applications related to surveying and navigation. It is based on a network of earth-orbiting satellites that lets users record near-instantaneous positional information (latitude, longitude, and elevation) with accuracy ranging from 100m to 0.01m. GPS-equipped drones or ground vehicles can be used to collect data on pests or diseases (Featherstone, 1995).

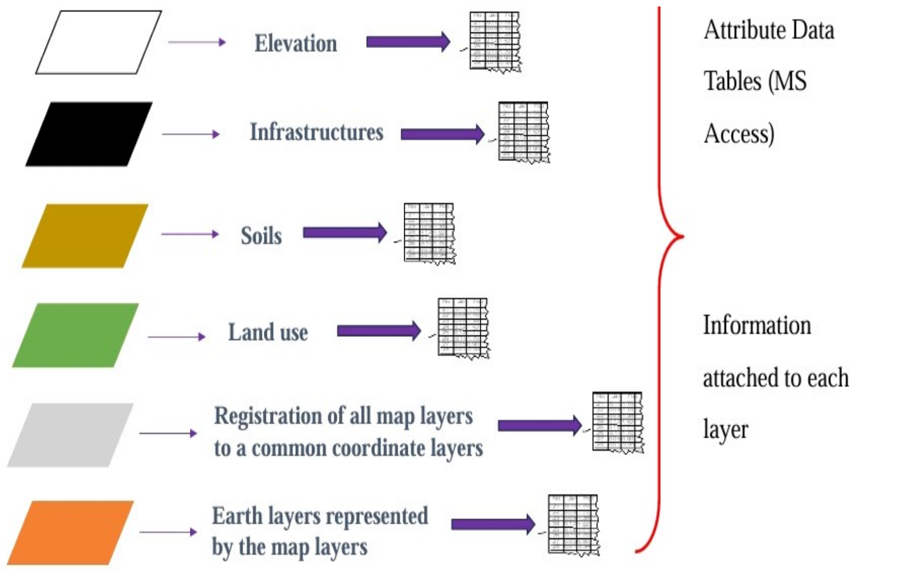


**Figure 3.** From map to GIS: the structure of GIS

GIS takes data collected from many sources in many forms as input and converts it into information depending on the process adopted by the user. It is widely used for preparing different types of maps in cartographic studies and also in environmental applications, etc. This technology allows to store field input and output data as separate map layers in a digital map and to retrieve and utilise these data for future input allocation decisions (Hu, 2010). GIS connects the spatial aspect of where things are located with the descriptive aspect of what those things are. Geographic reference pertains to the spatial coordinates, such as longitude and latitude, used to pinpoint specific locations on the Earth's surface, essentially constituting spatial data.

**Applications of GPS & GIS in plant protection**

There are two general areas where a GIS has been used in plant protection (Liebhold *et al*., 1993).

**Habitat Susceptibility Assessment:**

(i) Mapping
(ii) Data integration:
(iii) Identifying hotspots

**Census Data Compilation:**

(i) Precise enumeration
(ii) Spatial analysis and temporal analysis. Spears (1993) and Ravlin (1991) used a GIS to interpolate gypsy moth trap counts and egg mass densities in an IPM demonstration program.
(iii) Precision agriculture
(iv) Early warning systems
(v) Decision support systems tools (DSST)

**Remote sensing**

The reflectance or emittance of any object at different wavelengths follows a pattern that is characteristic of that object, known as a spectral signature. Proper interpretation of the spectral signature leads to the identification of the object. Crop spectral reflectance patterns reveal intriguing features. Absorption bands are prominent in the visible spectrum (0.4 to 0.7 microns) due to the presence of pigments. In contrast, the near-infrared region has a rise in reflectance due to the leaf's internal cellular structure (Wachendorf *et al*., 2018). There are distinct absorption peaks at 1.45, 1.95, and 2.6 microns, which correspond to the influence of water content. In general, healthy plants have a higher reflectance in the near-infrared region and a lower one in the visible region; the opposite is the case with infected plants. These features have practical applications in crop identification, the anticipation of yield, monitoring pest and disease impact, and evaluating crop health. Example, mapping of the Mississippi river delta's high-risk zones for aphid infestations in wheat (EHP, 2000). Aerial imagery captured through remote sensing identified hemlock trees infested by loopers (Abd El-Ghany *et al*., 2020).

**Mobile apps**

In India, several mobile apps and web portals are designed to assist farmers with plant protection and overall agricultural practices. Here are some notable ones:

(i) Kisan Suvidha: Launched by the Indian government, this app provides weather forecasts, market prices, agro-advisories, and plant protection information.

(ii) Pusa Krishi: Developed by the Indian Agricultural Research Institute (IARI), it offers information on crop varieties, resource-conserving cultivation practices, and farm machinery.

(iii) Agri App: A farmer-friendly app providing information on crop production, protection, and allied services, including expert chats and video-based learning.

(iv) Plantix: An AI-based app that diagnoses plant diseases, pests, and nutrient deficiencies through images, offering treatment advice.

(v) AgriCentral: Provides comprehensive crop advisory, weather updates, market prices, and information on government schemes.

(vi) BigHaat: Offers a marketplace for agricultural products, personalized crop advice, weather forecasts, and pest diagnosis.

(vii) Kheti-Badi: A social initiative app promoting organic farming and providing information related to sustainable agricultural practices.

(viii) Marathi Shetkari: Provides information on government schemes, crop management, agri-business guidelines, market rates, and success stories in agriculture.

(ix) e-NPSS: Latest launched in last leg of 2024 by ICAR-NCIPM, New Delhi is an AI-technology based system encompassing 61 crops for their IPM strategies and suggestions.

**Web portals**

(i) Termite Expert: It was launched in 2017, designed, developed by Dr. G.K. Mahapatro (National Fellow ICAR 2011-17). It provides information on termites, its management including the innovative approaches and ITKs. https://termitexpert.in/index.php.

(ii) Comprehensive Registration of Pesticides (CROP): Released in 2009, the portal automates the entire registration procedure, allowing applicants to submit applications online, track their status, and receive digitally signed registration certificates.

(iii) Kisan Call Center (KCC): Established on January 21, 2004, the portal provides agricultural information/advice through toll-free No. and online portal. https://www.manage.gov.in/kcc/kcc.asp

(iv) mKisan Portal: It was constituted in the year 2013. It facilitates in the dissemination of information, advisories, and services to farmers through SMS and other channels.https://mkisan.gov.in/Alpha/

(v) AgriClinics and AgriBusiness Centers: It was launched in April 2002. It provides support and information to establish agri-ventures, offering advisory and extension services to farmers.https://www.agriclinics.net/

(vi) India Statagri:It was established in 14th November 2000, which offers comprehensive statistical information on various aspects of Indian agriculture, including crop production and protection.https://www.indiastatagri.com/

(vii) NBAIR Portal: It is a nodal agency for collection, characterization, documentation, conservation, exchange, research and utilization of agriculturally important insect resources. It also reached > 8.4 lakh visitor counts.https://

www.nbair.res.in/services

(viii) National Pusa Collection Portal: It is an integral section of Division of Entomology, ICAR-IARI, New Delhi. NPC has directly contributed to the discovery and description of more than 1500 arthropod species. Since early 1900s, its online activity started and in the recent past (after 2021), and till date its visits/hits is 1.34 lakh.

**Social-media**

It is the means of interactions among people in which they create, share, and/or exchange information and ideas in virtual communities and networks by producing, storing, retrieving, and transferring material in any form *i.e.*, text, photos, video etc (Saravanan andSuchiradipta, 2016).

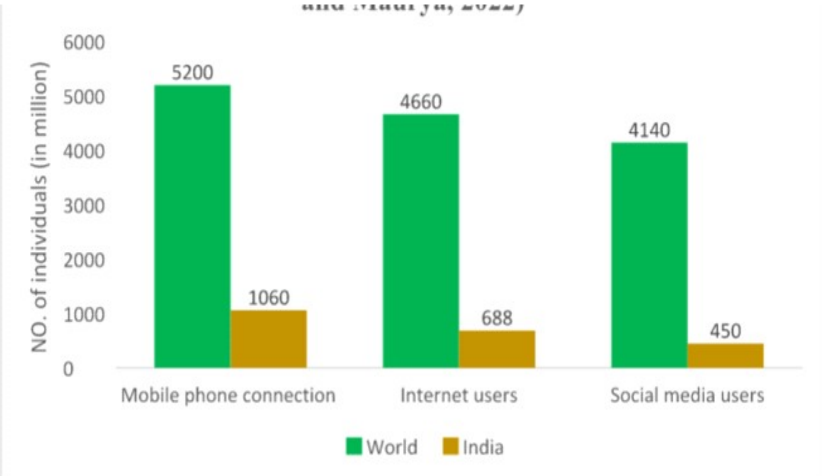


**Figure 4.** Level of Digital Penetration in World and India (Mishra and Maurya, 2022)

**Applications of social-media in plant protection (Singh *et al*., 2021)**

· **Information sharing:** Farmers can follow agricultural agencies, universities, and plant protection organisations on platforms like X (Twitter) or Facebook to receive real-time information.

· **Peer networking:** Joining or creating online farmer groups on platforms like WhatsApp or Facebook allows farmers to discuss plant protection issues with peers.

· **Visual identification:** Use Instagram or TikTok to share images and videos of diseased plants, pests, or symptoms. Other experienced farmers and experts can provide diagnoses and suggest treatment.

· **Live consultations:** Farmers facing an unexpected plant disease outbreak can host a Facebook Live or YouTube Live session with a plant pathologist to diagnose and discuss treatment options.

· **Educational content:** Farmers can create and watch instructional videos on platforms like YouTube tutorials and the needy can learn about proper plant protection practices from it.

· **Marketplace insights:** A farmer looking for a specific pesticide can connect with agricultural suppliers by using LinkedIn for Agribusiness.

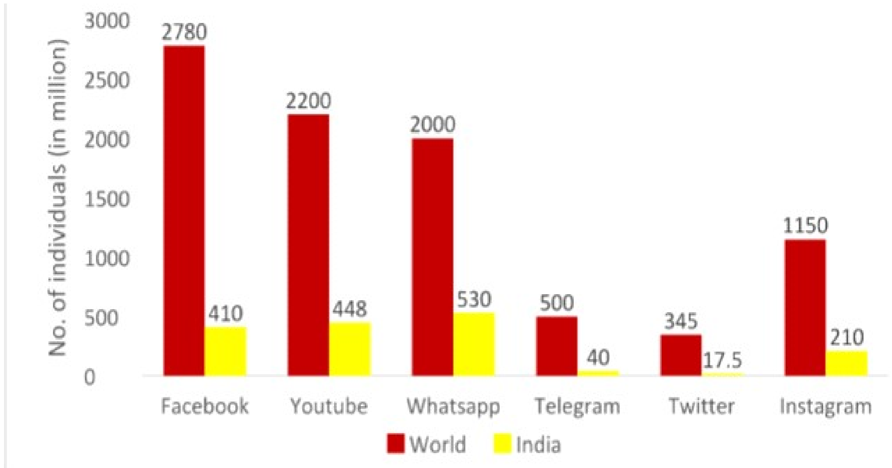


**Figure 5.** Social Media Users in World and India (Mishra and Maurya, 2022)

**Challenges for digital transformation (Khanna *et al*., 2022)**

**(i) Limited digital infrastructure (rural):** In many rural areas, there is inadequate digital infrastructure, such as internet connectivity and electricity supply, which hinders the adoption of digital technologies for plant protection.

**(ii) Access to technology (remote areas):** Remote agricultural areas may have limited access to modern technology, making it challenging to implement digital solutions for plant protection effectively.

**(iii) Digital literacy:** Many farmers and agricultural workers may not have the necessary digital literacy skills to use digital tools and platforms for plant protection effectively.

**(iv) Cost of technology:** The initial cost of implementing digital plant protection technologies, such as sensors, drones, and specialized software, can be prohibitively expensive for some farmers and organizations.

**(v) Data privacy & security:** Ensuring the privacy and security of sensitive agricultural data is a concern. Unauthorized access to data or cyberattacks could compromise the integrity of plant protection efforts.

**(vi) Language & region diversity:** The diversity of languages and regional differences in agricultural practices can pose challenges in developing and implementing standardized digital solutions that cater to a wide range of users.

**(vii) Resistance to change:** Farmers and agricultural communities may resist adopting digital technologies due to a preference for traditional practices or a lack of trust in new methods.

**(viii) Policy & regulation:** Inconsistent or unclear policies and regulations related to digital agriculture and plant protection can create uncertainty and barriers to implementation.

**Future scope**

Blockchain is a system for recording data in a way that ensures its integrity and transparency (Truong *et al*., 2019). It consists of a chain of blocks, with each block containing a list of transactions. Some of the applications of this technology are

· **Traceability:** For crop protection, this means tracking the use of pesticides, herbicides, and other chemicals on crops. Data Integrity: Crop protection often involves the use of data from various sources, including weather data, soil data, and pest data.

· **Smart contracts:** They can automate various aspects of crop protection, including the scheduling of pesticide applications based on weather conditions or the triggering of alerts when certain conditions are met, such as a sudden increase in pest activity.

· **Decentralised monitoring**: Blockchain can enable decentralised networks of sensors and devices to monitor crops for pests and diseases.

Robotics is a subset of artificial intelligence dedicated to the development of intelligent and effective robotic systems (Balaska*et al*., 2023). Robots equipped with sensors and cameras can regularly monitor crop health and growth. Agricultural robots can identify and remove weeds from fields. Robots can be programmed to perform tasks with high precision, such as applying pesticides.

## Conclusion

· **Increased efficiency:** Reduced manual labour, operational costs, improved resource allocation, and optimised workflows.

· **Data driven decision making:** Farmers can make more informed choices based on data-driven insights, leading to better pest and disease management strategies.

· **Automation and predictive analytics:** Automation of tasks like pesticide application has reduced human error and resource waste. Predictive analytics models optimise preventive measures.

· **Monitoring:** Digital solutions enable real-time monitoring by using cell phones.

· **Knowledge sharing and innovation:** Rapid sharing of knowledge, best practices, and information among farmers, researchers, and stakeholders is possible.

Also, digital transformation opens up avenues for communication among farmers, scientists, and government bodies, resulting in a multitude of indirect benefits: scientists gain better data access, governments improve their policy-making processes, and farmers attain increased crop productivity.

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# How Frontier Innovations are Enhancing Crop Disease Management

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**"Advanced diagnostics involve the development of disease-resistant crops with the use of portable molecular tools and gene editing technologies that enable the easy identification of pathogens in the field."**

Crop diseases pose one of the greatest threats to food supplies worldwide and creates unimaginable economic loss to the nation. Traditional approaches of managing crop diseases often falter because of constraints in the provision of high precision, early detection, and sustainability. In response, frontier innovations have emerged as game-changers, integrating advanced technologies and scientific methodologies to beat the persistent challenge of the crop diseases and revolutionize crop disease management. These do not only improve the management of the diseases but also make the environmentally sustainable approaches efficient and effective. These innovations are meant to help reduce crop losses, ensure food security and support sustainable agriculture. The integration of modern tools like genomics, CRISPR, artificial intelligence, and precision farming, have helped in finding better, more sustainable, and environmentally friendly solutions to grow food. These innovations eventually allow early detection, appropriate diagnosis, and timely interventions to prevent losses in crop yield and ensure food security.

Advanced diagnostics involve the development of disease-resistant crops with the use of portable molecular tools and gene editing technologies that enable the easy identification of pathogens in the field. Remote sensing through drones and Internet of Things (IoT) sensors add more accuracy to disease monitoring, and the predictive models for diseases through artificial intelligence (AI) help streamline decisions made through image recognition. The integration of biological control and RNA interference (RNAi) in controlling the effects of chemical pesticides by providing environmentally safe alternatives can reduce the impact on ecology. Digital platforms, advanced data analysis, and blockchain systems help maintain transparency and traceability, and engage farmers more, to adopt an inclusive approach toward pest and disease management. These frontier innovation technologies are creating a way to manage crop diseases that is forward-thinking and eco-friendly and have set the stage for proactive and sustainable crop disease management, crucial in feeding the world's growing population.

### A. Advanced diagnostics

The advancement of diagnostic technologies in plant pathology has significantly impacted theapproach to crop disease management. These developments are enabling quick identification, efficient management, and long-term control methods for plant diseases by utilizing technology such as genomics, CRISPR, and portable diagnostic tools.

