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Contents

1. AGRICULTURA ENGINEERING

Protected Cultivation Microclimate Engineering

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Climate Manipulation Techniques

Climate manipulation in protected cultivation hinges on elevating heat content to maintain suitable plant temperatures, increasing humidity to minimize transpiration stress, enhancing light conditions to foster growth, enriching CO_2 for enhanced photosynthesis, and promoting air turnover for health and comfort. Although humidity and airflow are often considered passive conditions, they can be actively modified through various techniques.

Heating and cooling can be implemented passively or actively, with passive methods generally being most energy-efficient. Passive heating relies on solar gain and requires sufficient glazing area, while passive cooling exploits nocturnal ground cooling or strong summer convection. The performance, complexity, and risk associated with passive layers, such as shading screens, depend on the seasonality of their use. Thermal screens improve passive heating by reducing nocturnal losses but can compromise light transmission; ventilation balances humidity and temperature without active energy use, but excessive moisture demand may necessitate auxiliary dehumidification.

Active climates also rely on heat and moisture fluxes, but energy is invested in the process. Internal sources or sinks are most resource-efficient, while external conditioning the only option for humidity control in cooling mode can be energy- or capital-intensive. The need for active processes increases with reduced external flux common for crops with high moisture vapor and low thermal loads. Direct humidification and dehumidification usually require significant energy inputs and should be strategically integrated to achieve uniformity while avoiding pathogen risk.

Passive versus Active Heating and Cooling

The distinction between passive and active heating and cooling is central to the overall energy efficiency and capital requirements of protected cultivation. For determining which method should be employed in any given stage of production, the relative efficiency of heating by the sun versus by an auxiliary source, together with the cost and complexity of controlling the chosen mechanism, must be balanced.

Solar heating is passive, whilst any other source of heat is active. Heat pumps transfer heat from the environment to the greenhouse for free when it is cold outside and are therefore considered passive as long as their electricity consumption is not taken into account. The relative merits of heating with electricity, and especially with gas, are often improved by using heat dissipated by production equipment, such as electrical lights or heaters, rather than drawing it from the outside. The demand for cooling in protected cultivation is almost always satisfied using active methods and hence usually dominates the total thermal costs. Such active cooling can be relatively efficient if it is operated in an open configuration that allows low external humidity and temperature; these conditions enable the greenhouse to be viewed as a simple evaporative cooler. Tuyers, which operate on this principle, can fulfill the summer thermal and humidity requirements for free, provided that they are installed in the right locations and not too many are used.

Thermal Screens and Insulation

Thermal screens and insulation both reduce heat flux. Thermal screens impede thermal exchange whenever conditions unfavourable to the greenhouse occur, while insulation is a fixed element with a thermal transmittance lower than that of the frame-glazing assembly. The total thermal transmittance of such a configuration. These aspects can be balanced by selecting material with low thermal transmittance. The optimal configuration will then depend on equating profitability gained through reduced heating costs to product quality losses.

Indeed, thermal screens are a capital-intensive operation. Their high thermal efficiency makes them usefully applicable over seasons when solar radiation inputs are large and shading treatment results are thus less critical.

Shading, Daylength Extension, and Light Diffusion

Shading strategies, daylength extension methods, and light diffusion technologies modulate illumination in a protected environment. Each aspect is treated separately, although they are often applied together, and the potential of cropping towards higher light-use efficiency is discussed.

Visual radiation management affects every aspect of crop growth, development, and quality. In warm periods, whether summer or sunny days across other seasons, appropriate light reduction is crucial. Excessive lighting may cause damage through strong radiation heat loads and increase diseases. In subtropical and tropical areas, approaches such as screening, covering with shade nets, and scribing with moisture-retaining materials are common. Properly managed shade allows a high root–shoot ratio at plant stage, with lower incidence of Phytophthora capsici, while generally improving fruit quality.

During the rest of the year, plant development often exceeds daylength requirements. Some crops can benefit from light extension, especially if associated with high DLI. Artificial lighting, often used in combination with other facilities such as thermal screens, seems to be inefficient when compared with higher light conditions during the available period. As a result, night-break lighting systems using lower light intensity and shorter duration may also meet needs with similar or lower energy input. Light diffusion from enclosed spaces or greenhouse aspects also gives advantages, especially under saturated light conditions. Greater diffusion increases light interception, facilitating plant area distribution and biomass accumulation, and can be seen as a partial alternative to shading. Stress factors due to light fluctuation and direct radiation on covered surfaces are also reduced.

Humidity and Fogging Systems

Humidity plays a pivotal role in plant growth, influencing nutrient availability, physiological processes, and susceptibility to disease. However, the humidity levels within greenhouses particularly in winter are typically lower than optimal, which can negatively affect growth. Furthermore, high humidity can be detrimental, consequently increasing demand for ventilation or air conditioning and providing a favorable environment for pathogen development. Reliable dehumidification and fogging systems can assist in maintaining humidity levels within these desired ranges.

Dehumidification is typically accomplished by temperature reduction, as the supporting medium's relative humidity is largely dependent on temperature. As with all climate control actions, the water vapor level can be lowered by ventilation; however, in cool conditions, this incurs a significant energy cost and internal climate control through heating requires parallel dehumidification with dry outside air. In pressurized systems, water mist of droplet size smaller than the saturation drop radius can be uniformly added to the air at a temperature higher than the crop surface temperature. Air is subsequently cooled below the dew temperature and moisture condenses on the foliage, thus increasing external relative humidity without affecting the plant's conductive heat loss. However, because distribution is dependent on-air movement, places with much less or much more humidity than optimum are created. It is also important to note that dehumidification not only reduces water condensation on the foliage, paving the way for infection, but also on the surrounding structures. At the same time, high humidity during flowering and harvest poses a high risk of botrytis, for which dehumidification can serve as protection.

