Review Article

Innovative Approaches for Climate-Resilient Farming: Strategies against Environmental Shifts and Climate Change

ABSTRACT

Climate change, driven predominantly by human activities such as burning fossil fuels and deforestation, is causing significant alterations to global weather patterns. This phenomenon results in more frequent and severe weather events, including prolonged droughts, intense rainfall, and shifting temperature regimes. Such changes pose a substantial threat to agriculture, a sector highly dependent on stable climatic conditions. Crop yields are increasingly unpredictable due to these extreme weather events and shifting growing seasons, impacting food security and livelihoods worldwide. To address these challenges, climate resilience agriculture has emerged as a pivotal solution. This approach involves adopting farming practices and technologies designed to withstand and adapt to changing climatic conditions. Strategies include diversifying crop varieties, precision agriculture, climate smart agriculture, nano biochar application, coated fertilizer applications, natural farming, site specific nutrient management, mulching, precise water management, seed bombing, direct seeding in rice, implementing soil conservation methods etc. Additionally, climate resilience agriculture promotes the integration of traditional knowledge with modern scientific advancements to enhance ecosystem robustness and productivity. By fostering adaptive capacity and reducing vulnerability, climate resilience agriculture aims to safeguard food systems and sustain agricultural productivity in the face of ongoing climate disruptions.

Keywords: Climate change, nano biochar, natural farming, resilience, seed bombing

1. INTRODUCTION

To meet the food needs of an anticipated 9 billion people by 2050 and counter the current decline in agricultural productivity, global food production must increase by approximately 70% [1]. However, climate change, driven primarily by human activities that release greenhouse gases into the atmosphere, presents a profound and pressing challenge. Addressing this issue will require not only boosting agricultural output but also implementing strategies to mitigate and adapt to climate impacts to ensure sustainable food security. As industrialization, deforestation, and the burning of fossil fuels continue to escalate, they increase concentrations of carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases. These gases trap heat from the sun, leading to the greenhouse effect, which is causing global temperatures to rise—a phenomenon known as global warming. This warming trend is altering weather patterns, intensifying the frequency and severity of extreme weather events, such as heatwaves, storms, and heavy rainfall. Consequently, ice caps and glaciers are melting, sea levels are rising, and ecosystems are being disrupted. These changes not only affect natural systems but also have far-reaching impacts on human societies, influencing agriculture, water resources, and overall environmental stability. Addressing climate change is critical to mitigating its effects and ensuring a sustainable future for the planet.

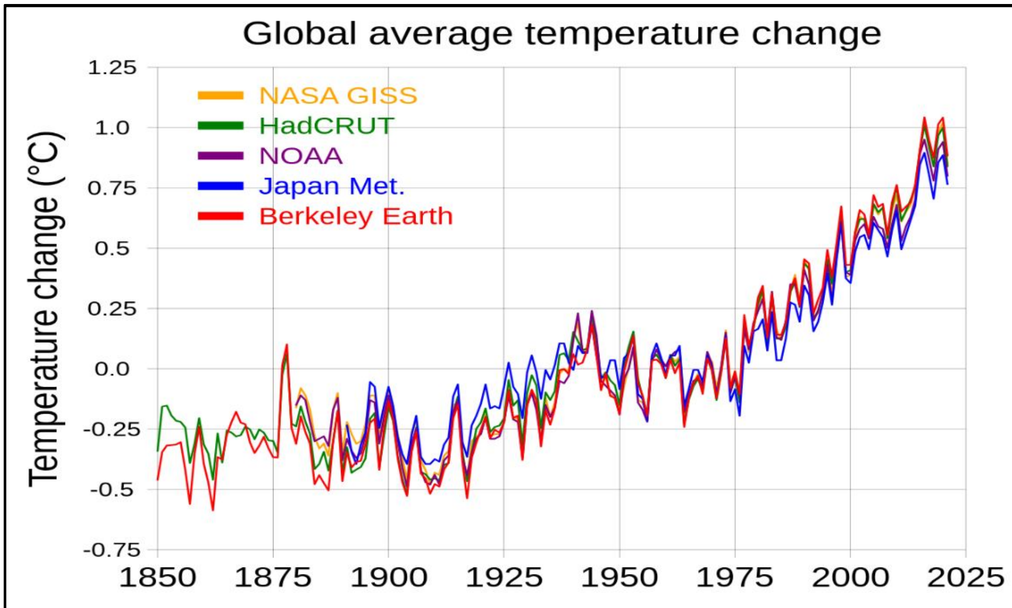

Fig. 1. Global average temperature change data
(**Source:**https://www.solutions-to-climate-change.com/climate-change-data-analysis/)

Climate change is significantly impacting global food production and agriculture, creating a host of challenges that jeopardize food security and sustainability. Below are some prevalent issues in agriculture resulting from climate change:

1.1 Altered Growing Conditions: Climate change leads to shifts in temperature and precipitation patterns, which directly impact growing conditions. Rising temperatures can disrupt crop growth cycles, reduce yields, and alter the geographic ranges of many crops. In an El Niño year, a warming phenomenon occurs in the central and eastern equatorial Pacific region, which disrupts atmospheric circulation and alters moisture transport and rainfall distribution patterns over the Indian subcontinent. This can result in reduced rainfall and drought conditions in certain areas of India [2]. Increased frequency of extreme weather events, such as droughts, heatwaves, and floods, further complicates the ability of farmers to maintain consistent production.

1.2 Increased Disease Pressure: Warmer temperatures and higher humidity levels create more favourable conditions for the proliferation of plant pathogens and pests. Diseases that were once confined to specific regions are now spreading to new areas. For instance, fungal diseases like wheat rust and blight are becoming more prevalent, causing significant crop losses. The changing climate also affects the lifecycle and behaviour of pests, leading to more frequent and severe infestations.

1.3 Weed Infestation: Climate change influences the growth and spread of weeds. Elevated carbon dioxide levels and warmer temperatures can accelerate weed growth and increase their competitiveness with crops. Weeds, generally considered as plants that grow unintentionally and out of place, have inherent competitive traits that enable them to dominate ecosystems [3]. Weeds adapted to higher temperatures and altered rainfall patterns may become more aggressive, making it harder for farmers to manage them using traditional methods. Weeds present a major challenge to crop production, and herbicides are the main tool used for their management in contemporary agriculture. Nevertheless, the widespread use of these chemicals has resulted in the development of weed strains that are resistant to herbicides [4]. This results in increased herbicide use, which can have additional environmental and health impacts.

1.4 Crop Failures: The combination of extreme weather events, shifting growing seasons, and increased pest and disease pressures contributes to higher rates of crop failure. For example, prolonged droughts can lead to water stress, reducing crop yields and affecting food availability. Flooding can damage crops and soil health, making it difficult to recover. As a result, crop failures are becoming more common, driving up food prices and leading to economic instability for farmers.

1.5 Soil Degradation: Climate change exacerbates soil erosion and degradation through increased rainfall intensity and more frequent extreme weather events. Degraded soils have reduced fertility and water-holding capacity, impacted crop productivity and increased the risk of crop failure.

1.6 Shifts in Agricultural Zones: Changing climate conditions are shifting agricultural zones, making some areas less suitable for traditional crops while opening new regions to farming. This transition requires adaptation and can disrupt local food systems, particularly in regions that are already vulnerable.

1.7 Impact on Livestock: In addition to crop impacts, climate change affects livestock production. Heat stress can reduce animal productivity and reproductive performance, while changing feed availability and quality can affect overall health and growth. Increased frequency of disease outbreaks and parasites further threatens livestock health and productivity.

1.8 Heavy metal toxicity: Climate change exacerbates heavy metal toxicity in plants by increasing the mobility and solubility of heavy metals in the soil due to rising temperatures and altered precipitation patterns. Higher temperatures can accelerate soil mineral weathering, releasing more metals into the soil, while extreme weather events such as heavy rainfall can cause soil erosion and runoff, spreading contamination to agricultural fields. Heavy metals persist in the environment and accumulate in living organisms because they are resistant to degradation and metabolism. Plants, due to their immobility, interact with heavy metal ions mainly through their roots. In aquatic environments, however, the entire plant structure is exposed to these metal ions [5]. Elevated carbon dioxide levels may also affect plant uptake and detoxification processes. Combined with stress from drought or flooding, these factors lead to higher metal accumulation in plants, reducing crop yields and posing health risks to humans and animals.