#### (a) Genomics and CRISPR technology

Genomics has turned out to be a key technique in the comprehension of the interactions between a plant and a pathogen which offers insights to the susceptibility and resistance mechanisms. One of the most groundbreaking technologies in this area is CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats). By focusing on genes that cause an organism to beprone to disease, CRISPR technology offers scientists the capability to adjust those genes inorder to make the organism resistant against them, because the genes can be altered with extremeprecision (Wang & Doudna, 2023).In order to address a potential plant disease, genes that facilitate pathogen entry or suppress plantimmune responses can be precisely altered can be efficiently altered. Furthermore, CRISPRtechnology permits the insertion of durable resistance traits which can sustain effectiveness evenagainst rapidly evolving pathogens (Borrelli *et al.*, 2018). Such changes not only decrease therequirements for use of chemical control measures requirements but also meet the increasing need for eco friendly agriculture (Eş *et al.*, 2019) This approach enables the rapid developmentof disease-resistant crop varieties, providing a more sustainable solution compared to traditionalbreeding methods. (Chen *et al.*, 2019). Through genomics of pathogens we can identify and altered important genes which areresponsible for pathogenicity which further weakening the ability to cause diseases. CRISPR allows us to target specific genetic factors that enable pathogens to infect and harm plants. Theidentification and silencing of these virulence genes using gene editing techniques and genomictargeting can lead to more resilient and disease-resistant crop varieties (Louwen *et al.*, 2014).

#### (b) Portable diagnostic tools

Genomics and CRISPR are long-term solutions, whereas portable diagnostic tools to identifypathogens are an immediate need. Lab-dependent culture-based pathogen identificationprocesses create a backlog and a time lag that can worsen an outbreak. Portable devices likelateral flow tests and mobile polymerase chain reaction (PCR) machines enable on-sitediagnostics (Yang *et al.*, 2023).Given their low cost, ease of use and the speed with which they yield results, which are no longerthan a matter of minutes, lateral flow assays enable the detection of specific pathogen proteins ornucleic acids. Additionally, portable PCR instruments amplify pathogen DNA or RNA at the siteof use – which is equally sensitive and specific to the method. These devices are very useful inthe diagnosis of latent infections where timely interventions can prevent substantial economiclosses from viral proliferation (Sánchez *et al.*, 2022).Furthermore, these plant disease diagnostic technologies are being designed to work with digitalplatforms. Recent models of many devices incorporate mobile phones which allow instantaneoustransfer of information for centralized disease outbreak surveillance. This function improves thequality of diagnostics, and at the same time enables collaboration against newly identified threats (Zhao *et al.*, 2020).

### B. Remote sensing and precision agriculture

Precision agriculture (PA) serves as a crucial element of sustainable agricultural practices in the 21st century. Although PA has been described in various ways, its core concept remains consistent. It involves a management approach that incorporates advanced tools for information, communication, and data analysis into the decision-making process (e.g., the application of water, fertilizers, pesticides, seeds, fuel, labor, etc.), aiming to improve crop yields while minimizing water and nutrient wastage as well as adverse environmental effects.

Remote sensing systems utilized in precision agriculture (PA) and in general, can be categorized based on two criteria: (i) the platform of the sensor and (ii) the type of sensor. Sensors are commonly mounted on platforms such as satellites, aerial vehicles, and ground-based systems. Satellite products have been extensively used in PA since the 1970s. In recent years, aerial platforms, including airplanes and unmanned aerial vehicles (UAVs), have also gained popularity in PA. Ground-based platforms used in PA can be classified into three types: (i) hand-held, (ii) stationary in the field, and (iii) mounted on tractors or other farming equipment. These systems are often referred to as proximal remote sensing systems because they are positioned closer to the target surface, such as land or plants, compared to aerial or satellite-based platforms.The sensors used in remote sensing vary in terms of their spatial, spectral, radiometric, and temporal resolution. Recently, solar-induced chlorophyll fluorescence (SIF) quantification from hyperspectral images has been increasingly utilized to assess photosynthesis, plant nutrients, and stress factors, including diseases and water stress. The chemical and structural properties of plants influence the amount of solar radiation they reflect. Factors such as plant type, water content, and canopy structure impact the light reflection in each spectral band in different ways. Light reflected in the ultraviolet, visible (blue, green, red), and near- and mid-infrared regions is often measured to create vegetation indices. These indices are mathematical formulas that use reflectance from multiple spectral bands to evaluate crop growth, vigor, and plant characteristics like biomass and chlorophyll content. Mapping these indices helps analyze variations in crop conditions over time and space, which is essential for precision agriculture (PA) applications (Sishodia *et. al.,* 2020).

**C. Artificial Intelligence (AI) and Machine Learning (ML)**

Plant diseases pose a significant thread to global food security causing billions of dollars in crop losses annually. Traditional methods of disease detection often rely on manual inspection by experts, which can be time consuming, labor intensive and prone to human error. In recent years, some artificial intelligence (AI) and machine learning (ML) associated modern methods like deep learning and transfer learning are being developed, that are revolutionizing agriculture by making farming processes more efficient, sustainable and profitable (Murugan *et al.*, 2021).

- **Image recognition:** AI-based tools can identify diseases through automated image recognition systems. These systems use high-resolution images of infected plants captured by smartphones, drones or cameras, which are then processed by machine learning models trained to recognize patterns associated with specific diseases (Christakakis *et al.*, 2024). This makes easier for farmers to diagnose the problem quickly at an early stage and adopt specific measures against it.

- **Disease prediction models:** AI algorithms analyze and predict weather patterns, soil data, and historical records to predict the onset and spread of crop diseases, enabling timely interventions and reducing losses (Yuan *et al.*, 2022).

**(a) Biological control**

Microorganisms, though invisible to the naked eye, play a pivotal role in maintaining the health and functionality of ecosystems. Beneficial microorganisms, in particular, are indispensable in agriculture, medicine, and environmental sustainability. These organisms contribute to nutrient cycling, disease suppression, bioremediation, and more.

**(b) Digital platforms and big data**

Big data and digital platforms are transforming crop disease management by giving farmers, researchers, and agricultural organizations the tools and technologies they need to more accurately identify, forecast, and manage plant diseases.

**(c) Farm management software**

By combining data from sensors, weather stations, and crop models, integrated platforms offer real-time updates and useful insights. By assisting farmers in monitoring, controlling, and mitigating plant diseases, farm management software (FMS) can significantly increase agricultural production, sustainability, and profitability.

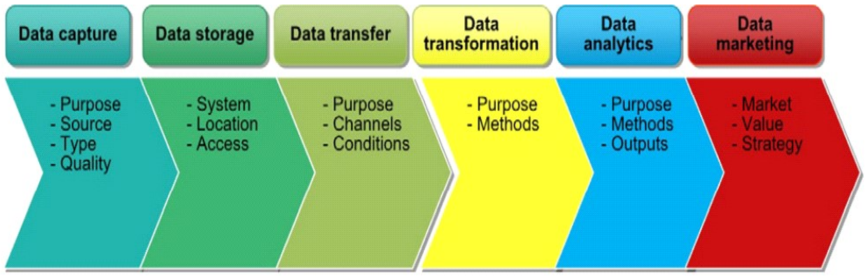


**Figure 1.** The data chain of Big Data applications (Chen *et al.*,2014)

**Benefits of farm management software in plant disease management:**

**Disease detection and monitoring:** Automatic methods of plant disease detection are advantageous because they minimize the amount of work required for crop monitoring in large farms and identify disease symptoms early on, such as when they manifest on plant leaves. Deep learning and artificial intelligence have greatly improved the identification of illnesses and pests in agriculture, giving modern farmers vital tools (Kumar, P. *et al.*, 2023).

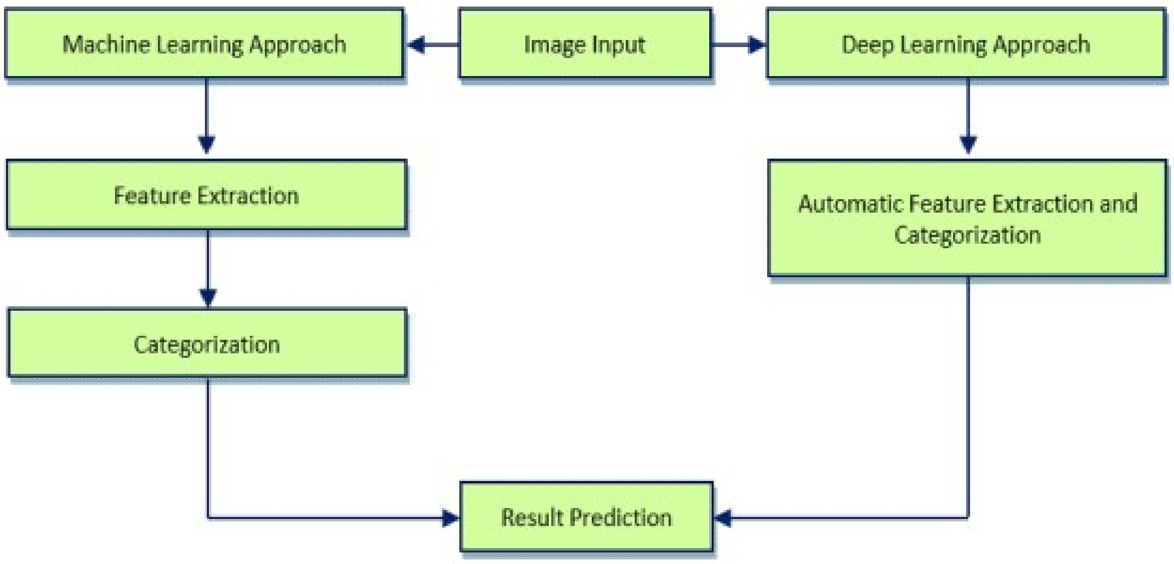


**Figure 2.** Two different methods for detecting and classifying diseases (Kumar, P. *et al.*, 2023)

**RNA Interference (RNAi) Technology in Plant-Pathology**

A less utilized method of virus targeting in plants is RNAi (or RNA interference), which lowers the expression of critical genes of the pathogen during the infection process. This immune system has been increasingly examined for its potential in the improvement of modern plant protection systems. Thus, RNAi provides a novel targeted approach for disease management.

RNAi can be utilised for plant disease management in the following ways:

**(a) Host-Induced Gene Silencing (HIGS)**

Exploiting RNA Trafficking Host-induced gene silencing uses the natural flow of RNAs between the host plants and their interacting pathogens or pests. Here, genetically modified plants are designed to express dsRNAs or sRNAs that are toxic to vital genes in the pathogen. The RNAs are transferred between kingdoms, knocking out critical genes in the invading pathogens and diminishing their ability to cause disease. This technique has been shown to possess tremendous promise in several plant-pathogen systems and is a new and sustainable means of crop protection at the molecular level. . ( Niu *et al.*, 2021)

**(b) Spray-induced gene silencing (SIGS)**

A non-genetic alternative SIGS takes advantage of the fact that some pests and pathogens absorb RNAs from their environment. This technique applies synthetic dsRNAs or sRNAs directly to plant surfaces, which are then taken up by the target organism to trigger gene silencing through environmental RNAi and suppress disease development. Researchers are working on stabilizing and delivering these RNAs using nanotechnology. As such, SIGS presents a promising non-transgenic approach for crop disease management. (Niu *et al.*, 2021)

**Blockchain for Traceability**

Blockchain traceability refers to the use of a decentralized digital ledger to securely, transparently, and permanently record transactions or data entries. Each entry is stored in a "block" that is connected to the previous one, creating an unbroken "chain." This system allows for tracking and documenting every step of a product's journey, from production to distribution, ensuring all stakeholders have access to a clear and verifiable record (Tripathi *et al.*, 2020)

**Application of Blockchain in Ensuring Disease-Free Seeds**

Ensuring the quality of seeds is crucial for agricultural productivity, as the use of low-quality or contaminated seeds can lead to poor crop yields and the spread of diseases. Blockchain technology offers a solution by providing a transparent, secure, and tamper-proof system to trace and verify seed quality throughout the supply chain. A detailed explanation of how blockchain ensures disease-free seeds involves the following aspects:

**(i) Seed Certification**

Seed certification is a process where seeds are tested and verified to ensure they meet certain quality standards, such as being free from pathogens, diseases, or genetic impurities.

**(ii) Supply Chain Monitoring**

Supply chain monitoring involves tracking the movement of seeds from the point of origin (producer) to the end user (farmer), ensuring that the seeds remain in optimal conditions and are not exposed to any factors that might degrade their quality (e.g., improper storage, exposure to pests, or diseases).

**(iii) Validation and Authenticity**

Validation and authenticity refer to the process of confirming that the seeds being sold are genuine, certified, and free from diseases. Blockchain ensures the authenticity throughQR Code for instant verification ,eliminating counterfeit or fraudulent Seeds and Building Trust with Stakeholders

**Benefits of Frontier Innovations**

- **Early Detection and Response:** Reducing crop losses.
- **Sustainability:** Promoting eco-friendly practices.
- **Cost Efficiency:** Reducing economic burden on farmers.

**Conclusion**

Crop disease management has seen a dramatic change as a result of frontier developments, which have produced state-of-the-art instruments and methods to address persistent agricultural problems. Farmers and researchers can now identify, anticipate, and treat crop illnesses with previously unheard-of sustainability and precision thanks to the integration of technologies like genomics, CRISPR, AI, IoT, and blockchain. These developments encourage eco-friendly and eco-conscious behaviours in addition to reducing financial losses and guaranteeing food security.However, issues like cost, accessibility, infrastructure, and farmer education need to be resolved if these technologies are to reach their full potential. To close these gaps and guarantee fair access to contemporary farming equipment, governments, the commercial sector, and scientific communities must work together. By doing this, we can build a robust agricultural ecosystem that will be able to feed the world's expanding population while protecting the environment for coming generations.

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# Recent Innovations in Tea Industry to Combat Climate Change

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**"One of the most promising breakthroughs in the tea industry is the development of climate-smart seed varieties, such as the TSS 2 seed introduced by the Tea Research Association (TRA)."**

**Introduction**

The tea industry is at a critical juncture, grappling with the escalating impacts of climate change. Rising global temperatures, erratic rainfall, and extreme weather events have begun to adversely affect tea production, particularly in major tea-growing regions such as India, Sri Lanka, and China. These changes not only threaten the quantity and quality of tea but also endanger the livelihoods of millions who depend on this industry.

As global demand for tea continues to grow, the industry faces the dual challenge of meeting increasing consumption while adapting to a rapidly changing climate. In response, researchers, scientists, and policymakers have developed groundbreaking innovations aimed at enhancing the resilience of tea cultivation. These advancements include climate-smart seed varieties, eco-friendly microbial formulations, predictive modeling projects, and international collaborative efforts. This article explores these innovations in detail, highlighting their role in safeguarding the future of tea production.

**Climate-smart seed variety - TSS 2**

One of the most promising breakthroughs in the tea industry is the development of climate-smart seed varieties, such as the TSS 2 seed introduced by the Tea Research Association (TRA). This seed variety is specifically designed to withstand high temperatures, making it a vital tool for tea growers in regions like Assam and North Bengal, where peak summer temperatures often exceed 35°C.

**Key features of TSS 2:**

**(i) High-temperature tolerance:** Engineered to endure prolonged heatwaves, TSS 2 helps mitigate the stress caused by rising temperatures.

**(ii) Sustained yield quality:** This variety ensures the consistent production of high-quality tea leaves, even under adverse conditions.

**(iii) Wide adaptability:** Suitable for diverse climatic zones, making it a versatile option for tea farmers across different regions.

An official from TRA remarked, “To combat the effects of climate change, TRA released the first climate-smart tea seed stock, TSS 2. This variety can withstand high temperatures and maintain high-quality production.”

The widespread adoption of TSS 2 has the potential to revolutionize tea farming, providing a resilient alternative for growers facing climate-related challenges. Farmers have reported improvements in productivity and profitability since adopting this innovation, making it a cornerstone of climate adaptation strategies in tea cultivation.

**Microbial formulations to reduce resticide use**

In addition to addressing climatic stresses, the tea industry has made strides in promoting sustainable agricultural practices. One such innovation is the development of microbial formulations—eco-friendly alternatives to chemical pesticides—by TRA in collaboration with Varsha Biotech.