CO_2 Delivery Systems and Regulation

Dedicated systems for CO_2 delivery allow its concentration to exceed ambient levels and fulfill plants' metabolic requirements.

Achieving high concentrations requires gas burners, increased cylinder numbers, or liquid CO_2 systems, with costs depending on attainable plant growth rates. When concentrations are non-limiting, delivery focuses on dilution due to insufficient enclosure volume or canopy size. Capital costs relate to maintenance, operation, and the need for specialized personnel.

This scientific premise also applies to passive cultivation. In winter, when ventilation is limited, CO_2 concentration meets key resources for increased plant growth. Companies producing non-tidal air-drying systems are reliable. However, though ambient vapor pressure concentrations created by chemical change may have a marginal effect, no disease-specific factors apply.

Ventilation Strategies for Plant Health

A variety of interrelated factors influence ventilation strategy selection. Perhaps most salient is the microclimate energy balance, in particular heat loss rates, since insufficient ventilation incurs thermal energy and humidity excesses and heightens pathogen pressure. Equally critical is the temperature–humidity coupling, particularly for structures managed without dedicated dehumidification systems; failure to remove excess humidity therefore tends to increase operating temperature. Economic factors weigh heavily in large-scale production, where owners may accept elevated disease pressure to satisfy ventilation energy costs. Organically managed crops typically require higher relative humidity and thus reduce ventilation rates. In short, the interplay of the heat balance, humidity control, and biosecurity risk profoundly informs air exchange conditions.

Disease pressure generally invites freer ventilation to promote drying, yet high exchange rates risk exposure to infective spores. Pathogen spread relies on a threshold density in the environment, warranting consideration of the inoculum reduction approach. This favors low-density inoculum over exposure duration, leading to extended exchange times with attenuated spore density. Similarly, filtering may be economically justified despite higher contamination rates, since the predominant spore types infect distantly. Once more, these considerations interact with the crop energy balance, since disease also affects plant thermoregulation.

Structural and Material Considerations

Structural and material aspects influence design choices for protected cultivation. The frame and glazing impact light transmission, heating, and cooling, while thermal mass affects temperature excursions and controls. System durability relies on frame materials, glazing properties, maintenance requirements, and aging.

Superstructures should resist wind, snow, and impact; glass, plastic, and mesh ordinarily transmit different heat fluxes. Durability, maintenance need, and spectral quality determine glazing choice for insulating structures. Thin-film polymers generally transmit more light; thinning reduces mass but increases stresses. Texturized surfaces enhance diffusive properties. Long-term viability requires durable plastics, transparent coating, or use beneath glass.

Footprint and orientation affect resource use efficiency. Groundwater, frost, and temperature management simplify positioning. Orienting the long facade along the solar path reduces shading, directly influences incident light, and regulates relative humidity. Shadows from nearby crops and structures impede radiation balance and temperature control; fine-mesh barriers prolong effect.

Greenhouse Frames, Glazing, and Thermal Properties

The structural frame of greenhouses supports the glazing and must be strong enough to bear local loads during the construction's service life, as well as wind loads during the construction and maximum-load phases. As for the glazing, its optical properties must be suitable for crop growth while providing minimal thermal resistance to heat transfer. Thermal mass or the mass of the plants themselves can influence the thermal performance and can be an element of the design.

Various greenhouses are built with different shapes, frames, and glazing materials; in terms of maintaining a microclimate and ensuring the durability of the structure, the pex frames (using cross-sectional pipes) are often considered the most effective. The advantages flowing from the use of the pex frame include optimal foot and gale section, minimum construction costs, a large number of internal or external gutter types, and the possibility of placing the greenhouse on open ground and under Havana – that is, to provide indirect irrigation using an arrangement of small canals; such elements also help in controlling the greenhouse temperature. Plastic film is the glazing material used in the majority of greenhouses; for a wide range of wavelengths, it has shown external transmittance levels of 90–92%. The thermal and hygrometric characteristics of the film material ensure great luminosity during the entire period of cultivation of the potted gardenia, while the closeness of the temperature value in the greenhouse with respect to the external one confirms the useful role of the gas inside the film. However, in terms of thermal resisting power and durability of the optical properties, the glazed surface does not show good performance.

Material Durability, Light Transmission, and Durability

Construction materials must endure throughout the operational lifespan of the structure. The consequences of aging consider not only their physical resistance but also the changes in optical, thermal, and mechanical properties that may arise. Aging can be accelerated due to exposition to high temperatures, humidity, solar radiation, wind speed, or salt concentration, or degrading chemicals. Parts undergoing faster aging require more frequent replacement.

Transparent and translucent coverings are subject to loss of transparency, yellowing, cracking or tearing. For coverings made of polymers, the coefficients of linear expansion are significantly larger than for glass, allowing higher level of curvature for equal thickness. Due to high light scattering, an uneven covering will lead to shading and nonuniformity; in extreme cases, light diffusion may even become too high and lead to reduced light use efficiency. Dust or biological contamination will additionally contribute to light filtering; the establishment of a cleaning program must reflect the environmental exposition to such factors and the effect on transmission drop.

Structure and covering design must also ensure that internal operating conditions meet not only structural integrity and comfort, but also acceptability from aesthetical, odor or noise points of view. These aspects may vary geographically and environmentally.

Greenhouse Footprint, Orientation, and Shadowing

Protected cultivation microclimate demands an objective, evidence-based treatment that integrates engineering principles with agronomic outcomes to assess design, operation, risk, and sustainability. It focuses on yield and quality production factors at minimum resource use levels. The protected-setting microclimate definition shapes hypotheses examining how control directly affects crop productivity, indirectly affects disease mitigation, resource use, and disease management. Research questions direct analysis into the microclimate management choice and impact of control methods, the principal supported-process components, the supported-process product-flow structure and response pattern, the introduction of wind and water vapor, response-pattern appearance, and the demand for decision-support frameworks.

