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Current Research Trends in Agriculture Science

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PREFACE

The field of agricultural science is undergoing a remarkable transformation, driven by the urgent need to address global challenges such as climate change, population growth, and sustainable resource management. Current Research Trends in Agricultural Science presents a comprehensive exploration of the innovative approaches and cutting-edge technologies that are shaping the future of agriculture. This volume brings together diverse perspectives from leading researchers and practitioners, offering valuable insights into the most pressing issues and promising solutions in modern agricultural science.

Agricultural productivity and sustainability are no longer just matters of local concern but have become critical global priorities. This book delves into key areas of research, including precision agriculture, where advanced technologies like drones, sensors, and artificial intelligence are revolutionizing farm management. It examines breakthroughs in crop biotechnology, such as CRISPR and gene editing, which hold immense potential for developing stress-resistant and high-yielding crop varieties. The book also explores sustainable soil management practices, agroecological approaches, and the integration of climate-smart agricultural techniques to enhance resilience in the face of environmental uncertainties.

A significant focus of this volume is on the role of digital agriculture, highlighting how big data, machine learning, and IoT are enabling smarter decision-making and resource optimization. Additionally, the book addresses emerging trends in vertical farming, organic agriculture, and circular economy models that promote resource efficiency and reduce environmental impact. Each chapter combines rigorous scientific research with practical applications, providing a balanced view of both theoretical advancements and real-world implementations.

This book is designed for a broad audience, including researchers, academicians, students, policymakers, and industry professionals. It aims to serve as a valuable resource for those seeking to understand the latest developments in agricultural science and their implications for global food security and environmental sustainability. We are deeply grateful to the contributors, reviewers, and publishers who have made this collaborative effort possible. Their expertise and dedication have been instrumental in bringing this project to fruition. It is our hope that Current Research Trends in Agricultural Science will inspire further research, innovation, and policy initiatives to build a more sustainable and food-secure future.

- Editors

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CURRENT RESEARCH TRENDS IN AGRICULTURAL SCIENCE: A FOCUS ON AGRIVOLTAICS

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Abstract:

An emerging multidisciplinary field combining solar photovoltaic (PV) technology with agricultural practices to maximize land use efficiency is agrivoltaics, sometimes referred to as agro-photovoltaics (APV). Agrivoltaics solves the energy-food-water nexus by grouping crop production and energy generation, offering sustainable solutions for agricultural output and renewable energy creation. The most recent studies in agrivoltaic systems, including developments in bifacial solar panels, semi-transparent PV modules, and dynamic tracking systems that improve both energy yield and crop growth—are examined in this review. The microclimatic effects of agrivoltaics are lower heat stress, better soil moisture retention, and more water conservation—are also covered in the paper. To grasp the possibility for general acceptance, also examined are the socioeconomic advantages, policy frameworks, and financial feasibility of agrivoltaics. Agrivoltaic implementation has difficulties including land-use conflicts, first investment costs, and legal obstacles even with its benefits. Emphasizing the part agrivoltaics can play in reaching the UN Sustainable Development Goals (SDGs) and lessening of climate change effects, this review features case studies from many climatic zones. In order to improve agrivoltaic performance and scalability, future research paths and creative ideas including artificial intelligence-based monitoring and smart farming applications are suggested at last.

1. Introduction:

For billions of people globally, agriculture is still a pillar of human civilization since it offers basic resources including food, raw materials, and employment chances. But climate change, limited land, water scarcity, and the always rising demand for energy provide hitherto unheard-of difficulties for the sector. These urgent issues demand creative and sustainable methods of producing energy and food. Agrivoltaics has become a promising and integrated solution in this context that allows the simultaneous development of crops and the generation of solar energy, so optimizing land-use efficiency and supporting environmental sustainability.

Agrivoltaics is the deliberate arrangement of photovoltaic (PV) panels above agricultural fields so enabling the coexistence of solar energy collecting with crop development. This creative approach makes use of the advantages of shading produced by the PV panels, so it helps to lower evaporation, control heat stress on crops, and increase soil moisture retention. Agrivoltaics are especially fit for arid and semi-arid areas, where severe temperatures and water shortage seriously affect agricultural output, because of such advantages. Moreover, agrivoltaic systems support rural electrification and provide farmers with another source of income, so they can help to distribute renewable energy generation. Agrivoltaics is a major answer for both energy and agricultural problems since it helps farmers to diversify their income sources, so improving food security and local economy strength (Omer *et al.,* 2025).

Fig. 1: Agrivoltaic System (Jain Agro-Voltaic Farming, n.d.)

Agrivoltaics are very important in reducing climate change even beyond its direct advantages for energy generation and agriculture. Agrivoltaic systems help to lower greenhouse gas emissions by substituting other fuels, so supporting worldwide efforts to counteract climate change. Furthermore, these systems encourage carbon sequestration by bettering organic matter retention and lowering soil erosion, so improving long-term carbon storage. Agrivoltaics also have a major ecological benefit in terms of possibly improving farm biodiversity. The special microclimate produced by solar panels can help several plant species grow, so supporting a stronger and more balanced ecosystem. Since agrivoltaics offers a multifarious way to solve food production problems while lowering environmental impact, their integration into farming environments closely corresponds with world sustainability goals (Mazzeo *et al.,* 2025; Mouhib *et al.,* 2024).

Driven mostly by the need for sustainable land use and climate resilience, agrivoltaic research has experienced explosive expansion recently. The notable research contributions from nations including the United States, France, and Germany which have advanced agrivoltaic system designs and implementation strategies showcase the growing interest in this field (Omer *et al.,* 2025). With some obtaining a Land Equivalent Ratio (LER) of up to 1.79, studies have shown that agrivoltaic systems greatly increase land productivity. Agrivoltaics can generate more food and energy per unit area than conventional land-use practices, this measure shows (Mazzeo *et al.,* 2025; Mouhib *et al.,* 2024). These results emphasize how practical and efficient agrivoltaic systems are in contemporary agricultural settings.

Agrivoltaic systems' design mostly determines their efficiency since it calls for a careful balancing between agricultural output and energy generation. Ground coverage ratio (GCR), clearance height, and PV panel tracking configurations define critical design criteria. Higher clearance heights and reduced GCRs have been found to generally improve agricultural output, especially for crops sensitive to shade like maize. Slightly lower energy yields (Mazzeo *et al.,* 2025) are the price paid for this though. With some studies even stating stable or higher crop yields under such configurations, the use of bifacial PV modules and vertical mounting systems has shown promise in reducing shading effects on crops (Mouhib *et al.,* 2024; Tiffon-Terrade *et al.,* 2024). These technical developments highlight how agrivoltaics might maximize renewable energy generation as well as agricultural output.

Ensuring system effectiveness also depends critically on the choice of crops fit for agrivoltaic systems. Under agrivoltaic conditions, crops with greater shading tolerance that is, leafy vegetables, legumes, some fruit-bearing plants have shown encouraging results. Vegetables such as lettuce and tomatoes keep or even increase their yields under moderate shade, so benefiting from better water retention and less thermal stress (Widmer *et al.,* 2024). Fruit crops including berries and olive trees have also shown promise; studies showing that shading levels below a 30% threshold can either sustain or enhance fruit quality and yield (Magarelli *et al.,* 2024; Mouhib *et al.,* 2024). These results imply that agrivoltaics can be sufficiently customized to fit different agricultural environments, so improving its viability as a major farming alternative.

Agrivoltaic systems provide several environmental advantages beyond only agricultural output. One clear benefit is lowered water consumption since solar panel shading lowers evapotranspiration rates, so increasing water-use efficiency. Agrivoltaics also helps to sustain long-term land by lowering erosion and preserving soil health, so supporting soil conservation. By substituting solar power for conventional energy sources and so encouraging carbon sequestration, agrivoltaic systems greatly reduce greenhouse gas emissions (Mohammad *et al.,* 2024; Chopdar *et al.,* 2024). Further improving these environmental advantages is the integration of conservation agriculture methods including cover cropping and low tillage inside agrivoltaic systems, so promoting climate-resilient food production (Time *et al.,* 2024). Particularly in underdeveloped nations where resource limitations provide further difficulties, society benefits include improved land-use efficiency, economic opportunities for farmers, and contributions to the water-energy-food nexus (Mehta *et al.,* 2024; Matulić *et al.,* 2023).

Although agrivoltaics has great promise, several factors prevent its general acceptance. The great initial investment needed for PV infrastructure is one of the main economic obstacles; small-scale farmers may find this to be prohibitive. Further impeding adoption are insufficient technical knowledge and limited access to finance (Matulić *et al.,* 2023). Critical in removing these obstacles and encouraging the broad implementation of agrivoltaic systems (Bím & Valentová, 2023) are policy interventions and financial incentives including subsidies and feed-in tariffs. Moreover, the main issues for legislators still are grid integration difficulties and the necessity of laws enabling agrivoltaic development.

Future studies in agrivoltaics are expected to concentrate on developing standardized indicators for system performance assessment, integrating resource management strategies, and advancing photovoltaic materials. Semi-transparent and spectrally selective thin-film PV technologies have shown promise in increasing crop development while optimizing solar energy collecting (Zotti *et al.,* 2024). Furthermore, under investigation is the combination of agrivoltaics with other renewable energy sources, such bioenergy, to improve agricultural system sustainability even more (Klokov *et al.,* 2023). Agrivoltaic systems are appropriate depending on the area; factors like climate, type of soil, and crop choice really matter. Agrivoltaics has been identified as a climate-resilient farming method with advantages including higher agricultural yields and water conservation (Mohammad *et al.,* 2024). In Europe, meanwhile, nations including Croatia are looking at aquavoltaics and agrivoltaics as complimentary renewable energy sources to lower greenhouse gas emissions (Matulić *et al.,* 2023).

Although agrivoltaics offers a transforming chance for the generation of sustainable food and energy, some issues still need to be resolved. Careful planning is necessary to balance energy generation with agricultural output since poor system design might result in trade-off between the two goals (Chopdar *et al.,* 2024). Furthermore, still a major research void is the absence of consistent approaches for assessing long-term environmental effects (Chalgynbayeva *et al.,* 2023). Still, agrivoltaics presents a convincing way to handle the related problems of food, energy, and water security. Refining agrivoltaic system designs, guaranteeing their general acceptance, and optimizing their contribution to worldwide sustainability goals will depend much on constant research and policy support.

2.1 Definition and Concept

Agrivoltaics is a twin land-use method combining agricultural output with photovoltaic energy generation. The primary goal is to make use of the same ground for both uses, so improving land output and lowering the trade-off between food production and energy generation. Through energy sales, this creative system not only maximizes land use but also gives farmers extra income, so it benefits the renewable energy industry as well as agriculture. Agrivoltaics addresses the rising need for renewable energy sources by using sunlight for both crops and electricity, so supporting sustainable farming methods. Agrivoltaics presents a potential solution that can improve resilience and adaptability in agricultural systems as climate change keeps presenting difficulties to conventional farming approaches.By building microhabitats supporting different species, this method not only lessens the effects of climate change but also promotes biodiversity, so contributing to a better ecosystem.

2.1.1 Photosynthesis and Evapotranspiration

Green plants, algae, and certain bacteria use a process called photosynthesis to transform sunlight into chemical energy. In chloroplasts, carbon dioxide (CO_2) and water (H_2O) react with sunlight to form glucose ($C_6H_{12}O_6$) and oxygen (O_2). This process forms the base of the food chain and is necessary for plant growth. The combined process of water loss from the soil through evaporation and moisture release from plants through transpiration is known as evapotranspiration. It is essential for controlling the climate, cooling plant surfaces, and preserving water balance. By offering partial shading, agrivoltaic systems can lower evapotranspiration rates, preserve soil moisture, and possibly improve photosynthesis in crops that can withstand extreme heat stress.

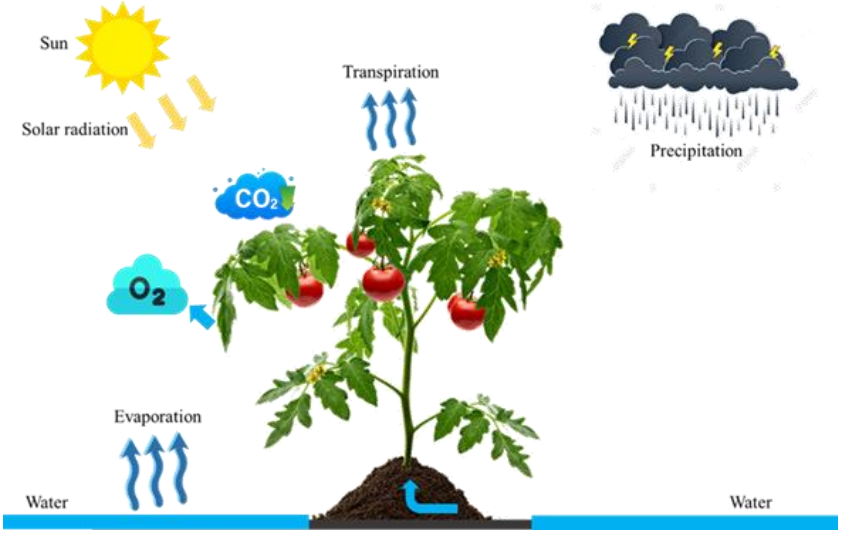

Fig. 2: Photosynthesis and Evapotranspiration (Anusuya *et al.,* 2024)

The presence of solar panels in agrivoltaic systems has a major impact on the interaction between photosynthesis and evapotranspiration. Agrivoltaics helps control temperature and light intensity by partially shading an area, which can improve photosynthetic efficiency in crops that can withstand shade. When plants receive more light than they can use, a condition known as photo-inhibition occurs, which lowers plant productivity. By avoiding such stress, the filtered sunlight beneath photovoltaic panels can maximize photosynthesis, particularly for crops that prefer diffused light. The shading effect of solar panels also reduces evapotranspiration, which increases soil moisture retention and reduces the need for irrigation. In arid and semi-arid areas, where conserving water is essential, this is especially advantageous. Agrivoltaic systems are a good way to support climate-resilient agriculture because they minimize water loss while allowing enough light for plant growth. This creates a synergistic balance that supports crop yield stability, efficient water use, and sustainable energy generation.

2.2 Types of Agrivoltaic Systems

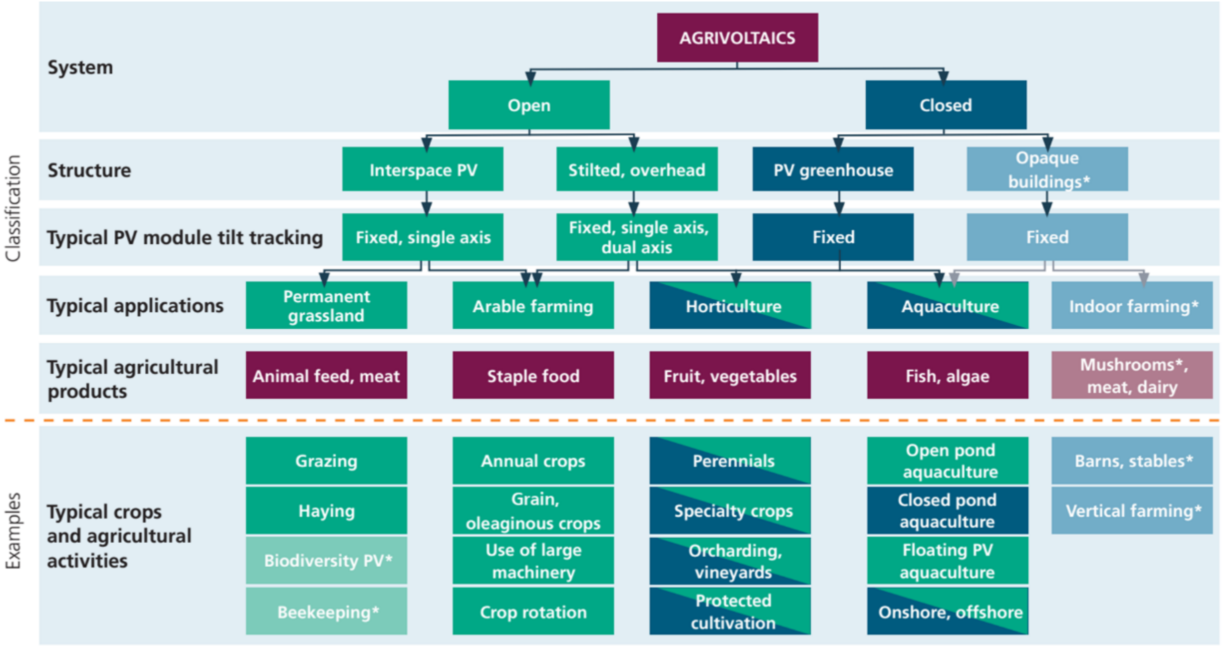

Fig. 3: Classification of Agrivoltaics (Agrivoltaics: Opportunities for Agriculture and the Energy Transition - Fraunhofer ISE, n.d.)

2.2.1 Stilted Agrivoltaic Systems (S-APV)

Among the most often used AV designs are stilted agrivoltaic systems. Under this arrangement, PV panels are positioned on an elevated construction with a minimum height of 2.10 meters, so enabling agricultural activities including mechanized farming and crop cultivation to continue beneath. Areas where both food production and energy consumption must coexist without compromising land availability will find this system especially helpful. Large-scale agrivoltaic projects and research facilities have often included these systems since their adaptability in supporting a variety of crops. For some crops, the elevation of the panels offers shade, so lowering water evaporation from the ground and mitigating severe temperature fluctuations. But the structural cost of the raised mounting system can be rather high, thus before deployment it is advisable to carefully evaluate its economic viability (Krexner *et al.,* 2024).

2.2.2 Vertical Bifacial Agrivoltaic Systems

Usually oriented East-West, vertical bifacial agrivoltaic systems make use of vertically orienting PV panels. These panels are made to gather solar radiation from both sides, so optimizing energy generation efficiency and preserving enough sunlight exposure for crops developing between the rows. In areas where land restrictions prevent the deployment of conventional horizontal PV arrays, this system is especially suited. Vertical construction maximizes land use and allows crops to be grown in the gaps between panel rows. For shade-tolerant crops, this system's main benefit is that it lets for consistent shading across the day. Additionally, shielding crops from overheating and too high transpiration is the lower direct exposure to strong sunlight. For row-crops and forage farming, vertical bifacial AV systems have proven rather effective. Developed commercial-scale vertical bifacial systems, mostly used in arable farms and cattle grazing areas, companies including Next2Sun GmbH have These systems generate energy differently than traditional PV farms, though, since the power output rises in the morning and evening but declines at midday (Asa'a *et al.,* 2024).

Fig. 4: Vertical Bifacial Agrivoltaic (Gupta, 2024)

2.2.3. Interspace Agrivoltaic Systems

Interspace agrivoltaic systems place PV modules either ground level or somewhat raised with enough distance between the panel rows to support agricultural operations. Inner space systems allow crop development in the open spaces between PV rows, unlike stilted systems whereby farming takes place straight under the panels. Low-growing crops that need direct sunlight and can withstand some shade will find these systems especially suited. Farmers can maximize crop yield and energy production by precisely varying the row distance. With the latter providing extra energy gains from reflected sunlight, the design can allow monofacial or bifacial PV panels. Since interspace AV systems only need minimal elevation structures, their rather low installation cost compared to stilted systems is a major benefit. Their efficiency, however, depends on correct alignment and spacing to guarantee that shading effects do not lower crop output (Bellone *et al.,* 2024).

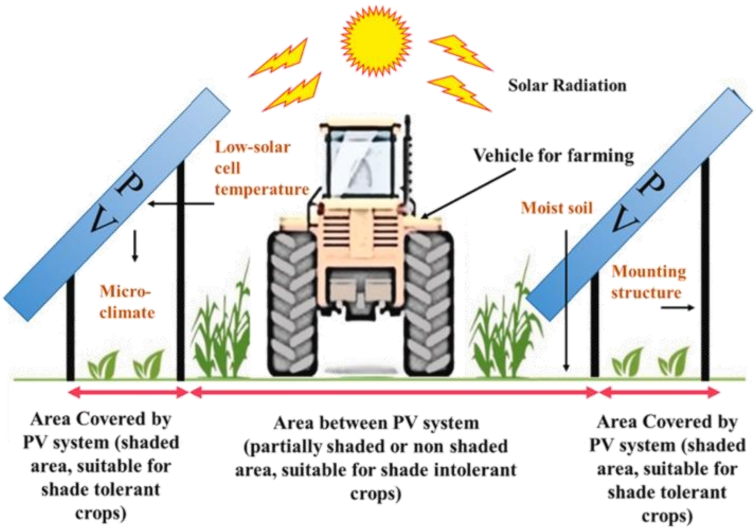

Fig. 5: Interspace Agrivoltaic Systems (Ghosh, 2023)

2.2.4. Overhead Agrivoltaic Systems

PV modules placed between 4 and 7 meters above ground enable overhead agrivoltaic systems to allow full-scale agricultural activities under them. For mechanized farming, this system is quite helpful since tractors and other agricultural tools can run free from interference. Large-scale agrivoltaic farms, especially in areas with high solar irradiation where shading can help some crops are increasingly using these systems. The raised panels help control microclimatic conditions, so lessening too much heat and water lost. Certain overhead AV systems also include sun-tracking systems, which let the panels change their angle over the course of the day to maximize energy capture and best distribute light for crops. Although overhead agrivoltaic systems have great advantages in terms of land use efficiency and crop protection, their structural costs and maintenance needs can be a disadvantage. Whether the extra expenditure is justified depends on proper site assessment (Asa'a *et al.,* 2024).

2.2.5. Single-Axis Tracking Agrivoltaic Systems

PV panels used in single axis tracking agrivoltaic systems dynamically tilt over the day to maximize solar energy capture. Usually from east to west, these systems turn along one axis to track the motion of the sun. Single-axis tracking AV systems have mostly one benefit: their higher energy yield than fixed-tilt systems. In areas with great solar variability, this design especially helps since it guarantees constant energy output all day. But the dynamic shading effects can affect crop development, thus it is important to choose shade-tolerant plants or modify the tracking system to best distribute light. Often combined with bifacial PV modules, which capture reflected sunlight from the ground and so improve energy efficiency, these systems. Although single-axis tracking systems have advantages, their additional operational expenses and maintenance requirements should be taken into account during project planning (Berrian *et al.,* 2025).

2.2.6 Agrivoltaic Greenhouses (Closed Agrivoltaic Systems)

Agrivoltaic greenhouses create solar energy by combining PV panels with greenhouse construction, allowing regulated agricultural output. These systems' PV panels can be either fixed or movable to control temperature within the greenhouse by varying sunlight penetration. High-value horticultural crops that call for exact environmental control will find these systems especially suited. Farmers can lower running costs by including solar energy generation, so preserving ideal growing conditions for their crops. Agrivoltaic greenhouses are also perfect for areas with strong weather since they can help year-round farming. The initial investment cost of agrivoltaic greenhouses is the primary difficulty since the integration of PV panels with greenhouse buildings calls for specific designs. But often the long-term advantages in terms of energy savings and higher crop yield exceed the initial costs (Soto-Gómez, 2024).

2.2.7. Agroforestry-Based Agrivoltaic Systems

Agroforestry-based agrivoltaic systems mix PV installations with tree crops fruit orchards, for example. This method generates solar electricity at the same time as supporting long-term agricultural cycles, so optimizing land productivity. For tree crops sensitive to too much sunlight, PV panels' shade can be especially helpful in improving their development and lowering irrigation requirements. Particularly in areas likely to experience drought and high temperatures, these systems are attracting interest as a sustainable agricultural model. Although agroforestry-based AV systems have advantages, careful planning is necessary to make sure that panel location does not to impede tree development or fruit output. Maintaining the equilibrium between solar energy production and agricultural output depends critically on appropriate spacing and height changes (Soto-Gómez, 2024).

2.2.8. Livestock Agrivoltaic Systems

Livestock agrivoltaic systems combine PV projects with animal grazing ground. These systems maintain pastureland for cattle and create renewable energy, so offering two advantages. This system's main benefit for animals is that it provides cover and shade, so lowering heat stress and raising general animal welfare. Furthermore, cattle can help to preserve vegetation under the panels, so lowering the maintenance expenses related to weed control. In areas where agricultural land is limited, this system is especially helpful since it guarantees that land stays valuable for both energy and cattle raising. Care should be taken, though, to guarantee that the PV structures withstand possible damage from grazing animals (Soto-Gómez, 2024).

3. Impact of Agrivoltaics on Agriculture

Agrivoltaic systems (APV) have shown great potential for the generation of renewable energy and sustainable farming. These systems have several benefits by combining photovoltaic (PV) panels with agricultural land: they increase land productivity, lower water consumption, and improve crop yields under circumstances. They also bring difficulties about shading, soil conditions, and crop adaptation, though.

3.1. Crop Growth and Yield Performance

Agrivoltaics' effect on crop development and yield is among the most important ones on agriculture. PV panels' shading effect changes the microclimate around crops, so lowering direct solar radiation and evapotranspiration. While perhaps lowering the yield of sun-loving crops like wheat and maize (Zheng *et al.,* 2024), this microclimate modification has been found to improve the yield of shade-tolerant crops including lettuce and spinach. Without a notable yield reduction, a study on broccoli under agrivoltaic conditions found that plants grown under partial shade displayed better consumer preference and enhanced green coloration than those in direct sunlight (Zahrawi & Aly, 2024). Agrivoltaics' efficacy, however, varies with crop type, planting density, and solar panel arrangement.

3.2. Soil Quality and Microclimate Modification

Through their modification of temperature, moisture retention, and nutrient cycles, agrivoltaic systems affect soil quality. Under PV panels, soil under dry-hot valley areas showed more moisture content and organic matter accumulation than in control plots free of shading. Better soil health and fertility followed from lower soil evaporation and higher microbial activity in shaded areas, so improving soil condition (Luo *et al.,* 2024). Agrivoltaic buildings also help control soil temperature by reducing extreme heat fluctuations, so it benefits root development and crop resilience in arid environments (Zahrawi & Aly, 2024). Some studies, however, have indicated possible negative effects including unequal water distribution resulting from the panels changing natural rainfall patterns, which would call for better irrigation plans (Zheng *et al.,* 2024).

3.3. Water Management and Irrigation Efficiency

Agrivoltaic systems offer one of the main benefits in terms of water-use efficiency in agricultural methods. Less direct solar exposure reduces soil evaporation, so increasing soil moisture retention. Under agrivoltaic systems, research on tomato and jalapeño farming revealed a 65% and 157% respectively increase in water-use efficiency, respectively, compared to conventional farming methods (Zahrawi & Aly, 2024). Furthermore, PV panel shading helps to reduce drought stress, especially in dry areas where water preservation is vital. But panel-induced runoff causes unequal water distribution under agrivoltaic systems, which, if improperly controlled, could lead to soil erosion in some areas (Luo *et al.,* 2024).

3.4. Biodiversity and Pest Control

In agricultural settings, agrivoltaic systems also affect biodiversity. Under PV panels, the shaded area forms a habitat that can support soil microbes, pollinators, and beneficial insects, so supporting the general state of the ecosystem (Zheng *et al.,* 2024). Some researchers have indicated that by restricting the environmental conditions favorable to some insect pests, the microclimate changes under APV installations could lower pest infestations (Zahrawi & Aly, 2024). But rising humidity under the panels could also encourage fungal diseases in some crops, thus careful crop selection and management techniques become even more important (Luo *et al.,* 2024).

3.5. Impact on Livestock and Animal Welfare

Agrivoltaic systems have been combined with cattle, sheep, and poultry to provide shade and thermal comfort beyond crop production. Shaded grazing areas have been found in studies to help cattle lower heat stress, so improving weight gain and milk output (Zheng *et al.,* 2024). APV installations can also be used to create renewable energy for farm operations including water pumping, fencing, and feed processing, so enhancing the general farm effectiveness (Zahrawi & Aly, 2024). But care must be taken to make sure that cattle movement does not compromise PV infrastructure, thus suitable fencing and installation heights are needed.

3.6. Economic and Social Benefits for Farmers

Agrivoltaic systems let farmers make money from solar energy as well as from agricultural output, providing financial incentives. Studies show that farms implementing APV systems have recorded up to a 30% rise in income when compared to conventional farming just by itself. In off grid farming communities especially, agrivoltaics improve rural electrification and energy access, so supporting agricultural mechanization and food processing operations. But the initial outlay for building agrivoltaic infrastructure can be significant, which calls for financial incentives for small-scale farmers (Zheng *et al.,* 2024) and supportive laws.

3.7. Challenges and Future Considerations

Agrivoltaics presents certain difficulties that must be resolved if it is to be widely used despite their advantages. If improperly controlled, the shading effects of PV panels can restrict photosynthetic activity in some crops, so lowering possible yields (Zahrawi & Aly, 2024). Furthermore, changes in land use patterns brought about by agrivoltaic projects call for careful design to guarantee that conventional farming methods are not disturbed. Furthermore, under investigation are technological developments including semi-transparent solar panels and movable tracking systems to maximize the harmony between agricultural output and energy generation (Zheng *et al.,* 2024).

4. Technological Advancements in Agrivoltaics

Agrivoltaics' technological developments have greatly raised energy generation efficiency and, by creative designs and integration techniques, raised agricultural productivity. Better light penetration made possible by semi-transparent photovoltaic panel development helps to maximize the photosynthetic active radiation (PAR) accessible for crop development even as it generates electricity. Likewise, vertically bifacial solar panels have been developed to maximize energy generation from both sides, so preserving their productivity by capturing sunlight from both sides and avoiding too shading of crops.