**Advantages of microbial formulations**

**(i) Environmentally friendly:** By minimizing the use of harmful chemicals, these formulations reduce the environmental impact of tea cultivation.

**(ii) Improved soil health:** Microbial formulations enhance the activity of beneficial microorganisms in the soil, promoting better nutrient absorption and plant growth.

**(iii) Efficient pest control:** These formulations effectively target pests without harming beneficial organisms, ensuring ecological balance.

In July 2024, the Central Insecticides Board approved TRA's microbial formulation, marking a significant milestone in environmentally sustainable pest management. By integrating these innovations, tea growers can reduce their reliance on chemical inputs while improving productivity and aligning their practices with global sustainability goals.

Moreover, microbial formulations address several long-term challenges in tea farming, including pesticide resistance and soil degradation. These eco-friendly solutions ensure that tea plantations remain productive and sustainable over time, benefiting both the environment and the economy.

**Disruption of traditional tea-growing calendar**

Climate change has disrupted the traditional tea-growing calendar, creating significant challenges for farmers. Optimal tea growth relies on a delicate balance of warmth and moisture, but erratic weather patterns—including extended heatwaves and irregular rainfall—have made it increasingly difficult to maintain these conditions.

**Effects of disruptions**

**(i) Soil dryness:** Prolonged heatwaves lead to the drying of soil, causing plant stress and stunted growth.

**(ii) Reduced yield:** Adverse conditions reduce the quantity and quality of tea leaves produced.

Increased Costs: To combat these challenges, farmers must invest in irrigation systems and other adaptive technologies, raising production costs.

Regions such as Assam and North Bengal have been particularly affected by these disruptions, emphasizing the urgency of implementing innovative solutions to mitigate the impact of climate variability.

To address these challenges, many tea growers are adopting advanced irrigation systems, soil moisture retention techniques, and shade management practices. These interventions not only enhance the resilience of tea plantations but also contribute to the efficient use of natural resources, aligning with sustainable development goals.

**The Tea-CUP project: co-developing useful predictions**

One of the most ambitious initiatives to tackle climate change in the tea sector is the Tea-CUP (Co-Developing Useful Predictions) project. This collaborative effort brings together scientists from the UK Met Office, tea farmers, and local experts in Yunnan Province, China, to create actionable climate information for tea growers.

**Objectives of the Tea-CUP project**

**(i) Data integration:** Merging scientific climate models with local expertise to produce precise and practical predictions.

**(ii) Farmer empowerment:** Providing farmers with actionable insights to adapt to changing weather patterns.

**(iii) Sustainability:** Promoting long-term resilience through tailored climate services.

Dr. Stacey New, an applied climate scientist at the Met Office, explained, "The collaborative approach between the UK and China has shown that integrating scientific knowledge with local expertise enhances the resilience of the tea sector to climate variability."

**Insights from the Tea-CUP [roject**

The project leverages data from plantation areas, tea yield, temperature, precipitation, and market prices to build predictive models. These models enable farmers to:

**(i) Plan seasonal activities:** Tailored forecasts help growers schedule planting and harvesting effectively.

**(ii) Mitigate risks:** Insights into potential climate risks enable proactive measures to protect crops.
**(iii) Enhance productivity:** By adapting practices to forecasted conditions, farmers can optimize yields and minimize losses.

Professor Shaojuan Li from Yunnan University of Finance and Economics highlighted, "In Yunnan Province, rainfall and temperature data are being used to develop seasonal forecasts that guide cultivation and harvesting activities."

**Climate science for service partnership China (CSSP China)**

The Tea-CUP project is part of the broader Climate Science for Service Partnership China (CSSP China) initiative, launched in 2014. This collaboration between UK and Chinese research institutions aims to develop climate services that support climate-resilient economic development.

**Key features of CSSP China:**

**(i) Scientific collaboration:** Bridging expertise from multiple disciplines to address climate-related challenges.
**(ii) Holistic approach:** Integrating scientific data with cultural, social, and local knowledge for comprehensive solutions.
**(iii) Scalable models:** Creating frameworks that can be adapted to other regions and agricultural industries.

Through CSSP China, innovative tools and techniques are being developed to enhance the adaptability of tea farmers to climate change. These advancements are not only benefiting the tea industry but also serving as a model for other agricultural sectors facing similar challenges.

**Future directions and recommendations**

While recent innovations have provided the tea industry with valuable tools to combat climate change, continued efforts are essential to ensure long-term resilience. Recommendations for the future include:

**(a) Investment in research and development**

Sustained funding for research is crucial to develop new climate-resilient seed varieties and eco-friendly agricultural practices. Innovations like TSS 2 and microbial formulations demonstrate the potential of scientific research to transform tea farming. Expanding these efforts can unlock further advancements that address emerging challenges.

**(b) Global collaboration**

Expanding international partnerships like CSSP China can facilitate the sharing of knowledge and resources. Collaborative projects bring together diverse expertise, fostering innovative solutions that are culturally and regionally appropriate.

**(c) Farmer training programs**

Educating tea growers on the use of predictive models, sustainable farming techniques, and adaptive technologies can enhance their ability to cope with climatic challenges. Training programs should be tailored to the specific needs of different regions, ensuring that farmers receive relevant and practical guidance.

**(d) Policy support**

Governments should implement policies that incentivize the adoption of sustainable practices and provide financial support for smallholder farmers. Subsidies for climate-smart technologies and eco-friendly inputs can accelerate their widespread adoption.

**Conclusion**

Climate change presents an existential threat to the global tea industry, affecting production, quality, and livelihoods. However, recent innovations such as climate-smart seed varieties like TSS 2, microbial formulations, and predictive initiatives like the Tea-CUP project offer hope for the future. These advancements, grounded in scientific research and local expertise, are equipping tea growers with the tools needed to adapt to a changing climate.

By embracing these innovative solutions and fostering continued collaboration between scientists, policymakers, and farmers, the tea industry can mitigate the adverse effects of climate change while setting a global example for sustainability and resilience in agriculture. As climate challenges intensify, it is imperative to prioritize research, education, and policy initiatives that safeguard the future of tea production and the communities that rely on it.

# Role of Agricultural Policies in Influencing Farming and Rural Development in the Era of Climate Change

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**"India's National Innovations in Climate Resilient Agriculture (NICRA) program focuses on developing climate-resilient technologies essential for safeguarding food security."**

The agricultural sector faces unprecedented challenges in the era of climate change. Rising temperatures, unpredictable rainfall, soil degradation, and frequent weather extremes reshape farming landscapes worldwide. In rural areas, where agriculture is often the primary source of livelihood, these challenges are exacerbated by existing vulnerabilities such as poverty, lack of infrastructure, and limited access to resources. Agricultural policies are crucial in mitigating these impacts, fostering resilience, and promoting sustainable development. Effective policies address immediate climate risks while setting the stage for long-term agricultural and rural transformation.

**Climate-smart agriculture: A policy priority**

Climate-smart agriculture (CSA) has emerged as a transformative and central policy framework to combat climate change in farming. By integrating adaptation, mitigation, and productivity goals, CSA aims to make farming systems more resilient and sustainable. Policies promoting climate-resilient crop varieties, such as drought-tolerant or salt-resistant seeds, play a critical role in achieving these goals. For instance, India's National Innovations in Climate Resilient Agriculture (NICRA) program focuses on developing climate-resilient technologies essential for safeguarding food security. Countries also prioritize research into biofortified crops to address nutritional and climatic challenges. Rooted in sustainability and resilience, CSA emphasizes the need for adaptive agricultural systems to changing climatic conditions while reducing greenhouse gas emissions. The concept revolves around three primary objectives: enhancing farm productivity and incomes, building resilience to climate change, and reducing or eliminating greenhouse gas emissions where possible.

One of the key pillars of CSA is the adoption of improved crop varieties and farming practices that can withstand the adverse impacts of climate change. Drought-tolerant, flood-resistant, and pest-resistant crop varieties are critical to ensuring food security in regions prone to climatic extremes. For example, drought-resistant maize or submergence-tolerant rice can significantly reduce the risk of crop failure during prolonged dry spells or floods. Similarly, intercropping and crop rotation practices help maintain soil fertility and reduce vulnerability to pests and diseases.

Efficient water management practices are another cornerstone of CSA. With water becoming an increasingly scarce resource due to erratic rainfall and rising temperatures, strategies such as rainwater harvesting, drip irrigation, and the use of water-efficient crops are gaining prominence. These techniques ensure optimal water use and help conserve this critical resource for future use. For instance, drip irrigation minimizes water loss by delivering water directly to the plant roots, significantly reducing evaporation and runoff.

Soil health management is integral to CSA, as healthy soils are fundamental to productive and resilient farming systems. Practices such as conservation agriculture, which includes minimal soil disturbance, maintaining soil cover, and crop diversification, are widely promoted. These practices improve soil structure, enhance water-holding capacity, and increase organic matter content, all contributing to better crop yields and greater resilience to climate stressors. Moreover, using organic fertilizers and biochar helps sequester carbon in the soil, contributing to climate mitigation.

Agroforestry, which integrates trees and shrubs into agricultural landscapes, is a critical CSA practice that provides multiple benefits. Trees act as carbon sinks, absorbing atmospheric carbon dioxide and reducing greenhouse gas emissions. They also improve soil fertility, provide shade, and serve as windbreaks, thereby protecting crops from extreme weather conditions. Additionally, agroforestry systems enhance biodiversity by creating habitats for various species, further contributing to ecosystem resilience.

Livestock management is another area where CSA principles are being applied. Improved animal husbandry practices, such as better feed management, breeding strategies, and healthcare, can enhance productivity while reducing emissions from livestock. Rotational grazing and the establishment of silvopastoral systems, where livestock grazing is integrated with tree planting, are effective strategies for maintaining pasture health and increasing carbon sequestration.

Digital technology and precision agriculture are playing an increasingly significant role in implementing CSA. Tools such as satellite imagery, weather forecasting, and mobile applications help farmers make informed decisions regarding planting, irrigation, and pest control. For instance, real-time weather updates and early warning systems enable farmers to prepare for adverse weather events, reducing potential losses. Precision agriculture technologies, such as GPS-guided machinery and sensor-based irrigation systems, ensure the efficient use of inputs like water, fertilizers, and pesticides, thereby minimizing environmental impact.

CSA also promotes the diversification of livelihoods to build resilience among rural communities. Encouraging farmers to engage in activities such as fish farming, beekeeping, or agro-tourism reduces their dependence on a single income source and spreads the risk associated with climate variability. Moreover, supporting smallholder farmers through access to credit, insurance, and markets is essential for enabling them to adopt CSA practices effectively.

The role of policy frameworks and institutional support in scaling up CSA cannot be overstated. Governments and organizations must create an enabling environment through policies promoting sustainable farming practices, providing financial incentives, and supporting research and innovation. For example, subsidies for adopting renewable energy solutions, such as solar-powered irrigation pumps, can significantly reduce the carbon footprint of agriculture. Similarly, investment in climate-resilient infrastructure, such as flood-resistant storage facilities and efficient transportation networks, is crucial for reducing post-harvest losses and ensuring food security.

Community-based approaches are central

to the success of CSA, as collective action enhances the effectiveness of adaptation and mitigation efforts. Farmer cooperatives and producer groups can facilitate knowledge sharing, improve resource access, and strengthen market bargaining power. Extension services and capacity-building programs are vital in educating farmers about CSA techniques and empowering them to implement these practices on their farms. Moreover, CSA emphasizes the importance of integrating traditional knowledge with modern science. Indigenous farming practices, developed over generations, offer valuable insights into sustainable resource management and climate adaptation. For instance, traditional water conservation techniques, such as step-wells and check dams, can complement modern irrigation technologies. Recognizing and incorporating such practices into CSA initiatives can enhance their effectiveness and cultural relevance.

**Sustainable water management and irrigation policies**

Water scarcity is one of the most significant challenges faced by farmers in the era of climate change. Erratic rainfall patterns, depleting groundwater, and inefficient irrigation practices exacerbate the problem. Policies encouraging the adoption of water-efficient irrigation techniques, such as drip and sprinkler systems, have proven effective in optimizing water use. For example, Israel's advanced irrigation policies have turned arid land into productive agricultural hubs. Additionally, rainwater harvesting and watershed management programs are being prioritized in countries like India and Ethiopia, where rain-fed agriculture dominates. Efficient water management policies not only increase crop productivity but also contribute to environmental conservation.

A cornerstone of sustainable water management is promoting micro-irrigation systems, which allow precise water delivery to crops, significantly reducing wastage. Governments and organizations increasingly offer subsidies and financial incentives to encourage farmers to adopt these technologies. In India, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) has been instrumental in promoting micro-irrigation and improving water-use efficiency. Such policies have a dual benefit: conserving water resources and enhancing agricultural productivity in water-scarce regions.

Integrated watershed management is another critical policy approach. By focusing on the entire watershed, these programs aim to conserve soil and water resources while ensuring sustainable agricultural practices. Initiatives like contour bunding, check dams, and afforestation help recharge groundwater, prevent soil erosion, and enhance moisture retention. Ethiopia's Sustainable Land Management Program (SLMP) demonstrates the potential of watershed management to improve water availability and boost agricultural productivity in vulnerable regions.

Rainwater harvesting has also emerged as a vital component of sustainable water management policies. Traditional practices, such as constructing farm ponds and tanks, have been revived and integrated with modern techniques to store and utilize rainwater effectively. This approach not only provides a buffer against erratic rainfall but also reduces dependency on groundwater extraction. Policies supporting rainwater harvesting ensure year-round water availability for irrigation and mitigate the impact of dry spells.

Promoting renewable energy for water pumping systems is gaining traction as part of sustainable water management policies. Solar-powered irrigation systems are being adopted in many regions to reduce dependency on fossil fuels and enhance energy efficiency in agriculture. These systems align with the broader goals of climate-smart agriculture by reducing greenhouse gas emissions and providing a cost-effective solution for smallholder farmers. Governments and international organizations are playing a pivotal role in scaling up these technologies through financial aid and capacity-building initiatives.

**Financial support mechanisms for farmers**

Climate change introduces new uncertainties to farming, making financial stability a cornerstone of agricultural policy. Crop insurance schemes, weather-indexed insurance products, and disaster relief funds have become essential policy tools. The Federal Crop Insurance Program provides farmers with indemnity payments for climate-induced crop losses in the United States. Similarly, India's Pradhan Mantri Fasal Bima Yojana (PMFBY) offers financial protection to farmers affected by climatic adversities. Access to affordable credit through rural banking initiatives also empowers farmers to invest in climate-resilient practices. Policies integrating financial safety nets with risk reduction strategies are pivotal in stabilizing farming incomes.

**Market access and trade policies in agriculture**

Global and regional trade policies significantly influence the commercialization of agriculture in the face of climate change. Policies that facilitate farmers' access to domestic and international markets are crucial for enhancing their incomes and livelihoods. Trade agreements focusing on reducing tariffs for agricultural goods can help farmers compete globally. For instance, the European Union's trade policies promote importing sustainable and organic agricultural products from developing countries. Market infrastructure, including cold storage facilities and digital marketing platforms, is vital in reducing post-harvest losses and ensuring fair prices for farmers. E-commerce platforms have become essential in connecting rural farmers directly with consumers, reducing dependence on intermediaries.

**Role of technology and innovation in policy design**

Technological advancements are at the forefront of climate-resilient agriculture. Agricultural policies increasingly emphasize adopting technologies such as precision farming, remote sensing, and biotechnology. Precision farming uses data analytics and Internet of Things (IoT) devices to optimize resource use, improve yields, and reduce environmental impacts. Remote sensing technologies help monitor crop health, water usage, and soil conditions, enabling informed decision-making. Biotechnology, including genetically modified (GM) crops, has also gained attention for its ability to develop plants resistant to pests, diseases, and extreme weather. Policies that incentivize the use of such technologies are reshaping farming systems worldwide.

**Rural development as a pillar of agricultural policies**

Agriculture and rural development are intrinsically linked, particularly in developing regions. Policies that invest in rural infrastructure, education, and healthcare strengthen the foundation of farming communities. For example, improved rural roads reduce transportation costs, while electricity and irrigation infrastructure investments enhance productivity. Vocational training programs equip rural populations with the skills needed to adopt sustainable agricultural practices or diversify their income sources. Social safety nets, such as rural employment schemes and minimum income guarantees, provide financial stability to vulnerable households, enabling them to withstand climatic shocks. Holistic rural development policies ensure that farming communities are better prepared to adapt to climate change.