Plant-environment interaction modeling and simulation help match control strategies to crop requirements. Initial simulation uses boundary data for equipment sizing and loss prediction. Decision-support integration enriches control models by exploring alternatives for all supported processes, scenario robustness, and user faults. Practical treatments illustrate quantitative risk delineation and highlight sustainability gaps; private sources offer supporting insight. A synthesis encapsulates the new objective and reveals further gaps. Protected cultivation is a promising risk-management microclimate and sustainability strategy, yet resource use is often unconsidered.

Crop-Environment Interactions

Adequate stomatal conductance is crucial for photosynthesis and transpiration, yet stomata often close in response to high humidity and low vapor pressure deficit (VPD). Air saturation leads to reduced transpiration, which can adversely affect plant cooling, nutrient uptake, and disease resistance. Many pathogens thrive in humid environments, making VPD a key controllable indicator for minimizing disease incidence and intensity. VPD also contributes to the potential transpiration rate and hence to the economic viability of controlled environments. However, high humidity levels may compromise the adequacy of root-zone aeration and hence affect nutrient uptake. Consequently, monitoring humidity and making provisions for ventilation become essential.

Several key physiological responses differentiate crops grown under controlled conditions compared to open-field systems. Elevated concentrations of carbon dioxide (CO_2) in a protected environment favor crop growth, boosting both biomass and yield. An increase of 2–5% in plant dry mass per 100 ppm of CO_2 is commonly accepted, although the CO_2 response may vary among different crops and cultivars. Enhanced CO_2 levels can lead to a more oxidized leaf color and have an interactive effect with light intensity; the combination of high CO_2 and high light tends to increase biomass partitioning into the plant canopy. Crops usually produce maximum photosynthesis rates at higher leaf temperature levels, and even a slight reduction in leaf temperature may adversely affect photosynthesis. Plants with a high-temperature requirement for physiological activities, such as the vegetable species curcuma and ginger, can also be grown with thermal mass in a controlled environment. However, not all crops respond equally well; Indian asparagus seedlings raised in an artificially heated and ventilated glasshouse exhibited a reduction in chlorophyll and carotenoid content compared to those grown in the open field.

Crop Physiology under Controlled Microclimates

Responses to temperature, humidity, and air movement extremes are well documented stomatal closure, respiration increases, wilting, and reduced photosynthesis at high temperatures; reduced transpiration, photosynthesis, and growth at low humidity; and stomatal closure, bud drop, and necrosis from windburn. Under controlled conditions, these extremes do not occur even though temperature, humidity, and wind speed differ from open air. Widening the range for the microclimate's growth-limiting factors should enhance yield. For example, Cucumis sativus grown at higher temperatures (30/22°C) increase photosynthesis, leaf area index (LAI), and leaf stomata size, leading to higher DLI consumption, growth, and yield. Broccoli (Brassica oleracea italica) grown at 25°C and below 70% RH has increased yield. An extended photoperiod induces stomatal opening and Tylophora indica (galangal) leaf expansion. Other experiments report stomatal opening with increasing DLI. However, using a small number of DLI adjuncts to any species may raise the yield. Expanding the bud- to flowering-dry fruiting stage humidity and air-dried flowering to harvest-air temperatures should not reduce flowering and fruiting. The absence of diseases or pests explains why protected horticulture ensures higher crop production.

Vegetative growth benefits from shading and a longer photoperiod. An increase in photoperiods (PPDs) and DLI improves the leaf area index and growth index of mulberry under foliar spraying. For Tylophora indica, a relative humidity of 55% with a PPD of 14 h induces maximum growth. However, not all crops respond favorably to long hours; sensitivity depends on the physiological characteristics of the species. Certainly, there is no yield contribution from a small increase in PPD or minor changes that become less than those above or below a shade or light-induced limit.

Species and Cultivar Selection for Protected Environments

The choice of species and cultivar strongly influences the success of protected production systems. Changeable weather patterns frequently challenge existing prophylactic measures, and those requiring adaptations should consider alterations in resistant or tolerant crop species. Protected environments enable the growth of a greater diversity of food crops, including the more demanding high-value horticultural species, in regions not suitable for open-field production. The warmer, more stable climate conditions help speed up crop development and the harvest cycle, but excessive use of nighttime heating, low-priced CO_2, and high-quality light supplementation can conveniently extend the production area or day-duration of natural less-demanding species.

Protected cultivation can be successfully achieved by developing more resistant or tolerant crop species, dwarfing and compacting natural plant species, creating new varieties with altered phenological behavior, or even by producing artificial genetically changed species. Experimental mutations in various crop species have been produced. Genetically engineered growth retardant crops with compact shape have attracted much interest for horticultural production in modern greenhouses. Superdwarf mutants and dwarf-hybrid lines of rice have been produced. Phytotron chambers have become an important tool for plant-species cultivation and serve as ideal devices for studying the effect of cord-hormones on plant-physiology.

Nutrient Relations and Root Zone Management

Nutrient availability and root zone conditions exert a strong indirect influence on all crops grown in closed environments. A thorough development of the root zone and its supporting parameters and implications is paramount to achieving productive plants. The integration of environments and crops covers a wide spectrum from the root, to local and regulating parameters, and links required nutrient management and moisture supply.

Diverse species and cultivars exhibit considerable variation in root structure and functioning, including air and water relations, mycorrhizae formation, nutrient distribution in the plant and at harvest, and niche establishment. Foliage features influence transpiration and evaporative cooling, and stomatal openness under VPD extremes is species dependent. Maintenance of a healthy initial growth period is critical. Control of the nutrient solution is also important. As for open-field crops, the nutrient regime must be adapted to the crop and local climatic conditions. However, some particular points for root zone solution in closed environments emerge: Salinity, segmenting, selection of crops with different requirements, and of substrates to facilitate uptake and placement of different salts. The analysis of the relationships between the concentrations of concentrations in the nutrient solutions and in the leaves of tomato plants grown in greenhouses are analysed.