Solar tracking systems where PV panels dynamically change their angles to follow the sun's movement ensure an ideal balance between light distribution for crops and solar power generation, so another breakthrough is their application. Smart sensors and automation are also included into agrivoltaic greenhouses to control microclimatic conditions, so creating a controlled environment that improves crop yield and lowers water use. Agrivoltaic systems have been further transformed by the integration of Internet of Things (IoT) technologies, remote sensing, and artificial intelligence, so enabling real-time monitoring of soil moisture, plant health, and energy generation. Agrivoltaics are increasingly important in the shift toward climate-wise smart agriculture since these developments not only improve agricultural efficiency but also help to sustain land use and energy resilience (De Francesco *et al.,* 2025).

5. Economic and Environmental Benefits of Agrivoltaics

Agrivoltaics (AV) presents substantial economic benefits by optimizing land use for both agricultural production and renewable energy generation. By integrating photovoltaic (PV) systems with crop cultivation, farmers gain an additional revenue stream from electricity generation, reducing dependency on traditional agricultural income sources. Studies have shown that agrivoltaic systems consistently outperform standalone PV farms in terms of economic viability due to their dual productivity. A techno-economic assessment revealed that AV installations require only 2–6 cents per kWh in incentives to surpass the profitability of crop-only farms (Ravilla *et al.,* 2023b). Additionally, the deployment of tracking-based AV systems enhances energy output, while optimizing panel placement helps maintain crop yields. Farmers benefit from increased economic security, as AV reduces the risks associated with extreme weather events by providing partial shading and microclimate regulation. In rural areas, AV further supports job creation through maintenance, system management, and agricultural processing facilities powered by solar electricity. The combined economic model of food and energy production ensures long-term sustainability while improving land use efficiency (Kumdokrub & You, 2025b) . Beyond economic advantages, agrivoltaics significantly reduces environmental impacts, making it a key technology in sustainable land management. Life cycle assessments (LCA) have demonstrated that AV systems have 15–55% lower environmental impact than conventional PV farms by minimizing land-use changes and reducing greenhouse gas (GHG) emissions associated with conventional farming (Ravilla *et al.,* 2023b). The shade provided by solar panels decreases soil moisture evaporation, leading to 30–50% reductions in irrigation water demand, particularly in arid regions where water conservation is critical. Moreover, agrivoltaic structures act as protective barriers against extreme weather conditions, preventing soil erosion and enhancing biodiversity by creating microhabitats for beneficial organisms. The carbon offset potential of AV is also significant, as co-locating solar PV and agriculture helps reduce reliance on fossil fuels while simultaneously lowering the embodied carbon footprint of agricultural operations. With optimized configurations, AV systems can further improve their sustainability by integrating smart irrigation systems, organic farming practices, and semi-transparent PV technologies, making them a model solution for the food-energy-water nexus (Kumdokrub & You, 2025b).

6. Challenges and Barriers

Although agrivoltaics (AV) offers a good way to combine solar energy with agricultural output, technical, financial, environmental, and policy-related issues that need to be resolved for greater acceptance surround its application. The great initial investment and running expenses connected with AV infrastructure constitute one of the main obstacles. Agrivoltaic systems demand more expenses than stand-alone photovoltaic (PV) farms or conventional agriculture to guarantee both crops and solar panels operate as best they could be for raised mounting structures, tailored tracking mechanisms, and farming practices changes. Studies show that AV installations need financial incentives of 2–6 cents per kWh to remain competitive with traditional farming; without these incentives, farmers may find it difficult to justify the investment (Ravilla *et al.,* 2023b). Furthermore, the complexity of maintenance rises since regular cleaning of PV panels in dusty surroundings guarantees that farm equipment can run without damaging solar structures and (Kumdokrub & You, 2025b).

Variability in crop yield resulting from shading conditions presents still another major obstacle. While AV lowers heat stress and water evaporation for some crops, others that depend on strong solar exposure may suffer from lower photosynthetic activity, so influencing their yield. Development of site-specific designs catered to various climates and crop types is dependent on panel spacing, tilt angle, and sun-tracking systems; hence, AV is quite effective (Ravilla *et al.,* 2023b.). Furthermore, solar panel shading patterns cause unequal water distribution, which calls for more advanced irrigation systems to preserve soil moisture balance (Kumdokrub & You, 2025b.). Long-term temperature and humidity changes could thus influence soil health and microbial activity, thus soil degradation and microclimate changes under PV panels also raise questions (Zheng *et al.,* 2024).

From a logistical standpoint, agrivoltaic systems can disrupt mechanized farming operations since the presence of solar structures limits the movement of big machinery including tractors and harvesers (Zahrawi & Aly, 2024). To help with this, vertically bifacial PV panels or raised AV systems have been proposed; but these fixes need further investment and careful planning (De Francesco *et al.,* 2025). Many areas still have underdeveloped regulatory and policy frameworks for AV; unclear rules on land-use classification, grid connectivity, and financial incentives for dual-use farming (Kumdokrub & You, 2025b). When trying to install AV systems, many farmers encounter administrative challenges since agricultural land zoning rules sometimes limit non-agricultural activities, so generating legal complexity (Ravilla *et al.,* 2023b).

Environmental issues also limit AV growth in some way. Particularly in underdeveloped countries where waste management infrastructure for solar components is insufficient, the end-of-life management of PV panels including recycling and material disposal remains a difficulty (De Francesco *et al.,* 2025). Further investigation is also necessary on biodiversity effects since land-use changes and shading effects could change nearby ecosystems, so influencing pollinators and soil organisms (Zahrawi & Aly, 2024).

Policy changes, technical developments, and financial incentives are required to get beyond these obstacles. Improved solar panel designs, such as semi-transparent PV modules, can optimize light penetration while generating electricity, addressing some of the shading-related concerns (De Francesco *et al.,* 2025). Financial support through subsidies, low-interest loans, and tax benefits can help mitigate the economic barriers, making AV systems more accessible for small-scale farmers (Kumdokrub & You, 2025b). Standardized regulatory policies that classify AV as an agricultural practice rather than an industrial energy project would also encourage broader adoption (Ravilla *et al.,* 2023b). By addressing these challenges, agrivoltaics can play a crucial role in creating a more sustainable and resilient agricultural system while contributing to global renewable energy targets.

7. Future Research Directions

The advancement of agrivoltaic (AV) systems requires continuous research to address existing challenges and optimize their benefits. One key area for future exploration is the development of adaptive and intelligent solar panel technologies that can dynamically adjust to optimize light distribution for crops while maximizing energy generation. Innovations such as semi-transparent solar panels, adjustable panel angles, and spectrum-selective PV modules could enhance crop productivity by allowing more photosynthetically active radiation to reach the plants. Another critical research direction is the long-term impact of AV systems on soil health and biodiversity. While initial studies suggest positive effects such as improved moisture retention and reduced heat stress, further investigation is needed to understand potential changes in soil composition, microbial activity, and nutrient cycling under prolonged shading conditions. Research on how different AV configurations affect pollinators, beneficial insects, and local ecosystems will be essential for sustainable deployment. Water management strategies in AV farms also require deeper investigation, particularly in regions facing water scarcity. Future studies should focus on integrating precision irrigation systems that leverage real-time soil moisture monitoring, rainwater harvesting, and solar-powered irrigation to optimize water use efficiency. Developing a holistic understanding of water-soil-energy interactions in AV systems can contribute to improved agricultural sustainability. Additionally, research should explore crop diversification and AV system compatibility across different climatic regions. While many existing studies have focused on leafy greens and shade-tolerant crops, understanding how AV can support staple crops, fruit-bearing plants, and high-value specialty crops will expand its applicability.

Experimenting different plant species under various AV structures will help establish best practices for different agricultural landscapes. From an economic perspective, further research is needed to evaluate the financial viability of AV systems under various market conditions. This includes analyzing cost reductions through advancements in PV technology, exploring new financing models, and assessing policy frameworks that encourage AV adoption. Economic modeling can help design incentive structures that support small-scale farmers while promoting large-scale implementation. Lastly, integration with smart agricultural technologies such as artificial intelligence, IoT-based monitoring, and data-driven farm management could revolutionize AV systems.

By leveraging automation and predictive analytics, farmers can optimize energy production, water use, and crop growth while minimizing resource wastage. Future studies should focus on developing integrated AV platforms that combine energy, agriculture, and digital technology to create more resilient and efficient food-energy systems. With these research directions, agrivoltaics can evolve into a mainstream solution that balances renewable energy production and sustainable agriculture, ultimately contributing to global food security and climate resilience.

Conclusion:

Agrivoltaics improves land use efficiency, water conservation, crop resilience, and water saving by combining solar energy generation with agricultural output. Through more income sources, it offers financial advantages; it also supports goals for renewable energy and climate adaptation. Nonetheless, optimal system designs, policy support, and technological developments help to solve problems including high initial costs, crop shading effects, and legal obstacles. Agrivoltaics has the potential to transform agriculture by means of ongoing research and invention, so establishing a sustainable food-energy-water nexus that advances energy security and climate resilience.

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IMPACT OF WESTERN DISTURBANCES ON COOL SEASON VEGETABLE CROP

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Abstract:

Western Disturbances (WDs) are extratropical weather systems that significantly impact the climate of South Asia, particularly during the winter months. These disturbances bring moisture-laden winds, leading to precipitation in the form of rain and snow. Their influence on cool-season vegetable crops is both beneficial and detrimental. While moderate precipitation improves soil moisture, aiding the growth of crops like cauliflower, cabbage, carrot, and spinach, excessive rainfall and unseasonal frost can damage crops, delay harvesting, and reduce yields. Temperature fluctuations associated with WDs can also influence pest and disease prevalence. Understanding the dynamics of WDs is crucial for optimizing crop management strategies, mitigating risks, and ensuring stable vegetable production during the winter season.

Introduction:

Western disturbances are storms that originate in the Caspian or Mediterranean Sea, and bring non-monsoonal rainfall to northwest India, according to the India Meteorological Department (IMD). They are labelled as an extra-tropical storm originating in the Mediterranean, is an area of low pressure that brings sudden showers, snow and fog in northwest India. The meaning of WD lies in its name. The disturbance travels from the "western" to the eastern direction. These travel eastwards on high-altitude westerly jet streams - massive ribbons of fast winds traversing the earth from west to east. Disturbance means an area of "disturbed" or reduced air pressure. Equilibrium exists in nature due to which the air in a region tries to normalise its pressure. In the term "extra-tropical storm", storm refers to low pressure. "Extra-tropical" means outside the tropics.

As the WD originates outside the tropical region, the word "extra-tropical" has been associated with them. A WD is associated with rainfall, snowfall and fog in northern India.

It arrives with rain and snow in Pakistan and northern India. The moisture which WDs carry with them comes from the Mediterranean Sea and/or from the Atlantic Ocean. WD brings winter and pre-monsoon rain and is important for the development of the Rabi crop in the Northern subcontinent. The WDs are not always the harbingers of good weather. Sometimes WDs can cause extreme weather events like floods, flash floods, landslides, dust storms, hail storms and cold waves killing people, destroying infrastructure and impacting livelihoods.

Variation In Western Disturbances in the year of 2021, Delhi witnessed the rainiest October in 65 years, with the Safdarjung weather observatory recording 122.5 mm of rainfall against a normal of 28 mm, on account of western disturbances. Excess rainfall was also recorded in January and February this year. In contrast, there was no rainfall in November 2021 and March 2022, and the summer saw an unusually early start with heat waves setting in at the end of March 2022. Multiple western disturbances that brought cloud cover had also kept the maximum temperature low in February 2022, when the lowest maximum temperature in 19 years was recorded. Active western disturbances eluded northwest India in March 2022, and absence of cloud cover and rain allowed temperatures to remain high.

Origin and Migration of Western Disturbances

WDs are in part extra-tropical cyclones originating as mid-latitude frontal systems and migrating eastward embedded in the subtropical westerly jet stream (SWJ) (Mull and Desai 1947. Typical extra-tropical cyclones develop due to the imbalance between colder polar and warmer equatorial air masses. This imbalance is signifi can't over the mid-latitudes and thus, these extra-tropical cyclones are also called mid-latitude fronts.

The temperature gradient between polar and equatorial regions is most pronounced during the winters and thus these storms are more intense during the winters (AIR Worldwide 2012). Sub-tropical Westerly Jet (SWJ) is a jet stream that is contained in the mid-latitudes in the upper layers of the troposphere which develops around the Himalayan and Tibetan high ground (Alexander and Srinivasan 1974).

Weather associated with WD

The precipitation experienced is mainly due to the large-scale interaction between the mid-latitude and the tropical air masses. In present study it was also seen that the interaction of southwesterly winds from Arabian Sea with easterlies winds from Bay of Bengal took place over northwest India, caused widespread to fairly widespread rain/snow over western Himalayan region and rain/ thundershowers over northern plains. In some cases, western Himalayan region received isolated to scattered heavy snowfall and thundersquall. Rain/thundershowers at a few places accompanied with hailstorm at one or two places also observed over northern plains. It has been observed from the satellite images and satellite derived winds that sometimes, an intense WD approached from the west suddenly weakened and passes off without causing any weather over the Indian region. In case of recent past the WDs during 27 January to 2 February and during 1-3 February-2013 have experienced very less precipitation over western Himalayan region.

Western disturbances (WDs) are extra-tropical storm systems originating in the Mediterranean region that travel eastward, affecting weather patterns in South Asia, particularly India, Pakistan, and Nepal. These disturbances significantly impact cool-season vegetable crops, which include peas, cauliflower, cabbage, spinach, carrots, radishes, and onions. The effects can be both beneficial and harmful, depending on the intensity, frequency, and associated weather conditions.

Western disturbances generally have a positive impact on cool season vegetable crops, particularly in North India, as they bring much-needed winter rainfall which is crucial for the growth and development of these crops, especially during their critical stages; however, excessive rain from a strong western disturbance can cause damage, particularly if it occurs close to harvest time.

1. Positive Impacts

- **Improved Crop Yield & Growth:** The moisture and temperature regulation provided by WDs can improve germination, growth, and yield of cool-season vegetables.
- **Beneficial Rainfall:** The light to moderate rain brought by western disturbances provides essential moisture for crops like wheat, barley, peas, cauliflower, cabbage, and carrots during their growing season.
- **Improved Soil Moisture:** Winter rain from western disturbances helps maintain good soil moisture levels, which is vital for healthy root development and plant growth. WDs bring moderate rainfall, which enhances soil moisture levels, reducing the need for irrigation. This benefits crops like spinach, lettuce, and cabbage, which thrive in moist conditions.
- **Temperature Regulation:** While not the primary factor, western disturbances can sometimes bring slightly warmer temperatures during cold spells, which can be

beneficial for certain cool season vegetables. Cloud cover and rainfall lower temperatures, preventing heat stress in winter crops. This is particularly beneficial for crops such as carrots and cauliflower, which prefer cooler climates.

2. Negative Impacts

- **Hailstorms & Crop Damage:** Occasionally, western disturbances can bring hailstorms, causing significant damage to crops. Some WDs bring hail, which can physically damage leaves, stems, and fruits, leading to lower yields in crops like cauliflower and cabbage.
- **Excessive Rainfall & Waterlogging:** Heavy precipitation from a strong western disturbance can lead to waterlogging, which can damage roots and cause crop losses. Intense WDs may cause heavy rainfall, leading to waterlogging and root rot, particularly in poorly drained soils. Crops like onions and garlic are sensitive to excessive moisture.
- **Delayed Maturity & Harvesting Issues:** Persistent cloud cover and high humidity can slow crop maturity and delay harvesting, affecting market supply and prices. If heavy rain occurs close to harvest time, it can delay harvesting and affect crop quality.
- **Pest & Disease Outbreaks:** Prolonged wet conditions increase the risk of fungal and bacterial diseases like downy mildew (affecting spinach and lettuce) and alternaria blight (affecting cauliflower and cabbage).

Overall, western disturbances play a crucial role in supporting the growth of cool season vegetable crops in North India by providing necessary winter rainfall, but their impact can vary depending on the intensity and timing of the weather event.

Many vegetable crops have growth cycle disruptions due to rising temperatures, changing precipitation patterns, and an increase in the frequency of extreme weather events, including storms, floods, and droughts. Elevated temperatures can potentially diminish the output of heat-sensitive plants such as broccoli, spinach, and lettuce. Drought strains plants, lowering growth and quality, while too much water can lead to root infections. Changes in growing seasons and the availability of water resources force farmers to adjust by altering crop varieties or planting times. Vegetables are susceptible to fluctuations in temperature and water availability, which affects their nutritional content. Prolonged exposure to harsh circumstances can deplete nutrient content, lowering food quality. Overall, climate change's influence on vegetables is causing increased concern about global food security, farmer livelihoods, and consumer nutrition. Sustainable methods are critical for mitigating these difficulties.

Climate change refers to the average change in climatic factors including temperature, rainfall, relative humidity, and gas composition throughout time in a certain geographical area (Raza *et al.,* 2019). Vegetables are typically vulnerable to climate extremes, high temperatures and low soil moisture are the main reasons for low yields since they have a significant impact on physiological and biochemical processes. Adjusting farming practices to changing weather patterns is a crucial component of sustainable vegetable production. Farmers must develop robust vegetable types that can flourish in a variety of conditions due to variations in temperature and precipitation patterns. Hydroponics and controlled environment agriculture are two more precision farming methods that minimize the ecological impact of vegetable farming while maximizing resource use (Babu *et al.,* 2024).

Climate change has led to more frequent droughts, floods, high and low temperatures, salinity, and changes in atmospheric CO_2 and ozone levels, affecting vegetable crop yield and quality (Bulgari *et al.,* 2019 and Raza, 2022). Plant growth and agricultural productivity are greatly impacted by climate change, particularly the growing season, growth rate, and growth distribution. The growth season for plants can be extended by climate change, and the areas that can be planted with crops can increase (Zhang, 2023). Additionally, the temperature, microbial activity, nutrient cycling and quality of the soil will also be affected by climate change, which will have an impact on plant development. (Jansson *et al.,* 2020).

Even though climate change is a gradual process that takes a long time and involves only modest variations in temperature and precipitation, it nonetheless has an impact on several soil processes, especially those that are connected to soil fertility. It is anticipated that changes in soil moisture conditions and subsequent rises in soil temperature and CO2 levels will be the primary ways in which climate change will affect soils (Qui *et al.,* 2023). Vegetable crops, including tomatoes, potatoes, onions, and cabbage, contribute to the local economy and food security. Understanding their vulnerability to climate change is vital for developing measures to protect and adapt against future environmental difficulties (Scheelbeek *et al.,* 2020). The agricultural sector has seen a rise in the frequency of extreme events that cause flood and drought disasters due to variations in global rainfall, average temperature, and carbon dioxide levels. These variations pose a serious threat to global crops and cereal productivity (Hussain *et al.,* 2019; Duchenne Moutien *et al.,* 2021). Crop growth and maturity are directly impacted by variations in temperature and precipitation, which exposes the crops to a range of biotic and abiotic challenges (Chaudhary and Sidhu *et al.,* 2022). Modern agriculture requires techniques that address soil health, crop yields, and climate change-related environmental challenges. There are various ways to improve soil fertility and plant growth, including standard soil additions and new solutions. Innovative farming practices can improve soil fertility and agricultural production while also mitigating the effects of climate change on agriculture.

Effect of temperature

The temperature of the earth has been rising steadily since the turn of the century. The temperature has increased by 1.1 °C between 1850 and 1900. Global temperatures are predicted to rise by more than 1.5°C on average throughout the next 20 years (IPCC 2022). Temperatures above 35 °C in carrots cause a reduction in cell-enhanced relative cell damage and membrane stability (Nijabat *et al.,* 2020). Furthermore, spinach and lettuce start flowering when exposed to high temperatures for extended periods, which lowers the quality of the veggies. When a plant experiences extreme heat stress, its enzymatic processes are interfered with, which causes an oxidative burst and a compromised metabolism that eventually results in senescence (Raza, 2022). Cold stress disrupts the integrity of intracellular organelles, causing loss of compartmentalization. It reduces and impairs photosynthesis, protein assembly, and metabolic activities (Atayee and Noori *et al.,* 2020). It alters the ultrastructure of chloroplasts, affecting light-harvesting chlorophyll antenna complexes and thylakoid structures. This reduces photosynthesis and osmotic adjustments in potato plants (Wu and Yang *et al.,* 2019) Minimum appropriate temperature (°C) for veggies and signs of cold stress injury.

Effect of water stress

Vegetable crops require consistent irrigation, but lack of precipitation, increased evapotranspiration from global warming, and depleted groundwater have led to water scarcity, negatively impacting crop productivity and quality (Seleiman *et al.,* 2021). Water stress can significantly impact vegetable output and quality due to their highwater content (90%). Drought stress occurs when soil moisture levels are low or precipitation is below normal for an extended period (Chaudhary *et al.,* 2022). Waterlogging occurs when soil moisture levels exceed optimal requirements. Water-logging fills soil pores, resulting in hypoxia (low oxygen concentrations) or anoxia (total lack of oxygen) (Fukao *et al.,* 2019).

Effect of salinity stress

Salt stress can be a serious issue for sustainable agriculture practices since it poses a significant risk to the agriculture industry in arid and semi-arid regions of the world (Hopmans *et al.,* 2021). Climate change, including temperature changes and water loss, raises salt levels, affecting agricultural growth and productivity (Arnell *et al.,* 2019; Zandalinas *et al.,* 2023). Salt stress is a complicated phenomenon that causes physical, physiological, and ionic abnormalities in plants (Seleiman *et al.,* 2022). Furthermore, over 10% of the total land area is salt-stressed, making it difficult for crops to develop and thrive (Behera *et al.,* 2022). According to (Giordano *et al.,* 2021), salinity disrupts the exchange of water and nutrients between roots and soil, thus impacting photosynthesis. Drought and low rainfall cause salts to accumulate in soils due to capillary rise and salt migration from the groundwater table to the surface (Corwin, 2021).

Effect of CO_2

Elevated CO_2 increased eggplant and tomato yield by 24% and 31%, respectively. Disorders in leaf and branch growth occurred, resulting in a decrease in active leaf surface area. Two onion cultivars had faster rates of photosynthesis and leaf area expansion during the pre-bulbing stage, increasing bulb production by 28.9-51.0 percent. However, the time of bulb maturity was also extended because of the increased CO_2 concentration. Elevated CO_2 (550 ppm) influenced growth and development in tomato variety. Arka Ashish, resulting in a 24.4% increase in production. Plant height, the number of secondary branches, and leaf area were the growth parameters that increased at higher levels compared to ambient values during the fruiting stage. As CO_2 levels increased, there was also the formation of dry matter in the fruits, leaves, and stems. At higher CO_2, photosynthesis increased, but stomatal conductance and transpiration decreased. Fruit production increased compared to the chamber control because there were more fruits per plant under higher CO_2 (Babu *et al.,* 2024).

Effect of ozone

Increased O_3 levels in the troposphere reduce plant growth and vegetable productivity in India's fertile agricultural regions (Mukherjee *et al.,* 2020). Impact of O3's on plant can cause reactive damage and accelerate leaf senescence, leading to reduced crop yield (Yadav *et al.,* 2019; Sicard *et al.,* 2020). (Suganthy and Udayasoorian 2020) found that exposing potatoes (*Solanum tuberosum* L.) to greater levels of surface oxygen during tuber initiation at a high altitude of Western Ghat reduces yield from 4.56 to 25.5%. Excessive O3 levels in soybeans reduce seed protein, which is associated with a negative response to nitrogen fixation (Broberg *et al.,* 2020).

Effect of climatic change on biotic factors as temperatures rise, pests like moths and butterflies will relocate to new places. As temperatures rise, pests such as the American leaf miner (Liriomyza) may expand northward. Non-indigenous pests may establish themselves in protected crops due to increased importation of plant material. Pests will gradually grow in field crops as climate changes. *Bactrocera zonata*, a fruit fly, is primarily found in northern India. Until the late 1990s, this fruit fly was overwintered in northern India. In recent years, adults have been caught during winter in Uttar Pradesh, likely because of rising soil temperatures caused by climate change. Climate change is expected to increase sucking pests in vegetables, including thrips, mites, and leafhoppers. The number of leafhoppers in okra will grow. The diamondback can increase up to 28-35 OC but decreases as temperatures rise (Nitta *et al.,* 2024).

Climate barriers are no longer effective, accelerating the movement of vectors, pests, and disease toward the north. This leads to more severe outbreaks of plant-disease vectors such as aphids, whiteflies, and thrips, extending disease transmission throughout the growth season and introducing new species. As more vectors survive from one vegetative phase to the next, disease spread faster. Citrus greening is transmitted by the psyllid Dysphoria citri (Nitta *et al.,* 2024).

Management Strategies

Management Strategies under a Changing Climate Scenario To counteract the negative effects of climate change on agricultural sustainability, several adaptation and mitigation techniques have been developed. Weather-smart activities (stress-tolerant varieties, ICT-based agrometeorological services), carbon-smart activities (zero tillage, legumes, crop residue management), and knowledge-smart activities (agricultural extensions to enhance capacity building) are among these technologies. Water-smart practices (laser land leveling, rainwater harvesting, micro-irrigation, crop diversification, raised-bed planting, and direct seeded rice) are among them. By limiting the negative consequences, these technologies improve crop adaptation to the changing climate. They also considerably lessen the effects of climate change on crops. Large-scale economic losses are expected in climate change, but some initiatives can help to offset those losses. Yet these actions need to be planned (Malhi *et al.,* 2021). (Rawat *et al.,* 2024) depict a list of recent studies on the sectoral consequences of climate change with global adaptation and mitigation strategies.

Strategies for Managing Weather and Disease Risks in Agriculture

1. Efficient Drainage Systems

Proper drainage is essential for preventing waterlogging, which can damage plant roots, reduce oxygen availability, and increase susceptibility to diseases. Effective drainage strategies include:

- **Surface Drainage:** Constructing shallow ditches or slopes to direct excess water away from fields.
- **Subsurface Drainage:** Installing drain tiles or perforated pipes beneath the soil to remove excess water.
- **Raised Beds:** Elevating planting rows to improve water runoff and prevent standing water.
- **Cover Crops:** Using plants like rye or clover to improve soil structure and drainage.

A well-designed drainage system ensures crops receive adequate moisture without becoming oversaturated, promoting healthier root development and reducing fungal disease risks.

2. Use of Protective Structures

Protective structures help shield crops from extreme weather conditions like excessive rain, hail, and strong winds. Common protective methods include:

- **Greenhouses:** Fully enclosed structures that provide controlled environments, reducing exposure to harsh weather and allowing for year-round cultivation.
- **Row Covers:** Lightweight, breathable fabrics that protect crops from heavy rain, frost, and pests while still allowing air and sunlight to pass through.
- **High Tunnels:** Similar to greenhouses but less expensive, these unheated structures extend growing seasons and provide protection against heavy precipitation.
- **Windbreaks:** Rows of trees or shrubs that reduce wind speed, helping to minimize damage from strong gusts and storms.

These protective methods enhance crop resilience, improve yields, and ensure more stable production.

3. Disease Monitoring & Control

Crop diseases spread rapidly under favorable conditions, particularly in warm, humid environments. Preventative strategies include:

- **Timely Application of Fungicides:** Using chemical or organic fungicides to control fungal diseases like powdery mildew and blight. It is crucial to apply them at the right time to maximize effectiveness.
- **Proper Ventilation:** Good airflow reduces humidity levels and prevents disease buildup, especially in greenhouses. Spacing plants properly and pruning excess foliage can improve ventilation.
- **Crop Rotation:** Changing crop types in a field each season reduces the risk of soil-borne diseases by disrupting pest and pathogen life cycles.
- **Sanitation Practices:** Cleaning tools, removing infected plants, and sterilizing greenhouses help prevent disease spread.

Early detection through regular monitoring ensures swift action, reducing potential losses due to plant diseases.

4. Crop Scheduling & Resistant Varieties

Adjusting planting schedules and selecting disease-resistant varieties can significantly minimize weather and disease-related risks. Key strategies include:

- **Optimized Planting Dates:** Planting crops at times when conditions are most favorable helps avoid periods of excessive rainfall or disease outbreaks. For example, delaying planting in wet seasons can reduce fungal disease risks.
- **Selecting Resistant Varieties:** Choosing crop varieties that are naturally resistant to common diseases (e.g., rust-resistant wheat, blight-resistant tomatoes) minimizes the need for chemical treatments.
- **Succession Planting:** Staggering planting dates ensures continuous harvests and reduces the impact of unpredictable weather events.
- **Use of Grafted Plants:** Grafting disease-resistant rootstocks onto high-yielding crop varieties enhances overall plant health and resilience.

By integrating these practices, farmers can maintain high productivity while reducing losses due to weather variability and plant diseases.

Conclusion:

Western disturbances play a crucial role in shaping the winter crop season. While they provide necessary moisture and cooling, excessive disturbances can harm crops through heavy rainfall, hail, and disease outbreaks. Adopting suitable agronomic practices can help maximize benefits while minimizing risks. Extreme weather events such as heat waves, cold snaps, droughts, flooding, salt stress, and variations in atmospheric CO2 or ozone levels have become more frequent in climate change. Vegetable crops' productivity and quality are decreased when they are subjected to certain kinds of abiotic stressors. Abiotic stressors have several important physiological and biochemical impacts, including membrane damage, oxidative burst, decreased chlorophyll concentration, and slowed photosynthesis. Thus, both adaptation and mitigation techniques are required to maintain the yield of vegetable crops in changing climatic circumstances. Adopting climate-smart production techniques, climateresilient cultivars, PGPR use, appropriate cultural practices, varied cropping systems, and mulching are necessary. Given that implementing crop management strategies is expensive, an economical mix of adaptation.