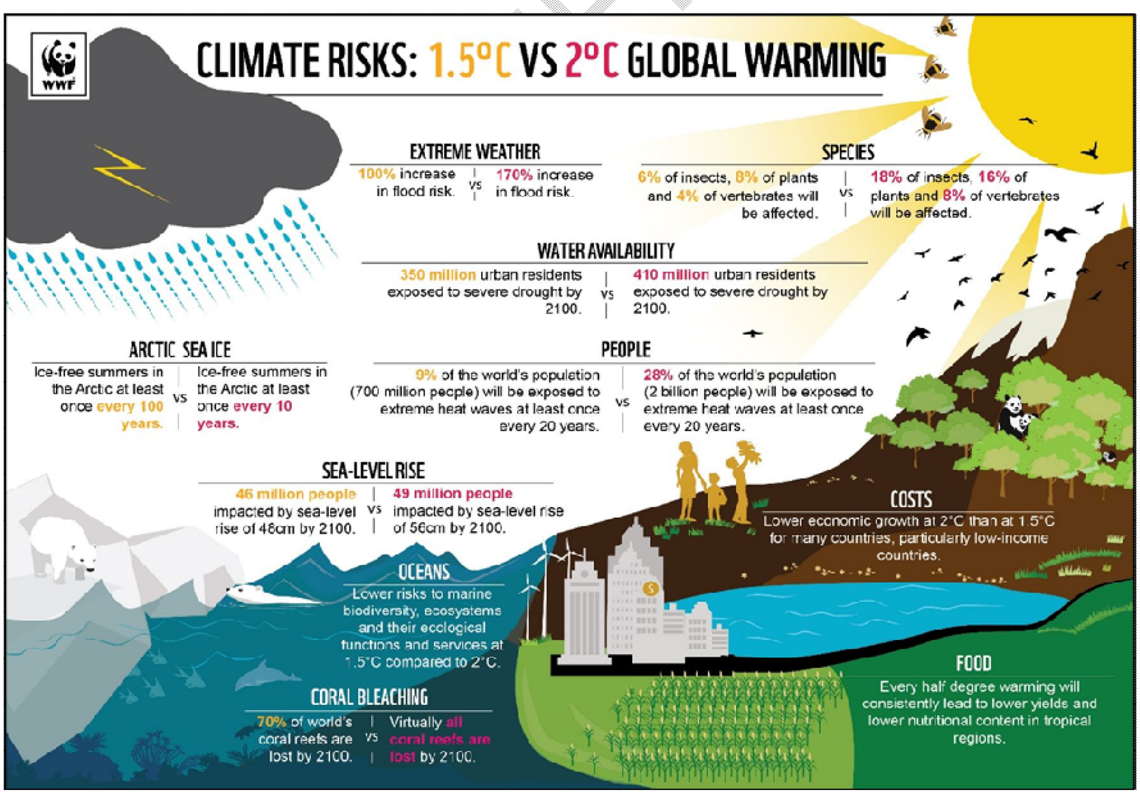

Fig. 2. Harmful risks of Global Warming and Climate Change
(Source:https://wwf.panda.org/wwf_news/?336701/Let-us-maintain-global-warming-at-15C-to-save-Madagascar **)**

1.9 Water Scarcity/Waterlogged Conditions: Climate change exacerbates flooding and water scarcity by altering weather patterns and increasing extreme events. Rising temperatures boost the frequency and intensity of storms, leading to severe flooding as warmer air holds more moisture. Conversely, changes in precipitation patterns cause prolonged droughts and reduced rainfall in some areas, worsening water shortages. Globally, waterlogging remains a significant obstacle to food production in areas with heavy rainfall and poor drainage. Over the past 50 years, the frequency of extreme water availability events, including droughts and floods, has risen markedly in agricultural regions worldwide [6]. Increased evaporation from higher temperatures further diminishes soil moisture, intensifying drought conditions. Overall, climate change disrupts natural water cycles, amplifying both flooding and water scarcity challenges.

1.10 Economic Impacts: The cumulative effects of climate change on agriculture result in economic challenges, including increased costs for crop management, pest control, and irrigation. Farmers face higher risks and uncertainties, which can lead to financial instability and reduced investment in agriculture.

Agronomic practices play a crucial role in enhancing climate resilience in agriculture by promoting sustainable farming techniques that adapt to changing environmental conditions. These practices include crop diversification, conservation tillage, efficient water management, the use of drought-resistant crop varieties, breeding for new traits etc. Soil and water conservation practices play a major role to counter harmful effect of climate change [7]. By implementing such strategies, farmers can improve soil health, reduce water usage, and increase crop yields despite climatic stresses. Recognizing the need for such adaptive measures, the Government of India launched the National Innovations in Climate Resilient Agriculture (NICRA) program [8]. This initiative aims to develop and promote climate-resilient agricultural practices through research, training, and the dissemination of innovative technologies. NICRA focuses on improving the adaptive capacity of farmers by integrating scientific research with practical solutions, thereby enhancing the overall resilience of the agricultural sector to climate change.

2. CLIMATE RESILIENCE APPROCHES FOR CLIMATE CHANGE MITIGATION

2.1Precision Agriculture: Precision agriculture leverages advanced technologies such as Global Positioning System (GPS), Geographic Information Systems (GIS), Remote Sensing, VRT, Soil and crop sensors, internet of things (IoT), artificial intelligence (AI) etc. [9] and data analytics to optimize farming practices. By providing detailed, real-time information on soil conditions, crop health, and weather patterns, it allows farmers to make precise decisions about planting, watering, and fertilizing. This targeted approach improves resource use efficiency, reduces waste, and enhances crop yields while minimizing environmental impacts. This also helps adapt to climate variability by tailoring practices to specific field conditions and adjusting inputs based on real-time data, thereby increasing resilience against extreme weather events and improving overall farm productivity.

Fig. 3. Precision Agriculture Strategy
(**Source**: https://humphreymalone.com/2024/01/19/uncategorized/advancing-agriculture-the-revolutionary-impact-of-precision-farming/)

2.2Crop Diversification Strategy: Crop diversion strategies involve changing the types of crops grown based on evolving climate conditions, soil health, and market demands. This approach enhances resilience by reducing the risk of crop failures due to pests, diseases, or extreme weather, as different crops have varying tolerances. It also improves soil health by utilizing diverse root structures and nutrient needs, and optimizes resource use by selecting crops better suited to current environmental conditions. Additionally, diversifying crops helps stabilize income by reducing dependence on a single crop and opening new market opportunities, ultimately making farming more adaptable and sustainable. It has mainly two types:

A. Horizontal diversification: This involves practices such as multiple cropping, cover cropping, inter-cropping, or mixed cropping systems. These methods are particularly beneficial for small-scale farmers with limited land, as they increase cropping intensity and enable higher returns.

B. Vertical diversification: It involves combining industrialization with multiple cropping practices. Farmers utilize their land for various purposes, including horticulture, livestock rearing, integrated farming systems, agroforestry, and the cultivation of aromatic plants.

Fig. 4. Crop Diversification
(Full Belly Farm, a DFS in California. Photo by Paul Kirchner Studios)

2.3 Drought-resistant varieties: These crops are capable of thriving with minimal water, improving resilience in water-scarce areas. They can endure dry periods and sustain stable yields.