**Mitigation strategies in agricultural policies**

While adaptation is a primary focus, agricultural policies also address the need for mitigation. Agriculture accounts for a significant share of global greenhouse gas (GHG) emissions, mainly from livestock, rice cultivation, and synthetic fertilizers. Policies encouraging the adoption of low-emission farming techniques, such as reduced tillage, organic farming, and agroforestry, play a critical role in mitigating these emissions. Carbon credit schemes incentivize farmers to adopt practices that sequester carbon, such as planting cover crops or reducing methane emissions from livestock. International initiatives, such as the Global Methane Pledge, highlight the growing importance of agricultural mitigation in climate policies.

**International collaboration and funding mechanisms**

Global cooperation is essential to address the challenges of climate change in agriculture. Multilateral agreements, such as the Paris

Agreement, emphasize the role of sustainable agriculture in achieving climate goals. International funding mechanisms, including the Green Climate Fund and the World Bank's agricultural projects, provide financial support for climate-resilient farming initiatives. These funds are often used to implement large-scale programs, such as afforestation, soil conservation, and renewable energy projects in rural areas. Collaborative research and knowledge-sharing platforms further enhance the effectiveness of agricultural policies on a global scale.

**The future of agricultural policies in a changing climate**

The role of agricultural policies in influencing farming and rural development has never been more critical. As climate change continues to reshape the agrarian landscape, policies must evolve to address emerging challenges while fostering resilience and sustainability. Agricultural policies can transform farming systems and uplift rural communities by integrating adaptation, mitigation, and economic development goals. However, their success depends on practical implementation, robust governance, and the active participation of all stakeholders. In the era of climate change, the ability of agricultural policies to adapt and innovate will determine the future of food security, rural livelihoods, and environmental sustainability. ●●

# Challenges of Emerging Climatic Change on Food-Nutritional Security

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**"Food security is related to nutrition, and conversely food insecurity is related to malnutrition."**

Food security is "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and preferences for an active and healthy life" (FAO, 2022).Food security encompasses dimensions such as food availability, access, utilisation, long-term aspects (like resilience), nutritional adequacy, and sustainability (the ability to make decisions on what to eat and how and where to produce it while maintaining harmony with nature's systems).Well-functioning agrifood systems provide the safe and nutritious foods that are needed for healthy diets, which are in turn a prerequisite for good nutrition. Healthy diets are defined as those composed of a balanced, diverse and appropriate selection of foods eaten over a period. Healthy diets ensure that the needs for both macronutrients (proteins, fats and carbohydrates – including dietary fibre) and essential micronutrients (vitamins, minerals and trace elements) are met.

Climate change denotes unforeseen alterations in temperature and weather patterns. By interfering with nature, humankind has caused climate change, loss of biodiversity, and heightened air, soil, water, and ocean pollution. Consequently, such events impact the environment, causing suffering to human wellbeing worldwide. In the context of agrifood systems, climate change affects the availability, accessibility, affordability, genetic diversity and quality of food.

On the other hand, climate induced abiotic stresses affect plant growth, development, and metabolic processes, thus, reducing the yield and quality of crop plants. As such, climate change impacts the composition and nutrient availability of certain foods, leading to changes in crucial plant metabolites (e.g. metabolites having health beneficial properties, showing potential bioactivities, such as antioxidant, anti-cancer, anti-microbial, and anti-neurodegenerative characteristics), nutritional quality. For instance, elevated carbon dioxide levels can decrease the protein and mineral content in crops, changing the nutritional value of foods, as well as crop yields and quality. Increasingly, in many parts of the world, it also affects the viability of food production, due to changes in weather patterns and the concomitant spread of pests and diseases. Unexpected floods can also limit access to clean water, giving rise to vector and rodent-borne diseases and other bacterial/viral illnesses such as diarrhoea, cholera, and salmonellosis. Climate change significantly influences human food as it is closely interconnected with food systems. Climate change and food systems are known to have a bidirectional relationship. Agricultural activities such as making and using fertilisers, cold chains, transportation, and cattle rearing are the second-largest contributors to GHG emissions. At the same time, climate change is reshaping weather patterns, resulting in emergencies such as floods, crop damage, droughts, and food price inflation. As a result, climate change directly impacts the health and livelihoods of people, especially those most vulnerable. At the same time, agrifood systems contribute to greenhouse gas emissions, natural resource degradation and biodiversity loss.

Climate change impacts reduce the yields of staples like wheat, rice, maize, barley, and soybeans; the yields of nutrient-rich foods like fruits, vegetables, legumes, and nuts; and also, ocean and inland fishery catches. For a number of crops, they have also been shown to reduce the micronutrient content, particularly of zinc, iron, and vitamin A. In rice, grown under higher concentrations of $CO_2$, the average loss of major B vitamins (thiamin, riboflavin, and folate) was shown to be 17–30%. The number of people that can be affected are staggering. One study finds that elevated $CO_2$ could cause an additional 175 million people to be zinc deficient. More than 1 billion women and children could lose much of their dietary iron intake, putting them at greater risk of anemia and other diseases.

Food security is related to nutrition, and conversely food insecurity is related to malnutrition. Malnutrition currently affects every single country on the planet. The relationship between poverty and poor diets may also be linked to unhealthy 'food environments,' with retail outlets in a locality only providing access to foods of low nutritional quality. Disease is a key contributor to malnutrition. In particular, diseases affecting the gastrointestinal tract (resulting from bacterial, viral or parasitic infections) can reduce the absorption of nutrients from food and diets. These and other infectious diseases also increase nutritional needs for calories and micronutrients such as copper, iron, selenium and zinc, as well as vitamins A, C, D, E, B6, B9 and B12, which are critical in the growth of immune cells and immune response. Poor nutritional status from undernutrition, micronutrient deficiency, or overweight and obesity can also increase vulnerability to disease or increase the risk of severe negative consequences from disease, creating a vicious cycle that can have long-term detrimental consequences; it is an underlying cause in nearly half of all deaths among children under five years of age. The prevalence of at least one micronutrient deficiency may be as high as 50 percent for preschool children and more than 60 percent for women of reproductive age and affects at least 2 billion individuals worldwide. These deficiencies can result in devastating consequences, including lifelong disabilities such as blindness, reduced physical performance, reduced cognitive functioning, and premature death. Overweight and obesity are also a major risk factor for non communicable diseases, which are currently responsible for approximately 74 percent of all deaths worldwide.

Climate change impacts on food security will be worst in countries already suffering high levels of hunger and will worsen over time. Food inequalities will increase, from local to global levels, because the degree of climate change and the extent of its effects on people will differ from one part of the world to another, from one community to the next, and between rural and urban areas. People and communities who are already vulnerable to the effects of extreme weather now will become more vulnerable in the future and less resilient to climate shocks. Extreme weather events are likely to become more frequent in the future and will increase risks and uncertainties within the global food system.

Food production changes in climatic conditions have already affected the production of some staple crops, and future climate change threatens to exacerbate this. Climate affects a range of biological processes, including the metabolic rate in plants and ectothermic animals. Changing these processes can change growth rates, and therefore yields, but can also cause organisms to change relative investments in growth vs reproduction, and therefore change the nutrients assimilated. Higher concentrations of atmospheric $CO_2$ reduce the protein and mineral content of cereals, reducing food quality and, subsequently, leading to a higher number of people affected by micronutrient deficiency. The concentration of many micronutrients in crops (e.g., phosphorus, potassium, calcium, sulphur, magnesium, iron, zinc, copper, and manganese) can decrease by 5–10 % under atmospheric $CO_2$ concentrations of 690 ppm (3.5 æ%C warming). The decline in zinc content is projected to lead to additional 150–220 million people being affected by zinc deficiency, with increasing existing deficiencies in more than 1 billion people. Similarly, a decrease in protein and micronutrient content in rice due to a higher $CO_2$ concentration (568 to 590 ppm) can lead to 600 million people, with rice as a staple at risk of micronutrient deficiency by 2050. Additionally, the impact on the protein content of increased $CO_2$ concentration (greater than500 ppm) can lead to an additional 150 million people with protein deficiency by 2050 (within the total of 1.4 billion people with protein deficiency) in comparison to the scenario without increased $CO_2$ concentration.

Food and nutritional security is affected by climate change through related impacts on food security, food accessibility, dietary diversity, care practices and health as follows:

(i) Decrease of agricultural productive lands; changes in temperature and precipitation due to anthropogenic greenhouse gas emissions affect land suitability and crop yields.

(ii) Climate change have a serious negative impact on crop productivity as the level of warming progresses *i.e.* reduced yields in crop and livestock systems.

(iii) Declining in nutritional quality resulting from increasing atmospheric $CO_2$

(iv) Hotter climates will shift production toward the poles and will also cause faster plant growth and ripening and decrease nutrient density.

(v) Declining of portable water supply affect water-intensive production systems, and dairying is the most affected. Decreases in milk production reduce the availability of an important source of calcium and high-quality protein.

(vi) Heavy rainfall, flooding, and hot weather associated with climate change are escalating the risk that waterborne diseases become more prevalent, increasing the micronutrient needs of affected individuals. Micronutrient-rich foods are more expensive and more vulnerable to price inflation than staple foods, and during economic crises households often cut back on purchasing these foods.

(vii) Reduced yields from lack of pollinators; pests and diseases: climate change has started to cause a decline in the diversity and population of pollinators, which are critical for the supply of nutrient-rich foods. A model of the worst-case scenario—a complete loss of pollinators—finds that it would result in a 23 percent decline in the global fruit supply, a 16 percent decline in the global vegetable supply, and a 22 percent decline in the global nuts and seeds supply. For humans, these losses would cause an additional 173 million people to be folate deficient and an additional 71 million people to be vitamin A deficient.

(viii) Yield reductions, changes in farmer livelihoods, limitations on ability to purchase food; effects of increased extreme events on food supplies; disruption of agricultural trade and transportation infrastructure; price rise and spike effects on low-income consumers, in particular women and children, due to lack of resources to purchase food; widespread crop failure contributing to migration and conflict.

(ix) Decreased yields can impact nutrient intake of the poor by decreasing supplies of highly nutritious crops and by promoting adaptive behaviours that may substitute crops that are resilient but less nutritious

(x) Adverse weather events will damage crops and disrupt harvesting, transportation, and storage.

(xi) Reduced food quality affecting availability (e.g., food spoilage and loss from mycotoxins); impacts on food safety due to increased prevalence of microorganisms and toxins

(xii) The increased number of insects, including locust plagues, cause crop damage, decrease crop yield, and result in greater costs with increased chemical residues. Chemical contaminants have become a food safety concern, owing to pesticide residues and environmental contaminants.

(xiii) Food variety will decrease - for human nutrition, food diversity is important, especially for children, because it increases the likelihood of meeting nutritional needs, including intakes of phytochemicals, and decreases the impact of contaminants and toxicants

(xiv) Rapid loss of biodiversity, including the diversity of genes, species, and ecosystems due to habitat destruction (i.e., settlement, changing agricultural practices, deforestation, industrialization), global warming, and the uncontrolled spread of invasive species. Pollution, nitrogen deposition, and shifts in precipitation further exacerbate biodiversity loss. A general reliance on fewer species to feed the world, the resulting loss of biodiversity due to non-utilization and lack of conservation puts food security and human nutrition at great risk.

(xv) Nuts have important benefits for nutrition, but yields will decrease with climate change.

(xvi) Increasing undernourishment as food system is impacted by climate change; increasing obesity and ill health through narrow focus on adapting limited number of commodity crops; increasing food insecurity due to competition for land and natural resources (e.g., for land-based mitigation)

(xvii) The socioeconomic factors that affect food systems, such as agriculture, animal production, international trade, demographics, and human behaviour.

Climate change could increase the prices of major crops in some regions. For the most vulnerable people, lower agricultural output would also mean lower income. Under these conditions, the poorest people — who already use most of their income on food — would have to sacrifice additional income to meet their nutritional requirements. Climate-related risks affect calorie intake, particularly in areas where chronic food insecurity is already a significant problem, thus it can exacerbate undernutrition. For example, reduced calorie intake due to lower food availability could affect nutrition outcomes. Inadequate care practices could be exacerbated due to difficulty in accessing clean drinking water. Potential increases in food prices due to climate change could reduce dietary diversity and hence reduce nutritional value of the diet, which impacts on nutritional status. Finally, health will be impacted through changing disease patterns as a result of climate change. As such, Climate and environmental change will affect all four dimensions of food security, namely food availability (i.e., production and trade), stability of food supplies, access to nutritious food and food utilization. In addition, food security depends not only on climate, environmental and socio-economic impacts, but also and crucially so, on changes to trade flows, stocks and food-aid policy.

Given its geophysical and climatic conditions, India confronts numerous hazards and is one of the world's most disaster-prone countries.Since 2018, India has consistently ranked among the top 10 countries severely affected by disasters, according to the Global Climate Risk Index.Additionally, over 97 million people in India face extreme flood exposure and about 68 percent of the country experiences varying degrees of drought susceptibility, making it the country with the most people affected by drought since 1900.

Climate change and unsustainable food systems interact reciprocally with adverse impact on food and nutrition security. Climate change impacts food systems via multiple pathways, including soil fertility, water availability, reduced food yield, reduced food nutrient concentration and bioavailability, increased food anti-nutrient content and increased episodes of infectious diseases. To date, the challenges of climate change and malnutrition – two major barriers to sustainable development – have been considered almost exclusively in isolation of one another. However, climate change and malnutrition are interlinked, and solutions can be mutually reinforcing. However, the aggregate impact of climate change on food and nutritional security is not fully understood. In particular, several of the impacts are difficult to quantify and depend on a range of assumptions. The available quantitative studies suggest that climate change will negatively affect food and nutritional security at the global level in the long run. The adverse effects of climate change on food and nutrition security can be mitigated by bolstering agricultural resilience, raising awareness of climate-related nutrition impacts, and promoting sound nutritional practices. Dietary diversification, fortification, biofortification, and the inclusion of alternative protein sources (e.g., edible insects) are some of the available alternative options. All of these food systems-climate change-diet and nutrition outcomes are made even more complex by other dynamic factors, including rapid population growth, urbanization, evolving eating habits, and emergent pandemics such as COVID- 19. Moreover, concerted efforts towards adaptation, resilience building, and policy interventions are imperative to address these multifaceted challenges and promote sustainable development in a changing climate. ●●

# Climate Resilient Agriculture for Managing Climatic Risks

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**"Increases in atmospheric $CO_2$ concentration and associated further warming are likely to pose a serious impact upon the food grain production, particularly in tropical and subtropical countries including India thereby risking the future crop production scenario within the 21st century."**

## Introduction

The fact that the world's climate is changing is undeniable in grounds of spontaneous increase in greenhouse gas (GHG) emissions and increasing global mean surface temperature (GMST). The Intergovernmental Panel on Climate Change (IPCC) has reported a global warming of 1.1°C above pre-industrial levels during the decade (2011-2020), mainly due to anthropogenic emissions including greenhouse gases and aerosols. If the current rate of warming continues, a rise of 1.5°C is anticipated between 2030 and 2052 even in the best-case scenario (IPCC, 2021). Besides, the atmospheric $CO_2$ concentrations, one of the major GHGs contributing to climate change, have risen by nearly 50% since the pre-industrial times, reaching its highest concentration during the period 2011-2020 in the last 2 million years. The implications of climate change (CC) are well documented by changes in rainfall patterns, increased frequency and intensity of extreme climatic events like floods, droughts, pronounced heat and cold waves, cyclones, etc. which are collectively termed as climate change indicators. However, climate related risks will differ with respect to geographical location, levels of vulnerability to climate change, developmental interventions and preferences in implementation of adaptation and mitigation options.

Increases in atmospheric $CO_2$ concentration and associated further warming are likely to pose a serious impact upon the food grain production, particularly in tropical and subtropical countries including India (Satapathy *et al*., 2015) thereby risking the future crop production scenario within the 21st century. The threat to agricultural production in different places has already been reported due to a rise in ambient temperature through impacts such as reduction in the availability of water for irrigation, soil degradation, and emergence of new pests and disease complexes. Increased temperatures may also shorten crop growth duration, enhance evapotranspiration rates leading to moisture deficit in the crop root zone, reduce fertilizer use efficiency, and ultimately decrease crop production.