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MOLECULAR MARKERS IN CROP IMPROVEMENT

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Introduction:

Crop improvement has been a cornerstone of agricultural development for centuries, with the goal of enhancing yield, disease resistance, quality, and adaptability to environmental stresses. Traditionally, crop improvement has relied on selective breeding based on phenotypic traits. However, the advent of molecular biology and biotechnology has ushered in a new era of crop improvement, where molecular markers play a pivotal role. These markers are specific DNA sequences associated with desirable traits, offering precise, rapid, and cost-effective tools for plant breeding. Molecular markers have the potential to revolutionize breeding programs by speeding up the development of improved varieties with enhanced characteristics.

This chapter explores the role of molecular markers in crop improvement, discussing their types, applications, advantages, and challenges, and providing examples of successful applications in major crops.

1. Types of Molecular Markers

Molecular markers are classified based on their molecular nature, detection methods, and inheritance patterns. Some of the commonly used molecular markers in crop improvement include:

1.1 Restriction Fragment Length Polymorphisms (RFLPs)

RFLPs were among the first molecular markers used in crop improvement. They involve detecting variations in DNA fragment lengths generated by restriction enzymes. The major advantage of RFLPs is their high level of polymorphism and their ability to be detected using Southern blotting techniques. However, their use is limited due to their high cost, time consumption, and the requirement for high-quality DNA.

1.2 Random Amplified Polymorphic DNA (RAPD)

RAPD markers are derived by using short, random primers to amplify unknown regions of the genome. These markers do not require prior sequence information and can detect polymorphisms in various crop species. RAPD is a fast and inexpensive technique but suffers from issues such as low reproducibility and limited use in large-scale breeding programs.

1.3 Simple Sequence Repeats (SSRs) or Microsatellites

SSRs are short, repetitive sequences of 1-6 base pairs that are scattered throughout the genome. Due to their high degree of polymorphism, ease of detection using PCR (Polymerase Chain Reaction), and codominant inheritance, SSR markers have become one of the most popular tools in molecular breeding. They are widely used for mapping genes, marker-assisted selection (MAS), and diversity studies.

1.4 Single Nucleotide Polymorphisms (SNPs)

SNPs are the most common form of genetic variation and occur when a single base pair is altered. Due to their abundance and ability to be detected using high-throughput sequencing or specific assays, SNPs are increasingly utilized in crop improvement. Their high density in the genome allows for fine mapping of genes and selection of desirable traits with high precision.

1.5 AFLPs (Amplified Fragment Length Polymorphisms)

AFLPs combine the principles of RFLPs and RAPDs. They involve the digestion of DNA with restriction enzymes, followed by PCR amplification of the resulting fragments. AFLPs are highly polymorphic, and their use is facilitated by the fact that they require only small amounts of DNA. They are useful in genetic mapping, diversity studies, and marker-assisted selection.

1.6 Copy Number Variations (CNVs)

CNVs refer to structural variations in the genome, where sections of DNA are duplicated or deleted. CNVs can have significant effects on phenotypic traits, making them useful markers for traits related to disease resistance, stress tolerance, and productivity. However, their detection requires advanced technologies such as next-generation sequencing.

2. Applications of Molecular Markers in Crop Improvement

Molecular markers play a crucial role in various aspects of crop breeding. Here are some key applications of molecular markers in crop improvement:

2.1 Marker-Assisted Selection (MAS)

Marker-assisted selection is one of the most powerful tools for accelerating crop improvement. MAS involves using molecular markers linked to desired traits to select plants with superior genetic make-up, thus speeding up the process of breeding. For example, markers linked to disease resistance genes allow breeders to select resistant plants without waiting for disease outbreaks in field trials.

2.2 Genetic Mapping and QTL Mapping

Molecular markers are used to create genetic maps that help identify the location of genes responsible for desirable traits. Quantitative trait loci (QTL) mapping is the process of identifying regions of the genome associated with quantitative traits like yield, drought tolerance, or disease resistance. By linking these QTLs to molecular markers, breeders can track and select for favorable traits with greater precision.

2.3 Development of Genetically Modified Crops

Molecular markers are instrumental in the development of genetically modified (GM) crops. They help identify transgenic plants and confirm the presence of inserted genes. Additionally, markers are used to ensure the stability and inheritance of transgenes across generations.

2.4 Speeding Up Breeding Cycles

Traditional breeding methods rely on phenotypic evaluation, which can take several years to assess the impact of a single cross. With molecular markers, breeders can rapidly assess genotype-phenotype relationships, allowing for faster development of improved varieties. This is especially valuable in crops with long breeding cycles, such as tree crops.

2.5 Genetic Diversity and Conservation

Molecular markers enable breeders to assess genetic diversity within a population. By evaluating genetic diversity, breeders can identify unique germplasm that can be used in breeding programs. Additionally, markers help in the conservation of genetic resources by facilitating the identification of rare or endangered varieties that may have useful traits.

2.6 Introgression of Desired Traits

In crop breeding, introgression refers to the incorporation of traits from a wild species or a distant relative into a cultivated crop. Molecular markers help track the introgression of specific genes, enabling breeders to improve traits such as disease resistance, stress tolerance, and nutrient content while maintaining the agronomic qualities of the crop.

3. Advantages of Molecular Markers

The use of molecular markers in crop improvement offers numerous advantages over traditional breeding methods:

3.1 Precision and Efficiency

Molecular markers provide a precise way to identify plants with the desired genetic traits, reducing the reliance on visual observation and field-based evaluations. This leads to more efficient breeding programs with faster results.

3.2 Increased Accuracy in Trait Selection

Because molecular markers are linked to specific genes, they allow for the accurate selection of plants with favorable traits, even if those traits are not visually apparent. This is particularly useful for traits controlled by multiple genes (quantitative traits) or for traits that are difficult to observe.

3.3 Reduced Breeding Time

By bypassing the need for prolonged field evaluations, molecular markers can dramatically reduce the time required to develop new crop varieties. This is particularly important in crops with long breeding cycles, such as tree crops or perennial plants.

3.4 Increased Genetic Gain

Marker-assisted selection allows for the pyramiding of multiple desirable traits in a single variety, leading to enhanced genetic gain in shorter periods of time. This can result in crops with superior performance under stress conditions, increased yield, and improved resistance to diseases and pests.

3.5 Sustainability

Molecular markers help breeders focus on traits related to environmental sustainability, such as drought tolerance, disease resistance, and nutrient-use efficiency. This ensures that crop varieties are better adapted to changing climates and diverse agro-ecosystems.

4. Challenges and Limitations

Despite their numerous advantages, molecular markers also face several challenges:

4.1 Cost

High-throughput genotyping technologies can be expensive, particularly when large numbers of samples need to be analyzed. While the cost of marker technologies has decreased over time, it remains a limiting factor for some breeding programs, especially in developing countries.

4.2 Complexity of Trait Inheritance

Some traits, especially those influenced by multiple genes (quantitative traits), may not have well-defined marker associations, making it difficult to select for these traits using molecular markers alone. Further research is needed to better understand the genetic basis of these complex traits.

4.3 Marker Linkage and Pleiotropy

Molecular markers are often linked to multiple genes, which can result in pleiotropic effects where the selection for one trait inadvertently affects other, unwanted traits. This complicates the selection process and requires careful marker validation.

4.4 Need for Specialized Expertise

Implementing molecular marker technology requires specialized expertise in molecular biology, bioinformatics, and genetics. This may pose a challenge for breeding programs without access to such expertise or resources.

Future Perspectives:

The field of molecular markers in crop improvement is continuously evolving. The integration of next-generation sequencing (NGS) technologies, genome-wide association studies (GWAS), and CRISPR-based genome editing tools promises to expand the potential applications of molecular markers. The use of big data and artificial intelligence (AI) in analyzing genomic and phenotypic data will further accelerate the pace of crop improvement, allowing breeders to develop varieties that are more resilient, nutritious, and environmentally sustainable.

Moreover, the development of low-cost, high-throughput genotyping platforms will democratize the use of molecular markers, making them more accessible to breeders worldwide.

Conclusion:

Molecular markers are revolutionizing crop improvement by providing a powerful, efficient, and precise tool for selecting desirable traits. With advancements in technology and a deeper understanding of plant genetics, molecular markers will continue to play a central role in developing crops that meet the challenges of global food security, climate change, and sustainable agriculture. Through the integration of molecular markers, breeding programs can achieve faster, more accurate, and more efficient results, ultimately leading to the development of crops that benefit both producers and consumers alike.

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A STUDY ON FARMERS' ATTITUDE TOWARDS ORGANIC FARMING

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Abstract:

Organic farming has the potential to reduce the ill effects of traditional farming. Organic farming adopts non- chemical methods of cultivation. Organic farming is good for the health of farmers of family of the farmers. Organic farming mains the high soli quality which increases the land productivity. The objective of this study is to identify the attitude of farmers towards organic farming. The study has used convenience sampling technique. The area for the study is selected villages of Amroha district of Uttar Pradesh, India. This study concludes that farmers have positive attitude towards organic farming.

Keywords: Organic Farming, Attitude, Agriculture, Perception, Productivity

Introduction:

The adverse impacts of the chemical farming methods that were used globally in the second half of the previous century made an eco-friendly alternative farming system relevant and much needed. The farming practices that our ancestors developed and used for millennia were less harmful to the environment. People started to consider different alternative farming systems that were centered on environmental preservation, which would improve human welfare in a number of ways, such as by producing clean and healthful food, creating an ecosystem that supports the survival of all living and non-living things, using fewer non-renewable energy sources, etc. The efforts of numerous specialists resulted in the development of numerous farming methods. But organic farming is thought to be Our ancestors' farming practices.

An ecology that supports the existence of all living and non-living organisms, etc. Numerous farming methods emerged as a result of the work of numerous specialists. However, due to its scientific methodology and increased global acceptability, organic farming is regarded as the greatest of all of them. Approximately 100 countries worldwide now practice organic farming. Around 24 million hectares of land were estimated to be used for organic farming globally in 2004. With 10.5 million hectares, Australia is the largest country. But a lot

"The plant or animal origin" is indicated by the term "organic." It also refers to the organizational structure of an organism. Lord Northbound coined the phrase "organic farming" in 1940. Organic Farming and Gardening journal and the Rodale Research Institute were founded by JI Rodale. As to the research conducted by the United States Department of Agriculture, "organic farming is a system which avoids or substantially excludes crop rotation, crop residues, animal manures, off-farm organic waste, mineral grade rock additives, and biological systems of nutrient mobilization and plant protection to the greatest extent possible before using synthetic inputs such as feed additives, fertilizer, pesticides, hormones, and so on. . The Food and Agriculture Organization (FAO) defines organic farming as a unique form of production management that supports and enhances the health of agro-ecosystems, including biodiversity, biological cycles, and soil biological activities, by using mechanical, biological, and agronomic methods on the farm rather than any artificial off-farm inputs.

The practice of organic farming dates back thousands of years. Farmers there use natural resources to begin growing crops along the banks of rivers. The use of organic agricultural inputs by farmers during that era is briefly described in the Indian texts Ramayana, Rig-Veda, and Mahabharata. The Kamadhenu cow, which is associated with agricultural methods, was discovered in the Mahabharata. The cycle of dead things and filthy waste that returns to the ground as nutrients is explained in the Ramayana. The basic term "Arya," which meaning to cultivate, is where the word "Aryans" originates. The term "Veda" refers to both knowledge and Vedic agriculture, which is based on Vedic knowledge. The fundamentals of organic farming are explained in Vedic writings such as the Manusmriti, Brihatsamhita, and Krishi Parashar. The application of organic manure and the significance of cow dung for plant growth are discussed in the Rigveda.

In India's rural economy, organic farming plays a number of roles. Rapid development has resulted in a shortage of agricultural land in rural India. India's population is growing at an exponential rate, making food sufficiency more important than ever. In addition, organic farming produces soil with high levels of antioxidants, vitamin E, and omega-3 fatty acids, which support plant growth by promoting photoprotection and blooming. Organic fertilizers and natural pest management are the only options available to farmers that lack the funds to investigate chemical remedies.

Literature Review

Kundan Kumar (2016) assesses farmers' attitudes on organic farming. The "Likert method of summated ratings" was used to prepare a total of 55 statements. Additionally, same statements were given to 30 farmers from two villages, each with 15 farmers, who were not in the sample region. A final list of 21 statements was chosen. The conclusion is that understanding farmers' attitudes is crucial, and to that, a scale consisting of 21 statements has been created to gauge farmers' attitudes regarding organic farming.

In her research, M. Priyadharshini (2016) created a scale to gauge Tamil Nadu farmers' attitudes toward organic agricultural methods. The scale was developed using Edward's evenly occurring intervals scale. Ten statements made up the final scale. This scale's administration was standardized.

A Study on Perception of Farmers towards Organic Farming (2015). Out of the 39 districts that make up the state of Madhya Pradesh, 100 respondents were chosen from 50 villages in the Khargone district in the Nimar area using a practical and purposeful selection technique. The study's findings were presented using descriptive statistics and factor analysis, and the study hypotheses were tested using chi-square analysis.

Individual conduct is mostly influenced by two elements, according to Ajzen and Fishbein (1980): the individual's nature and perceived societal pressure. The individual factor is the person's assessment of carrying out the conduct, whether favorable or unfavorable. This component is known as the "attitude towards the behaviour" since it pertains to individual sentiments (Ajzen and Fishbein 1980). Perceptions of social pressure to engage in or refrain from engaging in the conduct are the other component. Ajzen and Fishbein (1980) refer to this component as the "subjective norm" because it relate with perceived prescription. In general, individuals will plan to carry out an action when they both believe that many others would like to engage in the conduct, and they have a positive opinion of it. Ajzen and Fishbein (1980) created the Theory of Reasoned Action (TRA) in consideration of these considerations. According to this idea, humans are typically quite rational in that they use the information at their disposal methodically, think through the consequences of their choices, and act sensibly. According to TRA, a person's intentions—which are influenced by their attitude and perceived social pressure—are the best indicators of their behavior. Accordingly, the TRA offered a theoretical framework for investigating how attitudes and objectives impact volitional behaviors (Willock *et al.,* 1999).

Many actions have been successfully predicted and understood by the TRA, but it is unable to anticipate behaviors that are not fully controlled by an individual's choice. As a result, the TRA limits its scope to voluntary actions; opportunities, resources, or talents that are not freely accessible are either not regarded as falling under its purview or are probably not well predicted by it (Fishbein, 1993). In order to enhance the TRA, the Theory of Planned Behavior (TBP) was created.

To account for any creating or motivating elements that can influence an attempted behavior being carried out, the perceived behavioral control extension was included as an additional construct to the TRA (Beedell and Rehman, 2000). According to the TPB, a person's conduct is influenced by their attitudes, perceived behavioral control, objectives and intentions, and social norms (Bergevote *et al.,* 2004).

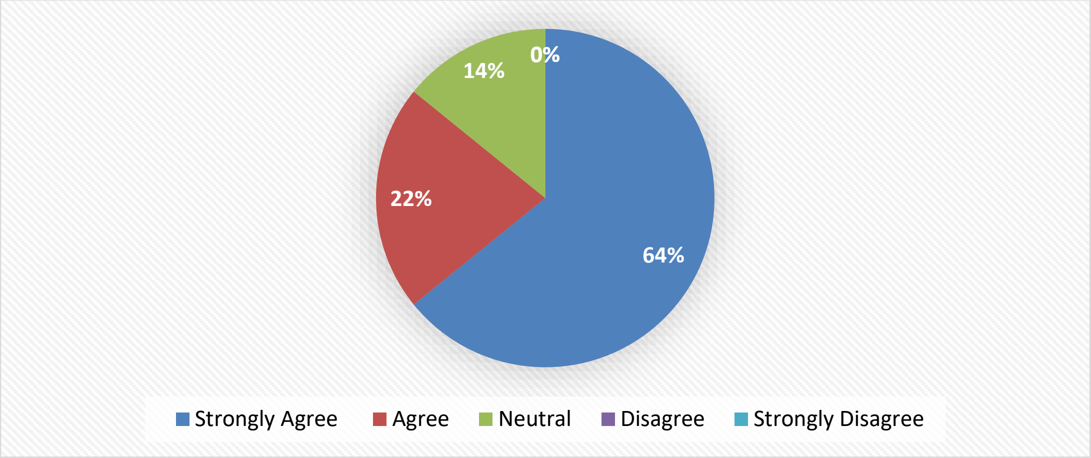
Research Methodology

The study was conducted in selected villages in Amroha district of Uttar Pradesh, India. The area is known for agriculture activities and farmers are well aware about the organic farming. The population for the study consisted of farmers in the selected villages of Amroha of Uttar Pradesh, India. A convenient sampling technique was used for this study. The descriptive research design will be followed in the study. The purpose of this study is identifying the factors affecting adoption of organic farming in selected villages of Amroha district of Uttar Pradesh, India. This research study is mainly quantitative which uses statistical tools and numbers. The sample size for the study is 120.

Data Analysis and Interpretation

Q. 1: Organic farming protects the good health of a farmer and farm family.

Response Pattern	No. of Response	Percentage
Strongly Agree	65	54.17
Agree	45	37.5
Neutral	10	8.33
Disagree	0	0
Strongly Disagree	0	0

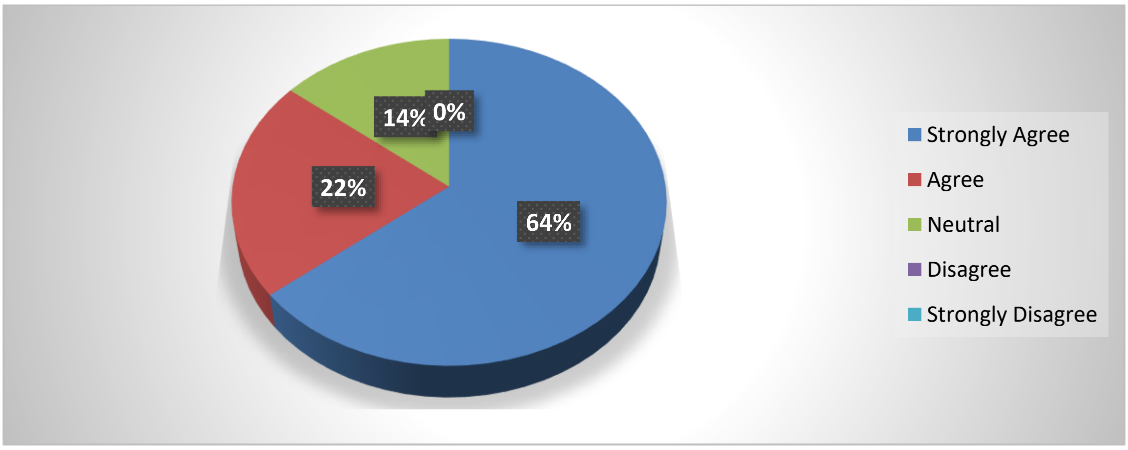


Interpretation

Near about 54% of the respondents are strongly agree with the statement that organic farming protect the health of the farmers and family members, and 38% are agree only so, total 92% of the respondent are in favor that organic farming can play a significant role in protecting the health of all citizen.

Q. 2: Organic food does not have any harmful residue.

Response Pattern	No. of Response	Percentage
Strongly Agree	75	62.50
Agree	33	27.5
Neutral	12	10.00
Disagree	0	0
Strongly Disagree	0	0

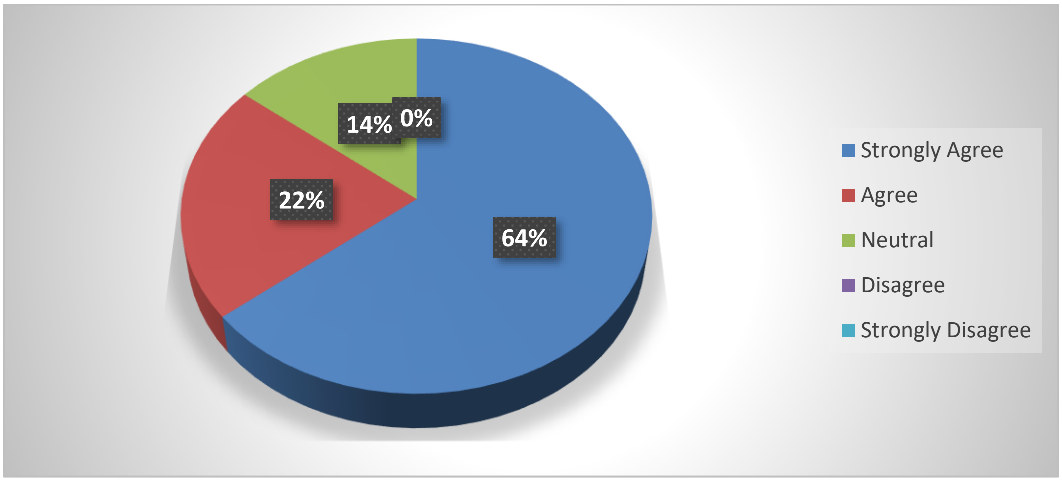


Interpretation

Almost 62% of the respondents are strongly agree that organic food does not have any harmful residue. This is good for the environment and the society as a whole. Further, 28% of respondents also agree that organic food is environmental friendly and does not leave any harmful residue.

Q. 3: The nutritional quality of organic food is higher than non-organic food.

Response Pattern	No. of Response	Percentage
Strongly Agree	80	66.67
Agree	22	18.33
Neutral	18	15.00
Disagree	0	0
Strongly Disagree	0	0

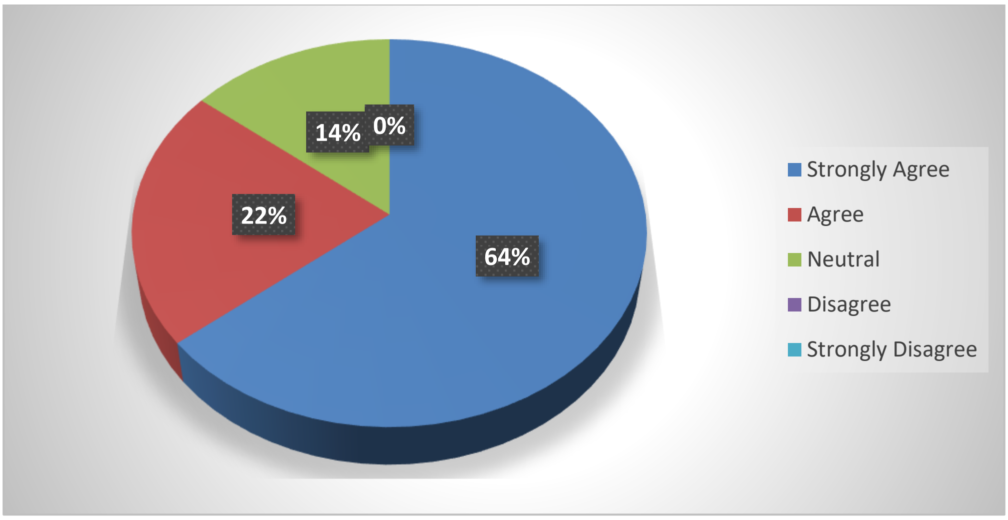


Interpretation

Almost 67% of the respondents are strongly agree that organic food is more nutritional than non-organic food which is good for the health of the consumers. Furthermore, 18% of respondents also agree that organic food is environmental friendly and less harmful.

Q. 4: Organic farming maintains long-term soil fertility

Response Pattern	No. of Response	Percentage
Strongly Agree	68	56.67
Agree	30	25.00
Neutral	22	18.33
Disagree	0	0
Strongly Disagree	0	0

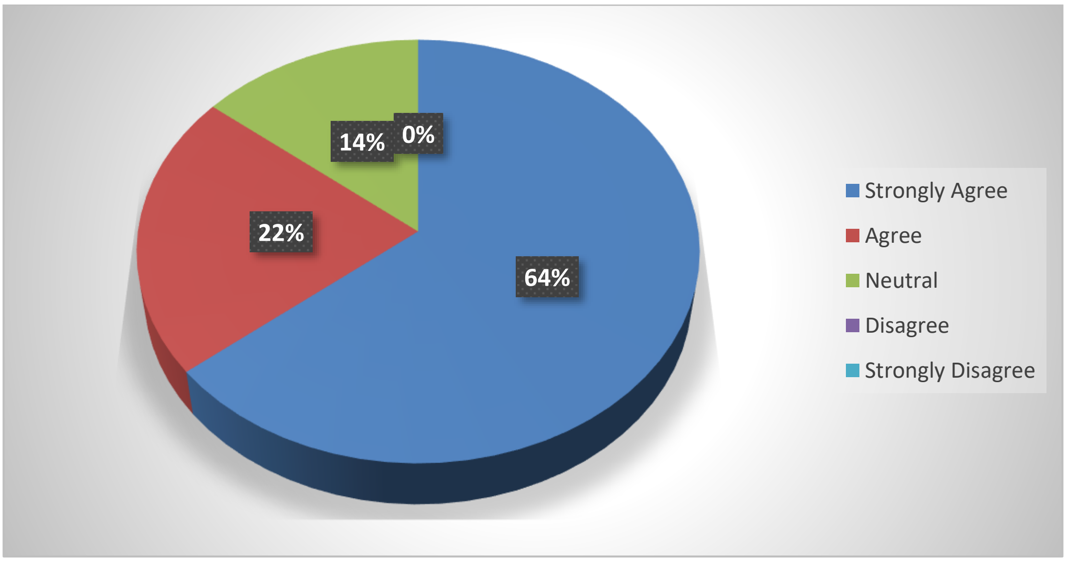


Interpretation

Nearby 57% of the respondents are strongly agree that organic food is helpful in maintaining soil quality. Improved soil quality increases land productivity and farmers desire to main high soil quality. In addition to it, 25% of the respondents also agree that organic farming maintain soil quality.

Q. 5: Organic farming is more complex than conventional farming.

Response Pattern	No. of Response	Percentage
Strongly Agree	77	64.17
Agree	26	21.67
Neutral	17	14.17
Disagree	0	0
Strongly Disagree	0	0



Interpretation

Nearby 64% of the respondents are strongly agree that organic farming is more complex than traditional farming that is why farmers are not very keen to adopt the organic farming.

Conclusion:

Sustainability and environmental consciousness are closely related with organic farming. To accomplish these two objectives, certain guidelines and standards were created. Food and fiber are produced in an environmentally, economically, and socially sustainable way under the organic farming method. Global demand for organic food is rising gradually. Because they think organic food is naturally produced, safe, healthful, and of superior quality, consumers now purchase it. Increased intake of polyphenolics and antioxidants has been associated with a lower risk of certain chronic conditions, such as cardiovascular and neurodegenerative diseases and some types of cancer, whereas organic crops have improved antioxidant exertion and attention to a variety of individual antioxidants. With its diverse agroclimatic conditions, India offers a wealth of opportunities for organic husbandry and a wide range of organically produced goods. The main obstacles to organic husbandry in India are the high cost of organic products and the absence of effective marketing strategies in response to domestic demand. Organic fertilizer actually possesses bones that promote longevity and well-being and has fewer harmful effects. Organic foods' health benefits are not only useful for individuals but society in general.

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PROTECTIVE AGRICULTURAL PRACTICES IN POLYHOUSE

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Introduction:

Agriculture is backbone of Indian economy. It is main source of food and raw material for people and also a source of income for the all farmers. In 2023-24, contribution of agriculture sector to GDP of our country is approximately 18.2% [3]. The agriculture involves many technologies day by day. The greenhouse and polyhouse farming is also a part. The first greenhouse with modern technology was made in Italy in the 13th century. In India, first time polyhouse setup started in 1985 at Leh Ladakh (J & k) for growing vegetables in seasonal period from 3 to 7months. In our country, greenhouse and polyhouse cultivation mainly in Maharashtra, Karnataka, Uttarakhand and Jammu & Kashmir [7].

The polyhouse is an alternative technique in agriculture, provide food in rural areas. It is a type of green house structure that can be used for protect the crops from extreme weather, controlled environment and provide higher quality crops over a long period time. The polyhouse is made up of plastic sheets with transparent walls and roof with the help of metal frames. The polyhouse is helpful for control and protect the crops from the attack of diseases and pests. It provides the suitable or favorable environment for growth and development of crops. It is very helpful to control the temperature and provide the heat in cold conditions [6].

How is Polyhouse different from Greenhouse Farming?

	Polyhouse	**Greenhouse**
Definition	Polyhouse is a type of greenhouse where plastic sheet is used as cover the house	Greenhouse is made up of transparent material such as glass to create a microclimate inside the house.
Material Used	Plastic sheets or polyethylene film are used	Glass or polycarbonate panels are used

Cost	Cheaper	Expensive
Size	Small	Large
Mobility/ Flexibility	Easily move	Difficult to move
Ventilation	Less ventilated	More ventilated

Why need of Polyhouse cultivation?