Table 1.Drought resistant varieties of some selected crops

SL. No.	Crop	Varieties
1.	**Rice**	Sahabhagi Dhan, Vandana, Anjali, Satyabhama, DRR Dhan 42 (IR64 Drt 1), DRR Dhan 43, Birsa Vikas Dhan 203, Birsa Vikas Dhan 111, Rajendra Bhagwati, Jaldi Dhan 6
2.	**Wheat**	PBW 527, HI 1531, HI 8627, HD 2888, HPW 349, PBW 644, WH 1080, HD 3043, PBW 396, K 9465, K 8962, MP 3288, HD 4672, NIAW 1415, HD 2987
3.	**Maize**	Pusa Hybrid Makka 1, HM 4, Pusa Hybrid Makka 5, DHM 121, Buland
4.	**Sorghum**	CSH 19 R, CSV 18, CSH 15R
5.	**Pearl Millet**	HHB 67 improved, GHB 757, GHB 719, Dhanshakti, HHB 234, Mandor Bajra Composite 2, HHB-226, RHB-177, Pusa Composite 443
6.	**Barley**	RD 2660, K603
7.	**Chickpea**	Vijay, Vikas, RSG 14, RSG 888, ICCV 10, Pusa 362, Vijay
8.	**Groundnut**	Ajaya, Girnar 1, TAG-24, Kadiri 6, ICGV 91114
9.	**Soybean**	NRC 7, JS 95-60

10.	**Sugarcane**	Co 98014 (Karan-1), Co 0239, Co 0118, Co 0238, Co 06927, Co 0403, Co 86032
11.	**Cotton**	HD 324, CICR-1, Raj DH 7, Jawahar Tapti, Pratap Kapi, Suraj, Surabhi, Veena, AK 235
12.	**Jute**	JBO 1 (Sudhangsu), JRO 204, JRO 524, JRC 80

(**Source**: https://pib.gov.in/newsite/PrintRelease.aspx?relid=123999)

2.4Water logging tolerance varieties: They are specially bred to grow under flooded conditions by developing several adaptive traits. They have enhanced root structures that can withstand prolonged submersion, allowing for better oxygen uptake. These varieties often possess aerenchyma tissues, which facilitate gas exchange in waterlogged soils. They also have mechanisms to adjust their growth and metabolism in low-oxygen environments, maintaining physiological functions despite excess water. Additionally, these crops can have increased stem elongation to stay above the water level and improved flood-resistance genes that help them survive and yield even when submerged for extended periods.

Table 2.Water logging tolerance varieties of some selected crops

SL. No.	**Crop**	**Varieties**
1.	**Rice**	Swarna Sub-1, Sambha Mahsuri Sub-1, Varshadhan, Gayatri, Sarla, Pooja, Prateeksha, Durga, JalaMani, CR Dhan 505, CR Dhan 502, Jalnidhi, Neerja, Jaladhi 1, Jaladhi 2, Hemavathi
2.	**Jute**	JRO 7835, JRO 878, JRC 321, JRC 7447, JRC 532, JRC-517, Bidhan Pat-1
3.	**Maize**	HM-5, Seed Tech-2324, HM-10, PMH-2
4.	**Sugarcane**	Co 98014 (Karan-1), Co 0239, Co 0118, Co 0238, Co 0233, Co 05009
5.	**Soyabean**	Misuzudaizu, Peking, Benning, Danbaekkong, I27, Pangsakong, Geumkangkong and 'Sohokong

(**Source**: https://pib.gov.in/newsite/PrintRelease.aspx?relid=123999)

2.5Climate Smart Irrigation: Climate-smart irrigation involves using advanced techniques and technologies to optimize water use in agriculture while adapting to changing climate conditions. It includes methods like drip irrigation, which delivers water directly to plant roots with minimal evaporation and runoff, and smart irrigation systems that use sensors and weather forecasts to adjust water delivery based on real-time soil moisture and weather conditions. With an automated irrigation system, farmers can access real-time data on soil moisture and crop growth through an Android app or automatic SMS service. This capability enables improved crop management practices by providing timely and accurate information [10]. Intelligent sensors continuously track soil moisture levels and send this information to central systems. Algorithms then evaluate historical data, current conditions, and weather forecasts to adjust irrigation schedules in real-time [11]. Nanoscale agrichemical formulations can enhance productivity and reduce waste. Moreover, the use of nanoporous materials that store and gradually release water can further improve crop yields and conserve water [12]. A highly effective approach to enhance both nutrient and water use efficiency in agriculture is fertigation. This method allows for the precise delivery of nutrients directly to the plant root zone, ensuring optimal absorption and utilization of these nutrients [13]. Draining agricultural lands in humid areas can enhance productivity, increase soil carbon capture, and reduce N_2O emissions by improving soil aeration [14]. This approach helps save water by ensuring that plants receive only the amount of water they need, reducing waste and improving efficiency. By aligning irrigation practices with climate realities, it helps manage water resources sustainably and enhance crop resilience to climate variability.

Fig. 5. Drip Fertigation
(**Source:**https://www.taropumps.com/blog/fertigation-in-indian-agriculture)

2.6 Application of Nano Biochar: Nano biochar enhances climate resilience in agriculture by improving soil health and fertility. Its increased surface area and reactivity allow it to effectively retain water and nutrients, reducing the need for frequent irrigation and fertilization. Nano biochar also promotes beneficial microbial activity in the soil, which can help crops better withstand stress from extreme weather conditions. This specialized type of biochar possesses distinct properties and improved reactivity because of its expanded surface area and modified chemical structure. These characteristics make it particularly useful for diverse applications, such as in agriculture, environmental cleanup, and energy generation [15]. Additionally, its ability to sequester carbon helps mitigate greenhouse gas emissions, contributing to overall climate change mitigation. By enhancing soil structure, water retention, and nutrient availability, nano biochar supports more resilient and sustainable agricultural practices.

Fig. 6. Application of Biochar in the farm

(**Source:**https://www.carbongold.com/improve-your-garden-by-using-carbon-golds-biochar-products/)

2.7Conservation Agriculture: Conservation agriculture is a farming system that emphasizes keeping a permanent soil cover, minimizing soil disturbance, and diversifying plant species. This approach boosts biodiversity and natural biological processes in the root zone, improving nutrient and water use efficiency. It involves managing soil by retaining crop residues from the previous year on fields before and after planting the new crop, which helps reduce soil erosion and runoff while enhancing carbon sequestration [16]. Key methods include no-till farming, minimum tillage, zero tillage, cover cropping, crop rotation, carbon storage, soil stability, intercropping, enhanced soil drainage, green manuring, crop weed allelopathy, agroforestry, riparian buffers, windbreaks, shelter breaks, permanent soil cover etc.

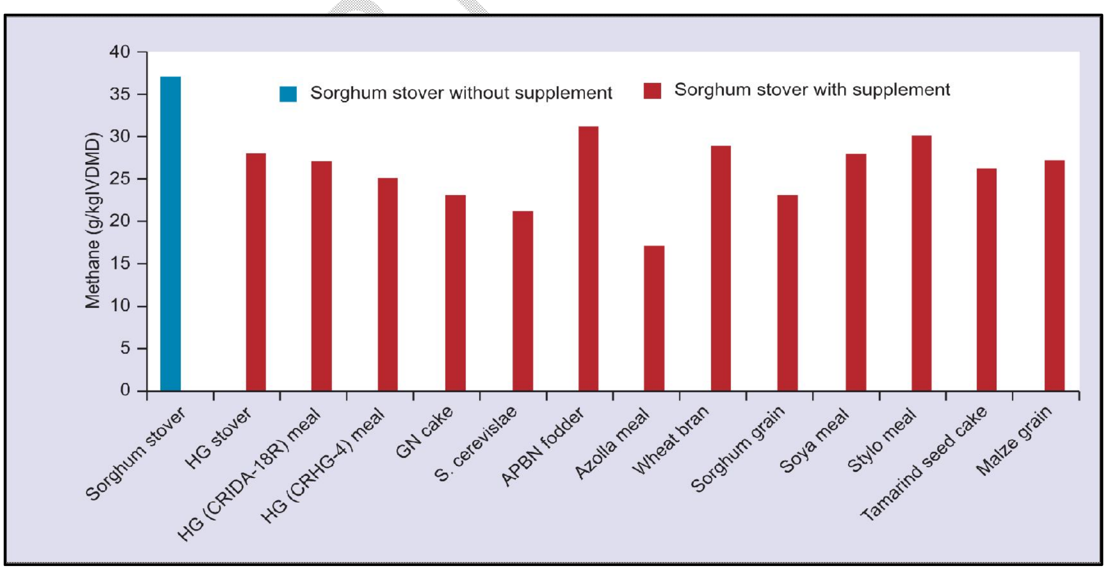

Fig.7. Methane production profiles from the fermentation of sorghum stover with or without supplementation

(**Source:**https://icar.org.in/sites/default/files/inline-files/climate-change-12-13.pdf)

2.8 Site Specific Nutrient Management (SSNM): Nutrient needs for crops can vary widely depending on factors such as field conditions, off season calamities, soil management, and climate and weather aberrations. Effective nutrient management thus requires a flexible approach that customizes the application of nitrogen (N), phosphorus (P), and potassium (K) to address specific crop requirements. Site-Specific Nutrient Management (SSNM) provides personalized recommendations tailored to individual farm conditions, aiming to enhance or maintain crop yields while reducing costs through optimized fertilizer use. SSNM equips farmers with guidelines, tools, and strategies to accurately determine the timing and quantity of nutrient applications based on current growing conditions specific to their location and season [17]. The 5 R's of SSNM include: applying the right input, in right amount, at the right place, at the right time and in the right manner. Some key sensors and tools used in SSNM are Optical Sensors, Crop Manager, Nutrient Expert, Real-Time Kinematic System (RTK), Soil fertility maps, Active Canopy Sensors (ACS), Green Seeker etc.