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2. AGRICULTURAL METEOROLOGY

The Indian Ocean Dipole: The Hidden Force Behind India's Monsoon

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Introduction

The southwest monsoon is more than just a season of rain in India. it is the foundation of the country's agriculture, water resources and food security. Every year, millions of farmers eagerly await its arrival, hoping for timely and well-distributed rainfall that can ensure healthy crops and stable incomes. A favourable monsoon replenishes rivers, reservoirs, and groundwater, while a weak or delayed monsoon can lead to droughts, crop failures, and economic losses, affecting millions of lives.

Although El Niño is widely known for influencing the Indian monsoon, another important climate phenomenon, the **Indian Ocean Dipole (IOD)**, also plays a crucial role. By altering sea surface temperatures between the western and eastern Indian Ocean, the IOD influences atmospheric circulation and the movement of moisture towards India. Depending on its phase, it can strengthen or weaken monsoon rainfall and sometimes even offset the adverse effects of El Niño. As climate change increases weather variability, understanding the Indian Ocean Dipole has become essential for improving monsoon prediction and supporting climate-resilient agriculture.

What is the Indian Ocean Dipole?

The Indian Ocean Dipole refers to the difference in sea surface temperatures between the western Indian Ocean near the coast of East Africa and the eastern Indian Ocean near Indonesia. The concept of the Indian Ocean Dipole was first identified by climatologists **N. H. Saji** and **Toshio Yamagata** in 1999. They found that periodic warming and cooling across the tropical Indian Ocean influence weather patterns over surrounding continents (Saji et al., 1999).

The IOD has three phases:

- Positive IOD: The western Indian Ocean becomes warmer than normal, while the eastern Indian Ocean becomes cooler. This condition usually strengthens the southwest monsoon over India and increases rainfall in many regions.
- Negative IOD: The eastern Indian Ocean becomes warmer, and the western Indian Ocean cools. This often weakens the Indian monsoon and may contribute to below-normal rainfall.
- Neutral IOD: Sea surface temperatures remain close to average, and the IOD has little influence on monsoon behaviour.

How Does the Indian Ocean Dipole Influence the Monsoon?

The southwest monsoon is driven by differences in temperature and pressure between land and ocean. During a positive IOD event, warmer waters in the western Indian Ocean enhance evaporation and cloud formation, while cooler waters near Indonesia suppress rainfall. This change strengthens the movement of moisture-laden winds towards the Indian subcontinent, often resulting in above-normal monsoon rainfall.

Conversely, during a negative IOD event, convection shifts towards Indonesia, reducing the amount of moisture transported to India. This can weaken the southwest monsoon, delay rainfall, and increase the probability of drought conditions in several parts of the country.

The influence of the IOD is particularly important because it directly affects rainfall distribution rather than simply the total seasonal rainfall. Well-distributed rainfall is critical for successful crop establishment, flowering, and grain filling in major crops such as rice, maize, cotton, soybean, and pulses.

The Indian Ocean Dipole Can Balance El Niño

One of the most remarkable characteristics of the Indian Ocean Dipole is its interaction with El Niño. Normally, El Niño suppresses monsoon rainfall over India by weakening large-scale atmospheric circulation. However, when a strong positive IOD develops simultaneously, it can compensate for the negative influence of El Niño.

A classic example occurred in **1997**, when one of the strongest El Niño events on record coincided with an exceptionally strong positive IOD. Despite fears of severe drought, India experienced near-normal monsoon rainfall because the positive IOD enhanced moisture transport over the Indian Ocean (Saji et al., 1999).

Another remarkable example was **2019**, when India received nearly **110% of its Long**

Period Average (LPA) seasonal rainfall. The India Meteorological Department reported that the strong positive IOD significantly strengthened the monsoon circulation, helping offset the weak El Niño conditions and producing above-normal rainfall over much of the country (IMD, 2019).

Climate Change and Future Challenges

Scientists are now investigating how climate change may influence the behaviour of the Indian Ocean Dipole. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), the Indian Ocean has warmed faster than many other tropical oceans during recent decades. This warming is altering ocean-atmosphere interactions and may increase the frequency of extreme positive IOD events.

More frequent positive IOD events could increase the occurrence of intense rainfall, floods, and landslides over parts of India while causing severe droughts across Indonesia and Australia. At the same time, greater climate variability may lead to more unpredictable monsoon behaviour, posing new challenges for agriculture, water management, and disaster preparedness.

Researchers continue to improve seasonal climate prediction models by combining information from the Indian Ocean Dipole, El Niño–Southern Oscillation (ENSO), and other oceanic climate oscillations. Better forecasting enables governments, farmers, and disaster management agencies to prepare months in advance for extreme weather conditions.

Conclusion

Although the Indian Ocean Dipole often remains unnoticed outside scientific circles, it is one of the most influential climate systems controlling the Indian monsoon. By regulating sea surface temperatures and atmospheric circulation across the Indian Ocean, the IOD determines the amount and distribution of rainfall that supports agriculture, water resources, and the livelihoods of millions of people.

As climate change continues to reshape global weather patterns, improving our understanding of the Indian Ocean Dipole has become more important than ever. Continued research, advanced climate monitoring, and reliable seasonal forecasts will strengthen India's resilience against droughts, floods, and other climate-related challenges. The future of monsoon prediction may not lie solely in the Pacific Ocean but also in the changing waters of the Indian Ocean.