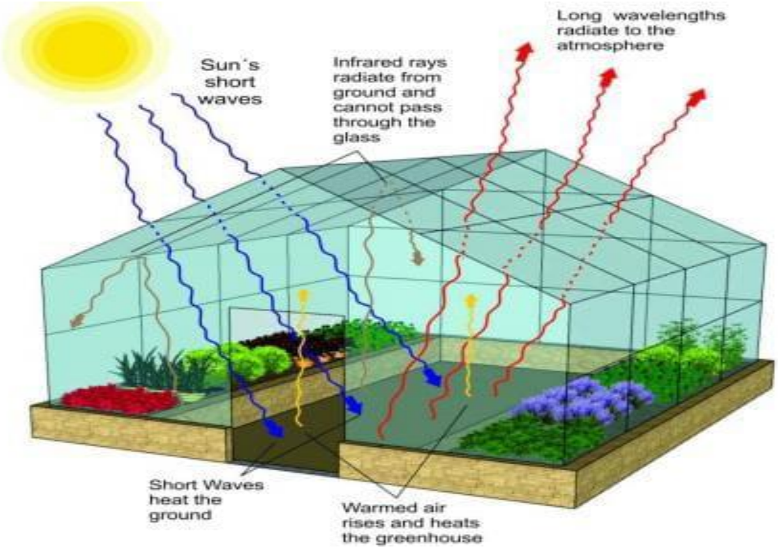
- Provide higher yield
- Better quality of crop
- Off- season production due to proper environmental control
- Provide self- employment for educated or uneducated people in rural areas
- Reduce the pesticide use
- Control the weather
- Easy to handle for plant protection
- Weed free cultivation

Present scenario of Polyhouse/ Greenhouse:

- ❖ In the world, more than 110 countries used a greenhouse/ polyhouse for growing crops such as vegetables, fruits, flowers etc. The largest five countries are China, Korea, Spain, Japan and Turkey.
- ❖ According to survey in India, approximately 3.08 lakh hectares area of land under protected cultivation including greenhouse cultivation [4]. The largest five states are Maharashtra (2,962ha), Haryana (1402 ha), Karnataka (1138 ha), Gujarat (952 ha) and Tamil Nadu (862 ha) [2].
- ❖ Govt. of India provided many subsidies for polyhouse farming which are under the National Horticulture Mission.
- ❖ In Himachal Pradesh, approximately 14.45 lakh square meter land under greenhouse cultivation [5]

Principle of Polyhouse:

- ❖ Polyhouse are structure covered with transparent sheet like as polythene or glass.
- ❖ The covering sheets act like a radiation filter and allow short wave length radiation to pass but long wavelength radiation trapped.
- ❖ The long radiations are observed from plants and other crops in the polyhouse. They can't pass out from the sheet. The result is increasing temperature inside the greenhouse due to greenhouse effect [10].



What type of site should be selected for playhouse? :

- The site should have difference in their functional and environmental operation of Polyhouse.
- The pH of soil should have 5.5 to 6.5.
- Source of water should be always available.
- Supply of electricity should be good.
- The irrigation water pH should be 5.5 to 7.0.
- For drainage, the ground surface is important factor for divert the way of surface water from the polyhouse.
- The location of polyhouse should be away from the buildings and area.
- For transportation, the road facility should be available.
- Availability of labours should be easy and cheap [9].

Table 1: Comparison between different types of covering materials

S. No.	Type	Duration	Transmission		Maintenance
			Light	Heat	
1.	Polyethylene	1 year	90%	70%	Very high
2.	Fiber Glass	7 years	90%	5%	Low
3.	Double strength Glass	50 years	90%	5%	Low
4.	Poly carbonate	50 years	90%	5%	Very low

Different Types of Polyhouses

1) Low cost polyhouse
2) Medium cost polyhouse

3) High cost polyhouse
4) Naturally ventilated
5) Plastic low tunnels

1) **Low cost polyhouse:** One of the simple polyhouse by cost that need less money for their setup and maintenance. This type of polyhouse, bamboo is used for construction. A UV stabilized is used to do cladding, and these polyhouse do not contain high technology adjusters. Shades are used on the transparent roof of the polyhouse to maintain the light entering the polyhouse. The polyhouse can be built in less time and used as a shelter for crops during heavy rainfall.

2) **Medium cost polyhouse:** The moderate cost polyhouse constructed and designed with the use of galvanized iron pipes. The arrangement of this type of polyhouse is grounded firmly to provide better protection against high winds and heavy climatic conditions. This type of polyhouse contains thermostats to manage the temperatures of polyhouse. This type of polyhouse is suitable for dry climate areas.

3) **High Cost Polyhouse:** It is one of the most advanced types of polyhouse. It is high-grade polyhouse with latest technologies and automated system to control every situation happening in polyhouse.

4) **Naturally Ventilated Polyhouse:** This is basic and traditional polyhouse with climatic control features. They are not proper control system but surely they intend the crop cycle and also the production.

5) **Plastic Low Tunnels:** This is miniature form of polyhouse. In the plants are protects from the rains, wing, low temperature, frost and other environmental factors. This type of polyhouse is very useful to off- season vegetable. This is mostly used for growing the nursery.

Merits of polyhouse:

i. **Controlled Environment:** Plant are grown under controlled temperature conditions which is helpful for reduces the chances of crop damage.

ii. **Pest and Disease control:** Polyhouses protect the crop from attack of pest and diseases.

iii. **Quality of Produce:** When condition is controlled under polyhouse than crop will provide higher production with proper size and colour of produce with nutritional quality as compare to open field.

iv. **Water Conservation:** In polyhouse drip irrigation system can use, which help to reduce the wastage of water as compare to traditional farming.

v. **Increase Yield:** Due to proper maintenance yield can increased around 5 to 10 times compare than open field.

vi. **Easy Fertilizer Application**: In polyhouse crops, fertilizer application is easy and it can be control automatically through the help of drip irrigation [8].

Demerits of polyhouse:

i. **High Initial Investment:** The cost of setup of polyhouse can be high due to environmentally controlled polyhouse.

ii. **Maintenance Costs:** In polyhouse, regular maintenance is necessary for proper growth.

iii. **Electricity Requirement**: For environmentally controlled polyhouse, electricity should properly available for operating the all equipments.

iv. **Cost of Materials Labor:**For naturally ventilated polyhouse the materials and labor requirement is high. So cost is also high.

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SMART FARMING AND CARBON SEQUESTRATION TO COMBAT THE CLIMATE CRISIS

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Abstract:

The global food security crisis, exacerbated by climate change, necessitates innovative agricultural solutions to meet future demands while mitigating greenhouse gas (GHG) emissions. Smart farming, integrating advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), and precision agriculture, offers a sustainable pathway to optimize resource management and enhance farm productivity. Additionally, carbon sequestration presents a vital strategy for mitigating climate change by capturing atmospheric CO_2 in soils, vegetation, and agroforestry systems. The agricultural sector, responsible for 19-29% of global GHG emissions, significantly contributes to CO_2, CH_4, and N_2O emissions. Implementing climate-smart agriculture (CSA) and carbon sequestration techniques can reduce agricultural emissions by up to 15%, increase soil organic carbon (SOC) storage by 40% through biochar application, and improve climate resilience. This chapter explores the role of smart farming and carbon sequestration in achieving sustainable food production, enhancing soil health, and reducing environmental footprints. Policies supporting CSA adoption, resource-efficient technologies, and carbon offset programs are critical for mitigating climate change impacts while ensuring food security.

Keywords: Smart Farming, Carbon Sequestration, Climate-Smart Agriculture (CSA), Greenhouse Gas Emissions, Precision Agriculture, Soil Organic Carbon (SOC), Food Security, Sustainable Agriculture, Climate Change Mitigation

Introduction:

The world has undergone rapid urbanization, population growth, and an escalating demand for food production in recent decades. As a result, the agricultural sector faces numerous challenges, including resource scarcity, climate change, and the urgent need for sustainable farming practices. In response to these challenges, a new paradigm known as "Smart Farming" has emerged, offering innovative solutions that are transforming traditional agricultural practices. Also referred to as precision agriculture or digital agriculture, Smart Farming leverages cutting-edge technologies, data analytics, and automation to enhance the efficiency, productivity, and sustainability of farming operations. This approach integrates advancements in the Internet of Things (IoT), robotics, artificial intelligence (AI), cloud computing, and big data analytics to revolutionize crop cultivation, livestock management, and natural resource utilization.

The incorporation of IoT devices and sensors allows real-time monitoring and data collection from farm fields, livestock, and environmental conditions. When combined with AI algorithms and data analytics, this information enables farmers to make informed decisions regarding irrigation, fertilization, disease detection, pest control, and other critical aspects of agricultural management. Additionally, automation and robotics facilitate precision interventions, optimizing resource utilization while minimizing environmental impact. One of the primary advantages of Smart Farming is its potential to enhance sustainability. By adopting data-driven precision practices, farmers can minimize the excessive use of water, fertilizers, and pesticides, thereby reducing the ecological footprint of conventional farming. Furthermore, Smart Farming promotes efficient energy use, biodiversity conservation, and the preservation of soil health.

Simultaneously, climate change poses significant threats to agriculture. Global sea levels have risen by approximately 6.7 inches (17cm) since 1970, with the past decade being the warmest on record. Since 1969, the upper ocean (700m) has warmed by 0.302°F, and Arctic ice has shrunk significantly, with Greenland losing 36-60 cubic miles of ice. Additionally, ocean surface acidity has increased by up to 30% (IPCC Fourth Assessment Report). Sea level rise can have direct and indirect effects on Smart Farming and carbon sequestration by increasing soil salinity, exacerbating flooding events, and contributing to soil erosion and farmland loss. Several studies have explored the potential of Smart Farming and carbon sequestration to mitigate the impact of sea level rise on agriculture. For instance, precision irrigation and drainage systems have been shown to reduce the adverse effects of sea level rise on crop yields and soil health in Vietnam's Mekong Delta (Le *et al.,* 2021). Similarly, agroforestry systems have proven effective in carbon sequestration and climate change mitigation in coastal areas (Zhou *et al.,* 2019). Implementing Smart Farming and carbon sequestration practices can help farmers adapt to climate change while contributing to broader mitigation efforts.

According to the World Health Organization (WHO, 2020), approximately 690 million people, or 8.9% of the global population, suffer from malnutrition. At the same time, global food consumption patterns are shifting towards diets richer in meat and biofertilized vegetables. By 2050, food production must increase by 60% from current levels to meet growing demand and address food waste (Alexandratos *et al.,* 2012). However, agriculture is under threat due to natural resource degradation and climate change, which negatively impact production stability, agricultural output, farmer income, and food security. Research indicates that rising temperatures reduce crop yields, whereas increased precipitation can mitigate some temperature-related impacts (Adams *et al.,* 1998). Expanding irrigated areas to boost yields may alter microclimates and contribute to ecosystem degradation (Kang *et al.,* 2009).

Modern agricultural practices, such as indiscriminate fertilizer use, heavy plowing, and residue burning, have led to severe environmental consequences, including greenhouse gas (GHG) emissions. Agriculture contributes 19-29% of total anthropogenic GHG emissions, primarily through carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions (IPCC, 2014). Although CO_2 is the most abundant GHG, N_2O and CH_4 have a greater long-term warming potential. The agricultural sector accounts for significant emissions through deforestation, soil and nutrient mismanagement, rice cultivation, and livestock production (IPCC, 2016). The Intergovernmental Panel on Climate Change (IPCC) classifies emissions from agriculture, forestry, and other land use (AFOLU) as major contributors to global warming, with AFOLU responsible for 21% of total emissions. Between 2001 and 2010, agriculture accounted for 50% of AFOLU emissions, followed by net forest conversion (38%), peat degradation (11%), and soil cultivation (Tubiello *et al.,* 2014). Climate models predict that a doubling of CO_2 concentrations could increase global temperatures by 2.33-4.78°C, with soil organic carbon (SOC) losses estimated between 1.1 and 2.0 Tg C yr^{-1} by the end of the 21st century. Factors such as soil disturbance, vegetation decline, fire, erosion, and nitrogen deficiency further contribute to SOC losses (Soussana *et al.,* 2004; McSherry & Ritchie, 2013).

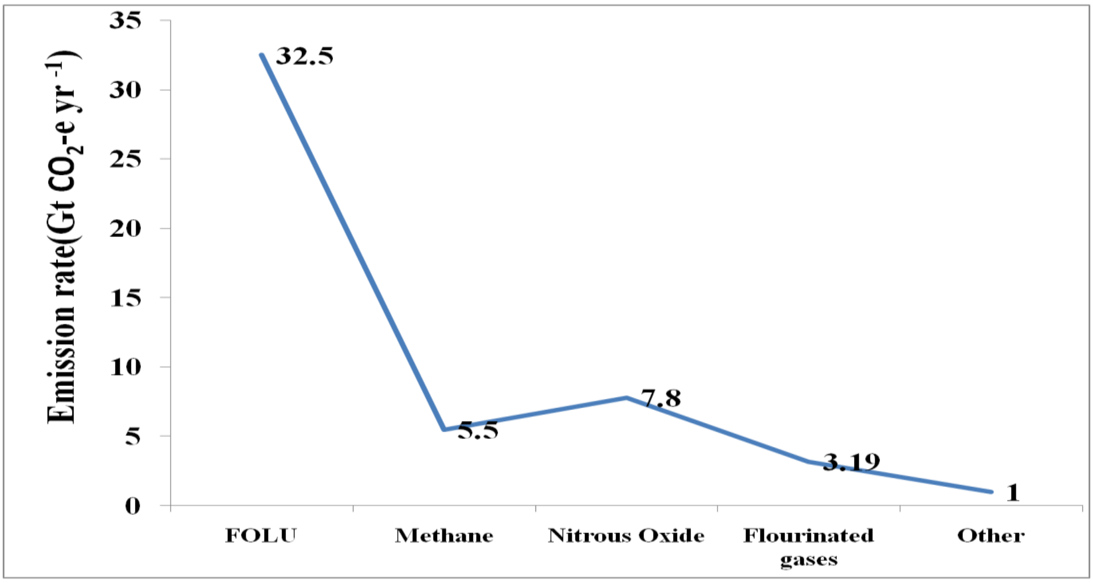

Fig. 1: Emission rates of different GHGs from different source per year from different sub-sectors of Indian agriculture. Source: MoEFCC (2021)

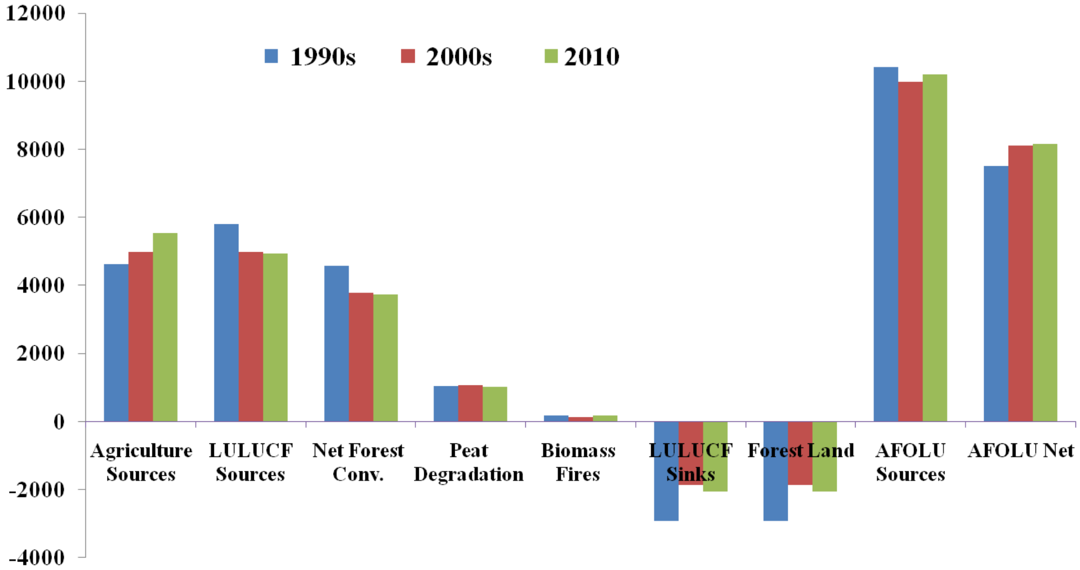

Fig. 2: AFOLU emissions by decade and in 2010 (Mt CO_2 eq) (Adopted from Tubiello *et al.,* 2014).

Climate change exacerbates abiotic stresses such as drought, salinity, heat stress, and water scarcity, leading to soil degradation, reduced fertility, and increased pest and disease infestations (Malhi *et al.,* 2020; Baul *et al.,* 2015). Access to relevant information and solutions enhances farmers' ability to adapt to climate change (Semenza *et al.,* 2011). Studies suggest that climate-resilient agricultural technologies, including agroecological practices, soil management, and water conservation, can help reduce emissions and enhance sustainability (Altieri *et al.,* 2017). However, adaptation measures are often preferred over emission reduction strategies, particularly among small and marginal farmers in Asia (Smith *et al.,* 2010; Arbuckle *et al.,* 2015). In India, 85% of farmers cultivate less than 2 hectares of land, making large-scale mitigation efforts challenging (Gupta & Pathak, 2016). Effective climate mitigation strategies involve resource conservation, improved cropping systems, and policy interventions (Venkateswarlu *et al.,* 2006).

Achieving net-zero carbon emissions requires significant reductions in methane and nitrous oxide emissions from agriculture (Leahy *et al.,* 2020). Strategies such as carbon sequestration and carbon farming can help balance productivity with sustainability. Carbon sequestration involves capturing CO_2 from the atmosphere and storing it in reservoirs such as forests, soils, and geological formations. This process can be enhanced through afforestation, soil carbon management, and carbon capture technologies. The "FARM" approach—Forecasting, Adopting, Responding, Mitigating, and Capacity Building—is essential for managing climate risks in agriculture. Climate-smart agriculture (CSA) and carbon sequestration technologies play a crucial role in achieving food security, increasing resilience, mitigating GHG emissions, and enhancing sustainability (FAO, 2013).

2. Scenario of Global Climate Crisis

Climate change, characterized by rising global temperatures and shifting precipitation patterns, has led to an estimated 9–18% decline in the yield of key crops in India. Currently, India emits approximately 2,822 million tonnes of CO_2 equivalent (CO_2 eq) of greenhouse gases (GHGs) annually, with the agricultural sector contributing 408 million tonnes CO_2 eq, accounting for 14% of total emissions (MoEFCC, 2021). Among agricultural sources, methane emissions from ruminant animals constitute the highest share (55%), followed by nitrous oxide (NO_x) emissions from soils (19%), methane emissions from rice fields (17%), and CH_4 and NO_x emissions from organic manure management (7%), while residue burning contributes 2% (MoEFCC, 2021).

Over the past century, atmospheric CO_2 concentrations have exceeded 415 ppm (IPCC, 2021). Global temperatures have already increased by 1.1°C, and under a business-as-usual scenario, they could surpass 1.5°C by 2040 and rise as high as 3.5°C by 2100. The past seven years (2015–2021) have been the warmest on record (IPCC, 2021). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report has confirmed the significant impact of climate change on agriculture. Projections indicate that climate change could reduce crop productivity in India by 4.5–10% (Naresh *et al.,* 2020).

Shifts in precipitation patterns and volumes are also affecting specific crops, such as tea yields in Assam (Nowogrodzki, 2019). Elevated atmospheric CO_2 levels, combined with lower nitrogen availability, are predicted to reduce wheat grain protein content by approximately 1% (Aggarwal *et al.,* 2021). Additionally, rising temperatures, along with changes in precipitation patterns, are expected to degrade soil fertility and health, reduce soil moisture content, and adversely affect microbial habitats and their growth (Gupta & Pathak, 2016).

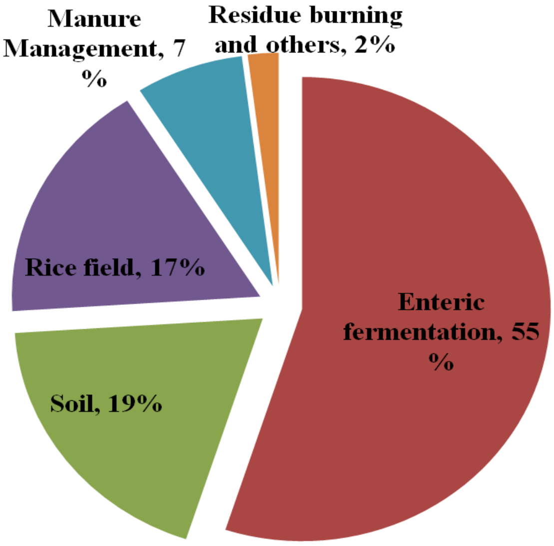

Fig. 3: Emission of GHGs form Indian agriculture system (total emission 408 Mt CO_2 eq.) (Adapted from MoEFCC, 2021).

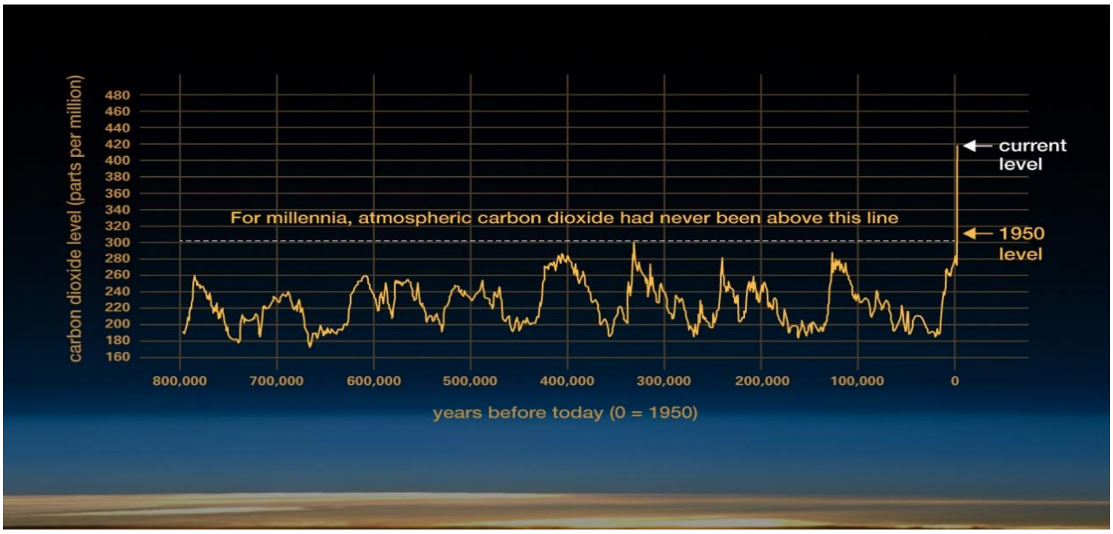

Fig. 4: The rising trend of CO_2 emissions, CO_2 concentration and CO_2 concentration level (Source: NASA satellite observations.)

3. Economic scenario of CSA (Climate-Smart Agriculture) on Climate Change

Climate-smart agriculture (CSA) is an approach to farming that aims to address the challenges of climate change while promoting sustainable agricultural practices. The economic landscape of CSA is complex, presenting both opportunities and challenges. Below is a brief overview of the economic scenario of CSA.

A) Opportunities:

1. **Increased Yields:** Climate-smart practices such as conservation agriculture, agroforestry, and improved water management can enhance agricultural productivity, leading to higher incomes for farmers.
2. **Diversification:** CSA techniques, including intercropping, crop rotation, and livestock integration, create diversified farming systems that reduce the risk of crop failure and improve resilience.
3. **Reduced Costs:** Practices such as no-till farming and the use of cover crops can lower input costs by reducing the need for fertilizers and herbicides.
4. **Carbon Sequestration:** Techniques such as agroforestry and conservation agriculture contribute to soil carbon sequestration, providing potential income through carbon markets.

B) Challenges:

1. **High Initial Investment:** Some CSA practices, like irrigation system installation, require substantial upfront costs, which may be prohibitive for small-scale farmers.
2. **Knowledge and Skills:** Many CSA techniques demand specialized knowledge and skills that may not be readily available to all farmers.
3. **Market Access:** Farmers may face difficulties in accessing markets for climate-smart products, which may require niche markets or certification.
4. **Policy and Institutional Support:** The success of CSA depends on supportive policies and institutions at national and local levels, which may not always be in place.

Beyond a 3°C rise in temperature, the net impact of climate change on agriculture becomes negative, and increases beyond 7°C could lead to catastrophic losses in agricultural productivity and overall welfare. Tol *et al.,* (2012) estimated that the global social cost of carbon emissions was projected to be USD 29 per tonne of carbon (tC) in 2015, increasing by approximately 2% annually.

Various CSA technologies have been developed to mitigate climate change effects and enhance resilience. These include:

- **Water-smart practices:** Rainwater harvesting, laser land leveling, crop diversification, micro-irrigation, direct-seeded rice, and raised-bed planting.
- **Weather-smart practices:** Stress-tolerant crop varieties and agro-meteorological services supported by information and communication technologies (ICTs).
- **Smart carbon management:** Zero tillage, minimum tillage, legume-based cropping systems, and residue incorporation.
- **Nutrient-smart practices:** Precision nutrient application using tools such as leaf color charts (LCC) and crop residue management (Malhi *et al.,* 2021).

Costinot *et al.,* (2016) predict that climate change will significantly impact agricultural markets, potentially reducing global GDP by 0.26%. Climate projections for the 2080s suggest that, if realized today, global family welfare would decline by 0.2–1% annually (Ciscar *et al.,* 2011). These economic insights highlight the necessity for integrated CSA strategies to ensure both climate resilience and economic sustainability in agriculture.

4. Carbon Sequestration a strategy towards combat climate crisis

The term "carbon sequestration" refers to both natural and intentional processes that remove CO_2 from the atmosphere or divert it from emission sources, storing it in reservoirs such as oceans, terrestrial environments (vegetation, soils, and sediments), and geologic formations. Before human-induced CO_2 emissions, the global carbon cycle maintained a relatively stable balance between CO_2 uptake and release (as depicted in Fig. below). Carbon naturally cycles between the atmosphere, vegetation, soils, and oceans over timescales ranging from years to millennia. However, human activities, such as fossil fuel combustion and deforestation, have significantly increased atmospheric CO_2 concentrations. While natural carbon uptake processes absorb some of this excess CO_2, a substantial portion remains in the atmosphere, contributing to climate change. Intentional carbon sequestration aims to mitigate this issue by storing carbon in oceans, vegetation, soils, and porous rock formations. According to the Intergovernmental Panel on Climate Change (IPCC), CO_2 is a greenhouse gas that traps heat in the atmosphere, contributing to global warming. By capturing and storing CO_2, we can mitigate climate change by reducing greenhouse gas levels. Soils act as both sources and sinks of carbon, with gains and losses determining their carbon sequestration capacity. Historically, the global carbon cycle-maintained equilibrium between carbon uptake (sinks) and release (sources) before the industrial revolution.

The rise in atmospheric greenhouse gases (GHGs) such as CO_2, CH_4, N_2O, and fluorinated gases has been a major driver of global temperature increases. Over the past 150 years, GHG levels have risen by approximately 40%, with half of this increase occurring in the last three decades. By the end of 2019, annual CO_2 emissions from industrial activities and fossil fuel combustion had reached 36.8 Gt, while total CO_2 emissions from all human activities, including land use and agriculture, stood at 43.1 Gt (Harvey and Gronewold, 2019). Scientists are exploring new methods to reduce GHG emissions, remove atmospheric CO_2, and store carbon using advanced technologies. Beyond carbon removal, researchers are investigating ways to utilize CO_2 as a resource.

Sustainable agricultural practices such as minimal tillage, conservation tillage, organic farming, crop rotations, and cover cropping can enhance soil carbon sequestration. Leaving crop residues on fields allows carbon absorption through photosynthesis, integrating carbon into the soil upon plant decay. However, the duration and extent of carbon sequestration depend on climate conditions and soil management practices. According to the IPCC, soil carbon sequestration could reduce CO_2 emissions at a cost of $0 to $100 per tonne, with an estimated potential to remove 2 to 5 Gt CO_2 per year by 2050 (Cho, 2018).

Smart agriculture technology and carbon storage strategies offer promising solutions to climate change while ensuring sustainable agricultural productivity. Climate-smart agriculture (CSA) focuses on managing landscapes to address food security and climate change. CSA encompasses crop production, livestock management, forest conservation, and fisheries. Given rising CO_2 levels, greater emphasis has been placed on accelerating carbon sequestration through land use changes, afforestation, and geo-engineering techniques such as carbon capture and storage (CCS). Carbon farming involves practices that enhance soil carbon sequestration, while novel carbon sequestration technologies are being explored to mitigate global warming (Selin, 2019).

Soils serve as significant carbon reservoirs, containing between 40% and 60% organic matter carbon by weight. Sequestering carbon in soil is a natural, low-energy, and cost-effective approach with minimal environmental impacts. Improved agricultural and land management techniques can enhance soil carbon storage, contributing to climate change mitigation. Globally, soils store approximately 2,500 Gt of carbon—four times the amount stored in living organisms and over three times the atmospheric carbon stock. Soils currently offset about 25% of annual global fossil fuel emissions.

A study estimated that to meet the 2°C climate goal, carbon sequestration must reach 15 Gt CO_2 per year. However, soil carbon sequestration can only store 4 to 5 Gt CO_2 per year, while total global emissions stand at 41 Gt CO_2 per year. The amount and duration of soil carbon storage vary by region and depend on land management practices. More than half of the Earth's plant-supporting land has been converted into rangelands, pastures, and croplands, resulting in a 50% to 70% loss of original soil carbon stocks. This land-use change contributes significantly to global GHG emissions and warming.

Agricultural practices such as intensive tilling, monoculture planting, crop residue removal, excessive fertilizer and pesticide use, and overgrazing expose soil carbon to oxygen, leading to its release as CO_2. Additional sources of soil carbon loss include deforestation, permafrost thawing, and peatland drainage. A 2017 study estimated that improved cropland management could store an additional 1.85 Gt of carbon annually—equivalent to current global transportation emissions. Some researchers believe soils can continue sequestering carbon for 20 to 40 years before reaching saturation (Zomer *et al.,* 2017).