Therefore, meeting the food requirement of immensely growing population without any damage to the ecological aspects now is the topmost priority of environmentalists or development planners. Livelihood can be sustainable only if it inculcates the capability to restrain the climatic shocks and enhance its potentialities, without undermining its precious natural resource base (Carney, 1998). This can be achieved by incorporating technological, managerial and institutional innovations in the agricultural sector in a way that the growing population can be fed without further depletion of our precious reserves of soil and water. This holistic approach to counter the challenges of climate change is termed as Climate Resilient Agriculture.

**Climate of Assam and observed changes**

Assam state experiences high rainfall and high humidity which is mainly influenced by both the south-west monsoon from the Bay of Bengal and the state's orographic features. Mean annual rainfall in Assam is about 2352 mm distributed over 120 days. The monsoon season (June-September), which is also the Sali rice growing season in the state, is characterized by cloudy weather, high humidity (>80%) and weak variable surface winds. Highest rainfall is received during these months, amounting to 61-72% of total annual rainfall and scattered over 18-20 days in a month. Rainfall during the withdrawal phase of monsoon, that is from mid of October starts declining and subsequently the post monsoon season receives 7-10% of the mean annual rainfall. The state experiences a mean annual temperature of 22.5 to 24.5°C. August is the hottest month and January is the coldest month in the state. Since agriculture in Assam is primarily rainfed, it is imperative to understand the rainfall distribution pattern and determine the major changes in rainfall and temperature that has occurred over time in the state.

The climatic parameters of Assam have changed significantly over the years with decreased annual and seasonal rainfall and rising average daily mean temperature. Mean annual rainfall in the Brahmaputra valley has declined by 66.6 mm/decade and monsoon rainfall decreased by 53.4 mm/decade during the period 1986-2015, with a significant decrease in July and September rainfall (Gharphalia *et al.,* 2018). A notable warming has also been observed in the Brahmaputra valley by 0.90°C during the period 1986-2015, with increase in annual maximum temperature (0.41°C/decade) being double than that of minimum temperature (0.20°C/ decade), leading to increase of warmer days and reduction of cooler nights in the valley (Tamuly *et al*., 2019). Besides, the nights are becoming warmer, particularly during the winter season due to significant reduction in winter rainfall. Though August is normally the hottest month in the state, in the recent years, it is observed that September is turning out to be the hottest month due to aberrant rainfall during later part of monsoon season.

**Impact of climate change on agriculture in Assam**

Being recognized as an agrarian economy, about 75 per cent of the total working force in Assam is engaged in agricultural activities. Assam has an estimated 40.87 lakh ha gross cropped area (GCA), of which net area sown is about 27.74 lakh ha and area sown more than once is 13.14 lakh ha, with a cropping intensity of 146 per cent. Fluctuations in amount and distribution of rainfall, and specifically the decrease in monsoon rainfall, have a negative impact on *sali* rice production which calls for contingency planning during *kharif* season. It is observed that the monsoon rainfall is significantly decreasing at Dhubri, Shillongani and Tezpur. If it continues to decrease at this rate for the next couple of years, farmers may be deprived of getting the estimated returns from their crop fields. Similarly, in the event of abnormally high rainfall eventually leading to flood, economic loss will be insurmountable. The predominantly small farmer-oriented mono-crop farming in Assam is often affected by floods and seasonal drought, which are also likely to increase in the future. On the other hand, an increase of maximum temperature by 1°C during summer or monsoon season may not have any harmful impact on temperature loving crops in Assam, like rice, provided water stress is absent. Warming during pre-monsoon season will hasten the maturity of *boro* rice and sowing time of *ahu* rice may be enhanced. During *rabi* season, if the minimum temperature is raised by 1°C or so, cole crops will mature early and water need of the crops will increase. The crop will establish soon and may suffer from early drought during January/February. In the event of decrease of winter temperature by 1°C or so, crop duration of rapeseed and mustard, vegetables etc. will increase and productivity will fall down. The flowering of horticultural crops like mango, jackfruit and litchi may be delayed and the fruit set may be poor. Livestock, which contributes to diverse agrifood systems, forms an important source of subsidiary income for most of the agriculture dependent families of Assam, particularly the small and marginal farmers (Borah and Halim, 2014). Rapid urbanization and globalization along with increasing global temperature have largely affected the sustainability in livestock production (FAO, 2018). Increasing air temperature accompanied by high relative humidity (>90%) can result in heat stress in dairy cattle especially during monsoon season (Das *et al*., 2020), which may affect their health and biological functioning leading to poor milk yield.

**Climate risk management**

Climate risk is the probability of damage, loss, and other negative consequences of a system under the influence of a climate or weather hazard. Vulnerability, on the other hand, is defined as a set of prevailing or consequential unsafe conditions or negative factors within a system that reduce its ability to resist or minimize damage and disruption caused by any hazards.

Climate risk arises from the interaction between climatological hazards and the existing vulnerabilities within a system. Therefore, the level of climate risk depends on two main factors, viz., (i) the nature of the climate hazard, which includes its frequency, magnitude, timing, and duration of exposure of the system to the hazard, and (ii) the vulnerabilities of the system. Generally, hazards with higher magnitude and intensity cause higher risk to the system. Similarly, if the vulnerability factors in the system are more, the system is at higher risk. Another factor that determines the climate risk is the element at risk or the economic value of the element. If the system has no valuable physical or living elements, the system is not at risk, however, if the system has valuable and living elements that are susceptible to hazards, the system is at high risk.

Assessing climate risks is crucial for effectively managing climate hazards in a particular area. Climate risk assessment involves understanding the nature, magnitude, and intensity of various climate hazards expected in a location, as well as identifying the existing vulnerabilities within the system. Preventing climate hazards is undoubtedly not easy, however, loss and damage from a weather aberration can be minimized by eliminating or reducing vulnerabilities in the system. That is why, though difficult, assessment of the vulnerability of the system is very important. Generally, climate risk assessment involves measuring weather and climate variability and their changing trends to identify the likelihood of weather hazards in a place and their potential damage to a system in the future.Another important aspect of climate risk management is capacity building through development of resources, means, and strengths required to improve the capability of a system to reduce the risk or cope with the disaster situation due to any climate hazard. Capacity building can be done through (i) Reduction of vulnerability factors by developing adequate resources in terms of physical or material, and living resources, (ii) Developing suitable technology and methodology to deal with the problem areas, and (iii) Enhancing the strength in terms of financial and other matters. Besides, organizing awareness programs, trainings, field days, exposure visits, demonstrations of climate-resilient technologies, making the availability of farm implements and machinery through the establishment of custom hiring centres, seed and fodder banks, etc. are some of the capacity-building measures that motivate farmers to adopt climate-resilient technologies.

**Adaptation/mitigation strategies**

The effect of weather aberrations can largely be counteracted in many situations, if not eliminated, with contingency crop planning. Contingency measures include technologies applied to land, soil, water, and crops, and institutional and policy-based approaches that are suggested to be implemented based on real-time weather patterns. These plans provide information on current farming systems and technological interventions to manage various weather aberrations such as droughts, floods, cyclones, hailstorms, heat waves, etc. in agriculture, horticulture, livestock, poultry, and fisheries. Agricultural contingency plans consist of four key stages, that is, preparedness, real-time response, relief, and rehabilitation.

Preparedness is a set of measures that converts a vulnerable system to a resilient one, enabling it to cope with abnormal weather conditions.

Initial preparedness measures include selecting appropriate crops and cultivars, ensuring availability of the seeds of suitable crops and varieties and fodder to farmers through the establishment of seed banks and fodder banks, seed treatments, need-based fertilizers application, management of pests and diseases, rainwater harvesting and recycling, establishment of custom hiring centers, etc. Real-time response is the planning for response and recovery during and after the occurrence of the weather crisis. Immediate response to reduce losses to standing crops can be achieved through midterm corrections such as draining out excess water from the crop field, gap filing through re-transplanting, re-sowing, life-saving irrigation, soil and foliar application of chemicals, etc. Relief means the measures to be taken to meet the immediate requirements of victims of weather aberrations. Raising community nurseries, supplying seeds or seedlings to the doorstep of farmers of the affected area, arranging for spraying of chemicals for controlling pests and diseases, creating awareness, and organizing need-based training programs, etc. during or after the crisis are some examples of relief. Rehabilitation is the act of restoring the system to its original state after its destruction by a weather hazard. The local authority, with support from state and national governments, and NGOs should assist farmers by providing seeds, fertilizers, diesel, farm machinery, and implements for the restoration of farming in the affected area.

Agriculture is not only sensitive to climate change but at the same time is one of the major drivers of climate change. In the present scenario where approaches like "think global, act local" are mostly in practice, adaptation measures must focus on benefitting the poor and the most vulnerable section as they are most directly dependent on natural resources for their livelihood. As such, they are the ones mostly prone to lose their livelihoods during the time of crisis. In Assam, climate change issue is still at a backstage with no clear responsibilities assigned to any particular department. Policy interventions and institutional mechanism with participatory processes, capacity building, inter-state and international cooperation are essential to cope with climate change impacts on agriculture and vast water resource sector of Assam. Review and reframing of state agriculture policy in the context of climate change vulnerability incorporating strategic guidelines for each of the agroclimatic zones is the need of the hour.

The most direct route for abating climate change is through the use of energy efficient technologies in different sectors or carbon neutral technologies or reducing or avoiding carbon emissions from economic activities. Evaluation of carbon sequestration potential of different land use systems including opportunities offered by conservation agriculture and agro-forestry is required. Another mitigation option is identification of cost-effective techniques for reducing methane generation and emission in ruminants by modification of diet, and in rice fields by proper variety development and water and nutrient management.

**Climate resilient agriculture**

A system is said to be climate resilient if it has the ability to absorb the shock of an extreme climatic event and still retain its basic function and structure and bounce back to normal conditions in a short time after the removal of the stress. This can be illustrated through an example of the management of flash floods in *Sali* rice cultivation in Assam. The extent of damage in *Sali* rice caused by the flood depends on several factors, *viz.*, the timing and duration of the flood, flooding depth, and crop growth stages. If submergence of the crop occurs during the panicle initiation and later stages of growth for even 3 to 5 days, no variety can survive. However, unlike other varieties, submergence-tolerant varieties like *Ranjit Sub-1* and *Bahadur Sub-1* can withstand submergence for up to 15 days during the tillering stage, and they can bounce back to normal condition after some time of the receding flood, and tips of plants come out of water. So, these two submergence-tolerant varieties can be referred to as climate-resilient varieties with respect to flash floods.

Building a climate resilient system comprises of two phases, *viz.*, risk management and crisis management. In the risk management phase, actions are to be taken before the occurrence of weather aberration to minimize potential loss or damage and aim to prevent a disaster-like situation. On the other hand, the crisis management phase involves addressing disaster situations through immediate actions, such as real-time responses, relief, and rehabilitation during and after the weather-related hazard strikes the area. In the risk management phase, once the disaster-like situation is over, an assessment of the losses due to hazards is conducted, followed by planning for future development to enhance the resilience of the system.

Another important intervention is the weather smart service, as it is directly related to the income security of the farmers. In order to develop and apply operational tools to manage weather related uncertainties through agro-meteorological applications, seasonal weather forecast and early-warning systems can help counteract the negative impacts of rapidly changing environments on agriculture. Practically, Government of India has been providing weather-based farm advisories with the help of Agromet Field Units (AMFUs) located in different agro-climatic zones of India under the Gramin Krishi Mausam Sewa (GKMS) scheme, where information regarding new seed varieties, climate smart farming practices and tips on conservation agriculture, etc. are disseminated to the farmers.

By identification and evaluation of climatic risks, different climate resilient technologies such as, demonstration of stress-tolerant cultivars, integrated water, nutrient, weed, and pest management, rainwater harvesting and recycling, use of improved farm machinery and tools, strengthening old-aged integrated farming system, exploitation of unused and misused areas through alternate land use, etc. may be explored as solutions for combating the challenges arising in agriculture due to climatic change.

## Conclusion

Considering the vulnerabilities of the agricultural sector in different agro-climatic zones, the risks associated with climate change and variability further gets aggravated with the increasing food demand for a growing population. To tackle the issues of climate change, climate-resilient agriculture serves to be an important and compulsory action that needs to be implemented rather than just discussing it. The predominantly small farmer-oriented mono-crop farming in Assam is often affected by climate-related risks, such as floods and seasonal drought. One of the ways to reduce vulnerability and enhance the resilience of the agricultural system is to opt for adaptation strategies along with appropriate mitigation measures. Harnessing improved technologies along with traditional wisdom available among the farmers should be captured and perpetuated to cope with climate variability.Implementation of appropriate contingency plans in real-time, have to be sorted out with critical observation of the cropping system vis-a-vis observed climatic variables. Besides, efforts are needed towards increasing climate literacy among all stakeholders of agriculture, including students, researchers, policy makers, science administration, industry as well as farmers. ●●

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# Simulation Modeling: a Process-Based Tool for Addressing *What-if* Uncertainties in Agriculture under the Changing Climatic Scenario

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**"The Intergovernmental Panel on Climate Change Synthesis Report documented several studies, which states that- climate change has already been negatively affecting agriculture, and these impacts will become more severe in the future."**

**Introduction**

The continued rise in population worldwide necessitates a boost in agricultural output under the scenario of ever shrinking land, water, labour and other input resources. These factors are further compounded by climate change caused by anthropogenic activity. Though agriculture is the backbone of the global economy, providing food, fiber, and raw materials for industries, perhaps, the sector is increasingly facing challenges due to weather variability and climate change, resource depletion, soil degradation, and growing food demand. The rise of industrialization and agricultural activities has led to an increase in the concentrations of atmospheric $CO_2$ and other greenhouse gases (GHGs). There is a broad agreement that this phenomenon is causing long-term alterations in weather patterns, including rising temperatures, increased flooding, and extended drought periods (Van der Wiel & Bintanja, 2021). The Intergovernmental Panel on Climate Change Synthesis Report documented several studies, which states that- climate change has already been negatively affecting agriculture, and these impacts will become more severe in the future (IPCC, 2023). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) has announced a new way of evolving scenarios. These scenarios explain the range of probable radiative forcing scenarios, and are called representative concentration pathways (RCPs), and later was replaced by more improved scenarios under the Shared Socioeconomic Pathways (SSPs).

Now, how can the science of system simulation can help addressing these complexities? As it is evident that- the interactions among the major components of agricultural systems have a major influence on responses of the systems. Hence it is highly necessary to study the individual system in isolation and draw an overall conclusion for agroecosystem as a whole (Hieronymi, 2013). And there comes the importance of "System Science". System Science is the study of various components of the real-world having significant interactions among its other and forms a complete system. Interaction among these major components and sub-components with their environment determines the overall behaviour of the system. In case of an agricultural system, the major components are-weather, soil, agronomic management practices, varietal characteristics etc. These components may have both desired and undesired effects on each other and accordingly, the final outcomes of the agricultural system will gets differ. Agroecosystem models offer a means of synthesizing and quantifying the impacts of management practices, crops, soils, water, and climate on the sustainability of agricultural production and the surrounding agroecosystem. In this context, crop simulation modeling has emerged as a crucial tool to predict crop growth, yield, and environmental interactions under various scenarios. By integrating agronomic, environmental, and management factors, these models help farmers, researchers, and policymakers make informed decisions to enhance productivity and sustainability. Better understanding and ability to predict crop production under varied climatic situations and management approaches will help the policymakers and farmers to get equipped with enhanced adaptation strategies to maximize crop growth as sustainably as possible. Crop model tools offer a way to evaluate trade-offs of potential adaptations in climate and can help form the basis of decision-support systems for the farming community.