2.9Genetic Engineering Approaches: Utilizing biotechnological tools to develop climate-resilient crops is a key strategy for improving agricultural adaptability. Breeding programs aimed at addressing abiotic stress caused by climate change have proven highly effective in enhancing food production and resilience. To tackle the challenges of climate change, it is essential to thoroughly explore the physiological, genetic, and molecular foundations of these crops. Identifying and focusing on traits that provide resilience to climatic stress is crucial for advancing next-generation breeding (NGB) strategies. For instance, genetically modified (GM) plants, such as herbicide-resistant soybeans (Roundup Ready™), have demonstrated significant carbon sequestration capabilities, with soybean crops in the USA and Argentina capturing approximately 63,859 million tons of carbon dioxide (CO_2) [18].
Genetic engineering accelerates the development of ideotypes and the discovery of superior alleles or haplotypes for breeding programs, as highlighted by Taranto et al. (2018) [19]. Key techniques in this field include QTL Mapping, Marker-Assisted Selection, Mutation Breeding, and Genome Editing (GE). Notable advancements include Monsanto's development of drought-resistant maize, 'MON 87460,' which performs well under severe drought conditions in the U.S. Salt tolerance in *Arabidopsis thaliana* has been enhanced by overexpressing 40 transcription factors, and maize transgenic lines have shown increased drought tolerance through improved stomatal conductance, photosynthesis, and grain productivity (Nelson et al., 2007) [20]. In rice, the DEEPER ROOTING 1 (DRO1) locus has been utilized to improve root structure, enhancing drought tolerance and nitrogen acquisition [21]. Monsanto researchers have also developed bacterial cold shock proteins (CSPS) to boost stress adaptation across plant species. Additionally, novel technologies leveraging OMICS data, including transcriptomes, proteomes, and metabolomes, facilitate molecular-level studies of climate stress responses, such as the identification of the SNAC1 gene in rice, which enhances salt and drought tolerance.

2.10 Seed Bombing: Aerial seed bombing is a cutting-edge method for large-scale ecological restoration, offering a revolutionary solution to the challenges of extensive vegetation recovery across various landscapes [22]. Seed bombs are prepared by mixing equal parts of clay and compost in a bowl, then incorporating seeds into the mixture. Water is gradually added until the mixture is moist enough to hold together but not too wet. The mixture is then rolled into small balls, roughly the size of marbles, and left to dry completely. Key features include its ability to reach difficult or inaccessible terrains, such as steep slopes or remote regions, which are challenging for traditional planting methods. This technique promotes biodiversity by introducing a variety of plant species, which can enhance ecosystem stability and resilience. Additionally, it accelerates the reforestation process, improving soil health, reducing erosion, Rapid ecosystem recovery, wide coverage, precision targeting and sequestering carbon, all of which contribute to mitigating climate change impacts and enhancing agricultural resilience.

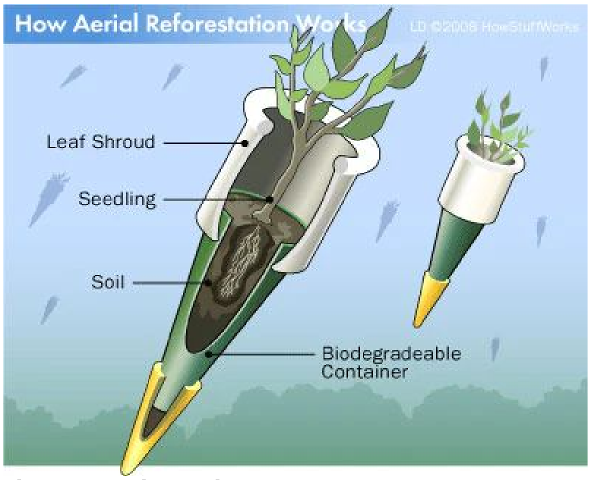

Fig. 8. Seed Bomb Capsule
(Source: https://www.trustbasket.com/blogs/how-to-grow/seed-bombs-the-environmental-friendly-bombs **)**

Fig. 9. Seed Bombs
(https://twobusybeeshoney.com/blogs/news/how-to-make-a-seed-bomb-easy-diy-seed-bombs)

2.11Natural farming: Natural farming is a comprehensive approach that promotes sustainable agriculture by emphasizing soil and human health, biodiversity, and minimal use of external inputs. Rooted in Indian traditions and modern ecological concepts, it integrates practices such as biomass recycling, mulching, and the use of on-farm cow dung-urine formulations, while avoiding synthetic chemicals [23,24]. This agroecology-based, multimodal farming system combines crops, livestock, and trees, focusing on recycling on-farm resources and reducing reliance on purchased inputs. It is a cost-effective method that can enhance employment and support rural development. Key components include Jivamrita, Bijamrita, Acchadana, Soil Mulch, Straw Mulch, Live Mulch, and Whapasa for moisture management [25]. Plant protection is achieved using Neemastra, Agniastra, Brahmastra, and Dashaparni. Benefits of this approach includes reducing greenhouse gas emissions, improving soil fertility, and boosting ecological health, while its potential for lowering input costs and fetching premium prices for organic products makes it economically advantageous.

Fig. 10. Pillars of Natural Farming
(https://www.tractorjunction.com/blog/what-is-zero-budget-natural-farming-advantages-features/)

2.12 Mulching: Mulching in agriculture involves applying a layer of organic or inorganic materials to the soil surface to boost crop growth and soil health. This method offers several benefits, including conserving soil moisture by limiting evaporation, controlling weed growth by blocking sunlight, and moderating soil temperature. It also enhances soil fertility as organic mulches like straw, leaves, and wood chips decompose, enrich the soil, while inorganic mulches such as plastic films and gravel provide durability without adding nutrients. Overall, it helps prevent soil erosion, improves soil structure, and supports sustainable farming by increasing crop yields and reducing water consumption.

2.13Adaptive nutrient management: Adaptive nutrient management plays a crucial role in climate-resilient agriculture by adjusting nutrient application strategies to align with varying environmental conditions and crop needs. This approach involves continuously monitoring and evaluating soil and crop conditions to make informed decisions about nutrient inputs. By tailoring nutrient applications based on real-time data and changing climate conditions, adaptive nutrient management helps optimize nutrient use efficiency, minimize wastage, and reduce environmental impacts such as runoff and leaching. It enhances crop resilience by ensuring that plants receive the right nutrients at the right time, improving their ability to withstand stressors like drought or extreme weather. This flexibility not only boosts crop yields but also supports sustainable farming practices by promoting soil health and reducing the reliance on synthetic fertilizers.

2.14Coated/Modified Fertilizers: Enhanced efficiency fertilizers are formulated to increase plant nutrient absorption and reduce environmental nutrient losses, such as through gas emissions, leaching, or runoff, more effectively than conventional fertilizers [26]. These fertilizers consist of slow-release and controlled-release varieties, along with nitrification inhibitors (NI) and urease inhibitors (UI). Slow-release and controlled-release fertilizers regulate nutrient availability by either postponing the initial release or prolonging the nutrient's presence in the soil during the plant's growth. This is accomplished by controlling the rate of nitrogen release, restricting ammonium exposure to nitrifying bacteria, and minimizing nitrate loss due to leaching or gaseous emissions. Placing urea briquettes at a depth of 5-7 cm greatly improves crop yields and nitrogen use efficiency, while significantly cutting down on nitrogen losses from nitrous oxide emissions and ammonia volatilization. This controlled-release method provides a consistent supply of nitrogen throughout the crop's growth cycle, reducing environmental pollution and lowering fertilizer expenses for farmers [27]. Slow-release fertilizers offer greater convenience by reducing the need for frequent applications. Unlike soluble fertilizers, they are less likely to cause fertilizer burn, even when applied at higher rates, although it remains crucial to adhere to application guidelines. While slow-release fertilizers can be more costly compared to soluble options, their advantages often outweigh the additional expense. Some examples of enhanced fertilizers are: Neem Coated Urea, Pelleted urea, Sulphur coated Urea, Isobutylidenediurea, Crotonylidenediurea, Humic acid coated Phosphorus and sulfur etc. Nitrapyrin, and pronitradine, dicyandiamide (DCD) are some examples of nitrification inhibitors.