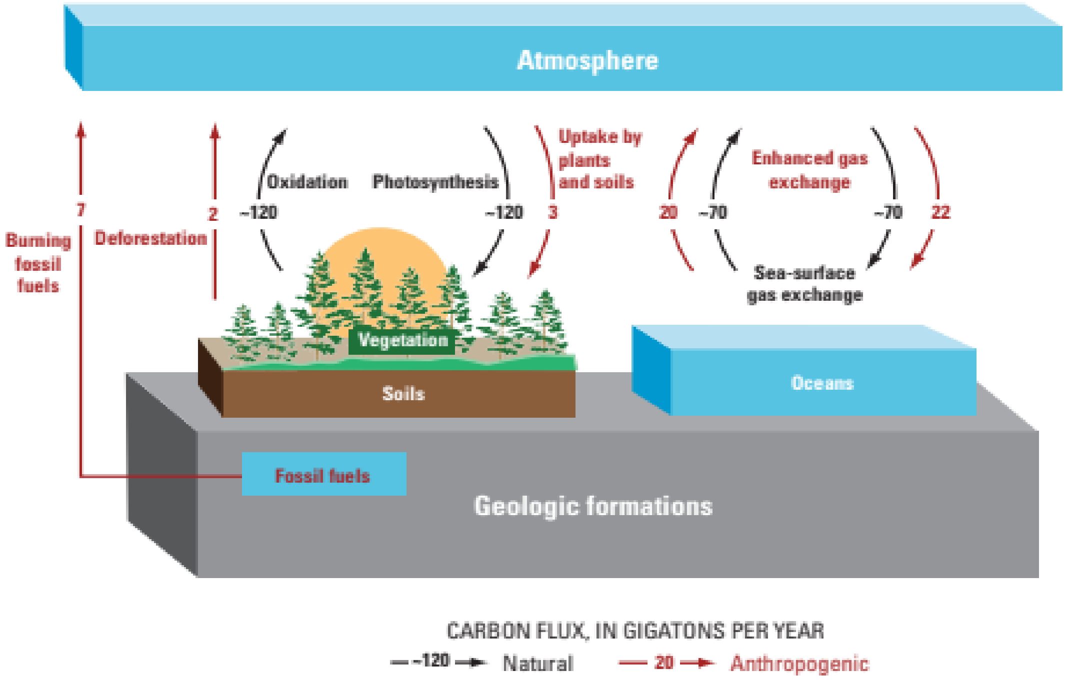

Fig. 5: The Global carbon cycle (Source: FLUX, C., & YEAR, I. G. P. (2008). Carbon sequestration to mitigate climate change.)

5. Carbon sequestration strategy based on climate scenario and CSA (climate-smart agriculture)

Smart farming techniques play a crucial role in enhancing carbon sequestration, thereby mitigating climate change. The following methods illustrate how precision agriculture and agroforestry contribute to carbon storage:

1. **Soil Carbon Sequestration**: Precision farming techniques, such as precision irrigation, precision fertilization, and no-till farming, improve soil health and enhance carbon sequestration. For example, no-till farming minimizes soil disturbance, helping to retain organic matter and increase soil carbon storage. Research indicates that precision-farming practices can boost soil carbon sequestration by up to 35% (Boru *et al.,* 2019).
2. **Agroforestry**: Agroforestry integrates trees into agricultural landscapes, which enhances carbon sequestration both in biomass and soil. Trees serve as significant carbon sinks, and smart farming techniques like precision planting and precision nutrient management optimize tree growth and carbon capture within agroforestry systems (Coomes *et al.,* 2019).

Measuring Carbon Sequestration

Carbon sequestration is typically assessed using two key metrics:

- **Inputs**: The amount of carbon removed from the atmosphere.
- **Transit Times**: The duration carbon remains stored in different carbon sinks, depending on the ecosystem type.

These metrics facilitate the comparison of climate impacts on carbon removal. The unified concepts of Carbon Sequestration (CS) and the Climatic Benefit of Sequestration (CBS) encompass both measures (Sierra *et al.,* 2021).

Application of the TECO Model

The TECO (Theory of Ecosystem Complexity) model can be applied to quantify Carbon Stocks (CS) and Carbon Balance Sheets (CBS) for linear systems at a steady state, representing equilibrium conditions. This study utilized a modified version of the TECO model, originally proposed by Weng and Luo (2011). The model parameters were determined through data assimilation, incorporating observations from the Duke Forest in North Carolina, USA.

The TECO model comprises eight main compartments:

1. **Foliage (x_1)**
2. **Woody Biomass (x_2)**
3. **Fine Roots (x_3)**
4. **Metabolic Litter (x_4)**
5. **Structural Litter (x_5)**
6. **Fast Soil Organic Matter (SOM) (x_6)**
7. **Slow SOM (x_7)**
8. **Passive SOM (x_8)**

The model captures carbon dynamics in a temperate forest predominantly consisting of loblolly pine. It was chosen for its simplicity and ease of application, though its framework can be extended to more complex models and ecosystems. For an example involving a nonlinear model, refer to the section titled "Executable Research Compendium (ERC)."

Advantages of the TECO Model

1. **Reliable Predictions**: The model provides reasonable predictions of net ecosystem carbon fluxes and biometric pool data (Weng & Luo, 2011).
2. **Complex Ecosystem Representation**: It is widely used to illustrate complex ecosystem-level processes, including matrix generalization of carbon cycle models, model traceability, and transient behavior (Luo & Weng, 2011; Luo *et al.,* 2012, 2017; Xia *et al.,* 2013; Sierra, 2019).

Carbon Transfer Mechanism in Biomass Pools

Carbon distribution in the model occurs across three biomass pools:

- **Fine Roots**
- **Woody Biomass**
- **Foliage**

From these pools, carbon moves to metabolic and structural litter pools, where it can either be respired as CO2 or transferred to soil organic matter (SOM) pools. Transfers between compartments are depicted with blue arrows, while CO2 releases to the atmosphere are shown with red arrows (Refer to below Fig.). By integrating smart farming techniques and utilizing models like TECO, agricultural systems can significantly enhance carbon sequestration and contribute to climate change mitigation.

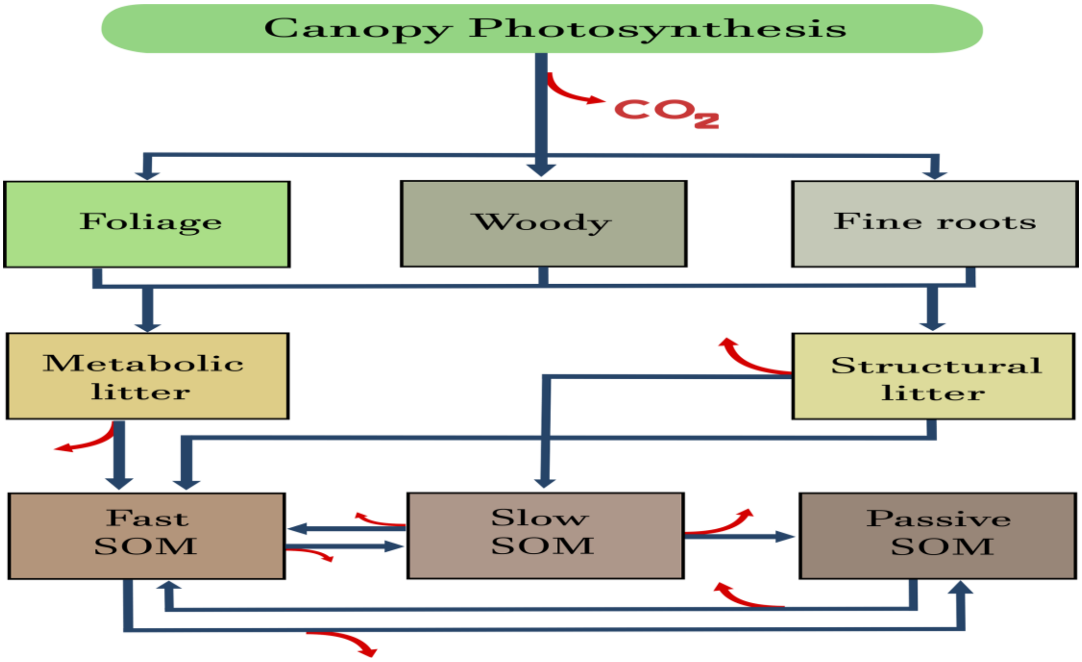

Fig. 6: Graphically presentation of the terrestrial ecosystem model (TECO), Weng and Luo (2011) and Luo *et al.,* (2012).

Effective analysis of carbon sequestration for mitigating climate change must consider both the volume of carbon inputs and the duration of carbon retention in the soil. Climate-Smart Agriculture (CSA), as proposed by the FAO (2013), serves as a systematic approach to developing agricultural policies that ensure long-term food security while maintaining environmental sustainability. To enhance soil carbon accumulation, promote carbon sequestration, reduce greenhouse gas emissions, and sustain crop productivity, various CSA management practices have been widely adopted globally. These include cover cropping, biochar application, and conservation tillage.

Meta-analysis indicates that biochar application is the most effective strategy for increasing soil carbon content, contributing to a 39% increase, followed by cover cropping (6%) and conservation tillage, including zero and minimum tillage (5%) (Bai *et al.,* 2019). To improve soil carbon sequestration, it is essential to increase carbon inputs while minimizing carbon losses. Recommended methods for enhancing soil organic carbon (SOC) sequestration include biochar amendments, integrating cover crops into the cropping cycle, and reducing soil tillage through conservation tillage practices such as no-tillage, zero tillage, or minimum tillage. While these CSA management techniques are frequently employed to improve soil health (Weng *et al.,* 2017), their effectiveness in SOC sequestration remains variable, largely depending on trial design and location-specific factors such as climate and soil properties (Poeplau & Don, 2015; Paustian *et al.,* 2016).

Biochar has the potential to influence Net Primary Productivity (NPP) by subtly modifying carbon inputs to the soil. The application of biochar can lead to increased root-derived carbon inputs, greater aboveground and belowground plant productivity, and enhanced SOC sequestration (Johnson *et al.,* 2006; Sohi *et al.,* 2009). The incorporation of biochar into agricultural soils has been shown to improve SOC by up to 40% (Liu *et al.,* 2016). Additionally, cover cropping and conservation tillage practices can enhance SOC by up to 10% (Aguilera *et al.,* 2013) and 3-10% (Zhao *et al.,* 2017), respectively. These practices also contribute to increased soil water retention (Abel *et al.,* 2013), improved soil aggregation, and enhanced cation exchange capacity (CEC) (Jien & Wang, 2013). No-tillage (NT) practices have been reported to improve SOC by 7% in the 0-3cm soil layer (Abdalla *et al.,* 2016), while nitrogen application has been shown to augment SOC stocks (Blanco-Canqui *et al.,* 2014).

To mitigate the risks associated with climate change, several smart technologies and policy solutions have been developed, including: (a) Integrated nutrient management (INM), biofertilizers, and site-specific nutrient management. (b) Weather forecasting, eco-regional crop planning, agro-advisory services, and geo-ICT-based delivery systems. (c) Selection of input-efficient and stress-tolerant crop varieties, introduction of new crops, and crop diversification. (d) Improved water efficiency through micro-irrigation systems, direct-seeded rice (DSR) cultivation in low-precipitation areas, rainwater harvesting, and well-maintained drainage systems. (e) Implementation of contingency crop planning, leveraging government incentives, insurance, and credit facilities, establishing seed banks, and initiating custom hiring centers. (f) Energy enhancement through conservation agriculture (CA), protected cultivation, solar-powered machinery, and energy plantations.

Smart farming integrates advanced technologies such as the Internet of Things (IoT), drones, robotics, and artificial intelligence (AI) to optimize farm management. By utilizing IoT hardware and Software as a Service (SaaS) platform, smart farming enables real-time data collection and actionable insights for managing agricultural operations, including pre- and post-harvest activities. These technological interventions facilitate continuous monitoring of financial and field operations from anywhere in the world. The primary objective of smart farming is to enhance farm productivity and output while simultaneously reducing greenhouse gas emissions and promoting carbon sequestration through the integration of hardware and software solutions.

Overall, CSA plays a crucial role in restoring carbon sequestration in agricultural systems. By fostering practices that build soil organic matter, enhance biodiversity, and mitigate greenhouse gas emissions, CSA contributes to climate change mitigation and promotes sustainable agricultural practices.

6. Adaptation and mitigation strategy of CSA and carbon sequestration against climate change

Nutrient management is crucial in modern agriculture, as conventional intensification leads to significant economic losses—more than 80% of which result from nutrient mismanagement (Lu *et al.,* 2015). Sustainable agricultural practices such as agroforestry, no-till farming, nutrient management, cover cropping, soil restoration, and organic manuring play a key role in enhancing carbon sequestration and increasing soil carbon content. Additionally, carbon sequestration has the potential to reduce global fossil fuel emissions by 5% to 15% (Lal *et al.,* 2004).

A study found that proper nutrient management can significantly reduce greenhouse gas (GHG) emissions. The application of the recommended nitrogen fertilizer dose in split applications—guided by the Leaf Color Chart (LCC)—led to an 11% reduction in methane (CH_4) emissions and a 16% reduction in nitrous oxide (N_2O) emissions. Specifically, when fertilizers were applied to rice crops at LCC ≤4, emissions were minimized. Similarly, in wheat cultivation, traditional nitrogen application methods resulted in approximately 18% nitrous oxide emissions, while LCC-based nitrogen application in the rice–wheat system reduced the Global Warming Potential (GWP) by 10.5% compared to blanket applications (Bhatia *et al.,* 2012; Khatri Chhetri *et al.,* 2016).

The adoption of laser land leveling (LLL) has improved farmers' income and crop yields while reducing cultivation costs and mitigating climate-induced losses (Pal *et al.,* 2020). In regions of Punjab and Pakistan, climate-smart agriculture (CSA) techniques have been studied, revealing increased cotton yields, higher returns, and improved resource efficiency (Imran *et al.,* 2018).

Farmers have shown a willingness to adopt CSA practices that enhance productivity over traditional methods. In the eastern Indo-Gangetic Plains (IGP), the most widely adopted CSA technologies include crop insurance, weather advisory services, and laser land leveling. Conversely, in the western IGP, farmers prefer crop insurance, zero tillage, LLL, direct seeding, and irrigation planning (Taneja *et al.,* 2019).

Carbon pricing also plays a crucial role in emission reductions. A high carbon price can lead to decreased production in carbon-intensive industries across cooperating countries, thereby lowering CO_2 emissions (Rolf *et al.,* 1995). The European Union's climate strategy is based on an emission trading system, where participating entities receive an "emission budget" or "non-binding target." If actual emissions remain within the budget, allowances can be traded, but entities exceeding their budget are not required to buy additional allowances (Philibert, 2000).

In India, the government has launched several initiatives to address climate change-related vulnerabilities in agriculture. The National Initiative on Climate-Resilient Agriculture (NICRA) was established to strengthen the resilience of Indian agriculture by developing and promoting site-specific climate-smart technologies and enhancing the capacity of researchers and policymakers. To further sustainable agriculture, the National Mission for Sustainable Agriculture (NMSA) was launched in 2010 by the Ministry of Agriculture and Farmers' Welfare, Government of India (DA&FW GOI).

Multiple government programs have been introduced to align with the Intergovernmental Panel on Climate Change (IPCC) goals of carbon reduction, GHG regulation, and technology adoption. These include:

- **PKVY (Paramparagat Krishi Vikas Yojana)** – promoting organic farming,
- **PMKSY (Pradhan Mantri Krishi Sinchai Yojana)** – improving irrigation efficiency,
- **RKVY (Rashtriya Krishi Vikas Yojana)** – supporting agricultural growth,
- **OFWM (On-Farm Water Management)** – enhancing water use efficiency, among others.

These efforts aim to ensure economic stability, food security, and sustainable livelihoods while mitigating the impact of climate change on Indian agriculture.

Conclusion:

The increasing Global Warming Potentials (GWPs) have raised concerns among agricultural stakeholders regarding the need to reduce emissions while maintaining soil health and production sustainability. Precision fertilization and conservation agriculture have been shown to decrease GWP by 11% and 14%, respectively, while improved management practices can reduce methane emissions from crops and the environment by 12%. Smart farming presents significant opportunities to enhance resource management, boost productivity, and improve the resilience of agricultural systems by integrating the Internet of Things (IoT), artificial intelligence (AI), and data analytics. These advancements enable precise crop monitoring, efficient resource utilization, and data-driven decision-making, providing essential pathways for climate adaptation and mitigation. By incorporating smart farming into existing agricultural systems, traditional farming practices can be transformed into highly efficient and environmentally sustainable operations. Additionally, carbon sequestration techniques play a crucial role in addressing climate change by capturing and storing atmospheric carbon dioxide in various ecosystems. Methods such as agroforestry, cover cropping, and conservation farming have demonstrated their potential to enhance soil health, increase carbon sequestration rates, and lower greenhouse gas emissions. Leveraging these natural solutions can significantly reduce agriculture's carbon footprint while promoting sustainable food production. To ensure the widespread adoption of smart farming and carbon sequestration strategies, collaborative efforts among scientists, policymakers, and stakeholders are essential. Rigorous research, technological advancements, and the establishment of supportive policy frameworks must be prioritized to scale up these solutions and integrate them into mainstream agricultural practices. A unified and coordinated approach will accelerate the implementation of these strategies and drive meaningful change within the agricultural sector. The integration of smart farming and carbon sequestration represents a powerful strategy in achieving global food security, climate resilience, and sustainable development. By harnessing the synergies between technology and nature, we can effectively tackle the dual challenges of increasing food demand and climate change mitigation. It is imperative to prioritize the implementation of these solutions and foster collaborative efforts to build a climate-resilient and environmentally sustainable future.

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ADVANCING AGRICULTURAL SCIENCE THROUGH SPEED BREEDING: A BIBLIOMETRIC STUDY

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Abstract:

Background: Food security is the biggest concern of today's world due to the constant growth in the global population. Speed breeding is considered a potential solution to address global hunger issues in the future. The study aimed to assess various aspects of the research area related to speed breeding, including time trends, author involvement, publication frequency, citations, sponsor willingness to invest, author impact, and public interest.

Material and method: The study extracted data from the Scopus database, identifying a total of 51 research publications. Among these, 31 were original articles, while the remaining 20 included review papers, short surveys, and notes from the year 2011-2023. All the articles are published in English with highest number of publications are from India.

Result: The analysis of authors, institutions, funding agencies, and citations revealed that only a select group of top authors, institutions, and funding agencies are actively engaged in research related to speed breeding, while others show less participation. The findings suggest a potential lack of awareness or interest among the broader academic and research community in this field.

Conclusion: In conclusion, despite being recognized as a potential solution to global food security challenges, speed breeding has not garnered widespread attention or engagement within the research community. The limited number of publications and the dominance of a few key authors and institutions suggest that more efforts may be needed to raise awareness, foster collaboration, and drive further research and development in the field of speed breeding.

Keywords: Speed Breeding, Crop Improvement, Food Security, Bibliometric Analysis, Network Mapping.

1. Introduction:

The population of world is growing at the fast rate and according to the latest report by united nation it has crossed the 8 billion mark and in upcoming 30 years it is believed to increase by 25% and reach upto 10 billion(*World Population Clock: 8 Billion People (LIVE, 2023) - Worldometer*, n.d.). Both Traditional and conventional breeding methods have so far produced the high yielding nutritious crop but the current pace of yield will be insufficient to fulfil the demands of the growing population (Qaim, 2020).

Breeders and plant scientists are under constant pressure to develop new crops that are climate-smart, resistant to pests and diseases, higher yielding, and more nutritious (Zaidi *et al.,* 2020). Crop improvement is an option to solve this problem and concern regarding the food security (Hickey *et al.,* 2019). Conventional technologies like genome editing, marked assisted selection, genome typing etc. work to produce the best results, but one of their limitations is that they can only produce one or two generations of crops per year(Ahmar *et al.,* 2020; Bhat *et al.,* 2016; Jighly *et al.,* 2019) . However, this limitation has been alleviated by the "Speed Breeding" protocol, which uses light and temperature control systems and is capable of producing at least six generations of crops per year (Ghosh *et al.,* 2018; Jähne *et al.,* 2020; Samantara *et al.,* 2022; Singh & Janeja, 2021).

The idea behind speed breeding dates back to around 150 years, when botanists first demonstrated that plants can thrive under artificial light. Later, the impact of light on the various plant species was examined. Midway through the 1980s, NASA partnered with Utah State University to study the wheat plant's quick growth cycle under the steady illumination of the space station. This led to the development of "USU-Apogee," while Russian scientists advocated the use of space mirrors. In order to turn night into day, Queensland University developed the technique known as "Speed Breeding" in 2003 (Bugbee & Koerner, 1997; Watson *et al.,* 2018).

Speed breeding has the potential to quickly advance our crop varieties. It is an artificial environment with increased light duration to produce longer days and to influence the life cycle of photo-resistant crops. A new variety typically takes 8 to 10 years to develop using traditional methods; however, speed breeding allows us to cut generation cycles by 2 to 3 times (Abdul Fiyaz *et al.,* 2020; Shivakumar *et al.,* 2018; Wanga *et al.,* 2021) Bibliometric analysis is a scientific methodology that can be used to identify core research or authors, as well as their relationship, by covering all the research publications related to a given topic or field. It uses Algorithmic, mathematical, and statistical techniques to process data and analyze large volumes of literature (Han *et al.,* 2020; Sood *et al.,* 2021). It is utilized broadly to quantify different kinds of information connected with the particular area, so far, this approach has been adopted in numerous research topics in the field of agriculture but to the best of our knowledge no specific bibliometric survey has been conducted on “Speed Breeding”.

The purpose of this study was to assess publications of all types on the research topic "speed breeding" during the course of history in the Scopus database using bibliometric mapping and visualization methods. This data would be of greatest importance for the scientific community, that has the same vision and mission of improvement in food security.

2. Data and Methodology:

2.1: Data description: The bibliometric data retrieved from the best database “Scopus” on 30 July 2023. The key words used to search the database was “speed breeding”. We formulate the following string for searching the published literature ((TITLE ("speed breeding") AND NOT TITLE ("plant breeding"))). Documents of all the time were taken into consideration and the first article of speed breeding was published in 2011, so the timeline between 2011-2023 were taken into consideration. Total of 51 publications were found and all the publications were in English language. To ensure the quality manual cleaning including the title and abstract analysis was done and all the 51 publications were included. The bibliographic information from selected publication was downloaded directly with the information such as author(s), title, abstract, keywords, source publications, publishing year, country, institution, literature type, citation frequency, research area and references. Total of 26 secondary documents were found, which were not indexed in Scopus but they are cited in our searched dataset. The literature extracted from the database predominantly have 28 (54.9%) articles, 11 (21.6%) reviews, 9 (17.6%) book chapters, 2 (3.9%) notes and 1 (2%) short survey. The source type of our search was 42 were from journals and 9 were from book. Table 1 summarize the bibliographic data extracted from Scopus database.

2.2: Bibliometric Mapping tools: The descriptive analysis of our data set data was estimated by using the Scopus, and the mapping of the dataset was created by VOS Viewer software version 1.6.5. it provides an effective way to construct and visualize bibliometric network of co-authorship, Co-occurrence, citation, bibliographic coupling, Co-citation. Following types of analysis is performed.

Table 1: Summary of the Speed breeding bibliographic data from the Scopus database

Variable	Results
Database	Scopus
Keyword	"Speed breeding"
String	((TITLE ("speed breeding") AND NOT TITLE ("plant breeding")))
Years	2011-2023
Primary Documents	51
Secondary Documents	26
English Language	51
Document type	
Article	28 (54.9%)
Review	11 (21.6%)
Book chapter	9 (17.6%)
Note	2 (3.9%)
Shorts survey	1 (2%)
Source type	
Journal	42
Book	9
Growth rate	19.34%

3. Result and Discussion:

In this section bibliometric analysis of downloaded dataset from Scopus is presented. There are two types of analysis in this section statistical analysis and network analysis:

3.1: Analysis of time trend: The overall growth rate of publication of speed breeding is 19.34%. yearly publication on specific area simply signifies the interest of population towards that area. In terms of publication in Scopus database the first publication regarding speed breeding was in 2011, then there was no publication till 2016 but after 2017 we observed increase in the publication like 2018 (n=4), 2019 (n= 6), 2020 (n= 11), 2021 (n=9), 2022 (n=9) and 2023 (n=10). Gradually increase in the publication number reflects the global awareness and interest towards the speed breeding process to put an end to hunger. Figure 1 summarizes the progression of publication observed through the time span.

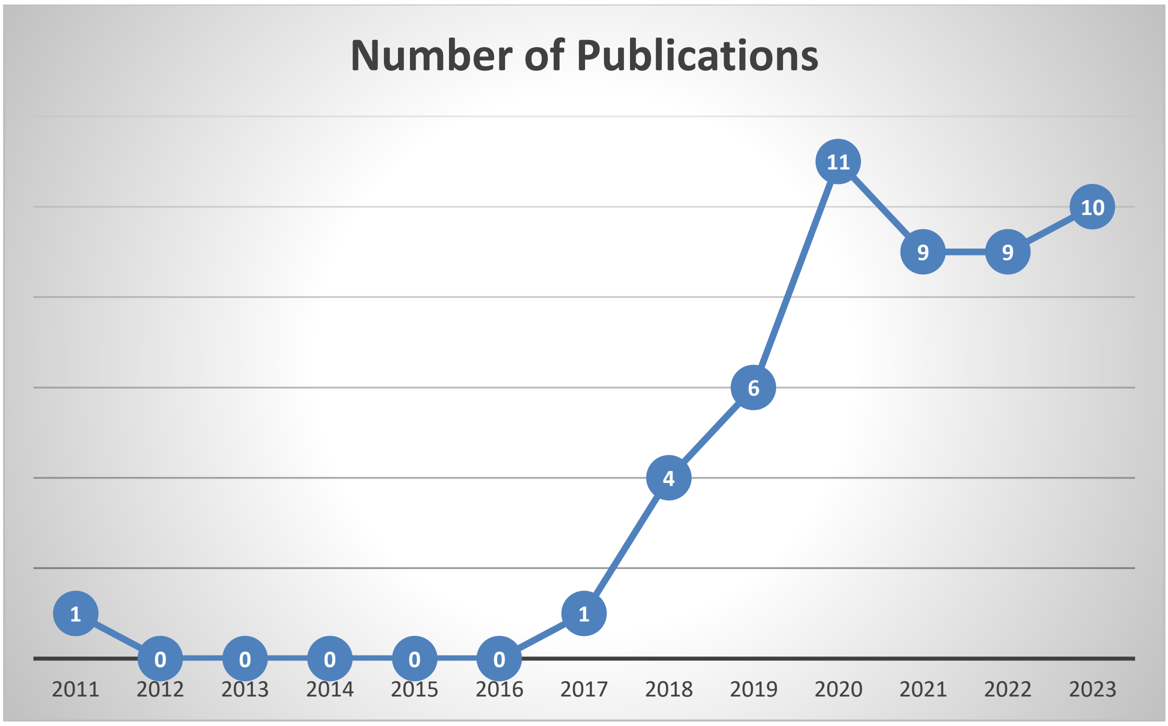

Fig. 1: Progression of publication from 2011-2023 on speed breeding in Scopus database (Source: http://www.scopus .com)

3.2: Analysis by country:

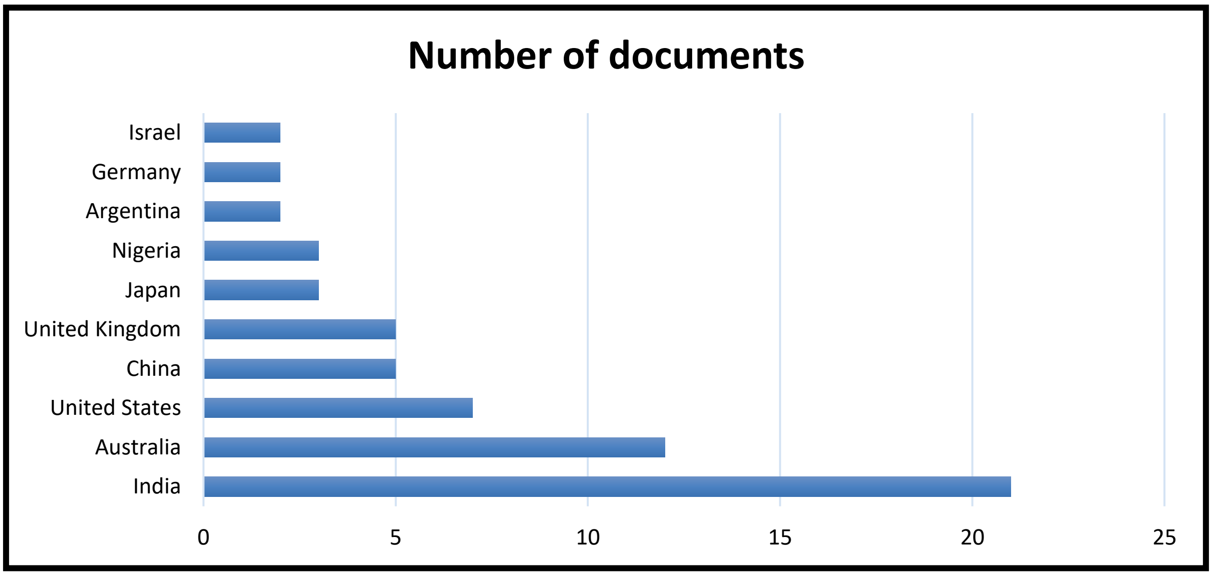

Fig. 2: Number of documents published by ten countries on "Speed Breeding" (Source: http://www.scopus .com)

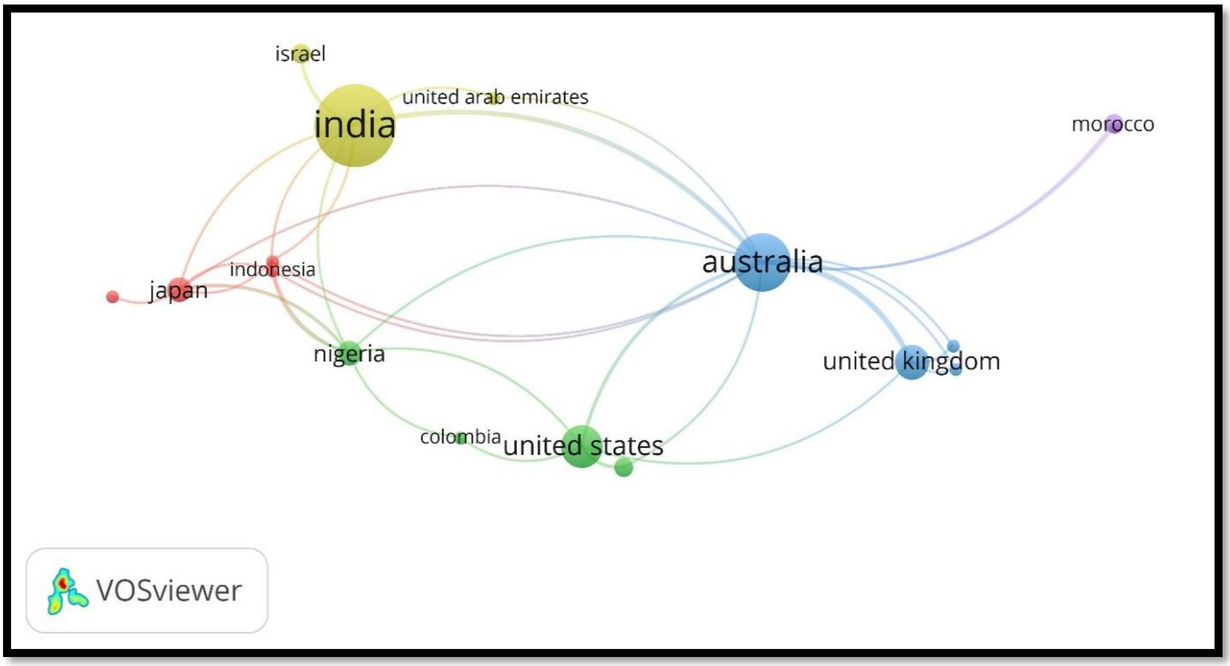

Fig. 3: Network analysis of the publications on the basis of countries

Our search results reflect that total of 27 countries are active in publication in the field of speed breeding. Most of the publications are from India, out of 51 publications India alone got n=21 publications followed by Australia (n=12), United States (n=7), China (n=5), United Kingdom (n=5) as shown in figure 2. This also somewhere reflects that India is probably more worried about the food shortage due to constant growing population and it is also reflection of developing nation. The network analysis by VOSviewer presents that the largest set of connected 17 items form 5 clusters with 34 links as given in figure 3.