**Importance of crop simulation modelling in the present agricultural scenario**

Models of agricultural production systems were first conceived during1960s; and one of the pioneers of agricultural system modeling was a physicist C. T. de Wit of Washington University, who believed that- agricultural systems could be modeled by combining the physical and biological principles (Jones *et al*., 2016). Later in the year 1969, based on the ideas of de With, W. G. Duncan and Herb Stapleton, a regional research project was initiated in the USA to develop and use production systems model for improving cotton production (Stapleton *et al*., 1973). These process-based models are more advantageous than empirical modes used in understanding the relationship amongst dependent and independent variables. It has wider scope for understanding "what if" uncertainty in agricultural system, which is not possible in simple statistical model. Afterward, a gradual development of agricultural system models is evolving through efforts of an increasing number of research organizations worldwide and through various global efforts, like the global AgMIP, 2014, CGIAR-led programs, such as the IFPRI-led Global Futures and Harvest Choice projects and the CIAT-led CCAFS project, CIMSANS Center and various global initiatives that aim for more harmonized and open databases for agriculture. Some of the examples of most widely used simulation models in agriculture are: Decision Support system for Agrotechnology Transfer (DSSAT), Agricultural Production Systems Simulator (APSIM), Crop System Model (CropSyst), Environmental Policy Integrated Climate Model (EPIC), World Food Studies (WOFOST), Information on Crop (InfoCrop) model etc. In the context of present climate change scenario, global agricultural sector is increasingly being affected by climate variability, extreme weather events, declining soil fertility, and water scarcity; and the science of system simulation provides an essential framework for addressing these challenges in several ways such as:

**(i) Climate change adaptation**

Crop simulation models play a vital role in climate change adaptation by assessing the impact of changing weather patterns on agricultural productivity. These models help predict the effects of rising temperatures, altered precipitation patterns, and extreme weather events on crop growth and yield. They assist in developing adaptive strategies such as modifying planting dates, selecting climate-resilient crop varieties, optimizing irrigation, and improving soil management practices. By integrating real-time data and predictive analytics, crop simulations enable farmers and researchers to make informed decisions, reducing risks and improving sustainability in a changing climate.

**(ii) Precision agriculture and resource optimization**

In precision agriculture, crop simulation models serve as vital instruments that facilitate the effective management of agricultural inputs like water, fertilizers, and pesticides. These models examine soil conditions, weather patterns, and crop needs to offer tailored recommendations for specific locations, ensuring optimal and precise resource use and waste reduction. They assist farmers in modifying irrigation plans, fine-tuning nutrient application, and minimizing ecological effects by forecasting crop growth and yield under different circumstances. This leads to higher productivity, cost savings, and sustainable farming practices, making crop simulation a key component in modern, data-driven agriculture.

**(iii) Sustainable agricultural practices**

Simulation models assist Researchers, Scientist and policymakers in advising farmers in adopting methods like crop rotation, conservation tillage, intercropping, and organic farming; thereby guaranteeing long-term soil fertility and the preservation of biodiversity. Moreover, they help lower greenhouse gas emissions by fine-tuning fertilizer use and reducing resource waste. Crop simulations facilitate effective management of land and resources, aiding in the development of agriculture that is environmentally sustainable and resilient to climate change, by offering insights based on data.

**(iv) Adopting crop improvement strategies**

Crop simulation models support genetic enhancement and crop breeding by assessing how different crop genotypes perform in various environmental contexts. By simulating growth and productivity, these models assist researchers in pinpointing varieties that yield well, resist drought, and withstand the ill effect of climate change. Crop simulations expedite the breeding process by predicting how various genetic traits interact with soil, weather, and management practices, thereby reducing the time and costs involved in field trials. This allows for the creation of superior crop varieties that bolster food security and sustainable agriculture.

**(v) Improved decision-making for farmers and policymakers**

Crop simulation models support data-driven decision-making by predicting crop growth, yield, and resource needs under different environmental and management conditions. Policymakers rely on simulations to forecast food production, assess climate change impacts, and develop agricultural policies for food security and sustainability. By integrating the modeling approach with the science of Remote Sensing and GIS, an accurate insights on crop can be achieved for strategic planning, enhance resource use efficiency, risk management and resilience in agriculture.

**Challenges in crop simulation modelling**

Despite of notable advancements in the science of system simulation, the application of crop simulation models at field level experiences several challenges:

- **Data availability and accuracy** – Reliable data on weather, soil, and crop responses are crucial for model accuracy, but such data are often scarce, especially in developing regions.

- **Complexity and accessibility** – Many models require specialized knowledge and computational resources, making them difficult for farmers to use directly.

- **Model calibration and validation** – Ensuring that models reflect real-world conditions accurately requires extensive calibration and validation, which can be time-consuming and resource-intensive.

**Understanding crop simulation modelling**

Crop simulation modelling refers to the use of computational models to simulate crop growth and yield under different climatic, soil, and management conditions. These models are built using mathematical equations and data derived from field experiments, allowing for scenario-based analysis of agricultural practices. They incorporate factors such as weather conditions, soil properties, crop genetics, water availability, agronomic management practices, soil nutrient status, etc. to predict outcomes under different agricultural interventions. Some of the widely used process-based models used for agricultural system simulation are:

**(a) DSSAT (Decision Support System for Agrotechnology Transfer)** – The major outcome of the International Benchmark Site Network for Agrotechnology Transfer (IBSNAT) is the DSSAT during the 1980s. Furthermore, it can be used effectively for understanding the factors responsible for delineating crop growth, development and yield, and also can be used for predicting the yield under the changing climatic scenario and agronomic management practices (Hoogenboom, *et al*., 2019).

**(b) InfoCrop**: The InfoCrop is a generic crop growth model that can simulate the effects of weather, soil, agronomic managements (including planting, nitrogen, residue and irrigation) and major pests on crop growth and yield. The key inputs and outputs used in InfoCrop model are- weather, soil, variety, management information and pests information. The InfoCrop model is written in FORTRAN Simulation Translator (FST) language and the time step of the model is one day. InfoCrop model was developed by Aggarwal and his co-workers from the Centre for Application of Systems Simulation, IARI, New Delhi (Aggarwal *et al.*, 2006).

**(c) APSIM (Agricultural Production Systems Simulator)** – APSIM is a modular framework comprising of numerous individual modules that describe plant, soil, climate, and management processes. The main strength of the APSIM framework is the ability to integrate models derived in fragmented research efforts; which enables research from one discipline or domain to be integrated to the benefit of some other discipline or domain. It also creates a provision for comparing the models or sub-models in a common platform. The APSIM framework was originally developed by the Agricultural Production Systems Research Unit (APSRU), based in Toowoomba, Queensland. APSRU was a partnership involving researchers from Australian Government research agency CSIRO (the Commonwealth Scientific and Industrial Research Organisation), the University of Queensland and the Queensland State Government, established in 1990 (Keating *et al.*, 2003).

**(d) WOFOST (World Food Studies Model)** – WOFOST is a member of the family of crop growth models developed in Wageningen by the school of C.T. de Wit. Related models are SUCROS (Simple and Universal CRop growth Simulator), MACROS (Modules of Annual CROp Simulator) and ORYZA1. WOFOST simulates the daily growth of specific crops, using the selected weather and soil data (De Wit *et al*., 2019)

**Future prospects**

The future of crop simulation modeling depends on incorporating advanced technologies like artificial intelligence (AI), machine learning, remote sensing, and big data analytics. These developments will boost the precision of models, automate the gathering of data, and enhance farmers' ability to make decisions in real-time. User-friendly mobile apps will help small-scale farmers to access the outcomes of crop simulations more easily in an user friendly framework. Moreover, the incorporation of climate models will assist in forecasting long-term agricultural patterns and bolstering climate-smart farming practices. As technology continues to advance, crop simulation modelling is set to become essential for sustainable agriculture, food security, and global climate resilience. Overall, system simulation deals with several complexities and uncertainties, which need to be justified critically with valid logical arguments. Often it was felt that- any attempt to simulate highly multifarious biological systems using statistical and mathematical algorithms in virtual system is full of doubts. Nevertheless, another school of thought apprehends greater future prospects amongst the researchers' community, especially in the field of crop improvement. Crop simulation modelling is a transformative tool in modern agriculture, helping to address the challenges of climate change, resource scarcity, and food security. By integrating environmental and agronomic data, these models provide valuable insights for optimizing agricultural practices, improving sustainability, and ensuring global food production. Despite existing challenges, continuous advancements in technology will further enhance their accuracy and accessibility, making them indispensable in the future of agriculture.●●

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# Empowering Farmers through Effective Agricultural Extension Services

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**"Small holdings are crucial to advancing agricultural development and reducing poverty. The agrarian crisis or rural distress observed in several districts, the enormous yield gaps and the growing number of people moving from rural to urban areas in search of work all indicate that extension services are unable to meet the knowledge and support needs of farmers."**

**Agriculture in India**

With around 47 percent of the workforce working in agriculture (*Labour Bureau 2019-20*) and with 69 percent of the population residing in rural areas, India has a primarily agrarian rural economy (*Aayog 2021*). Approximately 85 percent of India's 138 million agricultural holdings are owned by small and marginal farmers(*Census 2010-11*). Most of them are impoverished. Growth in agriculture is essential to ensuring food and nutritional security in rural areas, which are mostly rural economies with a significant reliance on agriculture for household livelihoods. Compared to growth in any other sector, there is a substantial correlation between agricultural growth with the eradication of poverty, malnutrition and the creation of an egalitarian society.

It is often known that small farms contribute to development and arecontinuously fighting against poverty. GDP growth originating in agriculture is at least twice as successful in decreasing poverty as GDP growth originating outside of agriculture, according to the global experience of growth and poverty reduction (*WDR, 2020*). Small holdings are crucial to advancing agricultural development and reducing poverty. The agrarian crisis or rural distress observed in several districts, the enormous yield gaps (between demonstration fields and farmer fields as well as the enormous variation in yields among farmers within the same block) and the growing number of people moving from rural to urban areas in search of work all indicate that extension services are unable to meet the knowledge and support needs of farmers.

Although there is currently a wealth of pertinent information on raising farmers' incomes and productivityand extension appears to be spreading much of it, it is becoming more and more obvious that farmers are unable to put this new information to use and take benefit from it. There seems to be a fundamental issue with the nation's extension practices. Below is a discussion of some of the existing obstacles that prevent extension from providing farmers with full support :

Farmers in India face a multitude of challenges that hinder their growth and sustainability. Key issues include poor integration of value chains, increased competition due to liberalization and globalization and market volatility, which expose them to significant risks. Climate change adaptation, commercialization difficulties and rapid urbanization further exacerbate the situation. Institutional changes like the rise of supermarkets and privatization of technical advancements often marginalize small farmers. Additionally, lack of access to credit, inadequate rural infrastructure and limited extension services restricts their ability to adopt modern practices and make informed decisions. Depletion of natural resources, technology fatigue, disruptions in trade networks and insufficient agricultural planning compound the problems. Farmers also struggle to meet the rising demand for high-quality food with fewer resources, while economic hardships, including debt, persist. Addressing these challenges requires holistic solutions focusing on infrastructure, resource management, market integration and farmer-centric support systems.

Education is essential, as it is essential for modernity, market connection, assistance, group decisions regarding marketing and resource usage and the restoration of public extension systems, among other things. A stronger, more dynamic and responsive extension with a broader mandate is necessary to achieve more rapid, sustainable and equitable agricultural growth.

Encourage collaborations and pluralism, increased financing, coordination and convergence, support for research to meet small farmers' needs and assistance with change management extension must expand its mandates and have a considerably wider range of skills to stay relevant and address the modern changes in agriculture and the broader support needs of farmers (organizational, marketing, technological, financial and entrepreneurial).

The discussion should shift from links between research and extension and the spread of technology to strategies for fostering innovation and increasing capacity for innovation, to adopt new frameworks and methodologies, such as innovation systems and innovation management, extension requires expert assistance and to test and assess new policies and extended delivery models that are suitable for each state, district or block, expert assistance is required.

**Extension and advisory services (EAS): bridging knowledge and practice**

Agricultural extension services provide critical links between innovation and practical applications, enabling farmers and rural economies to adopt and benefit from new technologies and practices. However, challenges like limited resources and ineffective performance, particularly in lowand middleincome countries, hinder these services.

Rural extension services face a "triple challenge" of market, state and community failures. Inadequate resources, insufficient training and lack of incentives for staff exacerbate these challenges. Modern EAS must address diverse issues, such as climate adaptation, disaster recovery, human nutrition, and post-emergency rebuilding. They need to harmonize short-term responses with long-term resilience strategies. Effective EAS also helps farmers by -

- Providing timely information on weather, markets, regulations and consumer demands.
- Identifying vulnerable households to ensure cost-effective interventions.
- Coordinating local, regional and national actors during crises.

Rural advisory services (RAS) empower farmers with knowledge, capacity-building, and innovation promotion. These services assist farmers in improving technical, organizational, and management practices, ultimately enhancing livelihoods and fostering inclusive rural transformation.

**Evolution of EAS providers**

**Public Sector:** Historically, public-sector EAS were the backbone of rural advisory systems, promoting education and technical support. Initiatives like the Agricultural Technology Management Agency (ATMA) and Krishi Vigyan Kendras (KVKs) have significantly contributed to agricultural innovation. Public extension services in India, for example, evolved with national priorities from the Green Revolution to modern-day diversification and market orientation.

Key public sector initiatives include:

- **ATMA**: A district-level agency supporting agricultural technology management and diversification.
- **KVKs**: Approximately 600 farm science centres run by the Indian Council of Agricultural Research (ICAR), focusing on technology transfer and innovation.
- **Media outreach**: Platforms like All India Radio's Farm and Home Program and Doordarshan's Krishi Darshan broadcast agricultural education to a broad audience.
- **Kisan call centres (KCCs)**: A scheme offering farmers localized agricultural advice over the phone.

**Private sector:** The private sector plays an increasing role in EAS, filling gaps left by under-resourced public systems. Companies provide services like:

- **Input and technology providers**: Agro-dealers and input suppliers deliver technical advice along with products. Programs like MANAGE's Diploma in Agricultural Extension Services for Input Dealers (DAESI) enhance dealer capacity.
- **Agribusiness Models**: Companies like Mahindra's Krishi Vihar and Tata's Kisan Sansar offer integrated solutions, including training, credit, market links, and technology access.
- **Contract Farming**: Firms like PepsiCo and Adani Agrifresh focus on post-harvest practices and farmer compliance, ensuring high-quality production for markets.

**NGOs:** Non-governmental organizations (NGOs) like PRADAN, Basix and the BAIF Development Research Foundation are instrumental in organizing self-help groups and farmer-based organizations. They provide demand-driven services that enhance rural livelihoods.

**Best Practices for Mobilizing Rural Advisory Service Potential**

1. **Best-fit approaches**

EAS programs must adapt to diverse rural contexts rather than applying one-size-fits-all solutions. The best-fit approaches promote:

- **Pluralism**: Leveraging public, private and NGO collaboration to meet varying needs.
- **Localization**: Tailoring strategies to local governance, farming systems and resource capacities.

**2. Pluralism in service provision**

Combining efforts from public, private and civil society sectors can enhance service reach and effectiveness. The key roles include:

- **Public Sector**: Coordinating and ensuring quality assurance for services with a public goods nature.
- **Civil Society**: Producer organizations identify needs and provide flexible service delivery.
- **Private Sector**: Linking producers to markets and offering high-value product advice.

Institutional and financial pluralism ensures accessibility for all, especially vulnerable groups. Targeted public investments remain critical, alongside subsidies for private providers.

### 3. Accountability and inclusivity

Shifting towards demand-driven, farmer-led RAS emphasizes bottom-up planning and evaluation. Policymakers must ensure services address gender, age, and ethnic disparities. Decentralization and participatory evaluation methods enhance accountability and effectiveness.

### 4. Human resource development

Capacity-building is crucial for both farmers and extension agents. Farmers need technical, management and market-oriented skills, while agents require expertise in organizational development, problem-solving, and facilitation. Agricultural education systems must prioritize these skills to address modern challenges like climate change and market volatility.

### 5. Sustainability and long-term strategies

RAS systems need sustainable government commitment and financing. Temporary project-based resources often fail to achieve long-term impact. Building institutional strength and capacity is essential to address future challenges, including food security and climate adaptation. Governments must prioritize strengthening RAS frameworks over quick-fix solutions.

### Role of extension and advisory services in building resilience of small-holder farmers

Market volatility, weak governance, violence and disease exacerbate the susceptibility of smallholder farmers and rural producers, who are among the most vulnerable groups to climatic shocks and weather-related calamities. By expanding rural and farming households' access to both tangible and intangible resources, such inputs and information, extension and advisory services may offer a chance to improve their resilience. In a broader sense, extension and consulting services might be able to significantly contribute to the advancement of rural and agricultural development as well as the strengthening of the sector's overall resilience. This theory is predicated on the idea that farmers do not have the resources, expertise or both necessary to effectively prevent, predict, plan for, deal with and recover from shocks.