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3. AGRICULTURE

The Role of Drones in Smart Agriculture and Sustainable Farming

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Introduction

Agriculture is undergoing a technological transformation to meet the growing demand for food while addressing challenges such as climate change, labor shortages, and resource depletion. Among the emerging technologies, drones, also known as Unmanned Aerial

Vehicles (UAVs), have become an essential tool in smart agriculture. Equipped with advanced sensors, cameras, and GPS systems, drones provide farmers with real-time data and precise control over farming operations. Their integration into agricultural practices promotes sustainability, increases productivity, and reduces environmental impact.

Applications of Drones in Smart Agriculture

1. Crop Monitoring and Health Assessment

Drones enable farmers to monitor crop conditions efficiently through high-resolution images and multispectral sensors. They can detect signs of plant stress, diseases, pest infestations, and nutrient deficiencies before they become visible to the naked eye. Early detection allows timely intervention, reducing crop losses and improving yields.

2. Precision Spraying

Agricultural drones can spray fertilizers, pesticides, and herbicides with high accuracy. This targeted application minimizes chemical wastage, reduces operational costs, and limits environmental contamination. Precision spraying also decreases farmers' exposure to harmful chemicals.

3. Soil and Field Analysis

Before planting, drones can assess soil conditions and generate detailed maps of agricultural fields. These maps help farmers identify soil variations, drainage issues, and nutrient levels, enabling informed decisions regarding crop selection and land management.

4. Irrigation Management

Thermal imaging sensors mounted on drones can identify areas suffering from water stress. Farmers can use this information to optimize irrigation schedules, conserve water resources, and improve crop health. Efficient water management is particularly important in regions facing water scarcity.

5. Crop Yield Estimation

Drones collect data on plant density, crop growth, and field conditions, allowing accurate yield predictions. Reliable forecasts help farmers plan harvesting, storage, transportation, and marketing activities more effectively.

6. Livestock Monitoring

In addition to crop farming, drones assist in livestock management. They can monitor animal movements, identify sick or injured animals, and track grazing patterns over large areas, reducing labor requirements and improving animal welfare.

Contribution to Sustainable Farming

Resource Conservation

Drone technology promotes the efficient use of water, fertilizers, and pesticides. By applying inputs only where needed, farmers can reduce waste and lower production costs.

Environmental Protection

Reduced chemical usage minimizes soil degradation and water pollution. Drones also support environmentally friendly farming practices by lowering the carbon footprint associated with conventional agricultural machinery.

Increased Productivity

Accurate and timely information enables farmers to make data-driven decisions, resulting in higher crop yields and improved farm profitability.

Climate Resilience

Drones help farmers monitor weather impacts, drought conditions, and crop stress, allowing them to adapt quickly to changing environmental conditions and enhance resilience against climate-related risks.

Challenges of Drone Adoption

Despite their benefits, several challenges limit widespread drone adoption:

- High initial investment costs
- Limited technical knowledge among farmers
- Regulatory restrictions on drone operations
- Data management and privacy concerns
- Battery life and operational limitations

Addressing these challenges through training programs, government support, and technological advancements can facilitate broader adoption.

Future Prospects

The future of agricultural drones is promising. Integration with Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) will enable autonomous farming systems capable of making real-time decisions. Advanced drones will provide more accurate data analysis, automated spraying, and predictive insights, further enhancing agricultural sustainability and efficiency.

Conclusion

Drones are transforming modern agriculture by enabling precision farming practices that improve productivity, reduce resource consumption, and support environmental sustainability. Their ability to monitor crops, manage irrigation, apply inputs accurately, and collect valuable data makes them a vital component of smart agriculture. As technology continues to advance and adoption barriers decrease, drones will play an increasingly important role in building sustainable and resilient agricultural systems worldwide.

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4. AGRICULTURE

Influence of Heat Stress on Agricultural Crops of Saurashtra Region

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Introduction

In Saurashtra, major crops like Cumin and Wheat (*Rabi*), alongside Cotton and Groundnut (*Kharif*), are highly sensitive to this devastating thermal stress. Semi-arid Climate of Saurashtra getting hit the hardest as well as irregular monsoons and limited groundwater this region is also facing rising temperatures and more frequent, intense and long-lasting heatwaves. Heat stress occurs when temperatures cross a critical threshold, permanently damaging plant growth and disruptive metabolic activity.

Causes of Heat Stress in Saurashtra Region:

Inter seasonal drought: An inter-seasonal drought happens when monsoon rains suddenly vanish for weeks. Without water, the soil bakes hard, and crops lose their ability to "sweat" (transpire) to cool down, causing them to quickly overheat and suffer severe stress.

Late Onset of Monsoon: A delayed monsoon stretches the blazing summer heat into June, turning Saurashtra's shallow soil into a boiling hot plate. When seeds finally sprout, the overheated ground and scorching winds instantly shock the young seedlings, causing severe early-stage heat stress. Saurashshtra black soil has shrinkage properties so it is cracked due to high unavailability of moisture and roots not penetrate easily and suffer from heat stress.

Hair Drying Effect: Hot, dry winds blow across the field just like a real hair dryer, rapidly sucking water out of the leaves. Because the roots cannot keep up with this blasting heat, the plant's leaves quickly scorch, dry up, and wilt.

Effect heat Stress on Crops:

Groundnut: groundnut is highly susceptible to heat stress; it's required 25 to 35°C for better growth. Require minimum temperature for germination is 15°C. if temperature increase from cardinal temperature reduce the number of pod and harmful effect on pegging and finally reduce yield.

Cotton: cotton require 28 to 45°C during its crop growth period and mean air temperature of 21 to 29°C is required at vegetative period. If this more than it saw harmful effect like Shedding of squares and bolls, sterile pollen formation, smaller bolls and poor fiber quality, stunted plant growth.