3.3 Analysis by Organization:

There were 154 research institutes involved in publishing the research regarding speed breeding and The university of Queensland contributed the most by publishing 9 research papers on speed breeding followed by 3 documents by ICAR, Indian research institute New Delhi , ICAR- Indian research institute of rice Hyderabad, International Crops Research Institute for the Semi-Arid Tropics, The University of Western Australia and 2 research documents by Punjab agriculture university. Figure 4 displays the ten top countries and research institutes published the researches on speed breeding. In figure 5 Network analysis shows all 154 organizations had at least one document on speed breeding and the largest set is of connected 15 items.

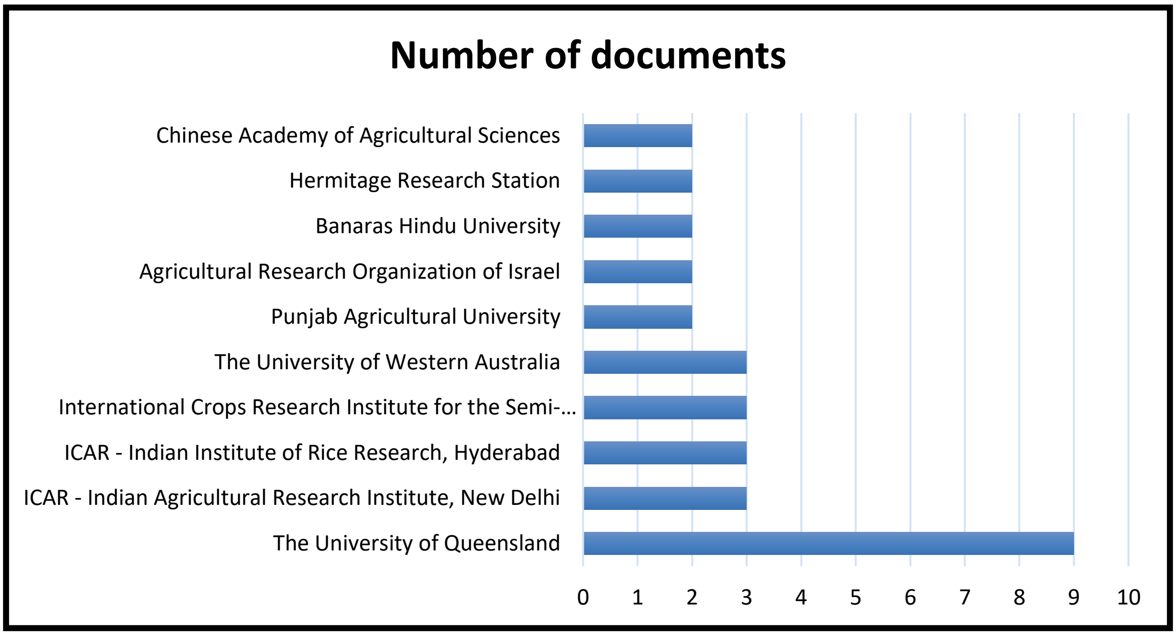

Fig. 4:List of top ten research institutes with number of documents published on "Speed Breeding" (Source: http://www.scopus .com)

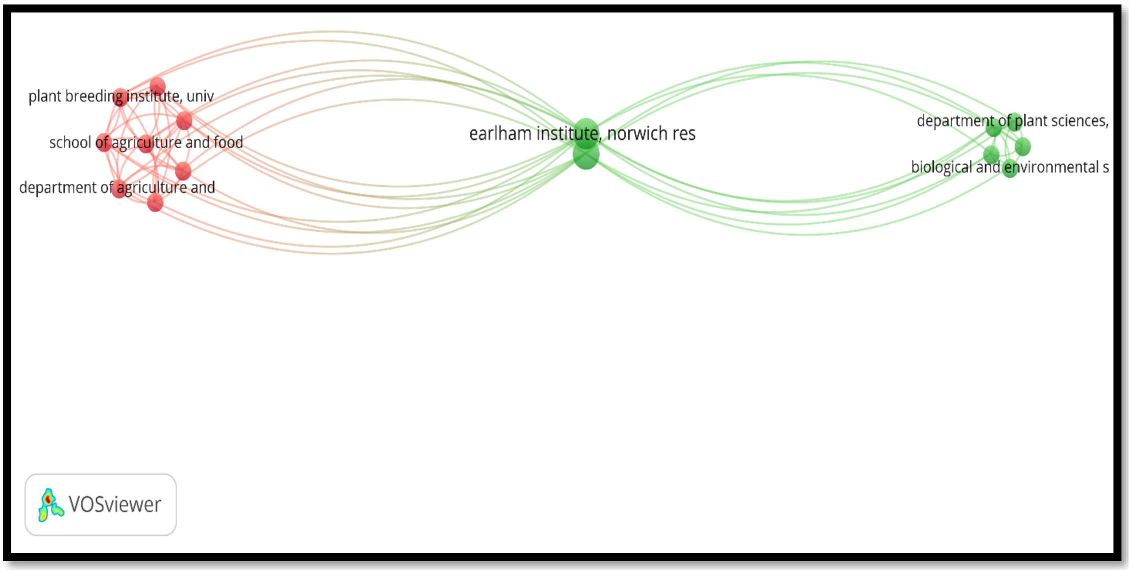

Fig. 5: Network connectivity and cluster formation on the basis of research organizations

3.7 Analysis by funding agency:

For 51 publications, total of 51 different research fundings organizations were involved. Figure 6 summarizes the top 10 funding agencies which provided funds on the speed breeding research work. Australian Research Council ranked first by funding five research publication, followed by Biotechnology and Biological Sciences Research Council and Department of Biotechnology, Ministry of Science and Technology, India by sponsoring 4 researches. Grains Research and Development Corporation, National Key Research and

Development Program of China Science and Engineering Research Board and University of Queensland were also active sponsors by sponsoring three researches.

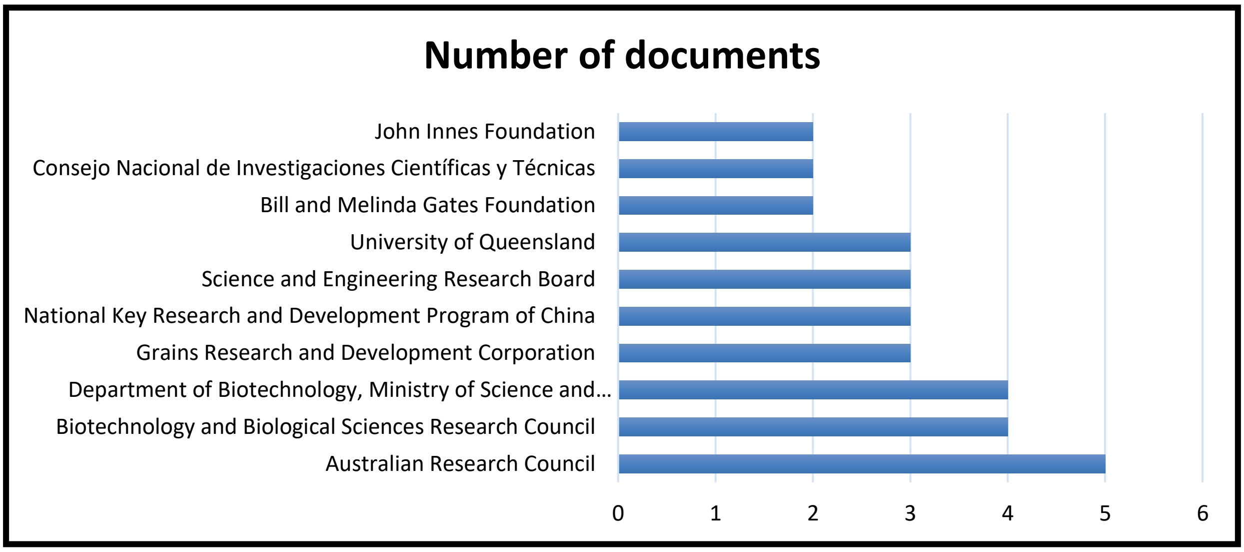

Fig. 6: Top ten funding agencies to sponsor the speed breeding research work (Source: http://www.scopus .com)

3.8 Analysis by Journals:

Table 2: Top 10 most relevant and cited journals related to speed breeding literature with cite score, SJR, SNIP, Citations and documents

Source	Documents	Citation	Cite Score	SJR	SNIP
Crop Science	4	49	4.8	0.648	1.02
Euphytica	4	104	3.7	0.504	0.844
Plant Breeding	4	39	4.3	0.506	0.82
Frontiers in Plant Science	3	30	7.1	1.231	1.58
International Journal of Molecular Sciences	2	207	7.8	1.154	1.263
Plant Journal	2	2	11.6	2.118	1.71
Plant Methods	2	58	10.6	1.121	1.904
Theoretical And Applied Genetics	2	110	9.8	1.403	1.676
CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources	2	9	3.1	0.323	0.461
Biology	1	13	4	0.779	0.981

The articles on speed breeding were published in 34 different sources and table 2 and figure 7 summarizes the top ten journals. Crop science, Euphytica and plant breeding are the most productive journals with largest number of research papers related to speed breeding (n=4) followed by frontier in plant science with (n=3) and international journal of molecular science, plant journal, plant method and CAB with (n=2) publications. This table also discuss about the citation of the particular paper in that journal with the highest citation of n=207 for the papers published in International Journal of Molecular Sciences followed n=104 for Euphytica. Figure 8 summarizes the journal citations term map showing most cited journals within the speed breeding research area.

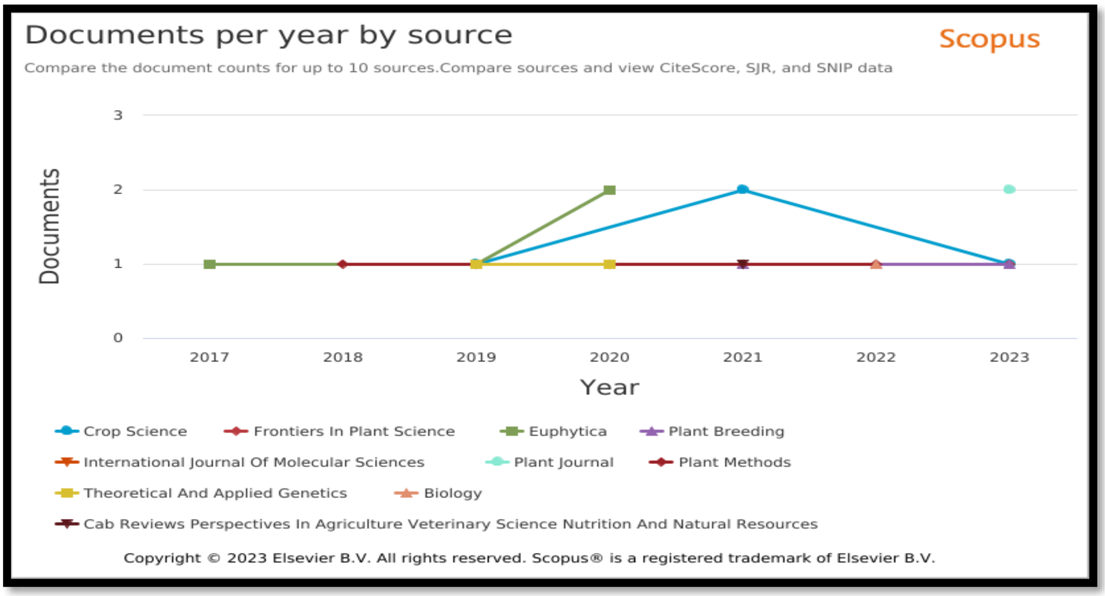

Fig. 7: Documents on "speed breeding" per year by source

(Source: http://www.scopus .com)

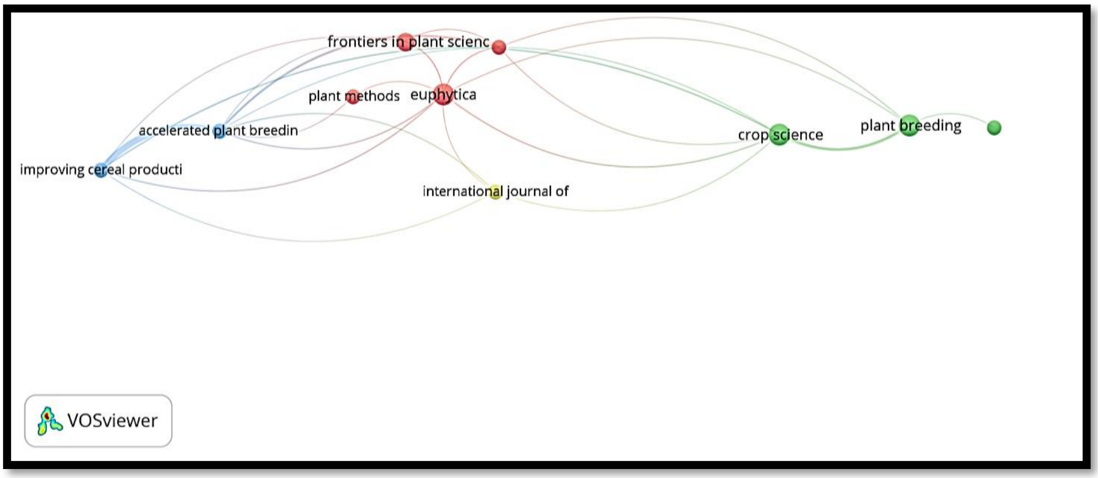

Fig. 8: The journal citations term map showing the most cited journals within the speed breeding research area.

3.9: Analysis by author: Total of 160 authors have published about the speed breeding, in which Hickey, LT. is ranked first in number of publications with n=8 followed by Watson, A and others with two articles (figure 9). On mapping co-citation (figure 10) from total 6220 authors only 33 meet the threshold on the criteria of minimum citation of 20 with three clusters of authors and 498 links among them.

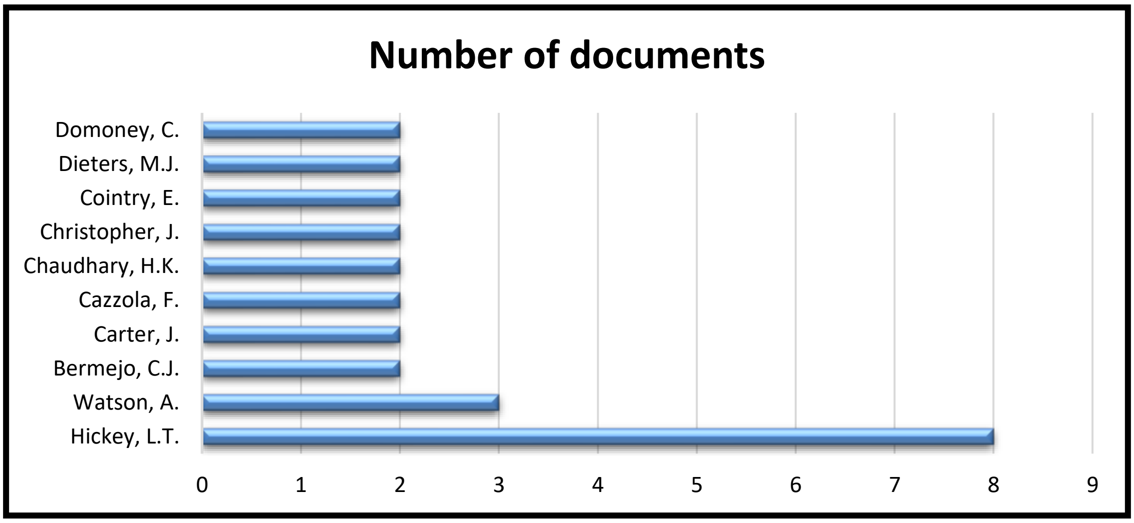

Fig. 9: Top ten authors with number of publications in this research area (Source: http://www.scopus.com)

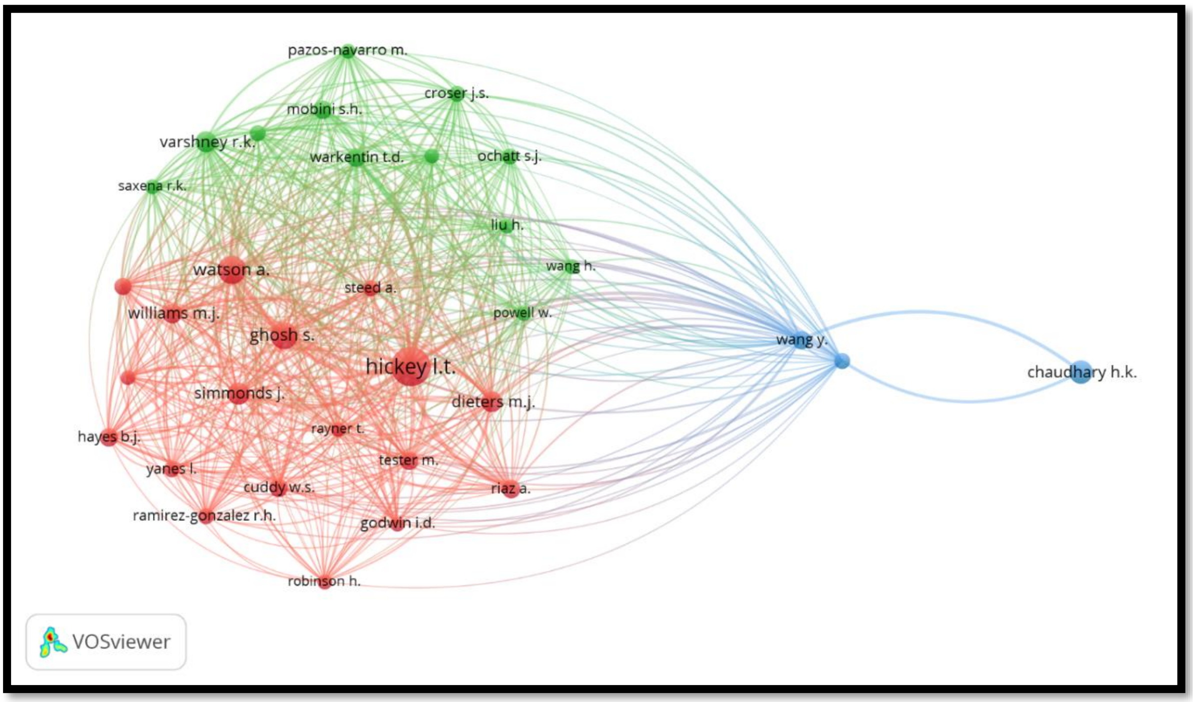

Fig. 10: The author's citation term map showing the most cited authors within the speed breeding research area.

3.10 Analysis of Co-occurrence of keywords:

The methods and outcomes of scientific study are reflected in keywords. Understanding frequently occurring terms might help one see study patterns and prospective research gaps more clearly. Table 3 and figure 11 summarize the co-occurrence of keywords, out of total 344 keywords, 75 meets threshold. With 6 clusters and 920 links. Figure 12 shows co-occurrence term map of the author keywords. Out of 148, 25 meets the threshold forming 7 clusters and 59 links. Figure 13 summarizes Index keywords and out of 221 index keywords, 49 meets threshold forming 3 clusters and 622 links.

Table 3: Summary of top 20 most used keywords

Keywords	Number of Publications
Speed Breeding	23
Plant Breeding	11
Genetics	8
Crop	7
Crops, agricultural	6
Wheat	6
Genomic selection	5
Photoperiod	5
Procedures	5
Article	4
Crop Improvement	4
Flower	4
Flowers	4
Gene editing	4
Growth, development and aging	4
Pea	4
Phenotype	4
Conventional breeding	3
Flowering	3
Food security	3

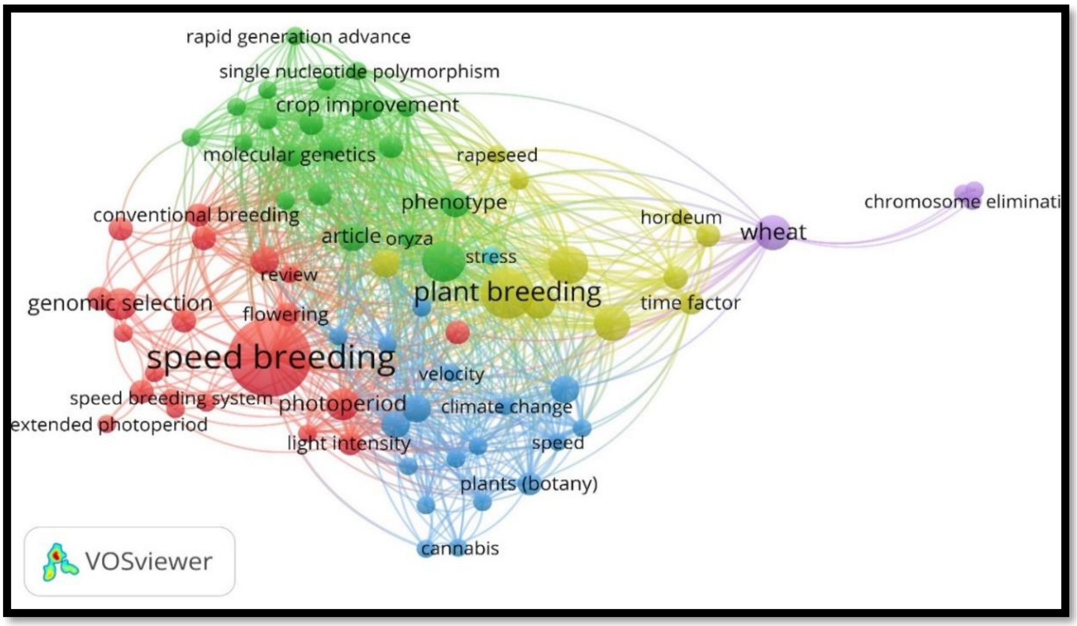

Fig. 11: The co-occurrence term map of the keywords showing the highly occurring keywords within the speed breeding research area.

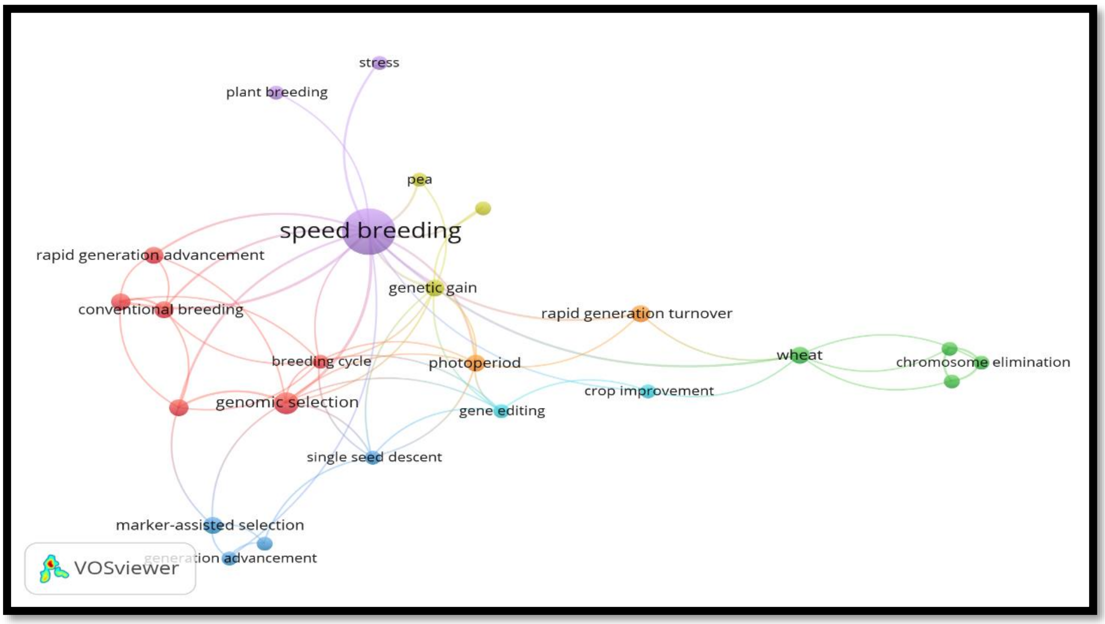

Fig. 12: The co-occurrence term map of the author keywords showing the highly occurring keywords within the speed breeding research area

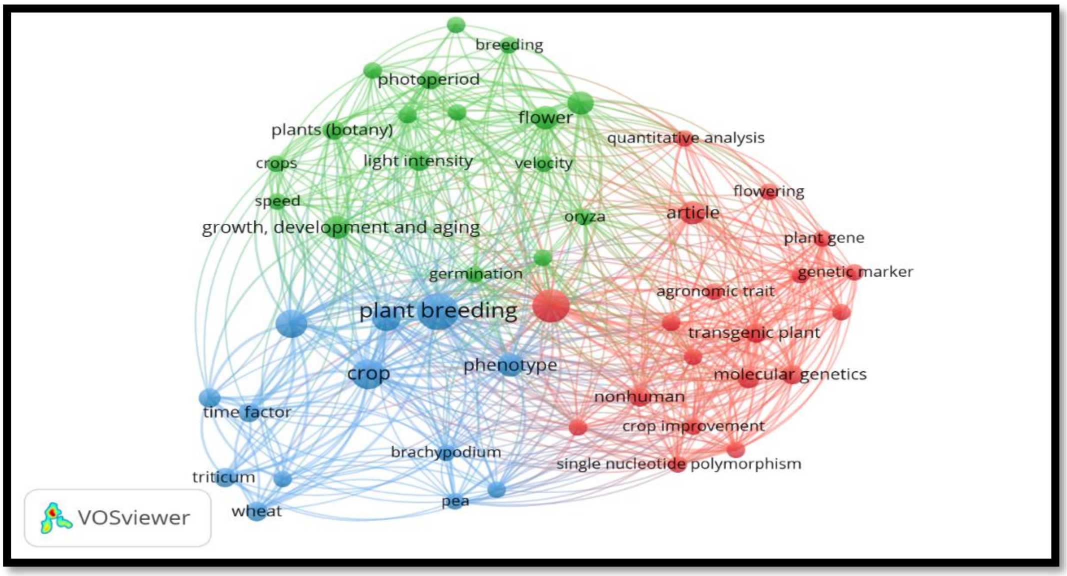

Fig. 13: The co-occurrence term map of the Index keywords showing the highly occurring keywords within the speed breeding research area

3.11: Analysis of citation:

Citation represents the impact of the research publication. Table 4 summarizes the 10 most cited articles on speed breeding literature in the Scopus database. Figure 14 highlights Watson Amy's (2018), "Speed breeding is a powerful tool to accelerate crop research and breeding" as the most cited paper with (n=538) followed by "Speed breeding in growth chambers and glasshouses for crop breeding and model plant research" by Ghosh, S. (2018) (n=151). Figure 15 summarizes the term map of cited references, total of 2717 references 9 meets the threshold, 3 clusters are formed having 13 links.