By offering or enabling access to a range of resources, extension and advisory services may be able to address this knowledge imbalance, also known as information asymmetry. By promptly communicating farm-level issues and possible solutions to politicians, these services could help support resilient agricultural systems by empowering them to make more informed policy decisions.

- Strengthening Human Capital through Extension and Advisory Services
- Seed and input provision
- Regarding climate change, a core challenge for extension and advisory services in the future is shifting from providing "packages" of technological and management advice to supporting farmers with the skills and information they need to make informed decisions
- Information sharing tools such as information and communication technologies (ICTs) are another area at the nexus of these services and resilience

Hence, Effective extension and advisory services are essential for agricultural innovation, rural development and resilience-building. By addressing resource gaps, fostering collaboration among stakeholders and focusing on localized, inclusive strategies, EAS can empower farmers to face contemporary challenges and achieve sustainable livelihoods. Long-term success requires government commitment, innovative approaches and the collective effort of public, privateand civil society sectors.

### Role of extension and advisory services in mitigating climate change in agriculture

Extension and advisory services play a crucial role in helping farmers mitigate the effects of climate change on agriculture. These services can disseminate knowledge about climate-resilient crops, sustainable farming practices and efficient resource management techniques. They can train farmers on adopting conservation agriculture, water-saving irrigation systems like drip and sprinkler irrigation and integrated pest and nutrient management. Extension programs can also promote agroforestry, crop diversification and organic farming to enhance ecosystem resilience.

By offering timely weather forecasts, early warning systems and climate data, extension services enable farmers to make informed decisions regarding planting, harvesting and input applications. Moreover, they facilitate access to climate-smart technologies such as drought-resistant seeds and precision agriculture tools, while linking farmers to government schemes and subsidies aimed at promoting climate adaptation.

Extension services can foster community-based approaches such as collective water management and participatory research, to enhance local capacity in addressing climate challenges. Additionally, they provide platforms for knowledge exchange, enabling farmers to share successful practices and innovations. Strengthening these services with adequate funding, training and technology can significantly enhance farmers' ability to adapt to and mitigate the impacts of climate change.

## Conclusion

Agricultural extension services (EAS) serve as vital links between innovation and practice, aiding farmers and rural economies in embracing new technologies. Nevertheless, these services often confront challenges, particularly in low- and middle-income countries, such as limited resources and inadequate performance. They grapple with a "triple challenge" involving failures in markets, states, and communities, compounded by insufficient training and lack of staff incentives. To effectively address contemporary challenges, EAS must tackle diverse issues including climate adaptation, disaster recovery, and human nutrition. This requires balancing immediate responses with long-term resilience strategies.

Key functions of effective EAS include providing timely information on weather, markets, and regulations; identifying vulnerable households for targeted assistance; and facilitating coordination among various stakeholders during crises. Rural advisory services (RAS) further empower farmers through knowledge dissemination, capacity-building, and innovation promotion, consequently enhancing technical, organizational, and management practices. This support ultimately improves livelihoods and fosters inclusive rural transformation.

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# Need of Frontier Technologies for Resurgent Horticultural Sector

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**"Advanced innovations such as artificial intelligence (AI), the Internet of Things (IoT), biotechnology, precision farming, and automation can significantly enhance productivity, efficiency, and sustainability in horticulture."**

The horticultural sector plays a crucial role in ensuring food security, economic growth, and employment generation worldwide. However, it faces numerous challenges, including climate change, land degradation, water scarcity, pest outbreaks, and fluctuating market demands. To revitalize and sustain the sector, the adoption of frontier technologies is imperative. Advanced innovations such as artificial intelligence (AI), the Internet of Things (IoT), biotechnology, precision farming, and automation can significantly enhance productivity, efficiency, and sustainability in horticulture. However, these technologies also present potential drawbacks and risks that need to be addressed for long-term viability.

**Different types of frontier technologies relevant to indian horticulture**

**(a) Precision farming and smart agriculture**

Precision farming integrates satellite imaging, GPS, and IoT sensors to optimize water, nutrient, and pesticide use. Smart irrigation systems powered by AI and machine learning analyze real-time data to ensure optimal water utilization, reducing wastage and enhancing yield. Automated drones and robots further aid in monitoring crop health, pest control, and efficient harvesting. John Deere's precision agriculture technology uses AI and GPS to optimize crop management, reducing input costs and maximizing yields.

**(b) Biotechnology for improved crop varieties**

The use of biotechnology and genetic engineering has led to the development of high-yielding, disease-resistant, and climate-resilient crop varieties. CRISPR gene-editing technology enables targeted modifications to enhance fruit quality, shelf life, and resistance to pests and diseases, reducing the dependency on chemical pesticides. For example, the development of the Arctic Apple, which does not brown due to gene silencing, has extended shelf life and reduced food waste.

**(c) Automation and robotics**

Automation in horticulture includes robotic weeders, sprayers, harvesters, automated irrigation systems, and AI-driven autonomous pest control mechanisms including application of UV light emitting system for disinfection. Unmanned Aerial Vehicles (UAVs) and Drones offer tremendous scope for surveillance and mapping, precision spraying and pollination assistance. These innovations help address labor shortages, improve efficiency, and enhance productivity. For instance, Agrobot's robotic strawberry harvester can detect and pick ripe fruits, reducing dependency on manual labor.

**(d) AI, Internet of Things (IoT), smart censors and data analytics**

IoT devices collect real-time farm data, allowing farmers to make informed decisions regarding irrigation, fertilization, disease management etc.. IoT-based soil sensors, like those developed by AgriTech startups, provide real-time data on soil moisture, pH, and nutrient levels, allowing precise fertilization and irrigation management. Smart fertilizer recommendation systems, such as India's 'Bhuvan' soil fertility mapping program, assist small farmers in optimizing nutrient application, reducing input costs, and improving soil sustainability. AI-based soil analysis tools aid in assessing soil properties, topography, and microclimatic conditions to determine the best locations for cultivation. AI-powered data analytics help predict crop yields, detect diseases, and suggest optimal farming practices. TCS mKRISHI is an IoT-based platform that provides Indian farmers with personalized farming advice based on real-time data. The use of AI-powered grading machines for apples in Himachal Pradesh has significantly improved quality control and market returns.

**(e) Block chain technology**

Block chain technology provides a decentralized and tamper-proof ledger system that enhances transparency, traceability, and trust in the horticultural supply chain. By recording each transaction in real time, blockchain ensures that all stakeholders—farmers, wholesalers, retailers, and consumers—can track the journey of agricultural produce from farm to fork. IBM Food Trust, a blockchain-based platform, enables traceability in the food supply chain, ensuring food safety and reducing fraud.

**(f) Renewable energy solutions**

Solar-powered cold storage, irrigation systems, and greenhouse automation can provide sustainable and cost-effective solutions for horticulture, reducing dependence on fossil fuels and lowering production costs. For example, solar-powered cold storage units developed by *Ecozen Solutions* help farmers reduce post-harvest losses by maintaining optimal storage conditions.

**Scope and relevance of frontier technologies for smart farming in india**

India's horticultural sector is dominated by small and marginal farmers who face constraints in landholding size, financial resources, and access to advanced technology. The relevance of frontier technologies for such farmers lies in their ability to enhance productivity while optimizing resource utilization. Some key areas where these technologies can benefit smallholders include:

**Precision Farming:** Affordable sensor-based solutions and mobile apps such as the *Kisan Suvidha* can provide real-time data on soil health, weather patterns, market prices etc. helping farmers make informed decisions with minimal resource wastage.

**Biotechnology:** Disease-resistant and high-yielding crop varieties can reduce dependency on expensive pesticides and fertilizers, making cultivation more cost-effective. Hybrid and genetically improved horticultural crops such as disease-resistant tomatoes and bananas developed by Indian research institutions help small farmers reduce losses and improve yield.

**Nanotechnology:** Nano-encapsulation of pesticides enhances stability and controlled release thereby reducing residues. Nano-Biosensors detect pathogens and pest infestations at an early stage for timely interventions. Likewise, Nano-Fertilizers improve plant health, making crops more resistant to pest and disease attacks.

**Artificial intelligence, IoT and data analytics:** Smartphone-based AI applications can guide farmers in crop protection and yield prediction. Affordable mobile applications that use IoT sensors to monitor soil health and alert farmers about required interventions. Drip irrigation systems integrated with IoT sensors and AI-driven monitoring platforms, like those developed by Jain Irrigation Systems, enable farmers to apply the right amount of water based on real-time soil moisture and weather data. Advanced technologies such as Geographic Information Systems (GIS) and Remote Sensing (RS), can integrate digital soil mapping and geospatial technology to provide farmers with detailed soil fertility assessments, guiding them in crop selection and nutrient management. Application of AI and machine learning is also effective in pest & disease detection, predictive analytics and automated decision support system. IoT coupled with smart censors offers scope for real- time monitoring, automated traps and remote pest control. AI-powered sorting and grading systems ensure uniform quality assessment and reduce human errors in classification while automated washing, peeling, and cutting machines improve efficiency and reduce labor dependency. Cold chain logistics and IoT-based monitoring help maintain optimal storage conditions, reducing spoilage and improving shelf life.

·**Automation and drones:** Low-cost, shared automation solutions such as community-owned drones can be used for monitoring crop health, spraying pesticides, reducing labor costs, and improving efficiency in farm management.

**Block chain and digital platforms:** Block chain and digital platforms provide real-time tracking, facilitate efficient market linkages, ensure fair pricing and reduce dependency on intermediaries. Block chain-powered platforms as AgriLedger allow small-scale farmers to access secure transactions and real-time supply chain visibility.

**Big data and cloud computing:** IPM platforms may offer **c**entralized cloud-based systems process data to guide farmers on pest control decisions. Weather-based pest forecasting analyzes historical and real-time data to predict pest outbreaks.

**Digital marketplaces:** Online platforms enable small farmers to bypass middlemen, ensuring better prices and reducing post-harvest losses.

**Renewable energy solutions:** Solar-powered irrigation systems and cold storage units can provide cost-effective alternatives to conventional energy sources, reduce operational costs for small farmers and improve sustainability.

**Cold chain logistics and IoT-based monitoring:** Can effectively help maintain optimal storage conditions, reducing spoilage and improving shelf life.

**Automated packaging technologies:** Smart packaging solutions, including biodegradable films and active packaging, extend shelf life and improve product quality.

**Solar-powered cold storage units:** Suitably offer an energy-efficient solution to preserve perishables, benefiting small and marginal farmers.

**Advanced food processing technologies:** Can enhance value addition in primary, secondary, and tertiary processing, supporting agro-industries.

**Bioengineering and fermentation technologies:** Effectively improve product diversification, such as converting surplus produce into juices, purees, or nutraceuticals.

**Smart logistics and traceability systems:** Ensure better connectivity and reduce wastage during transportation.

**Challenges and barriers to the adoption of frontier technologies in indian horticulture**

Despite the immense potential of frontier technologies, several physical, technological, financial, social, and administrative challenges hinder their widespread adoption in Indian agriculture and horticulture.

**(a) Physical challenges**

· Land Fragmentation: The small and scattered landholdings of marginal farmers make it difficult to implement large-scale automation and precision farming.

· Infrastructure Deficiencies: Limited access to rural roads, electricity, and cold storage facilities affects the adoption of technology-driven solutions.

· Climate Variability: Unpredictable weather patterns and extreme climatic events make it challenging to rely solely on AI-based forecasting models.

**(b) Technological challenges**

· Lack of Digital Literacy: Many small farmers lack the technical know-how to operate AI-based applications, automated machinery, and IoT-enabled devices.

· Connectivity Issues: Poor internet and mobile network coverage in remote agricultural areas restrict the effectiveness of digital platforms and real-time data collection.

· Compatibility with Traditional Practices: Many advanced technologies may not seamlessly integrate with conventional farming techniques, requiring extensive modifications.

**(c) Financial challenges**

· High Initial Investment Costs: The adoption of precision farming tools, robotics, and biotechnology requires significant financial investment, which is often unaffordable for small and marginal farmers.

· Limited Access to Credit: Many farmers struggle to obtain loans or subsidies for purchasing advanced equipment due to bureaucratic hurdles and lack of collateral.

· High Maintenance and Operational Costs: Technologies such as drones, automated irrigation, and climate-controlled greenhouses require continuous maintenance, increasing the financial burden.

**(d) Social challenges**

· Resistance to Change: Many farmers are skeptical about adopting new technologies due to traditional mindsets and fear of failure.

· Loss of Employment: Increased mechanization and automation may displace agricultural laborers, creating socio-economic tensions in rural areas.

· Trust Issues with Agri-Tech Companies: Farmers often face difficulties in trusting private agritech firms due to concerns about data security, unfair pricing, and lack of transparency.

**(e) Administrative challenges**

· Regulatory Hurdles: The approval and regulation of genetically modified crops and biotech solutions face stringent government restrictions, delaying their implementation.

· Lack of Policy Coordination: Fragmented policies and lack of coordination between central and state governments create obstacles in scaling up technology-driven initiatives.

· Inadequate Extension Services: Government agricultural extension services are often insufficient in training farmers on new technologies and providing necessary support.

While the frontier technologies hold immense promise, the affordability, accessibility, and digital literacy remain key challenges for their adoption by small and marginal farmers. Government initiatives, cooperative models, and private-sector interventions will play a crucial role in making these technologies viable at the grassroots level. The integration of frontier technologies in horticulture is crucial for overcoming modern agricultural challenges and ensuring long-term sustainability. However, for small and marginal farmers in India, accessibility, affordability, and ease of use must be prioritized. Government initiatives such as the Digital India and Pradhan Mantri Krishi Sinchayee Yojana schemes, along with agritech startups, can bridge the technological gap by providing cost-effective and scalable solutions tailored to small-scale farming. With the right policy support, training, and financial assistance, frontier technologies can revolutionize India's horticulture sector, ensuring inclusive growth and enhanced resilience to future challenges.

# Innovative Tech-Driven Solutions for Advancing Agricultural Productivity and Rural Prosperity

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**"The preliminary aim of these technologies is to provide abundant agricultural yield with minimal resources and value-added food products with extended shelf life."**

**Abstract**

Modern agriculture is the backbone of India's economy; the majority of the population is dependent on it for their livelihood. But the agricultural sector has a lot of challenges that include primarily climatic change, water resource management, and degradation of the soil with different environmental aspects. In order to overcome these problems, cutting-edge technologies help enhance agricultural production and sustainable livelihoods. The multimodal and innovative technologies implement a range of methods to conduct research and development for translational products. The technologies involved in precision agriculture and aquaculture, such as IoT-based sensors and devices for monitoring crop health, soil moisture, temperature, and impacts on different climatic conditions. It includes AI-driven applications such as predictive analytics, crop yield analysis, and other decision support systems. UAV and drone technology facilitated the development of these models for crop health monitoring, soil mapping, and precision farming. These models utilize and implement modern climatic farming for precise irrigation, pest control, and crop fertilization, with the aim of maximizing yields and reducing agricultural waste. The preliminary aim of these technologies is to provide abundant agricultural yield with minimal resources and value-added food products with extended shelf life. Government of India-sponsored initiatives and Vel Tech R&D were instrumental in the development of all these technologies. The interdisciplinary research helps to collaborate and promote sustainable agricultural practices, increased rural wealth, and assured food supply.

**Keywords:** Precision Agriculture, Artificial Intelligence (AI), Internet of Things(IoT), Unmanned Aerial Vehicles (UAV), Food products.

**Introduction**

Agriculture remains the backbone of our economy, particularly in North-East India, where diverse agro-climatic conditions support the cultivation of high-value crops. Recognizing the potential for technological advancements to revolutionize this sector, Vel Tech has actively contributed by developing cutting-edge solutions that enhance agricultural productivity and provide valuable advisory support for farmers. Through our state-of-the-art research laboratories, we have pioneered non-destructive sensing systems, value-added agri-products, AI-driven precision farming, UAV-based monitoring, and machine intelligence for aquaculture. These innovations aim to empower farmers with real-time data, sustainable practices, and cost-effective solutions, ultimately fostering growth, efficiency, and resilience in the agricultural sector. The following are key initiatives and technological advancements developed by Vel Tech.