2.15 Direct seeded rice: Direct-seeded rice helps combat climate change by offering a more sustainable alternative to traditional transplanting methods. This practice involves sowing rice seeds directly into the field, which reduces the need for water-intensive puddling and nursery preparation. The use of direct-seeded rice has grown due to issues like groundwater depletion, rising pumping costs, labor and time constraints, and the need to minimize transplanting shock. Direct-seeded rice (DSR) provides benefits such as quicker and easier planting, reduced initial production costs, lower water needs, earlier crop maturation by about 10 days, and decreased methane emissions [28,29& 30]. By minimizing water usage, direct seeding lowers methane emissions, a potent greenhouse gas associated with flooded rice fields. Additionally, it reduces labor costs and increases efficiency by eliminating the need for manual transplanting. It also promotes soil health and reduces soil erosion, contributing to overall environmental sustainability and resilience in the face of climate change.

Fig. 11. Drum Seeding technique in direct seeded rice (DSR)
(Source: Hridesh Harsha Sarma, MSc. Agriculture, Assam Agricultural University, Jorhat**)**

2.16 Data driven Agriculture: In today's agriculture sector, software technologies are becoming crucial. These tools provide transformative solutions for the challenges farmers face, offering advanced capabilities for planning, decision-making, and managing farm operations. With these applications, farmers can precisely manage various aspects of farming, such as crop planning, weather forecasting, irrigation, fertilization, pest detection, soil testing, and nutrient tracking, which ultimately enhances resource efficiency and boosts productivity [31]. Popular software applications used are Plantix, Meghdoot, Mausam, UMANG, DoctorP, Outgrow-farming Solutions, Yara farm care, AgriCentral, Krishi Safal, Agrostar, Ninja Kisan-Krishi etc.

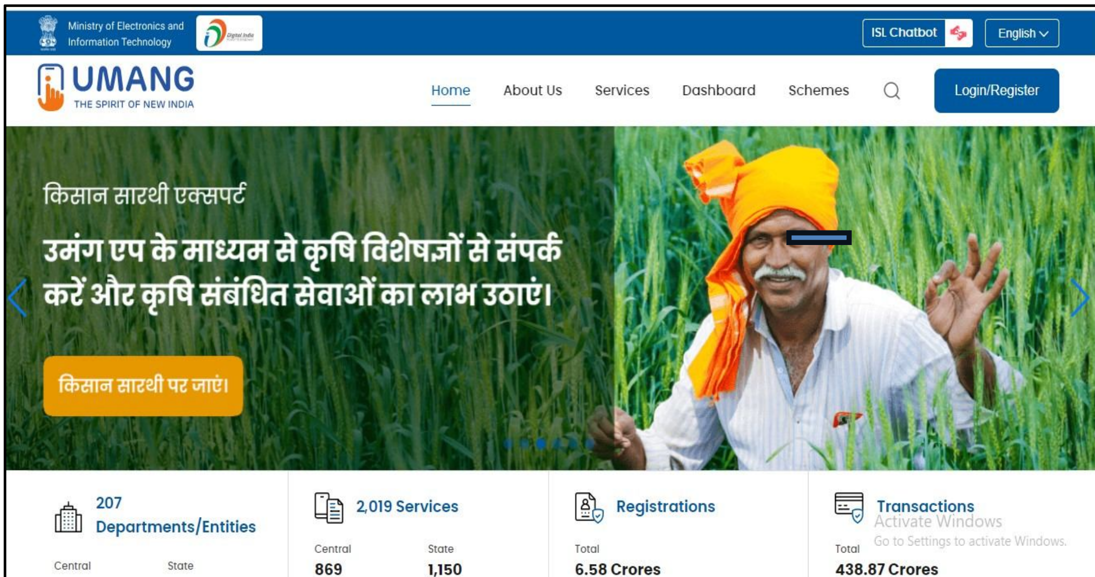

Fig. 12. UMANG application
(Source: https://web.umang.gov.in/landing/)

2.17Digital Data Sequencing: Digital sequencing data significantly enhances climate-resilient agriculture by providing detailed genetic insights that aid in developing crops better suited to changing environmental conditions. This data enables the identification of genetic traits associated with drought tolerance, heat resistance, and other stress responses. The rise of digital sequencing technologies has dramatically transformed agricultural and horticultural sciences by providing unparalleled insights into the genetic, transcriptomic, and metabolic profiles of crops [32]. Advances in genome sequencing, such as next-generation sequencing (NGS) and third-generation sequencing (TGS), have greatly reduced the costs and time involved in sequencing, enabling thorough analysis of crop genomes. For example, CRISPR-Cas9 genome editing technology has facilitated precise genetic modifications, leading to the creation of crop varieties with improved traits like better resistance to diseases and environmental stresses [33]. Additionally, what was once considered "junk DNA"—the extensive non-coding regions of plant genomes—is now recognized for its vital role in regulating gene expression and maintaining genome stability. The International Maize and Wheat Improvement Center (CIMMYT) used genomic selection to develop maize varieties that are both high-yielding and drought-resistant [34]. Similarly, the Tomato Genome Consortium's sequencing of the tomato genome has provided valuable insights into the genetic foundations of disease resistance and fruit quality traits [35]. This approach ensures that crops can maintain productivity and stability in the face of climate change.

2.18 Role of Salicylic acid: Salicylic acid is vital for various plant physiological processes. It enhances the plant's ability to respond to both biotic and abiotic stressors, boosts resistance through Systemic Acquired Resistance (SAR), and modulates internal signaling pathways to help plants endure a range of stress conditions [36]. Salicylic acid (SA) also has the ability to form conjugates with specific amino acids like proline and arginine, enhancing the plant's resilience to environmental stresses and sustaining systemic acquired resistance. One of its most notable effects is its role in generating antioxidants. SA contributes to various physiological functions, including promoting flowering, improving ion uptake, facilitating nutrient transfer, increasing CO_2 assimilation, regulating stomatal movement, and supporting photosynthesis, gas exchange, and protein synthesis. Additionally, it accelerates the production and accumulation of plant pigments such as chlorophyll and carotene, and inhibits ethylene production, counteracting the effects of abscisic acid (ABA) that triggers leaf drop. Furthermore, SA boosts metabolic rates, aiding the plant in conserving energy by utilizing alternative pathways and adjusting levels of nucleic acids and amino acids [37].

2.19Organic farming: Organic farming enhances climate resilience by promoting soil health, increasing biodiversity, and reducing reliance on synthetic inputs. Practices such as composting, crop rotation, and reduced tillage improve soil structure and fertility, which enhances its ability to retain water and resist erosion. Organic systems also encourage diverse plant and animal life, which can buffer ecosystems against climate fluctuations and pests. By minimizing chemical inputs, organic farming reduces the environmental footprint and supports sustainable agricultural practices that are better suited to adapt to changing climate conditions. Panchagavya is an organic preparation that promotes plant growth and boosts immunity. It consists of nine key ingredients: cow dung, cow urine, milk, curd, jaggery, ghee, banana, tender coconut, and water. When these elements are properly mixed and applied, they provide significant benefits to plants. Dasagavya, another organic formulation, includes ten ingredients, combining Panchagavya with specific plant extracts. The term "Gavya" denotes substances derived from cows—such as dung, urine, milk, curd, and ghee—which, when blended effectively, significantly enhance plant growth. Both Panchagavya and Dasagavya adhere to sustainable farming principles, offering farmers eco-friendly alternatives to chemical inputs while fostering ecological balance and improving crop resilience against climate change [38].