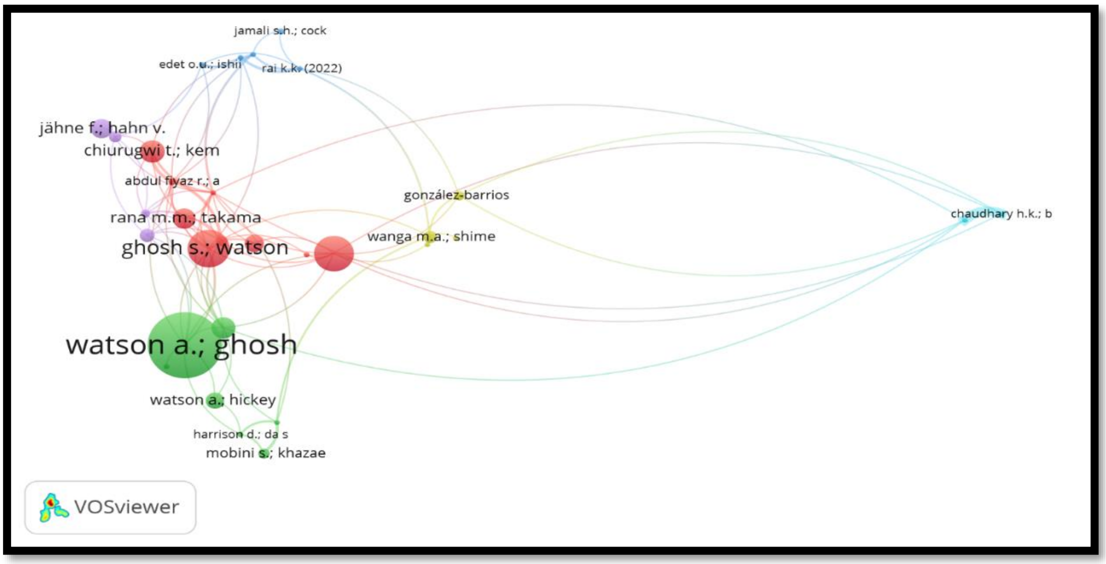

Fig. 14: The citation term map of the documents showing the highly cited publication within the speed breeding research area

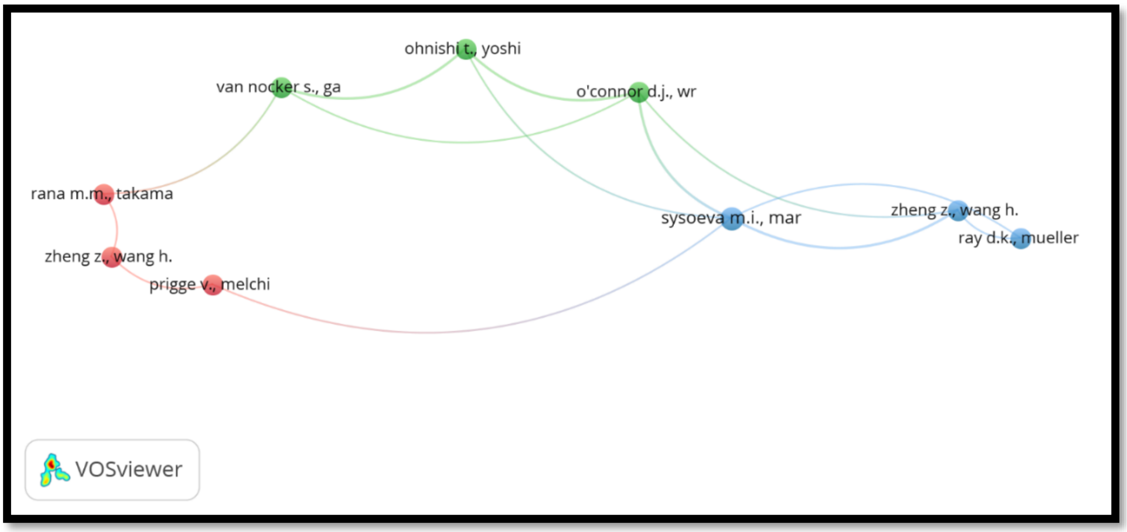

Fig. 15: The citation term map of the cited reference showing the highly cited reference within the speed breeding research area

Conclusion:

The aim of this study was to analyze the time trends, author involvement, frequency of publications, citations, sponsors willingness to invest, author impact, interest of public in this research area. Although this method is one of the saviors in the future to save the world from the hunger but still the world is not focused on this field. There is increase in the publication but the number is very less. Analysis of authors, institutions, funding agencies, citations determines that only top authors, institutions, funding agencies are interested in this area but others are not so much actively participation. On data extraction from Scopus database only 51 research publications were found and other than these 26 secondary documents were matched with our search. In these 51 publications 31 are the original articles and other 20 are review papers, short survey, notes etc. this determines either lack of knowledge among the people regarding speed breeding or lack of interest regarding this research area.

Conversely these reflects there is a lot of room and lot of research gap which we can fill to solve the problems to be faced by our future generation.

Acknowledgement:

I would like to thank Elsevier, for providing us Scopus database and inventors of VOS viewer.

Table 4: The 10 most cited articles on speed breeding literature in the Scopus database

Publication Year	Document Title	Authors	Journal Title	<2019	2019	2020	2021	2022	2023	total
2018	Speed breeding is a powerful tool to accelerate crop research and breeding	Watson A., Ghosh S., Williams M.J., Cuddy W.S., Simmonds J., Rey M.-D., Asyraf Md Hatta M., Hinchliffe A., Steed A., Reynolds D., Adamski N.M., Breakspear A., Korolev A., Rayner T., Dixon L.E., Riaz A., Martin W., Ryan M., Edwards D., Batley J., Raman H., Carter J., Rogers C., Domoney C., Moore G., Harwood W., Nicholson P., Dieters M.J., Delacy I.H., Zhou J., Uauy C., Boden S.A., Park R.F., Wulff B.B.H., Hickey L.T.	Nature Plants	33	77	113	105	141	69	538
2018	Speed breeding in growth chambers and glasshouses for crop breeding and model plant research	Ghosh S., Watson A., Gonzalez-Navarro O.E., Ramirez-Gonzalez R.H., Yanes L., Mendoza-Suarez M., Simmonds J., Wells R., Rayner T., Green P., Hafeez A., Hayta S., Melton R.E., Steed A., Sarkar A., Carter J., Perkins L., Lord J., Tester M., Osbourn A., Moscou M.J., Nicholson P., Harwood W., Martin C., Domoney C., Uauy C., Hazard B., Wulff B.B.H., Hickey L.T.	Nature Protocols	0	13	38	49	59	22	181

2020	Conventional and molecular techniques from simple breeding to speed breeding in crop plants: Recent advances and future outlook	Ahmar S., Gill R.A., Jung K.-H., Faheem A., Qasim M.U., Mubeen M., Zhou W.	International Journal of Molecular Sciences	0	0	6	44	73	32	155
2011	Application of a high-speed breeding technology to apple (Malus×domestica) based on transgenic early flowering plants and marker-assisted selection	Flachowsky H., Le Roux P.-M., Peil A., Patocchi A., Richter K., Hanke M.-V.	New Phytologist	63	8	15	12	10	5	113
2019	Speed breeding orphan crops	Chiurugwi T., Kemp S., Powell W., Hickey L.T.	Theoretical and Applied Genetics	0	5	10	20	21	7	63
2017	Speed breeding for multiple disease resistance in barley	Hickey L.T., German S.E., Pereyra S.A., Diaz J.E., Ziems L.A., Fowler R.A., Platz G.J., Franckowiak J.D., Dieters M.J.	Euphytica	8	5	8	13	23	3	60
2018	Speed breeding for multiple quantitative traits in durum wheat	Alahmad S., Dinglasan E., Leung K.M., Riaz A., Derbal N., Voss-Fels K.P., Able J.A., Bassi F.M., Christopher J., Hickey L.T.	Plant Methods	3	6	10	11	20	5	55

2019	Salt tolerance improvement in rice through efficient SNP marker-assisted selection coupled with speed-breeding	Rana M.M., Takamatsu T., Baslam M., Kaneko K., Itoh K., Harada N., Sugiyama T., Ohnishi T., Kinoshita T., Takagi H., Mitsui T.	International Journal of Molecular Sciences	0	3	11	11	19	8	52
2020	Speed breeding short-day crops by LED-controlled light schemes	Jahne F., Hahn V., Wurschum T., Leiser W.L.	Theoretical and Applied Genetics	0	0	3	16	18	10	47
2020	Rapid generation advance (RGA) in chickpea to produce up to seven generations per year and enable speed breeding	Samineni S., Sen M., Sajja S.B., Gaur P.M.	Crop Journal	0	0	9	8	13	7	37

Credit authorship contribution statement

Hemant Singh:

Conceptualization, Funding acquisition, Formal analysis, writing – original draft, Conception and design of the study, acquisition of data, analysis, and interpretation of data, Drafting the manuscript, revising the manuscript critically for important intellectual content.

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AGRICULTURE DISEASE CONTROL: RECENT TRENDS

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Abstract:

Current trends in crop disease control emphasize the convergence of new technologies, sustainable management, and innovative research to improve crop health management. Precision agriculture, driven by drones, remote sensing, and artificial intelligence, enables early diagnosis and precision intervention for better disease management efficiency. Biological control strategies, including biopesticides and beneficial microorganisms, are increasingly used to replace chemical pesticides to minimize environmental influence. Technological developments through genetic engineering, especially CRISPR and genetically modified (GM) crops, allow disease-resistant varieties to be developed as long-term solutions. Integrated pest management (IPM) is still an important strategy with a focus on ecological harmony and resistant crop varieties. Crop rotation and soil health management are becoming more important in preventing disease accumulation. Moreover, climate resilience to change, disease forecasting algorithms, and surveillance systems worldwide are being utilized for the prediction and prevention of outbreaks of disease. All these developments combined seek to make agriculture more sustainable, create greater food security, and ensure fewer chemical-intensive interventions.

Keywords: Agriculture, Disease Control, Crop rotation, AI

Introduction:

Agriculture has never been at the center of world food security and economic growth. Nevertheless, with the world dealing with issues like climate change, expanded international trade, and a rising human population, the agriculture sector is facing new and more challenging threats [1]. Of these threats, plant disease has become one of the major concerns because it has the ability to lower crop yields significantly, jeopardize biodiversity, and destabilize food supply chains. The fight against plant disease is complicated further by the fact that disease agents are evolving and adapting to control measures, thus making conventional disease management tactics less effective in the long run [2]. To address these challenges, the latest trends in agricultural disease management are more and more defined by a convergence of sophisticated technologies, sustainable approaches, and interdisciplinarity research. These trends are revolutionizing the way farmers and agri-stakeholders manage disease and are introducing more efficient, targeted, and eco-friendly solutions.

One of the most significant changes is the incorporation of precision agriculture, which uses advanced tools like remote sensing, drones, and AI to track crop health in real time [3]. Using these technologies, farmers can identify early symptoms of diseases, usually before they are detectable by the naked eye, enabling more targeted and cost-saving interventions. The other dominant trend is the increasing focus on biological control strategies, including biopesticides and the employment of beneficial microorganisms [4]. These biological control agents are being created and marketed as eco-friendly substitutes for traditional chemical pesticides, which are frequently damaging to the environment and non-target organisms [5]. This method not only controls the pathogens but also fosters ecological balance by maintaining useful organisms in the agroecosystem.

At the same time, there has been renewed investment in the creation of genetically modified (GM) crops and application of CRISPR technology for gene editing [6]. These biotechnology advances make it possible to develop crops with built-in immunity to certain diseases, providing a long-term solution to repeat plant disease attacks. These GM crops have the potential to drastically minimize the application of chemical treatments and promote a more sustainable management of disease. The Integrated Pest Management (IPM) concept remains a pillar of plant disease management in agriculture [7]. IPM promotes an integrated approach by integrating biological, cultural, mechanical, and chemical control of pests and diseases in such a way that the environmental and economic costs associated with these controls are minimized. Not only does IPM minimize pesticide use but also stimulates practices like crop rotation, soil health management, and resistant crop varieties to avoid disease accumulation [8].

Increased focus on sustainability has also propelled major shifts in disease control strategies. Organic agricultural practices that focus on natural controls tend to use neem oil, sulfur, and composting [9]. These practices help to sustain soil health and diversity while controlling pathogens in a manner that minimizes damage to the environment. Besides, the impending specter of climate change has shifted the dynamics of disease outbreaks [10]. Climate fluctuations in terms of temperature and rainfall patterns have caused new disease problems, prompting the creation of climate-resilient crops and sophisticated disease prediction models that assist in predicting outbreaks depending on the evolving climatic patterns. These forecasting models facilitate farmers to take action proactively to safeguard their crops, which could potentially counteract the effects of future disease epidemics. In addition, a greater emphasis on global coordination and surveillance networks has ensued. Since diseases in plants have a tendency to cross international frontiers by international trade and transit, governments, researchers, and private organizations now need to cooperate with each other to handle looming threats [11]. Online monitoring and the sharing of information are enabling scientists and farmers to monitor the diffusion of disease more easily and therefore respond more speedily and efficaciously. The management of agricultural diseases is facing a revolution, spurred by demands for greater efficiency, sustainability, and flexibility [12]. Through the leveraging of the potential in contemporary technology, biological substitutes, and creative agriculture, these emerging trends are set to defend crops against disease while lowering the ecological cost of farming. As these methods keep evolving, they have the potential to increase food security, advance the strength of farm systems, and protect ecosystems for generations to come.

Precision Agriculture, Data-Driven Approaches, and AI:

The integration of new technologies such as drones, remote sensing, and artificial Intelligence (AI) with real time monitoring of crop health has transformed precision agriculture disease management [13]. Drones have cameras and sensors that are able to capture high-resolution images of plants and asses their health and detect stress, nutrient deficiency, or disease long before they become visible [14]. Because issues can be identified earlier in the development process, there is less potential for diseases to spread and less pesticides would need to be applied. The role of AI involves analyzing data from different sources which includes satellite images, sensors, and even history of diseases to develop predictive models. AI algorithms estimate the likelihood of disease onset and pest problems by assessing the available data on the crops and environmental state. Farmers can utilize these models to implement proactive interventions [15-16]. Moreover, specific prescriptions can be given by AI powered decision support systems, which enables cost-effective, efficient, and eco-friendly practices. Elimination of convoluted disease management practices will result in sustaining cleaner crops, healthier yields, and sustainable farming services [17].

Limitations and Challenges:

Though precision agriculture, data-driven techniques, and AI hold a lot of promise in managing diseases, a number of restraints and hurdles must be resolved. A foremost challenge is the heavy up-front expense of the technology, such as drones, sensors, and AI-based platforms, which is unsustainable for small-farm operators or those in low-income areas [18]. Furthermore, the data analysis complexity needs experts to analyze the vast amounts of data produced, and trained staff is usually in short supply in rural or developing regions. Data accuracy and quality are also at risk, as sensors and remote technology can be impacted by environmental conditions like weather, soil heterogeneity, and sensor failure, which can result in incorrect disease diagnosis or prediction [19]. Additionally, connectivity problems in rural agricultural areas can hamper the gathering and transmission of data in real-time, slowing down decision-making. There is also the possibility of dependence on technology, where farmers become too dependent on AI recommendations, possibly at the expense of conventional knowledge and grassroots understanding [20]. Finally, the integration of new technologies into conventional farming methodology and infrastructure can prove to be cumbersome, entailing considerable time, effort, and resources. To overcome these challenges, there must be sustained research, investment, and training to make precision agriculture more affordable, effective, and expandable.

Solutions:

Numerous approaches are being used to address the problems posed by AI, data-driven tactics, and precision agriculture. The development of less expensive sensors, drones, and AI software is one of the main ways to lower the cost of technology and make it more affordable for smallholder farmers. Governments, non-governmental organizations, and the private sector working together can also help finance the adoption of technology in rural places and subsidize its costs. For farmers and farm workers to be able to appropriately analyze and react to data, education and training are essential. Farmers can employ AI tools without much technical expertise by using mobile applications and user-friendly web platforms that make data interpretation simple. Machine learning algorithms can be continuously retrained to improve over time, and sensor technology and calibration methods are being improved to give data accuracy and make collected data more dependable [21]. Enhancing rural broadband networks or adding offline functionality to AI-based systems that can store data locally and sync when connectivity is available are two ways to combat connectivity issues. Another crucial answer is to integrate modern technology with indigenous expertise, where AI enhances rather than replaces native knowledge. Last but not least, in order to create tailored, scalable solutions that work with various farming systems and geographical areas, farmers and technology developers must work together to make technology adoption practical, helpful, and sensitive to local conditions [22].

Conclusion and Future Perspectives:

Current trends in agricultural disease management reflect a movement towards more sustainable, efficient, and technology-based approaches. The convergence of precision agriculture, artificial intelligence, and biological control practices has transformed the management of plant health for farmers, with early detection, site-specific treatments, and lower dependency on chemical pesticides [23]. Despite this, high costs, data interpretation issues, and infrastructure constraints are still hurdles to large-scale adoption. In the future, ongoing innovation of digital technologies, gene editing, and cooperative worldwide endeavors will progressively enhance disease control methods to become more accessible, scalable, and versatile to varying farm settings. In addition, greater emphasis on climate change adaptation and sustainable management will inform disease control practices that find a balance between productivity and ecosystem conservation [24]. With further advances in research and innovation, the future of agricultural disease management will probably see more integrated, proactive, and data-based measures in place, maintaining the long-term health of crops and global food security.

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CARBON BUDGETING FOR CLIMATE-RESILIENT AGRICULTURE

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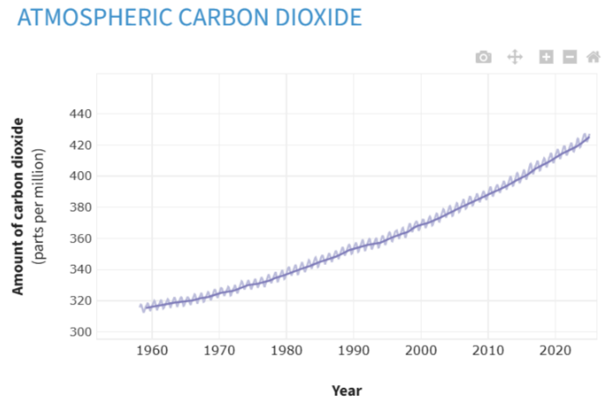
Introduction:

Climate change is the most critical issue in the world today. This is a significant topic of our concern. Climate change can be defined as the changes in climatic conditions in the Earthand it refers to the rise in temperature all over the world. It is happening because of increase in greenhouse gas concentration in atmosphere. Reasons for climate change can be of two types. The first one is the natural causes which include volcanic eruptions, fluctuations in solar radiation, and tectonic shifts. The second one is the human-driven causes which include the emission of greenhouse gases due to human activities. Carbon dioxide, nitrous oxide, and methane contribute to greenhouse gases. These gases create an envelope around the world which entraps the radiation and increases the temperature.



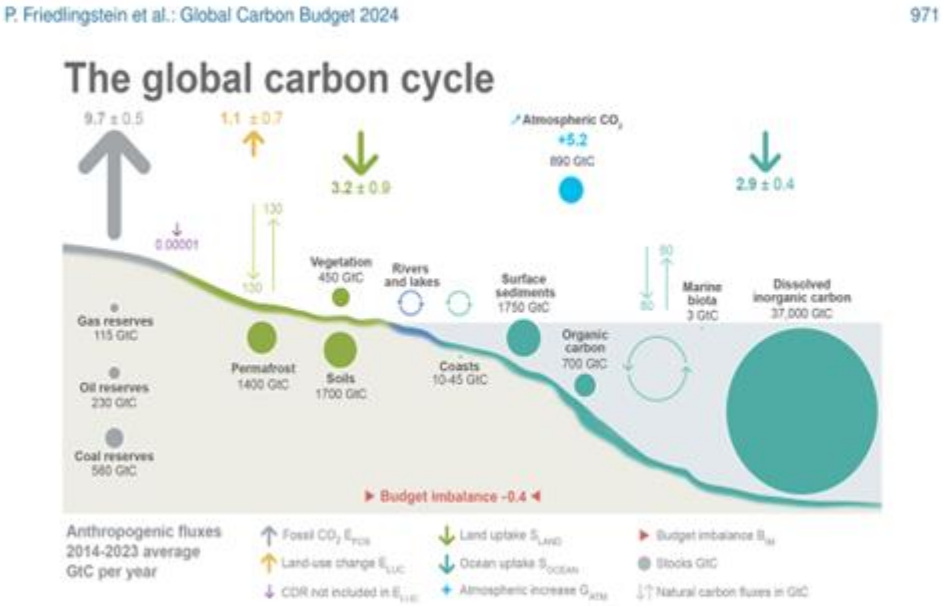
The modern record of atmospheric carbon dioxide levels began with observations recorded at Mauna Loa Observatory in Hawaii. This graph shows the station's monthly average carbon dioxide measurements since 1958 in parts per million (ppm). The seasonal cycle of highs and lows (small

Carbon dioxide emission is the major reason for global warming.According to NASA, atmospheric carbon dioxide content has increased by 50% in less than 200 years. In 1960, CO_2 concentration in the atmosphere was about 316 ppm. It has increased to 426 ppm by 2025. This graph shows the increasing concentration of CO2 in the `atmosphere from 1960 to 2025. It leads to rising sea levels, extreme weather conditions, and changing rainfall distribution that ultimately affects agricultural production.

Due to the huge carbon dioxide emission from different sources and industries, the global surface temperature shows an increase of 1.09°C in 2011-20 than 1900-1950. According to NASA, Earth's temperature will increase 1.47°C in 2024 than in the 19th century (NASA). The impact of global warming can be seen in climate exposed sectors like agriculture, forestry, fishery and others. Particularly, economic damages can be seen in agricultural sectors.

To mitigate these problems, carbon budgeting is a great concept that is used to set emission reduction targets. Carbon budget can be defined as the maximum amount of carbon dioxide emissions that can be released into the atmosphere to limit global warming. To calculate the carbon budget, carbon dioxide emission, and carbon sequestration through plants into the soil are the major factors. To quantify carbon budgeting, calculations of five major componentsare necessary. These are fossil CO_2 emissions (E_{FOS}), emissions from land-use change (E_{LUC}), atmospheric CO_2 concentration (G_{ATM}), the ocean CO_2 sink (S_{OCEAN}), and the terrestrial CO_2 sink (S_{LAND}). This paper describes all the components of global carbon budgeting in the recent period and the effect of adopting climate-resilient agricultural strategies. With the help of all the components, Budget Imbalance (B_{IM}) is calculated by the following formula:

$$B_{IM} = E_{FOS} + E_{LUC} - (G_{ATM} + S_{OCEAN} + S_{LAND})$$



Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2014–2023.

According to the data from Global Carbon Budget2024, fossil CO_2 emissions show an increase of 0.8% in 2024 relative to 2023 (-0.2% to 1.7%), bringing emissions to 10.2 GtCyr^{-1}. 1.1-0.7GtCyr-1 carbon has been emitted from land-use, land-use change, and forestry (LULUCF) for the 2014–2023 period (Global Carbon Budget, 2024). The atmospheric CO_2 concentration shows an increasing pattern of 5.2 GtCyr^{-1} during the decade 2014-2023(Global Carbon Budget 2024). The ocean CO2 sink was about 2.9GtCyr-1 during the decade 2014-2023 (26% of total CO2 emissions) (Global Carbon Budget 2024). The land sinkwill contain 2.3GtCyr-1in 2023 (Global Carbon Budget 2024).

There are two main objectives to estimate the global carbon budget. First, the demand for up-to-date information is large. Many scientists, journalists, stakeholders, and other educational organizations rely on the dataset provided in the global carbon budget. Second, we have seen many unpredictable changes in the environment over the last decade. To mitigate these challenges, we have to assess and select a better approach to save our planet. To reduce greenhouse gas emissions, the Kyoto Protocol was the first international agreement that committed industrialized countries and economies. Paris Agreement is an international treaty that calls on all countries to set emission targets and to limit global warming below 2°C above pre-industrial levels, and ideally to 1.5°C. To reach the emission targets and to deal with climate change, agricultural systems must be resilient and able to adapt to changes in the environment. Reduction of GHG emission and Carbon sequestration are both necessary to achieve emission targets.

Climate resilient technologies created a mitigation potential of 42,317 Mg CO_2 eq. in (Journal of Environmental Management). Climate resilient agriculture is the management strategy by which the agricultural sector can adapt the climate change and reduce its impact on the environment. Agricultural technologies, innovations, and management practices can affect the two components of the carbon budget i.e. emissions from land-use change (E_{LUC}) and the terrestrial CO_2 sink (S_{LAND}). Indian agriculture has the potential to mitigate 85.5 Mt CO_2eq per year with the adoption of improved agricultural practices (Saptoka *et al.,* 2019).

A few CRA practices are depicted below.

First, Agroforestry includes the cultivation of trees along with crops, which helps in soil moisture retention. Agroforestry, as a practice for climate-resilient agriculture, holds a greater potential but challenges are there. Roshan Pancholi *et al.,* (2023) stated thatagroforestry systems should planned, monitored and managed through technological advancements, such as remote sensing, machine learning.

Second, contour bunding, farm ponds and check dams can help in soil and water conservation. In an experiment conducted at loamy soil of semi-arid region of Rajasthan, due to increasing soil moisture availability, mean mustard seed yield increased by 14.4% and biological yield by 15.3% in field bunding rather than no bunding (Regar *et al.,* 2007).

Third, sustainable agriculture can also reduce GHG emissions and improve farmer's income and food security. Spatial and some analytical techniques can be helpful to boost up the agriculture industry and challenges regarding food security can be mitigated by adapting better land resources in changing climatic conditions (Bonfante *et al.,* 2015).

Fourth, the concept of developing climate smart villages. Climate-smart village is a concept thatincreases the potential of the research for better agricultural practice development and increased crop production via integrating scientific approaches, technical issues, and institute participation to mitigate the negative effects of climate change (Bayala *et al.,* 2016; Aggarwal *et al.,* 2018).

Few major steps are taken by the government to support climate-resilient agriculture such as the National Action Plan on Climate Change (NAPCC) which provides a policy framework for climate action in the country. The NationalMission for Sustainable Agriculture (NMSA)was introduced in 2018 to minimize the risk associated with climate variability. A project named National Innovations in Climate Resilient Agriculture (NICRA) was launched in 2011 by ICAR to promote climate-resilient agriculture. The most important thing is awareness among the people. It is necessary to aware people about these governmental projects and to increase demand for climate-resilient agriculture.

Conclusion:

To predict future climate changes, it is necessary to study the components of the carbon budget. With the help of the information, experimental models should be made. The virtual human-made planet can become the best laboratory for studying future climate change. Climate change adaptation and flexibility of the crops are the main aspects for the future. First, it is needed to reach the carbon emission target set by the different agreements. Second, improved measurement systems, techniques for adaptation, different tools, and mitigation strategies should be taken for climate change adaptation.

So, "What will be the future of climate resilient agriculture in the next decades?". Although the answer is unknown, scientists and researchers are trying to solve all the problems related to climate change and to adopt climate-resilient agriculture. People all over the world should support and try to cooperate with the policies and the agreements taken by the government. Together we can create a better future for climate resilient agriculture.

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MYCORRHIZAL PARTNERSHIPS:
AN ESSENTIAL APPROACH FOR CONTROLLING ROOT DISEASES

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The term mycorrhiza originates from the ancient Greek words for "mushroom" and "root." In a mycorrhizal relationship, the subterranean mycelium interacts with plant roots without inflicting any damage on the plants. Fossil records and DNA sequencing indicate that this beneficial partnership emerged between 400 and 460 million years ago. Vesicular arbuscular mycorrhizal fungi are classified within the Zygomycetes class, the Endogonales order, and the Endogonaceae family. Mycorrhizal fungi play a crucial role in enhancing the growth of host plant species by facilitating greater nutrient absorption, producing substances that promote growth, and increasing resilience to drought and salinity, as well as fostering beneficial interactions with other microorganisms. The soil conditions typically found in sustainable agricultural practices are generally more conducive to arbuscular mycorrhizal (AM) fungi compared to those in conventional farming. These fungi are extensively found in both natural and agricultural settings, and they have been associated with over 80% of terrestrial plants, including liverworts, ferns, woody gymnosperms, angiosperms, and grasses. The role of mycorrhizosphere organisms has likely been diminished in intensive agricultural practices, as the microbial communities in conventional farming have been altered due to tillage and the excessive use of inorganic fertilizers, herbicides, and pesticides. This alteration has led to a decline in microbial diversity, and the implications of this loss remain largely unexplored. While the widespread application of inorganic fertilizers has significantly boosted agricultural output both regionally and globally, it is crucial to consider its detrimental effects on soil fertility, environmental sustainability, soil biodiversity, runoff concentration, and pollution in aquaculture. Growing environmental awareness has gradually prompted a transition from conventional intensive farming to low-input crop production. There are various management strategies available to address disease challenges in different crops, but their successful application hinges on a thorough understanding of how plants physiologically respond to these stresses. This article seeks to examine the primary mechanisms involved in the biological control of diseases caused by soil-borne phytopathogens following root colonization by arbuscular mycorrhizal fungi.

Exploring the Mechanisms Behind Root Disease Control

Soil-borne pathogens have been managed through various agricultural practices, including the use of resistant plant varieties, seed certification, chemical fungicides, crop rotation, and soil fumigation. However, controlling these pathogens poses significant challenges due to their long-lasting survival structures, which complicate efforts to reduce pathogen inoculum and the limited availability of effective plant resistance sources. As a result, many researchers are exploring alternative strategies that involve either manipulating or introducing beneficial microorganisms to bolster plant defenses against pathogens. These beneficial microorganisms, such as antagonistic bacteria like Pseudomonas fluorescens and Bacillus subtilis, as well as fungi like arbuscular mycorrhizal fungi (AMF) and Trichoderma, engage in competition with plant pathogens for nutrients and space. They achieve this by producing antibiotics, parasitizing the pathogens, or triggering resistance mechanisms in the host plants.