Wheat: Wheat require optimum temperature for growth and grain filling is 20-25°C and 14-16°C respectively. In high temperature condition, early senescence, sterile flowers, shriveled grains, reduced tillering.

Soybean: soybean well grow in 26 to 32°C temperature and 15°C for germination. In more adverse temperature pollen and flower drop, pollen and flower drop, green island effect, small, oil-deficient seeds.

Pulses: Increase of temperature heat stress effect on massive flower drop, moisture vaporization & "Scorching", destruction of root nodules, yellow mosaic virus explosion and shrivelled grain and forced maturity.

Cumin: Cumin is highly sensitive to heat stress. It is requiring optimum growth temperature 15 °C -25 °C and critical heat threshold more than 30°C. due to heat stress drying of flowers, shrivelled seeds and low essential oil content and increased vulnerability to diseases, photosynthesis shutdown & visual scorching.

Adaptation Strategies:

Micro irrigation strategies: use drip irrigation /sprinkler irrigation techniques for irrigation as per suitable soil type and based on suitable climate.

Follow forcasting: every farmer should follow forecasting bulletins for conduct intercultural practise. For irrigation application follow nowcast on daily bases and select crop on bases of seasonal forecast at particular area also use drought and heat-resistant variety.

5. AGRICULTURE

Weather Forecasts: Helping Farmers Grow More with Less Risk

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Introduction

Agriculture is the backbone of the Indian economy, contributing nearly 18% to the country's Gross Domestic Product (GDP) and providing employment to about half of the workforce. India is among the world's leading producers of rice, wheat, pulses and spices, making agriculture vital for food security and economic growth. As farming is highly dependent on weather, timely and accurate weather information is essential for improving productivity and reducing risks. Weather forecasting is the scientific prediction of future atmospheric conditions using weather observations, physical principles, statistical methods and advanced technologies. It provides information on rainfall, temperature, humidity, wind, cloud cover and extreme weather events, helping farmers prepare for changing weather conditions and make informed management decisions. Reliable weather forecasts support day-to-day agricultural operations such as land preparation, sowing, irrigation scheduling, fertilizer and pesticide application, pest and disease management and harvesting. Seasonal forecasts help farmers select suitable crops, plan cropping systems and adopt climate-resilient farming practices. They also assist governments in planning for droughts, floods and other weather-related emergencies. Among all weather parameters, rainfall is the most critical factor influencing agricultural production in India. Accurate rainfall forecasts enable farmers to conserve soil moisture during weak monsoons, prepare for floods during heavy rainfall and manage farm resources more efficiently. With increasing climate variability, weather information has become indispensable for crop diversification, efficient resource use and sustainable agriculture. Integrating weather forecasts with farm management helps farmers reduce production risks, improve crop yield and quality, minimize unnecessary expenditure on irrigation and agrochemicals and enhance overall farm profitability. Therefore, weather forecasting has become an essential component of climate-smart agriculture, contributing to food security, sustainable agricultural development and improved livelihoods of farming communities.

Why Weather Forecasting Matters in Agriculture

Weather influences every stage of crop production-from land preparation and sowing to irrigation, fertilizer application, pest management and harvesting. Reliable forecasts allow farmers to make timely decisions that improve crop yield and quality while reducing unnecessary expenses.

Weather-based advisories help farmers to:

- Prepare land and schedule sowing according to expected rainfall.
- Select suitable crops and varieties for prevailing climatic conditions.
- Plan irrigation efficiently and conserve water.
- Apply fertilizers and pesticides at the most effective time.
- Monitor and manage pests and diseases before outbreaks occur.
- Protect crops and livestock from extreme weather events.
- Harvest crops at the right time to reduce post-harvest losses.

Seasonal weather forecasts are equally valuable for long-term planning. They assist farmers in crop diversification, choosing appropriate cropping systems and preparing contingency plans during droughts or floods. Governments also use seasonal forecasts for planning food security measures, water management and agricultural policies.

Weather Information Needed by Farmers: Agricultural weather forecasts include several important weather parameters that directly affect crop growth and farm operations. These include:

- Rainfall amount and distribution
- Maximum and minimum temperatures
- Relative humidity
- Wind speed and direction
- Cloud cover
- Dew point
- Extreme weather events such as frost, fog, hailstorms, cyclones, heat waves and cold waves

Combining weather information with crop growth stages enables farmers to make better management decisions, leading to higher productivity and environmentally sustainable farming.

Types of Weather Forecasts: Weather forecasts are classified according to the forecast period and their applications.

Now casting (0–6 hours): Provides immediate information on rapidly developing weather events such as thunderstorms, lightning, heavy rainfall and cyclones. It is useful for issuing early warnings and protecting lives, crops and property.

Very short- range forecast (up to 12 hours): Helps predict local weather events including heat waves, cold waves and severe storms.

Short – range forecast (2-3days): Supports routine farm activities such as irrigation scheduling, fertilizer application, pesticide spraying and harvesting. It generally provides high forecast accuracy.

Medium range forecast (3-10 days): Enables farmers to plan sowing, harvesting, labour management and livestock care. These forecasts are widely used for preparing agro meteorological advisories.

Extended-Range Forecast (10–30 days): Useful for farm planning, resource allocation and agricultural input management.

Long-Range Forecast (monthly to seasonal): Provides information on expected weather trends over weeks or months, particularly useful for planning Kharif and Rabi cropping seasons .

Forecast Needs During Crop Seasons: Different crop seasons require different types of weather information.

Kharif season:

- Onset and withdrawal of the southwest monsoon
- Breaks in monsoon rainfall
- Heavy rainfall events

Rabi season:

- Winter rainfall
- Cold waves and frost
- Heat waves during spring
- Hailstorms before harvest

Conclusion

Weather forecasting has become an indispensable component of modern agriculture. Accurate and timely forecasts enable farmers to reduce production risks, improve resource use efficiency and enhance crop productivity. They also support better planning at farm, community and government levels, contributing to food security and climate resilience.