**Leveraging technology for precision agriculture and aquaculture**

The merging of technology with agriculture led to the development of precision agriculture and precision aquaculture, which have completely changed the food production industry. With the integration of artificial intelligence, IoT, and data analytics, farmers and aqua culturists are able to maximize productivity, minimize waste, and support sustainability. This souvenir looks into new developments and technologies in precision agriculture and precision aquaculture that leverage technology to address the growing demand for food.

**UAV & AI-based precision agriculture**

In collaboration with Assam Agricultural University (AAU), our team from Centre for Autonomous System Research has developed AI-driven precision agriculture solutions for crop health monitoring, biomass estimation, and evapotranspiration studies in rice and rapeseed cultivation focusing the regions of Majuli, Assam. Advanced drone and multispectral sensor technologies have been used to optimize yield estimation and resource utilization. Currently, the centre is also conducting research on the use of unmanned systems, such as Amphibious UAVs, for inland fisheries and aquatic ecosystem management of Loktak Lake, Manipur, in collaboration with the College of Fisheries, Central Agricultural University (CAU), Tripura.

**Drone-assisted mapping of seaweeds and value addition**

Our UAV-based project successfully mapped seaweed species (Gracilaria sp. and Enteromorpha sp.) along the Odisha Coast and Chilika Lake to explore commercial applications.

**(i) Project Highlights:** 3D mapping for environmental monitoring, landslide detection, and water quality assessment. Developed a mobile application for classifying seaweeds (Enteromorpha vs. Gracilaria) to assist farmers.

**(ii) Biological Significance:** Seaweeds exhibit high nutritional properties, with low Na/K ratios, making them ideal for heart-healthy diets.

**Precision brackish water aquaculture technology using machine intelligence**

Our team from IoT and Expert systems in collaboration with CIBA, has developed Aquabouy, a smart water quality monitoring system that provides real-time data on pH, Dissolved Oxygen (DO), and Total Dissolved Solids (TDS). Using machine learning, this system predicts prognostic water quality trends for different aquaculture business models—high-risk, high-profit or low-risk, low-profit strategies.

**Key benefits:** Continuous real-time water quality monitoring for optimized fish and shrimp farming.

**Non-destructive sensing systems for quality assessment**

Vel Tech's Centre for Biomedical Spectroscopy in collaboration with Jadavpur University-Kolkata, and DBT-IBSD-Imphal, has developed a non-destructive sensing system using spectroscopic techniques (NIR and Raman) for rapid, in-situ quality assessment of Black rice, Ginger (Zingiber Officinale), Elsholtzia griffithii, and Cinnamomum zeylanicum. This technology enables real-time quantification of chemical compounds such as cinnamaldehyde and citral, ensuring standardization and grading of high-value agricultural products. The portable, battery-operated sensing system minimizes reliance on costly lab testing, empowering small-scale farmers to assess product quality directly. This project stands as a testament to Vel Tech's commitment to interdisciplinary research and technological advancements in agricultural assessment.

**Key benefits:** Real-time, non-destructive assessment of product quality, Reduces dependence on traditional lab testing, making quality assessment accessible, Supports domestic and export markets by standardizing product grading.

**Value-added products from finger millet milk extract – agri-entrepreneurship opportunity**

Finger millet is a rich source of calcium (382mg/100g), but traditional cooking methods are cumbersome. To solve this, our Centre for Bioenergy and Bioproducts Research, has developed finger millet milk flour, which is easy to prepare while retaining high nutritional value. In addition, the centre has developed finger millet-based products to address calcium and iron deficiencies in diets. Additionally, the centre also has a deep focus on conversion of coal washery reject into biomethane, providing a sustainable bioenergy solution.

**Developed products**

Concentrated Calcium and Iron-rich Finger Millet Milk Powder Extract, Non-dairy Fermented Batter with Starter Culture, Ice Cream Cones, Waffle Biscuits, fish feeds and poultry feed from Millet Fiber Husk – Ragi husk.

**Supercritical foamed 3D-printed polymer for marine applications**

In collaboration with IIT Guwahati, the Centre for Additive Manufacturing is currently engaged in developing supercritical foamed biopolymer composites with high buoyancy, strength, and corrosion resistance for Remotely Operated Vehicle (ROV) construction. These lightweight, eco-friendly materials are being designed for sustainable marine applications.

**Key focus areas:** Biodegradability and recyclability of polymer-based ROV materials. Life cycle analysis to assess the environmental impact of these biopolymers.

Through collaborative efforts with NER-based universities, our research lab has pioneered several cutting-edge agricultural and aquaculture technologies. We have established multiple Centre of Excellence dedicated to precision farming, bioproduct development, and AI-driven agricultural solutions. We invite active collaborations with academia, industry, and government bodies to further strengthen the agricultural ecosystem in North-East India. Together, we can drive innovation that benefits farmers and the agrarian community, ensuring sustainable and scalable agricultural advancements.

In addition, we have several other ongoing research initiatives handled by different centre, as listed below, which are also open for collaborative research. ●●

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6. Centre for Interfaces and Nanomaterials
7. Centre for Metabolic engineering and synthetic biology
8. Centre for Thermal Management
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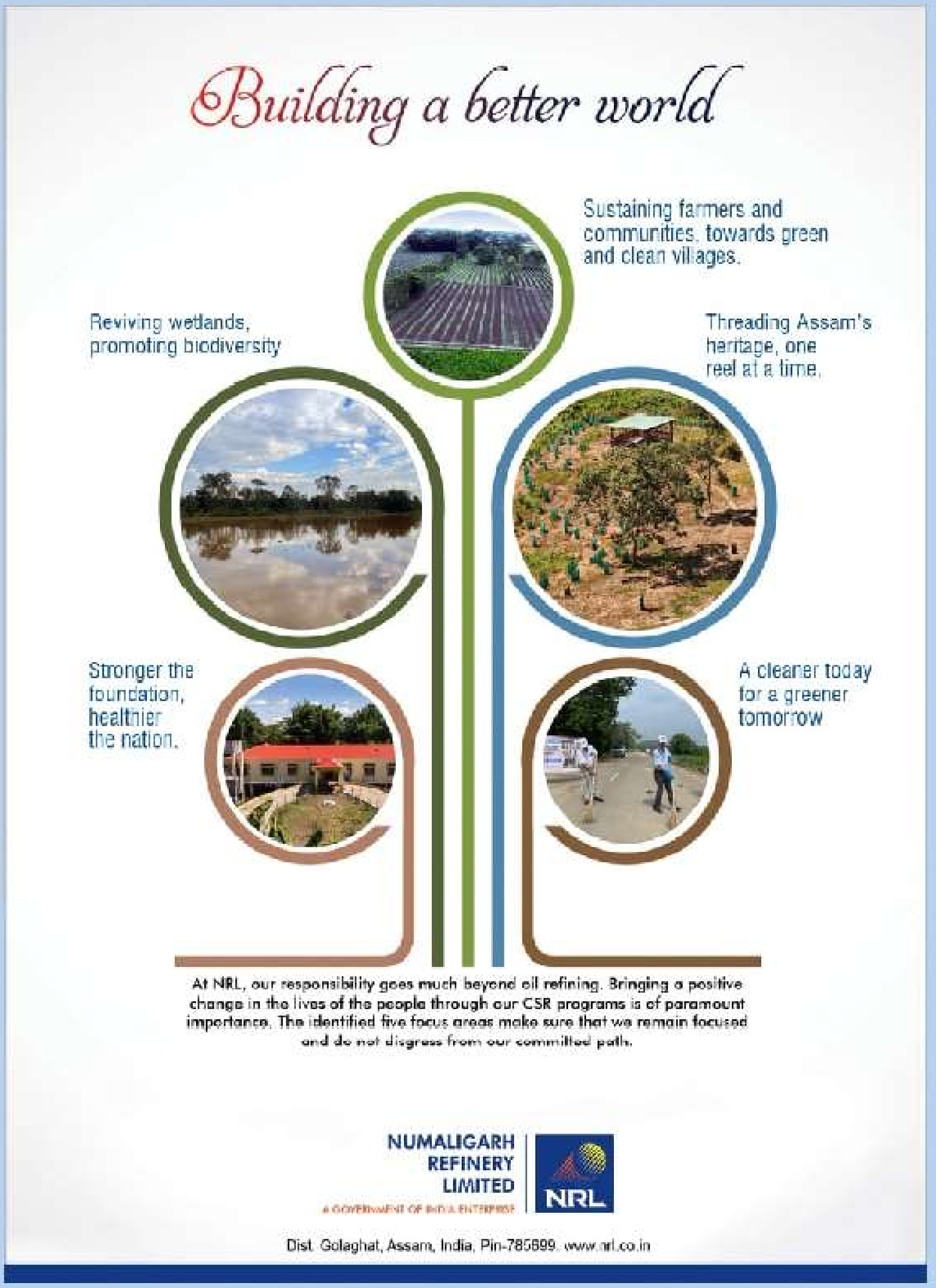
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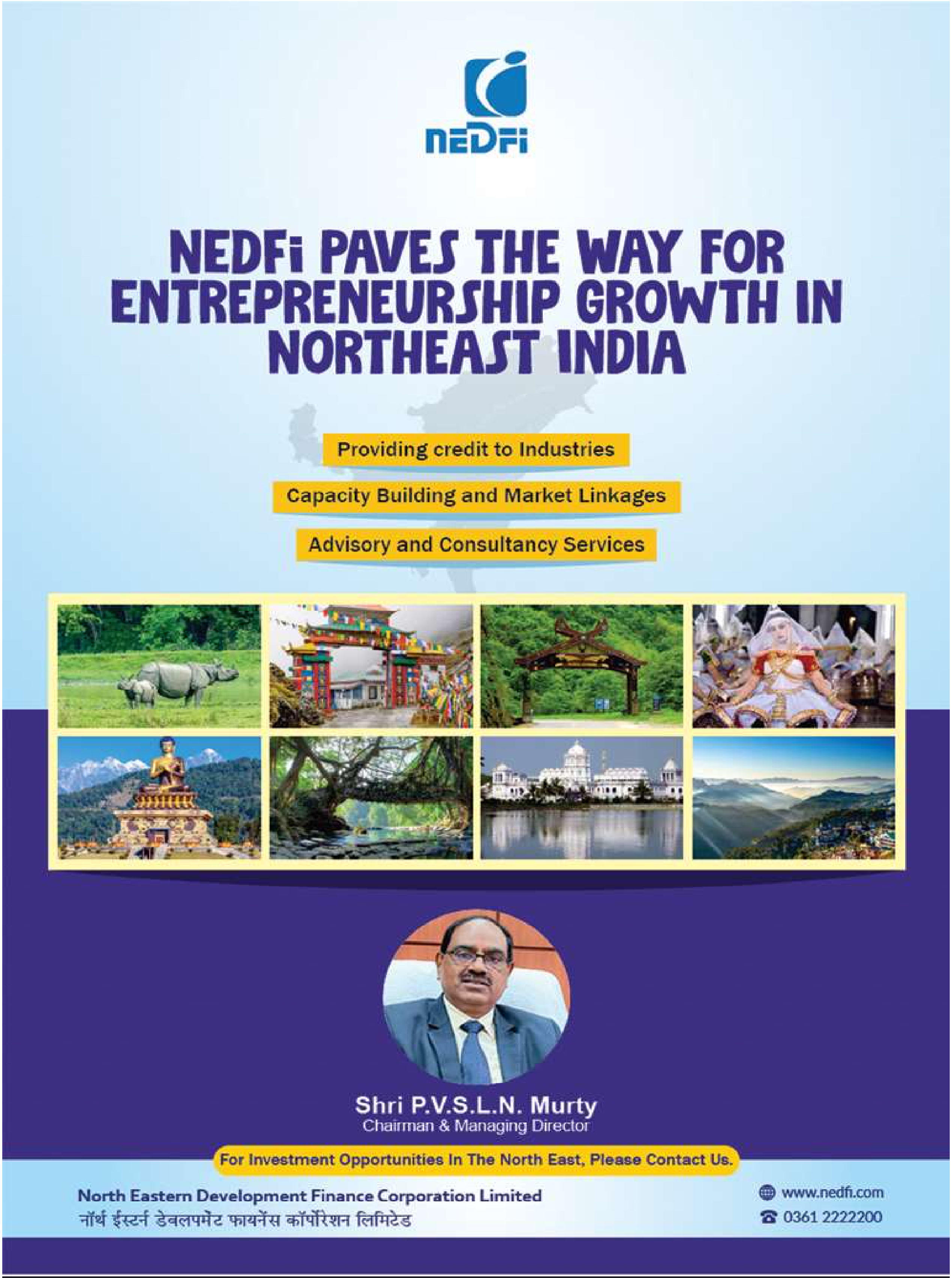
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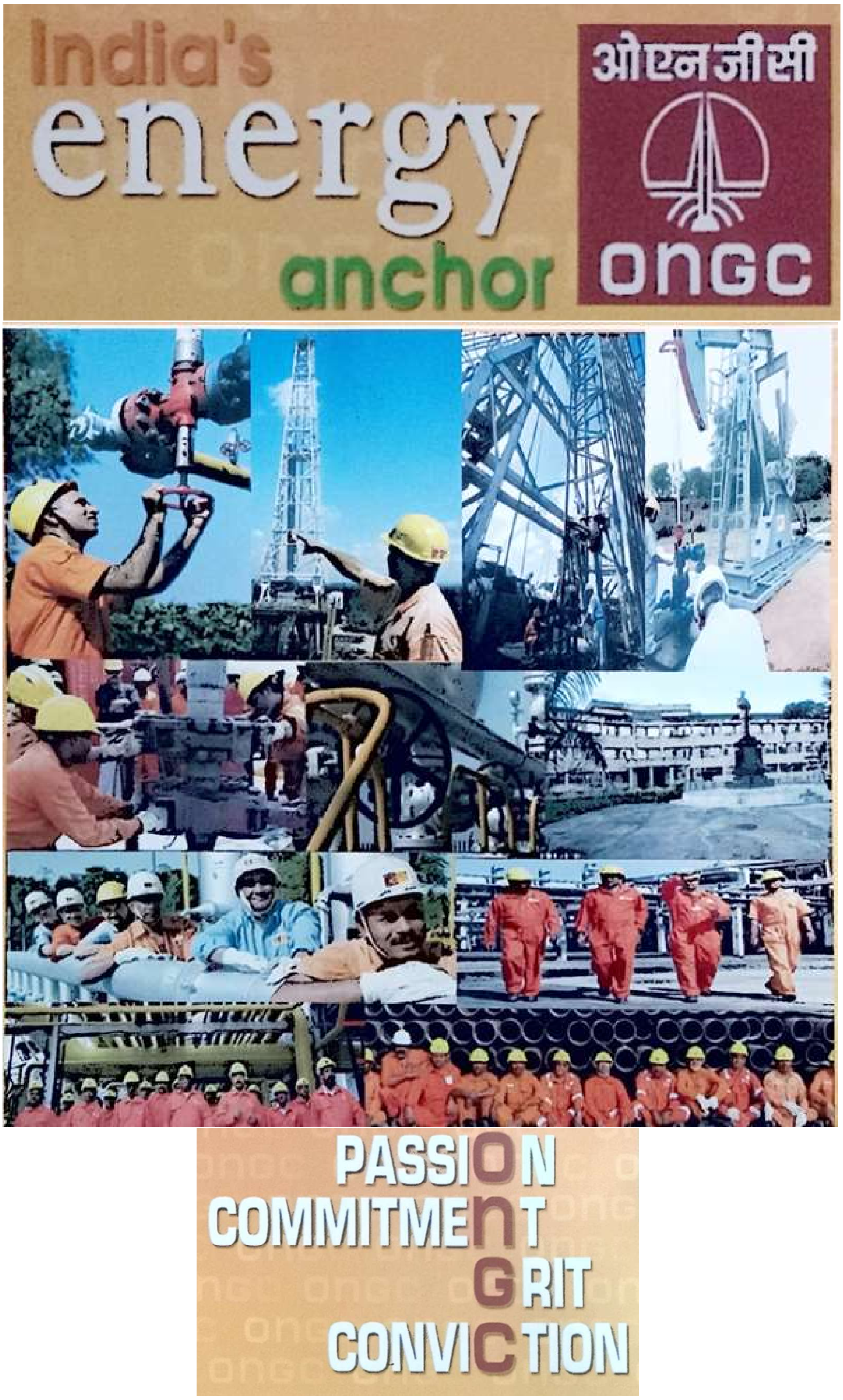
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