2.20Seed priming and testing: Seed priming is a pre-sowing method that involves controlled hydration of seeds to kickstart the metabolic processes required for germination, without allowing the radicle to emerge. This approach is commonly used to boost seed performance, ensure uniform germination, and enhance seedling vigour. It addresses challenges like adverse environmental conditions, low soil moisture, and soil salinity that affect seed germination and seedling growth [39]. There are different types of seed priming like Halo priming, Hydro priming, Osmo-priming, Hormonal priming, Biopriming, Chemo priming, Thermo priming, Nano priming,Solid matrix priming etc. Several organic methods of seed priming include *Panchagavya*, Sweet Flag Extract, ProsophisKashayam, *Amirthakaraisal*, *Jivamirtham*, and Amrit Pani [40]. Recognized for its effectiveness in improving germination rates, speeding up emergence, and ensuring better stand establishment, seed priming is a simple and cost-effective technique.

Seed testing is a vital process conducted to assess the quality, viability, and genetic purity of seeds before planting. It evaluates key factors such as germination rate, moisture content, vigor, disease resistance, and genetic identity. By analyzing these parameters, seed testing provides critical information that helps farmers and seed producers make informed choices. This process not only helps prevent the spread of diseases and pathogens but also promotes sustainable farming by refining seed selection, planting techniques, and crop performance. Ultimately, seed testing boosts agricultural productivity, enhances food security, and builds trust and reliability within the global seed industry [41].

2.21 Weather forecasting: Weather forecasting aids farmers in climate mitigation agriculture by providing timely information on upcoming weather patterns. This allows farmers to make informed decisions on planting schedules, irrigation, and crop protection strategies, thereby reducing crop losses and optimizing resource use [42,43]. Founded in 1875, the India Meteorological Department

(IMD) is the foremost national meteorological service in India and the principal governmental authority responsible for meteorology and associated disciplines [44]. IoT weather stations gather real-time meteorological data such as temperature, humidity, wind speed, and barometric pressure [45].Accurate forecasts help manage risks associated with extreme weather events and adjust practices to mitigate climate impacts, enhancing overall resilience and sustainability in farming.

There are five main types of weather forecasting:

A. **Short-Range Forecast**: These forecasts, which provide daily predictions based on current weather conditions, focus on changes in pressure, temperature, and cyclonic activity. They are essential for irrigation engineers, mariners, and aviators, offering timely alerts for storms, cyclones, and heavy rainfall.

B. **Extended Forecast**: Covering a period of 5 to 7 days, this forecast details specific weather conditions, including rainy patterns and agricultural risks like strong winds or extended dry or wet periods. With an accuracy rate of 60% to 70%, it helps farmers with planning sowing, harvesting, and pesticide application by providing critical information for effective agricultural management.

C. **Long-Range Forecast**: This type forecasts seasonal trends for the next 1-2 months, helping farmers adjust their cropping strategies. It supports decisions on soil moisture management, crop selection, irrigation planning, and cropping patterns based on anticipated climate trends.

D. **Nowcasting**: Offering predictions for 2 to 3 hours ahead, nowcasting benefits sectors like aviation and navigation. Utilizing radar and satellite data, it provides short-term forecasts, including the prediction of phenomena like lightning, up to 6 hours in advance.

E. **Climatological Forecasting**: This forecasting method projects long-term climate variables such as temperature, precipitation, and sea levels over decades to centuries. It relies on climate models that simulate interactions between the atmosphere, oceans, land, and ice, including the impact of human activities like greenhouse gas emissions.

2.22Alternate Wetting and Drying: In the Alternate Wetting and Drying (AWD) method, fields experience cycles of flooding and drying instead of being continuously submerged throughout the crop season. The fields are reflooded once the soil surface becomes aerobic, allowing water to drain through percolation and evapotranspiration [46]. This method contrasts with the traditional practice of keeping paddy fields constantly flooded by introducing alternating wet and dry conditions. Transitioning from continuous flooding to aerobic soil conditions under AWD changes soil aeration, moisture levels, and nutrient availability, enhancing soil organic matter mineralization and reducing nitrogen immobilization due to improved oxygen levels. AWD leads to a 48% reduction in methane emissions while maintaining yield levels. This approach also conserves water by reducing excessive irrigation, promoting sustainable water management, especially in water-scarce regions.

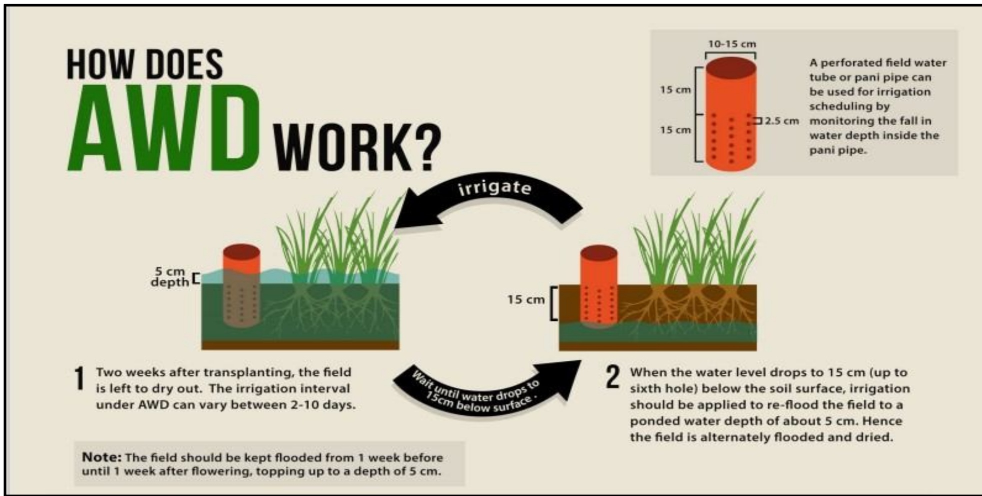

Fig. 13. Working principle of Alternate Wetting and Drying

(**Source:**https://ghgmitigation.irri.org/mitigation-technologies/alternate-wetting-and-drying)

Fig. 14. Alternate Wetting and Drying in field
(**Source:** https://ghgmitigation.irri.org/mitigation-technologies/alternate-wetting-and-drying)

2.23Crop Modelling: Crop modeling aids climate resilience in agriculture by simulating how crops respond to various environmental conditions, including temperature changes, precipitation patterns, and extreme weather events. Combining crop models with remote sensing technology provides a robust method for improving agricultural assessments. By incorporating remote sensing data to assess yield variables throughout crop model simulations, missing model parameters can be addressed during field-scale recalibration. Additionally, integrating field-level data from crop models with remote sensing allows for the scaling of results to regional levels, enhancing the scope of agricultural evaluations [47]. Bassu et al. (2009) [48] employed the APSIM-Wheat model to examine the impact of different planting dates on wheat yields under various degrees of waterlogging. Their results indicated that early planting could improve yields in areas with low to moderate waterlogging risk, but it was less effective in regions prone to frequent waterlogging.
These models help predict crop performance, growth stages, and yields under different climate scenarios, enabling farmers to make informed decisions on planting schedules, crop selection, and resource management. By providing insights into potential impacts and optimizing agricultural

practices, crop modeling supports better adaptation strategies and enhances the resilience of farming systems to climate variability and change.

2.24 Broad Bed and Furrow (BBF) System: The broad bed and furrow (BBF) system, developed by the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) in Hyderabad, is an effective land management technique for conserving in-situ moisture in deep black soils. After harvesting the previous crop, primary tillage is performed using available soil moisture, followed by secondary tillage with summer and pre-monsoon rains. The land is leveled to achieve a uniform slope of 0.4-0.8%. BBF beds are created using a specialized tool called the "Tropiculator," with beds measuring 120 cm in width and furrows 30 cm wide and 15 cm deep. The length of the furrows varies from 100 to 200 meters, depending on the land slope. This system offers numerous benefits, including moisture conservation, reduced erosion, improved surface drainage, weed control, lower power requirements, and enhanced drainage and supplemental irrigation for crops [16].

2.25Post harvest Management: In India, where more than 70% of the population depends on agriculture, pulse and grain production have seen substantial growth in recent decades. Nevertheless, post-harvest losses continue to be a major issue, with around 10% of crops being damaged, and storage-related losses making up about 6% of this damage. The lack of adequate storage and processing facilities is leading to significant losses of food grains after harvest [49]. Post-harvest management enhances climate resilience in agriculture by minimizing food waste and optimizing resource use. Proper storage, handling, and processing of crops reduce spoilage and loss, which helps conserve resources and energy. Techniques like improved drying, cooling, and pest control maintain the quality and longevity of produce, making it more resilient to climate variability. Major approaches in post-harvest management are timely harvesting, proper handling and transport, optimal storage conditions, quality grading and sorting, cleaning and sanitation, use of post-harvest treatments like edible waxing, controlled atmosphere storage (CAS), value addition and processing etc. [50]. Effective post-harvest practices also contribute to better planning and distribution, ensuring that crops are used efficiently and reducing the environmental impact associated with excess waste.