As climate variability and extreme weather events become more frequent, the effective use of weather forecasts and agro meteorological advisories will play an increasingly important role in sustainable agricultural development. By integrating scientific weather information into day-to-day farming decisions, farmers can safeguard their crops, improve profitability and build a more resilient agricultural future.

6. AGRICULTURE

Impact of changing monsoon pattern on agriculture in the Saurashtra region of Gujarat

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Introduction

The South west monsoon is the lifeline of agriculture in Saurashtra region of Gujarat, In this region of Gujarat farmers growing crops like cotton, groundnut, sesame and millet. Agriculture of this region depended on the south west monsoon. In the recent years, the monsoon pattern has become unpredictable. Delayed rainfall, long dry spells, sudden heavy downpours, and rising temperatures are creating new challenges for farmers. These changes are related to climate change and are affecting both agricultural productivity and rural livelihoods.

How the Monsoon is Changing

Traditionally, farmers in Saurashtra could predict the arrival and distribution of rainfall with reasonable accuracy. Now, the situation is different. Rainfall has become more unpredictable and some areas facing drought like conditions while others facing flood within the same season. Scientists suggest that global warming is increasing atmospheric temperatures, which directly affects weather systems and rainfall patterns. Warmer air can hold more moisture, leading to intense rainfall events over short periods. As a result, Saurashtra often receives most of its rainfall within a few days rather than evenly distributed throughout the monsoon.

Effects on Agriculture

The changing monsoon directly affects crop production. Delayed rainfall postpones sowing activities, reducing the growing period of crops. If rain arrives late, farmers may be forced to re-sow seeds, it increasing their expenses. On the other hand, sudden heavy rainfall can cause water logging and soil erosion. Groundnut and cotton, which are widely grown in Saurashtra, are highly affected by excess moisture. Heavy rains may damage roots, reduce crop quality, and increase infestation of pests and diseases. Long dry spells are another major concern. Crops require moisture at critical stages of growth, and a lack of rain during these periods can significantly reduce yields. As a result, farmers face uncertainty in production and income.

Economic and Social Challenges

Agricultural losses caused by irregular monsoon affect the economic stability of farming community. Reduced crop yields reduce farmers' incomes, making it difficult to repay loans and invest in future cultivation. Small and marginal farmers the most affected because they have limited irrigation facilities and financial resources. Crop failures may force some families to find other sources of income or temporarily migrate to urban areas for work.

The changing monsoon also affects livestock, which is an important part of rural livelihoods in Saurashtra. Reduced rainfall can cause shortages of fodder and drinking water, making life more difficult for farming communities.

Adaptation and Possible Solutions

Despite these challenges, farmers and policymakers are adopting various strategies to deal with changing climatic conditions. Water conservation methods such as check dams, farm ponds and rainwater harvesting have helped improve groundwater levels in many parts of Saurashtra.

Farmers are also using drought resistant varieties and adopting micro irrigation systems such as drip irrigation to use water more efficiently. Weather forecasts and climate information help farmers make better decisions about sowing, irrigation, and crop management. Government support through crop insurance, agricultural extension services, and climate-resilient farming programs can help farmers adapt to uncertain monsoon conditions.

Future Outlook

Climate projections show that weather variability may increase in the coming decades. This means that farmers in Saurashtra need to adopt more resilient and flexible farming practices. Sustainable water management, improved agricultural technology, and greater awareness of climate risks will play a crucial role in securing the future of agriculture in the region.

Conclusion

The changing monsoon is one of the biggest challenges for farmers in Saurashtra today. Unpredictable rainfall, extreme weather events, and rising temperatures are affecting crop production, incomes, and rural livelihoods. Although these challenges are serious, adaptation strategies and sustainable farming practices can help farmers deal with changing climatic conditions. Ensuring a resilient agricultural system is essential for the future of Saurashtra and its farming communities.

7. AGRICULTURE

Climate Resilience Assessment in Agriculture: Indicators, Methodologies, Applications, and Future Perspectives

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Abstract

Climate change has emerged as one of the most significant challenges to global agriculture, threatening crop productivity, water availability, soil health, and food security through increasing temperatures, erratic rainfall, droughts, floods, and other extreme weather events. Evaluating the resilience of agricultural systems has therefore become essential for designing effective adaptation strategies and supporting evidence-based policymaking. Climate resilience indices provide quantitative measures of the ability of agricultural systems to resist, adapt to, and recover from climate-induced disturbances. These indices integrate multiple dimensions, including climate exposure, vulnerability, adaptive capacity, sensitivity, and recovery potential, allowing comparison across regions and production systems. This review summarizes the conceptual framework, indicator selection methods, data requirements, and analytical approaches used in climate resilience assessment. It also discusses practical applications of resilience indices in crop production, livestock systems, water resource management, and climate-smart agriculture. Recent developments in remote sensing, geographic information systems (GIS), artificial intelligence (AI), machine learning, and Internet of Things (IoT)-based monitoring are highlighted as promising tools for improving resilience assessment and decision support. Finally, the review identifies major challenges, including data limitations, indicator standardization, and uncertainty analysis, while suggesting future research directions for developing dynamic, location-specific, and policy-oriented resilience assessment frameworks. Climate resilience indices offer valuable support for sustainable agricultural planning, disaster risk reduction, and long-term adaptation under changing climatic conditions.

Keywords: Climate resilience, Agriculture, Vulnerability, Adaptive capacity, Climate-smart agriculture, Remote sensing

1. Introduction

Agriculture is highly vulnerable to climate change because crop production depends directly on climatic variables such as rainfall, temperature, humidity, and solar radiation. The increasing frequency of droughts, floods, heat waves, and unpredictable rainfall patterns has significantly affected agricultural productivity worldwide. Developing resilient agricultural systems has become a global priority for ensuring food security and sustainable rural development.

Climate resilience refers to the capacity of agricultural systems to anticipate, withstand, adapt to, and recover from climate-related disturbances while maintaining productivity and ecosystem functions. Climate resilience indices have emerged as valuable decision-support tools that combine environmental, social, economic, and technological indicators into a comprehensive assessment of agricultural resilience. These indices help policymakers identify vulnerable regions, prioritize adaptation measures, and evaluate the effectiveness of climate-smart interventions.

Agriculture is an economic activity that sustains the food and nutrition necessary for human life and plays a pivotal role in socioeconomic development (Latruffe et al., 2016). Agricultural production is strongly influenced by weather/climate, and its instability and vulnerability will increase with climate warming (Liu et al., 2010, Zhang et al., 2017). Extreme weather events, such as droughts, heatwaves, and floods, directly threaten food production and security, especially in rural communities with high populations of small-scale producers who are highly dependent on rain-fed agriculture for their livelihoods and food (Acevedo et al., 2020). For instance, the worst drought in the past 40 years affected the southern part of Madagascar in 2021, causing approximately 1.14 million people to face high levels of acute food insecurity, of which nearly 14 000 people were in the 'Catastrophe' phase (Phase 5 - the highest on the five-step scale of the Integrated Food Security Phase Classification (IPC)) (FAO, 2021). Water conflicts between the agricultural sector and cities will intensify with changes in rainfall patterns and urbanization (Flörke et al., 2018). In addition, a warming climate also increases the likelihood and severity of agricultural pests and pathogens, thus increasing the potential risk of food production (Bebber et al., 2013, Ma et al., 2021). According to the 2021 report from the Food and Agriculture Organization of the United Nations (FAO), the conflict between rapid global population growth and incompatible food supplies has become more serious. Rapidly growing populations and changing diets will increase the demand for meat and dairy products in developing economies, which will further expand the exploitation of natural resources and increase food production and its security risks (Acevedo et al., 2020).

2. Framework of Climate Resilience

Assessment

Climate resilience assessment is generally based on five major components:

- **Exposure:** Degree to which agricultural systems experience climatic hazards such as droughts, floods, and heat stress.
- **Sensitivity:** Extent to which agricultural production is affected by climate variability.
- **Vulnerability:** Combined effect of exposure and sensitivity considering socioeconomic conditions.
- **Adaptive Capacity:** Ability of farmers and institutions to respond through technology, infrastructure, knowledge, and financial resources.
- **Recovery Capacity:** Ability of agricultural systems to restore productivity after climatic disturbances.

The integration of these components provides a comprehensive resilience index that supports agricultural planning and climate adaptation.

3. Methodologies for Climate Resilience Indices

Several methodologies have been developed for resilience assessment.

Indicator-Based Assessment

Composite indices combine environmental, socioeconomic, and institutional indicators into a single resilience score. Common indicators include rainfall variability, irrigation coverage, soil quality, farm income, education level, crop diversity, and access to extension services.

Statistical Approaches

Frequently used methods include:

- Principal Component Analysis (PCA)
- Analytical Hierarchy Process (AHP)
- Entropy Weighting Method
- Composite Indicator Method
- Multi-Criteria Decision Analysis (MCDA)

GIS and Remote Sensing

Satellite-derived datasets provide spatial information on vegetation health, soil moisture, land use, drought severity, and water availability. GIS enables vulnerability mapping and regional resilience assessment.

Artificial Intelligence and Machine Learning

Recent studies employ machine learning algorithms for predicting drought risk, crop resilience, and adaptive capacity using multi-source datasets. AI improves prediction accuracy and supports real-time monitoring.

4. Applications in Agriculture

Climate resilience indices have diverse applications in agricultural management.

- Identification of climate-vulnerable districts and farming communities.
- Assessment of drought resilience in rainfed agriculture.
- Monitoring crop performance under climate variability.
- Evaluation of climate-smart agricultural practices.
- Water resource management and irrigation planning.
- Livestock resilience assessment.
- Policy formulation for sustainable agricultural development.

Several countries have successfully integrated resilience indices into agricultural planning to improve resource allocation and disaster preparedness.

5. Emerging Technologies and Future Perspectives

Technological advancements are transforming climate resilience assessment.

Remote sensing platforms such as Sentinel and Landsat provide continuous monitoring of vegetation dynamics, drought severity, and land degradation. Artificial intelligence and deep learning facilitate automated climate risk prediction using large datasets. Internet of Things (IoT) sensors enable real-time monitoring of soil moisture, temperature, and crop health, improving farm-level resilience management.

Future research should emphasize:

- Standardized resilience indicators
- High-resolution spatial datasets
- Dynamic resilience monitoring
- Integration of socioeconomic and environmental data

- AI-enabled decision support systems
- Climate-resilient policy development

Conclusion

Climate resilience assessment has become an essential component of sustainable agricultural development under changing climatic conditions. Climate resilience indices provide a scientific framework for evaluating the capacity of agricultural systems to withstand, adapt to, and recover from climate-related disturbances. By integrating environmental, socioeconomic, institutional, and technological indicators, these indices support evidence-based decision-making, vulnerability mapping, and adaptation planning. Recent advances in remote sensing, GIS, artificial intelligence, machine learning, and IoT technologies have significantly enhanced the accuracy and timeliness of resilience assessments. Despite considerable progress, challenges remain regarding data quality, indicator standardization, uncertainty analysis, and regional customization. Future research should focus on developing dynamic, scalable, and policy-oriented resilience assessment frameworks that integrate climate projections with real-time monitoring systems. Such approaches will strengthen climate-smart agriculture, improve food security, and enhance the long-term sustainability of agricultural systems in the face of increasing climate variability.

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