2.26 Other approaches:

- Laser levelling is a technique used to achieve a uniform land surface, typically within ± 2 cm of the average elevation, using drag buckets with laser technology. This method adjusts the land to create a consistent slope of 0 to 0.2%. Introduced recently in India, laser levelling is a cutting-edge resource-conservation technology that offers several benefits, including increased precision and accuracy, improved water efficiency, reduced soil erosion, optimized irrigation, better field quality, and more efficient fertilizer application [51]. It has the potential to transform food production by greatly enhancing resource efficiency while supporting the ecosystem's productive resilience.

Fig. 15. Laser Land levelling
(**Source:**https://www.irri.org/laser-land-leveling-philippines)

- Cover cropping improves climate resilience in agriculture by enhancing soil health and structure, which helps in managing water and reducing erosion. Cover crops, including legumes and grasses, are sown during off-seasons to maintain soil coverage [52]. Cover crops increase soil organic matter, boost moisture retention, and improve nutrient cycling. They also suppress weeds and reduce the need for chemical inputs. By mitigating soil degradation and improving the overall resilience of the farm ecosystem, cover crops help crops withstand extreme weather conditions and climate variability more effectively. Intercropping, which involves cultivating two or more crops together on the same land, has been shown to enhance both the yield and nutritional quality of forage crops [53].

- Different types of composting, such as traditional composting, vermicomposting, anaerobic composting, in-vessel composting, trench composting, farmyard composting etc. each play a vital role in enhancing climate resilience in agriculture. Traditional composting and vermicomposting enrich soil with organic matter, improving its structure, moisture retention, and fertility while sequestering carbon and reducing greenhouse gas emissions. Anaerobic composting offers a way to process a broader range of organic waste, contributing to soil health and reducing methane emissions. Composted Coco pith is essential in sustainable farming practices due to its benefits in improving soil structure and water retention, as well as its potential as a nutrient-rich compost [54]. Composting sugarcane trash helps mitigate environmental pollution from burning while enhancing soil fertility by releasing nutrients such as nitrogen, phosphorus, and potassium. This approach improves soil structure, boosts water retention, and ultimately increases crop yields [55]. Boruah et al. (2024) [56] found that using the recommended fertilizer dose combined with vermicompost increases the levels of organic matter, nitrogen, phosphorus, and potassium in the soil for finger millet cultivation. This practice ensures proper soil nutrition, supports soil health, and boosts soil microorganisms, thus fostering the long-term sustainability of soil resources. Collectively, these methods enhance soil resilience, support sustainable farming practices, and help crops adapt to climate variability.

- Integrated farming systems (IFS) boost climate resilience by combining various agricultural practices to create a more balanced and sustainable farm ecosystem. This approach often integrates crop production, livestock, aquaculture, and agroforestry, which diversifies income sources and reduces dependency on a single crop or livestock type [57]. By promoting biodiversity, improving soil health, and optimizing resource use, IFS enhances the farm's ability to withstand climate variability and extreme weather conditions, ultimately supporting more sustainable and resilient agricultural practices.

- Green manuring is the practice of growing specific plants, such as legumes or cover crops, and then incorporating them into the soil while they are still green. This process enriches the soil with organic matter and nutrients, improves soil structure and fertility, enhances moisture retention, and helps control erosion and weeds. Additionally, green manures improve nutrient cycling by fixing atmospheric nitrogen and suppress weeds, reducing reliance on chemical inputs. Popular plant species valuable for green leaf manure include neem, mahua, wild indigo, Glyricidia, Karanji (*Pongamia glabra*), calotropis, avise (*Sesbania grandiflora*), subabul and various other shrubs. By strengthening soil health, green manuring helps crops better withstand climate variability and extreme weather conditions, contributing to a more resilient agricultural system [58].

- Hydroponics and aquaponics enhance climate resilience in agriculture by offering efficient, sustainable growing methods. Hydroponics involves cultivating plants in a nutrient-rich water solution instead of soil, allowing precise control over nutrients and water, thus reducing land use and conserving water through recirculation. Hydroponic cultivation offers significant savings in time, labor, and expenses by eliminating the need for soil preparation, bed setup, and the application of fertilizers, herbicides, insecticides, and fungicides [59]. This method, which can utilize systems like nutrient film techniques or deep-water culture, is often employed in controlled environments like greenhouses to shield crops from extreme weather and pests. Aquaponics, on the other hand, integrates hydroponics with aquaculture, where fish waste provides nutrients for plants, and the plants help filter and clean the water, which is then recirculated back to the fish tanks. This system, which can be configured in media beds or nutrient film techniques, conserves water, reduces the need for chemical fertilizers, and promotes a symbiotic environment. Both methods are particularly effective in regions with water scarcity, land degradation, or extreme weather, optimizing resource use and maintaining stable crop production amidst climate variability.
- Agripreneurship in climate resilience agriculture presents significant prospects as it focuses on innovative solutions to adapt to and mitigate the impacts of climate change on farming. Agripreneurs can capitalize on this opportunity by developing and implementing technologies and practices that enhance agricultural sustainability. For instance, Assam, with its numerous water bodies, has become a center for water hyacinth crafting. Local artisans expertly convert water hyacinth stems into a variety of handmade items, such as shoulder bags, sling bags, baskets, mats, and home decor. This plant yields over 200 tons of dry matter per hectare annually under typical conditions, with potential outputs reaching up to 657 tons per hectare in waters with heavy sewage. The Assam State Rural Livelihood Mission (ASRLM), a government initiative, aims to promote sustainable livelihoods in rural areas by empowering women through Self Help Groups (SHGs). This support includes skill development, access to credit, and market assistance. Products from these SHGs are marketed under the brand 'ASOMI,' which stands for unity, companionship, women's empowerment, and identity, embodying Assamese culture. The ASOMI range features a wide selection of handloom and handicraft items from 20 craft clusters in Assam, with artisans creating diverse products tailored to various needs. The initiative focuses on establishing water hyacinth crafting as a sustainable income source, particularly benefiting women economically [60].

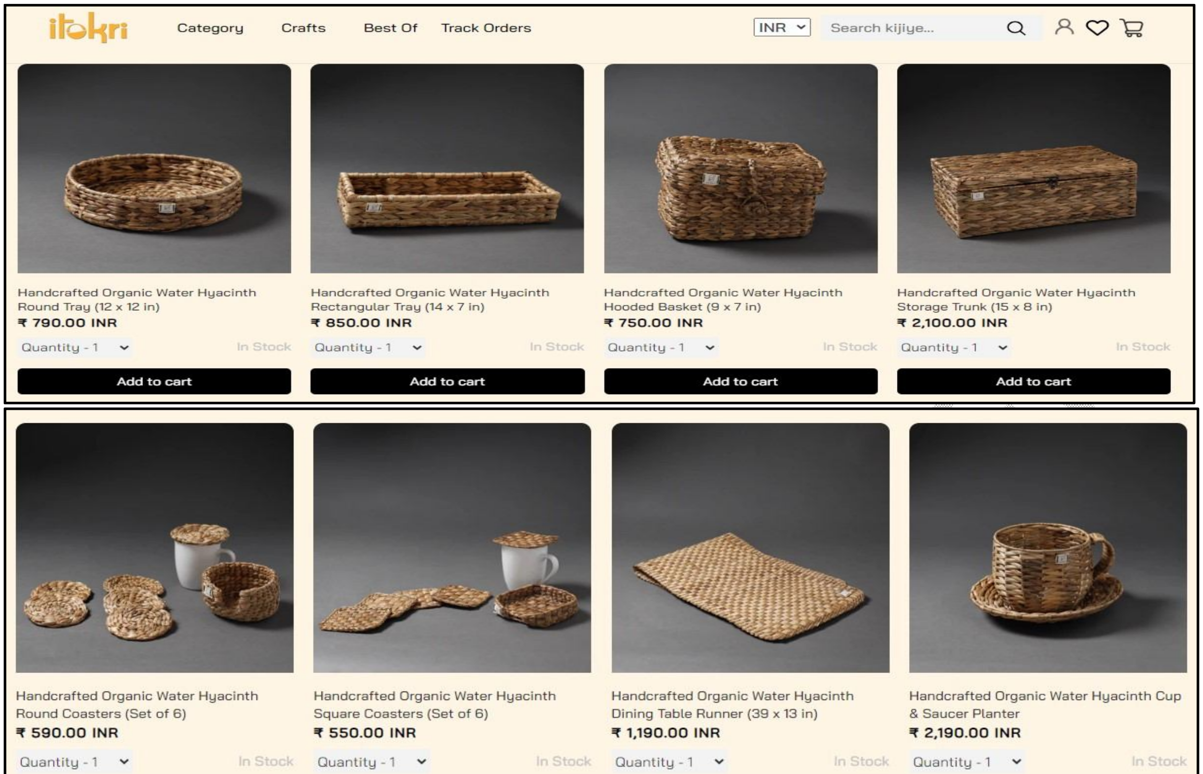

Fig16. Commercial products prepared from water hyacinth (Source: itokri.com)

3. GOVERNMENT OF INDIA INITIATIVE ON CLIMATE RESILIENT AGRICULTURE

3.1 National Innovations in Climate Resilient Agriculture (NICRA): TheIndian Council of Agricultural Research (ICAR), under the Ministry of Agriculture and Farmers Welfare, Government of India, initiated the flagship project 'National Innovations in Climate Resilient Agriculture' (NICRA) in 2011. This project is designed to address climate change impacts on agriculture through targeted research, technology demonstration, and stakeholder awareness.
The strategic research component of NICRA focuses on several key areas: (i) pinpointing the most vulnerable districts or regions, (ii) developing crop varieties and management practices to enhance adaptation and mitigation, and (iii) evaluating the effects of climate change on livestock, fisheries, and poultry, along with identifying relevant adaptation strategies.

Objectives:

1. To improve the resilience of Indian agriculture—encompassing crops, livestock, and fisheries—to climate variability and change by advancing and applying innovative production and risk management technologies.
2. To implement site-specific technology packages on farmers' fields to address current climate risks.
3. To build the capacity of scientists and stakeholders in climate-resilient agricultural research and its practical application.

Key Features:

1. Deployment of advanced equipment, such as flux towers, for measuring greenhouse gas emissions across large agricultural areas to evaluate the impact of management practices and fulfil national data requirements.

2. Large-scale screening of crop germplasm, including wild relatives, for drought and heat tolerance using phenomics platforms to swiftly identify promising varieties and facilitate the development and release of heat and drought-resistant crops.
3. Extensive field testing of new paddy cultivation methods, such as aerobic rice and System of Rice Intensification (SRI), to assess their effectiveness in reducing greenhouse gas emissions and conserving water.
4. Enhanced focus on livestock and aquaculture sectors, which have historically received limited attention in climate change research, including documenting adaptive traits in indigenous breeds.
5. In-depth exploration of crop-pest/pathogen dynamics and the emergence of new biotypes due to climate change.
6. Scaling up of research outputs through Krishi Vigyan Kendras (KVKs) and the National Mission on Sustainable Agriculture to facilitate broader adoption by farmers.

3.2 National Mission on Sustainable Agriculture (NMSA): The National Mission on Sustainable Agriculture (NMSA) is a key component of the Sustainable Agriculture Mission, one of the eight missions outlined in the National Action Plan on Climate Change (NAPCC). The Mission Document, which received ‘in principle’ approval from the Prime Minister’s Council on Climate Change (PMCCC) on September 23, 2010, sets out strategies and action plans to advance sustainable agriculture through various adaptation measures. These measures target ten critical aspects of Indian agriculture, including: 'Enhanced crop seeds, livestock, and fish cultures,' 'Water Use Efficiency,' 'Pest Management,' 'Improved Farm Practices,' 'Nutrient Management,' 'Agricultural Insurance,' 'Credit Support,' 'Markets,' 'Access to Information,' and 'Livelihood Diversification.'During the Twelfth Five-Year Plan, these strategies are being integrated into ongoing and proposed missions, programs, and schemes of the Department of Agriculture & Cooperation (DAC&FW) through a process of restructuring and convergence. The NMSA framework consolidates and integrates all existing and new activities related to sustainable agriculture, with particular emphasis on soil and water conservation, water use efficiency, soil health management, and development of rainfed areas. The mission will focus on the prudent use of communal resources through community-based approaches.

Objectives:

1. Enhance agricultural productivity, sustainability, profitability, and climate resilience by promoting location-specific Integrated/Composite Farming Systems.
2. Implement effective soil and moisture conservation techniques to safeguard natural resources.
3. Employ comprehensive soil health management practices, utilizing soil fertility maps, soil testing for macro and micro nutrient applications, and the careful use of fertilizers.
4. Maximize water use efficiency to achieve higher crop yields per unit of water through improved water management strategies.
5. Strengthen the capabilities of farmers and stakeholders in climate change adaptation and mitigation by collaborating with ongoing missions such as the National Mission on Agriculture Extension & Technology, National Food Security Mission, and the National Initiative for Climate Resilient Agriculture (NICRA).
6. Test and refine models in selected blocks to improve productivity in rainfed farming, integrating technologies developed through NICRA and leveraging resources from other schemes such as the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), Integrated Watershed Management Programme (IWMP), and Rashtriya Krishi Vikas Yojana (RKVY).
7. Ensure effective coordination within and between departments and ministries to meet the objectives of the National Mission for Sustainable Agriculture under the National Action Plan on Climate Change (NAPCC).

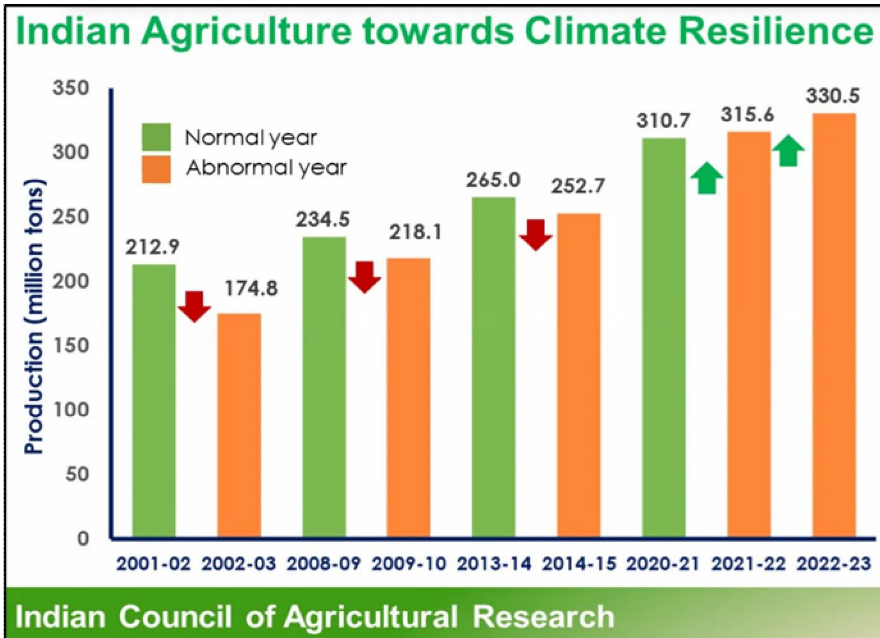

Fig. 17. Production of food grains under Climate Resilience Agriculture
(Source: https://x.com/rajvarshney/status/1797522056319516720/photo/1 **)**

4. CONCLUSION

Climate resilience agricultural practices play a crucial role in both enhancing food production and mitigating the impacts of climate change. By incorporating innovative techniques such as crop diversification, efficient water management, and soil conservation, these practices enable farmers to adapt to shifting climatic conditions and extreme weather events. This adaptability not only stabilizes crop yields but also ensures more sustainable and efficient use of resources. Furthermore, resilient agricultural systems contribute to reduced greenhouse gas emissions and improved soil health, supporting broader environmental goals. Ultimately, adopting climate resilience practices fosters a more robust and adaptable food production system, crucial for meeting the challenges of a changing climate while securing global food supplies.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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