Boosting the Efficiency of Nutrient Uptake in Plants

Enhancements in plant growth associated with root colonization by arbuscular mycorrhizal fungi (AMF) stem from improved mineral nutrient availability for the plants. Some studies suggest that changes in root exudation induced by phosphorus can inhibit the germination of pathogen spores. Additionally, research indicates that the competition for space between AMF and pathogens may bolster the host's resistance to pathogens by facilitating the absorption of essential nutrients, which are often lacking in plants without mycorrhizal associations. The spores of AMF germinate, and their thick-walled hyphae invade the host roots, leading to internal infections. Once inside, the hyphae proliferate both inter- and intra-cellularly within the root cortex while preserving cell integrity. This enhanced nutrient uptake contributes to the development of more robust plants, potentially increasing their resistance or tolerance to pathogen attacks.

Compensation for Damages

Furthermore, the interaction between AMF and plant roots not only aids in mitigating the adverse effects of pathogens but also promotes overall plant health. By fostering a more robust root system, AMF plays a crucial role in enhancing nutrient uptake and resilience against environmental stressors, ultimately contributing to improved plant growth and productivity. This symbiotic relationship underscores the importance of AMF in sustainable agricultural practices and ecosystem management.

Modifications in Morphological and Anatomical Features

The morphology of root systems can be significantly influenced by the colonization of arbuscular mycorrhizal fungi (AMF). Roots that are colonized by AMF exhibit a greater degree of branching compared to those that are not, and the diameters of adventitious roots tend to be larger. This structural enhancement can create additional sites for potential pathogen infection. Research has indicated that the infection of tomato and cucumber plants by Fusarium wilt may be mitigated due to the morphological adaptations observed in the endodermal root cells of AMF-colonized plants, which include increased lignification. This heightened lignification may serve as a protective barrier against pathogen invasion while also boosting phenolic metabolism within the host.

Arbuscular mycorrhizal fungi (AMF) significantly enhance the effective root surface area, allowing plants to access larger volumes of soil and effectively navigate zones where water and nutrients are depleted around active root surfaces. Mycorrhizal roots exhibit greater weight, length, quantity, and diameter compared to non-mycorrhizal roots. The average diameter of fungal hyphae, measuring 3-4 μM, is notably smaller than that of root hairs, which exceed 10 μM. This size difference enables fungal hyphae to penetrate soil pores and make contact with soil particles that root hairs cannot reach. Consequently, arbuscular mycorrhizal roots substantially improve the uptake of essential mineral nutrients in plants. Research has demonstrated that mycorrhizal plants show enhanced nutrient absorption, particularly phosphorus (P), compared to their non-mycorrhizal counterparts. The absorption of soil phosphorus by mycorrhizal plants occurs more rapidly and completely, as the diffusion distance for HPO4-2 and H2PO4 ions is shorter to the hyphae than to the roots. The enhancement of phosphorus nutrition in plants is one of the most recognized and well-documented benefits of mycorrhizal associations. Phosphate is converted into polyphosphate-by-polyphosphate kinase within vacuoles, where it is stored and transported between hyphal tips and the symbiotic interface. The rate of translocation is influenced by the net efflux of phosphorus at the hyphal tips and the net uptake. The unusually high phosphorus loss from arbuscules has been explained through two proposed mechanisms: first, a high concentration of phosphorus in arbuscules may inhibit the reabsorption of lost phosphorus by hyphae, which correlates with a lower expression of high-affinity phosphorus transporters in the fungal tissue within roots compared to their levels in external hyphae. Second, phosphorus efflux may be facilitated by changes in the operation of transmembrane proteins that regulate ion channels. Mycorrhizal fungi are adept at mobilizing phosphorus and nitrogen from their organic substrates.

The fundamental nature of mycorrhizal associations lies in their ability to support primary producers by fighting off diseases and providing vital nutrients necessary for growth. Given the current circumstances, it is crucial to explore the mechanisms and types of interactions involved, as well as to identify the key genes in both fungi and plants that govern these relationships. However, modern agricultural practices pose a threat to these beneficial partnerships. Human activities such as slash-and-burn farming, mining, waste disposal, and deforestation significantly harm mycorrhizal networks. The excessive use of pesticides and fertilizers has not only led to environmental degradation but also jeopardized the survival of countless organisms. Therefore, there is an urgent need to emphasize eco-friendly alternatives like mycorrhizae. Additionally, efforts should focus on discovering more effective strains of mycorrhiza that can adapt to various environmental conditions. A comprehensive understanding of the trade-offs associated with mycorrhizal relationships, along with a thorough grasp of the interaction mechanisms, will be vital for advancing mycorrhizal technology and ensuring a sustainable future.

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ASSESSING AND MAPPING OF SOIL QUALITY: INDICES AND GEOSPATIAL APPROACHES FOR SUSTAINABLE LAND MANAGEMENT

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Abstract:

Unsustainable use of land resources leads to degradation of soil resulting decline in soil functions such as crop productivity, regulation of the hydrological cycle, water quality and soil quality. Soil quality is influenced by inherent and anthropogenic factors. It is used to evaluate soil resource functions as how well soil performs for all its functions at present and how these functions will be preserved for future use. It cannot be measured directly, so we evaluate indicators. Indicators are measurable properties of soil, they can be physical, chemical and biological properties or characteristics of soils. Soil quality indices are usually used for the objective measurement of soil quality. These are useful tools for assessing the overall soil condition and response to management towards natural and anthropogenic factors. It helps to determine what conservation practices are needed to protect soil and water resources. The geospatial technique helps in providing spatial distribution of soils and representation of soil quality. Satellite remote sensing data and derived digital elevation models (DEMs) are used to map soils and landforms to evaluate soil quality. Soil quality assessment has been recognized as an important step towards understanding the long-term effects of various land management practices. It will help the land managers in preparing land use plans and management decisions for optimal use, hence assisting in sustainable land management. The chapter discusses various geospatial modelling methods in soil quality assessment.

Keywords: Geographic Information System (GIS); Remote Sensing (RS); Soil Health (SH); Soil Quality (SQ); Soil Quality Indicators (SQI).

1. Introduction:

The ever-growing world population leads to enormous pressure on land resources to produce almost 70% higher agricultural produce by 2050 compared to 2005 (Lal, 2015). Overexploitation of land may lead to degradation, and at present, 33% of arable land suffers from various kinds of degradation processes. These land degradation processes may result in a decline in soil quality or soil health and a decrease in ecosystem goods and services. It may severely affect our chances of achieving the increased agricultural productivity necessary to nourish the expected global population of 9.5 billion by 2050 (Lal, 2015; Meena *et al*., 2018). Thus, sustainable land management practices to maintain or improve soil quality and achieve optimum agricultural production levels are extremely needed.

S oil quality refers to "the inherent capacity of a soil to function within natural or managed ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health" (Doran and Parkin 1994; Meena *et al*., 2018a). A thorough understanding of soil quality or its parameters enables us to gain insight into the status of soil as a natural resource and also enables us to make necessary alterations in different soil parameters to improve the functioning of a particular soil (Herrick, 2000). The various functions of soil or ecosystem services derived from it necessitate defining soil quality from other perspectives too. For example, the definition of soil quality from an environmental perspective states it as "the capacity of the soil to promote the growth of plants, protect watersheds by regulating the infiltration and partitioning of precipitation, and prevents water and air pollution by buffering potential pollutants such as agricultural chemicals, organic wastes, and industrial chemicals" (Sims *et al*., 1997). Thus, the definition of soil quality varies as per its functions and services derived from it.

Soil quality evaluation has widely been accepted as a vital step towards realizing the long-term consequences of various land management practices. Soil quality assessment is essential to show the influence of various agricultural management practices on soil productivity as well as environmental quality. Several physical, chemical, and biological indicators are being used to assess soil quality from a crop production perspective. Among these indicators, biological indicators are considered most sensitive to changes compared to other physical/chemical indicators and could effectively describe the soil quality in an overall view. Several conceptual frameworks for monitoring soil quality have been proposed by various researchers (Andrews *et al*., 2004; Viscarra Rossel *et al*., 2006; Basak *et al*., 2016; Biswas *et al*., 2017). Selection of a minimum dataset (MDS) consisting of different physical, chemical, and biological properties vital in terms of soil functioning has been usually described as a common initial step in all these frameworks (Rezaei *et al*., 2006).

Geospatial techniques widely used for assessing soil quality and mapping involve visual interpretation of aerial photographs as well as satellite images to delineate soil physiographic units, which form the basis of soil survey and characterization. This technique helps to understand how the complex relationships among landforms, land use land cover (LULC), and the terrain will result in variations of soil properties on aspatial domain. Thus, the mapping of soil quality involves two steps: The first step involves the generation of the different soil property maps, while the second one involves the interpretation of the soil properties for a specific soil function or service of our interest, which will help to guide the decision-making process (Miller, 2017). Li *et al*. (2005) used 13 soil quality indicators to generate soil quality map for sustainable agriculture management by integrating remote sensing (RS)-derived LULC maps and soil map along with soil information of the study area. They demonstrated the use of geospatial techniques and modelling for soil quality assessment and mapping with adequate as well as accurate soil properties data. Though the soil quality tends to give an overview of the functional capacity of the soil, it is yet to be widely adopted as a land management indicator worldwide. Among the different limitations which tend to restrict its adoption, one of the main barriers is that most soil quality assessments provide information at small scale or point scales, while management of various ecosystems are majorly undertaken at landscape levels, thus necessitating the representation of soil quality over large spatial extends. This spatial representation of soil quality could help to bridge the gap between its current use and its potential use for land management (Jaenicke, 1998). The localized nature of soil quality information can be expressed over a large spatial extent with the aid of various geospatial techniques through the amalgamation of remote sensing data and field generated soil information in a geographic information system (GIS) environment. The chapter discusses various soil quality indicators, their measurement and geospatial methods for assessing soil quality, and how they can be used for sustainable land (soil) management.

Geospatial techniques involving the use of RS, Global Positioning System (GPS)and GIS, provide new approaches for studying various soil quality aspects indifferent spatial as well as temporal domains (Schiewe, 2008). It has been widely documented as a vital tool for soil/land resource inventory at different scales extending from local to regional and even up to global scales. Reliable and timely soil information regarding their extent, nature, spatial distribution, and limitations due to land degradation caused by water/wind erosion, soil salinity and/or alkalinity, soil compaction, wetness, etc. is necessary for soil health and quality assessment. The prime role RS plays in land resource management is providing information regarding soil, terrain, and LULC types and is the most effective tool for land resources monitoring. Availability of high-spatiotemporal-resolution RS datasets has facilitated the monitoring of various land resources regarding their diverse uses, soil health, wetlands, and land degradation status. Spaceborne RS data is widely being used for mapping soil resources. The main use of RS data is for the segmentation of landscape into more or less homogeneous soil-landscape units. Subsequently, soils occurring in each unit are characterized by dominant soil type (Dwivedi, 2001). Digital soil mapping techniques, incorporating different secondary(non-soil) data sources into the mapping process, have been identified as potential means of soil mapping and can improve the detailing as well as geographic coverage of soil databases (Mulder *et al*., 2011). Various DEM-derived terrain parameters were found to be efficient in characterizing different soil-forming environments as well as delineating soil patterns at various scales. The integration of RS data (with high precision and synoptic coverage) with GIS will help in decreasing the cost and time as well as increasing the information content for effective soil quality estimation. The availability of remote sensing data ranging from coarser resolution to very high spatial resolutions will help in the preparation of soil/soil quality maps at diverse scales to meet the planning requirements at different levels. Advanced RS technique such as hyperspectral remote sensing as well as microwave remote sensing have opened new vistas for soil mapping especially concerning the quantification of soil properties including nutrients, texture, and soil moisture status at varying resolutions.

2. Soil Quality Indicators and Measurement

2.1 Soil Quality Indicators:

Assessing soil quality with respect to desired function or attribute involves the identification and subsequent quantification of certain sensitive parameters, referred to as soil quality indicators. Soil quality indicators, which reflect the changes due to land management practices, may include various chemical, physical, and biological soil properties. At any given point of time, a baseline or reference value of these soil quality indicators is essential to identify the impact of the different management practices (Bunemann *et al*., 2018). Indicators are identified as a soil property or attribute, which needs to be estimated for assessing soil quality pertaining to a given soil function. The measurement of many of these indicator properties is possible through routine laboratory analysis, while some require more sophisticated measurement techniques. Soil quality can be classified into (i) inherent and (ii) dynamic soil quality (USDA-NRCS, 2003). The inherent soil quality is constant and does not show much temporal variation. The various management practices have little or negligible influence on the inherent soil properties, and they do not change over a given timeframe. They are a direct derivation of the different soil-forming factors and include properties like soil texture, mineralogy, soil depth, pattern *etc*. On the other hand, the dynamic soil properties are easily influenced by anthropogenic activities or disturbances occurring in nature, and they are subject to change in a given timeframe. These include various physical, chemical, and biological properties like bulk density, porosity, infiltration rate, soil organic carbon (SOC), available nutrients, soil pH, various soil enzyme activities *etc*. The dynamic soil quality is subject to changes depending on the management practices such as the quantity of soil organic matter (SOM), the soil structure, cation exchange capacity (CEC) *etc*. that change with the variation in the soil management practices. Soil quality research generally revolves around the concept of managing these dynamic parameters to improve the soil functions and maintain the fitness of soil resources (de La Rosa and Sobral, 2008). In general, for efficient characterization of the different soil functions, a group of soil quality indicators is assessed which is referred to as the minimum dataset. This minimum dataset helps us to measure the capability of soil to execute a definite function and also capture the change in temporal scale. The minimum dataset should include such parameters, which will easily aid us to detect the changes brought about by different soil management practices. In most cases, minimum data sets are sensibly chosen by combining different soil properties, which would reflect the key soil function under consideration (Franzlubbers and Haney, 2006; Meena *et al*., 2020). Soil Quality Institute (USDA-NRCS, 2003) has laid down the pre-requisites for a minimum dataset for measuring soil quality. The most commonly used soil quality indicators forming components of the minimum dataset that includes different chemical, physical and biological parameters (USDA-NRCS, 2003).

Soil Quality Measurement

Though the concept of soil quality and its systematic measurement was introduced during the late twentieth century, the evaluation of soil and land existed much before in terms of fitness of a particular land unit for specific land use (FAO 1976).Measurement of the suitability of land or soil is to assess potentials or limitations of the land towards a particular use, whereas soil quality measurement gives us more quantifiable and detailed information regarding the current state of soil and helps to quantify the deviation of soil from the optimal functioning state. Physical properties considered for soil quality measurement includes bulk density (BD), total porosity (TP), saturated hydraulic conductivity (SHC), moisture saturation (MS), aggregate stability (AS) larger than 2 mm, aggregates between 2 and1 mm, and aggregate stability index (ASI). The chemical properties primarily used as soil quality indicators consist of pH, soil organic matter (SOM), CEC, exchangeable cations, available phosphorus (P), total nitrogen (N), and base saturation (BS).Whereas, the different biological properties are total organic carbon (TOC), total carbon stock (TCS), microbial biomass carbon (MBC), total organic N (TON), the metabolic quotient (qCO2), total N stock (TNS), and C/N ratio. The Soil Management Assessment Framework (SMAF) has proposed interpretation algorithms for13 soil properties to be used as soil quality indicators. Those properties include BD, plant available water (PAW), water-stable macro-aggregation (WSA), water-filled pore space (WFPS), pH, electrical conductivity (EC), SOC, extractable P, sodium adsorption ratio (SAR), and extractable K in addition to potentially mineralizable N(PMN), MBC, and b-glucosidase (BG) activity (Andrews *et al*., 2004). The SMAF has been widely adopted in the United States and other similar countries abroad for evaluating near-surface (0-5 and 5-15 cm) soil properties and processes (Imaz *et al*., 2010; Stott *et al*., 2011). Ezeaku (2015) assessed soil quality based on various biological and physico-chemical soil quality indicators to study the sustainability of various management and land-use systems. The most sensitive indicators observed in the study were soil pH, porosity, CEC, available P, BD, TOC, earthworm population, and plant available water holding capacity (PAWC). However, total N, exchangeable K, total P and K were found to be moderately sensitive, and percentage base saturation was observed to be a weaker indicator. Mukherjee and Lal (2014) used various physical indicators, namely, potential AWC, soil penetration resistance, BD, mean weight diameter (MWD), aggregate size distributions, a fraction of water-stable aggregates (WSA), and geometric mean diameter (GMD) along with other chemical indicators for assessing soil quality. Sofi *et al*. (2016) used various SOC fractions as well as activities of different soil enzymes such as dehydrogenase, phosphatase, aryl sulphatase and fluorescein diacetate hydrolase (FDAse) as biological indicators for soil quality assessment under diverse cropping systems in the northwestern Himalayas. Basak *et al*. (2016) and Biswas *et al*. (2017) assessed soil-quality indices for subtropical rice-based cropping systems in Eastern India. Luo *et al*. (2017) used different biological soil quality indicators comprising microbial biomass, microbial count, and activities of various soil enzymes (such as urease, catalase, invertase, alkaline phosphatase) along with different physical and chemical indicators as the minimum dataset for assessing the impact of long-term tillage systems on soil quality indicators, in Northwest China. Similarly, Bhaduri *et al*. (2017) have reported the effectiveness of biological indicators for soil quality assessment under a long-term rice-wheat cropping system in the semi-arid Indo-Gangetic plains with different tillage-water-nutrient management scenarios. They used MBC, dehydrogenase activity (DHA), soil respiration, PMN, and qCO_2 as quality indicators. In addition to the various indicators discussed above, Stefanoski *et al*. (2016) used macro-porosity, micro-porosity, SHC, MS, effective saturation, aggregate size distribution, ASI, exchangeable Ca and Mg, exchangeable acidity, potential acidity, aluminum saturation, basal respiration, C stock, and N stock also as potential soil quality indicators. Apart from the above-mentioned indicators that need quantitative measurement in the laboratory, there are more generalized indicators like the visual indicators, which help to detect or identify the current state of the soil resources. Unlike the quantitative ones, observations of the visual indicators can be undertaken by a layman and can have wider acceptability to common masses. Some of these visual indicators are changes in soil color, above-ground vegetation and weed species, earthworm population, and signs of soil erosion, water stagnation or undulations in topography *etc*. (USDA-NRSC 2008). Synthesizing the numerous studies help us in identifying some soil properties, which are widely adopted and used as soil quality indicators across the world, maybe due to their ease of measurement as well as higher sensitivity to variations in management practices. The various standard available protocols for measuring these widely adopted indicators and their relation to various soil management practices.

2.2 Soil Quality Assessment

Soil quality assessment is required to assess the sustainability of soils under the present ecosystem as well as to predict the sustainability of the ecosystem in the future for the present environmental conditions. Unsustainable use of land resources leads to degradation of soil, which results in a decline in the functionality of soils such as crop productivity, hydrological cycle, water quality, biochemical cycle, and soil quality. Soil quality parameters are in general defined by considering the sustainability of soils under changing management practices or based on soil resilience under varying environmental conditions (Hartemink, 1998). Physical, chemical and biological parameters of soils of natural undisturbed lands are considered as the highest soil quality and hence used as reference level (Doran *et al*., 1994; Mitran*et al*., 2018). Precise assessment of soil quality requires a systematic method to measure and interpret soil properties. These properties vary with agro-ecosystems to serve as soil quality indicators (Granatstein and Bezdicek, 1992). Soil quality indicators refer to soil processes and properties that are sensitive to changes in soil functions. These indicators should be simple, sensitive, and measurable to use for soil quality assessment. Soil quality indicators are comprised of physical, chemical and biological properties of soil. There are sets of soil quality indicators proposed to assess soil quality (Doran and Parkin, 1994; Karlen *et al*., 1997). Researchers have used various evaluation methods to assess soil quality such as soil quality card design and test kit (Ditzler and Tugel, 2002), indicator kriging, soil quality indices (Doran *et a*l., 1994; Doran and Jones, 1996), and soil quality models (Larson and Pierce 1994). Among these methods, soil quality indices are the most widely used due to their ease to application in a quantitative manner (Andrews *et al*., 2002). Soil quality indices are based on indicators of site-specific soil conditions under specific soil management practices. They reflect the integrated effects of dynamic and inherent soil propertie sunder the specific management practices over the period (Wang and Gong, 2014; Arshad and Martin, 2002). There is no universally accepted method for developing soil quality indices. Several researchers have evaluated soil quality and proposed a self-defined indicator method and equation in developing soil quality indices (Sun *et al*., 2003; Zhang *et al*., 2006). There are various quantitative soil quality assessment methods to evaluate soil quality. These are classified under two groups: (i) soil quality index (SQI)-based approach and (ii) soil quality modelling approaches. They are discussed below.

2.3 Soil Quality Indices

Soil quality indices integrate different physical, chemical, and biological soil properties. There are various soil physical indicators such as soil aggregate stability, BD, porosity, infiltration rate, hydraulic conductivity, effective soil depth, and WHC of the soil, which are commonly used. Whereas, most important chemical indicators used are soil pH, EC, CEC, nutrient availability, and deficiency/toxicity of micronutrients in the soil. The most relevant biological indicators used are SOM, MBC, soil respiration, or soil enzyme activities. Optimal integration of these soil properties improves crop productivity, water use efficiency, nutrient availability, and sustainability of agro-ecosystems. Soil quality indicators vary with soil types, climatic condition, and land use/land cover and management types. Various soil quality indices commonly used to assess soil quality can be discussed as follows:

Simple Ratio Based Index, Multi-parametric Soil Quality Index, NIR Spectra for Measurement of Soil Quality, Spectral Soil Quality Index (SSQI), Fertility Capability Soil Classification (FCC) System, Soil Quality Index

2.4 Examples for Modelling Soil Quality

Modelling Change in SOC, RothC Model, CENTURY Model, Crop Simulation Models,

3. Geospatial Methods in Soil-Landscape Delineations for Soil Quality Assessment

3.1 Visual Method of Analysis

Geospatial techniques using various RS data have been widely adopted for soil survey at different scales as well as mapping of various soil quality parameters. Dwivedi (2018) provided a detailed review of RS for various soil-related applications. Among the various applications of geospatial technology, the use of RS data for soil surveys including the delineation of soil mapping units needs special mention. It involves the delineation of soil scape boundaries, which act as sampling units for soil survey, soil profile study, and characterization of various soil properties leading to soil resource inventory. A detailed description and knowledge about the different kinds of soils and their geographic distribution are essential pre-requisites for rational land use planning, improved agricultural production, and identification of the potentialities and limitations of different areas.

The soil-scape boundary delineation and mapping using RS data are based on physiographic soil analysis, where different physiographic units are delineated to account for the climate, soils, vegetation, geology, water, surface form and their interrelationships. The different factors involved in physiographic processes approximately correspond to the different soil-forming factors; hence, knowledge regarding physiographic processes serves to indicate the broad general pattern of soil development. This approach is based on the concept that analogous physiographic processes at two widely diverse places are anticipated to support almost alike soil forming processes resulting in similar soils with broad general characteristics. Similarly, the spatial variations in surface features such as vegetation, topography, relief, and slope can also aid in the delineation of soil boundaries, due to their relation with physiographic processes. Various landforms or surficial features of the earth at different scales and resolutions can be easily identified by the interpretation of various remote sensing data products which helps in reconstructing and studying the dominant physiographic processes at different locations. The soils within different physiographic units will be studied in detail to characterize the soil properties. Detailed study and interpretation of RS images help us in the identification and geomorphic description of landforms with varying origin such as structural origin, denudation origin, fluvial origin, and aeolian origin. The delineated landforms will be further subdivided systematically based on relief as well as land use/land cover. This accounts for various soil farming factors influencing variations in soil properties especially landform (parent material), relief (topography), and land use/landcover (vegetation). Whereas in the case of smaller spatial extents, time, parent material, and climate being almost identical, the soil property variations can be credited to variations in relief along with vegetation factors (Dobos *et al.*, 2000; Srivastava and Saxena, 2013). Thus, the delineated physiographic units will have similar soil forming factors and will result in similar soils due to the similar pedogenic processes. Detailed scale (cadastral-level) soil mapping can be achieved by delineating various landforms through the integration of information derived from the 3Dperspective view of different slope class areas, employing high-resolutionCartosat-1 DEM following visual interpretation (Nagaraju *et al.*, 2014). The landforms were further segmented into different precise land use and land cover classes using Cartostat-1 sharpened LISS IV image. The physiography-land use (PLU) units generated by integrating slope, landform, and LULC information were more or less internally homogenous in terms of factors of soil formation and served as soil11 Geospatial Modelling for Soil Quality

Assessment 405boundaries for further soil sampling as well as classification. Chattaraj *et al*. (2017) developed a semi-automated object-based modelling methodology for landform classification as well as delineation. They employed geospatial object-based image analysis (GEOBIA) technique with knowledge-based modelling. Landform classification was carried out through a multiscale mapping workflow comprising various procedures, viz. digital terrain analysis, multiresolution segmentation (MRS) (using raster datasets of Cartosat-1 Digital terrain model and IRS P6 LISS IV images as input), knowledge-based landform classification, and accuracy assessment.

4. Digital Method of Analysis

Digital soil mapping (DSM) refers to an innovative technique for mapping primary as well as secondary (derived from primary properties) soil properties or soil classes employing spatial inference models. It is defined as the “computer-assisted production of digital maps of soil types as well as soil properties using various mathematical/statistical models, which combine information from soil observations with thein formation contained in correlated environmental variables and remote sensing images” (McBratney *et al*., 2003). Digital soil mapping can aid in extrapolating point-scale information to bigger areas. It offers a unique opportunity to tide over the scales between ground-based soil properties (point or field data) to model for larger extents. DSM attempts to integrate RS data derived soil-related information with proximally sensed as well as conventionally estimated soil property data at bigger spatial scales. The forthcoming studies will focus on improving the amalgamation of data derived from proximal as well as remote sensing through scaling based methods to make the best use of all available data sources (Mulder *et al*., 2011). DSM can also be used for upscaling from field observations to more regional areas. It makes use of various RS data including hyperspectral images, field measurement sand spectroscopy in combination with various processing algorithms (including statistical, mathematical, and machine learning) for extrapolating field-collected information to the scale of remote sensing data.

Various environmental covariates or so-called scorpan factors (an acronym for the various factors for soil attribute prediction, *i.e.* “soil, climate, organisms, parent materials, age, and spatial position”) have been suggested by McBratney *et al*. (2003). They can be obtained in digital form from various sources like remote sensing images, digital elevation models, and existing soil maps. The DEM-derived terrain parameters help us in quantifying the (geo) morphology of the terrain (soil scape or soil landscape), thus accounting for accretion and deposition potential, as well as to adjust the effect of climatic elements on the local topography. The RS images of different resolutions reveal and help us to capture the overall variability in environmental conditions, form, and state of the vegetation affected by various soil properties, colour, surface roughness, moisture content, and other soil surface features. Many researchers have used these numerous environmental covariates for the generation as well as updation of soil maps in raster format at different resolutions, employing various spatial soil prediction functions (Minasny *et al*., 2008). Several procedures of kriging, as well as decision tree-based analysis (classification/regression trees), have been used together with various RS data for predicting soil properties at unvisited locations pointing towards attaining continuous area coverage (Mulder *et al*., 2011).

Several regression models correlating DEM-derived terrain parameters with soil properties have been reported with a high degree of success (Oldak *et al*., 2002). MehammednurSeid *et al*. (2013) provided spatial distribution information of soil properties using topographic parameters along with the normalized vegetation index (NDVI) employing clustering and other statistical techniques. A methodology for automatic soil texture mapping by integrating ground, satellite, and ancillary data was successfully developed and employed by Maselli *et al*. (2008). Artificial neural networks (ANN) and decision trees are the novel methods extensively used in soil studies, especially for predicting soil properties. ANN modelling can predict soil types at locations devoid of any existing soil maps, by integrating soil map data from other regions with similar landscape characteristics known to be accountable for the spatial variability of soils. Zhao *et al*. (2009) predicted soil texture at improved resolution using a combination of soil attributes (from existing coarser-resolution soil maps) and various DEM-derived terrain indices employing ANN modeling technique. Ugbaje and Reuter (2013) described a methodology to employ DSM procedures for predicting available water capacity of soils making use of pedo-transfer functions (PTFs). DSM has been used to predict pH, bulk density, soil texture, and organic carbon (OC) content using different environmental covariates as probable predictors including terrain parameters, land cover information/images, vegetation indices (e.g. NDVI), and land surface temperature. Regional-scale soil parameter prediction has been reported by Martelet *et al*. (2013). Casa *et al*. (2013) estimated and mapped soil properties at field scale by utilizing and comparing different methodologies, integrating information obtained from hyperspectral RS data (vegetation/bare soil images) with geophysical data. Kalambukattu *et al*. (2018) mapped various soil quality parameters in a hilly watershed using remote sensing–derived inputs using ANN technique. They were able to map spatial SOC distribution and other nutrients using various spectral and terrain indices. Dharumarajan *et al*. (2019) have discussed the need and importanceof digital soil mapping in India with special emphasis on soil quality parameters. They had given an account of the limited attempts done in India for digital soil mapping of soil quality parameters along with the approaches for achieving the digital soil map of India.

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APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN SOIL SCIENCES

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Abstract:

Artificial intelligence, or AI, is the intelligence exhibited by machines that is devoid of the consciousness and emotionality displayed by living things. AI is now used in all areas of technology and study. It also has some influence over how we live our daily lives. The development of agriculture has been a top priority for the Indian government, as it is one of the oldest industries and the foundation of the nation. Numerous causes are concerning, including population increase, climate change, and food security. Since artificial intelligence (AI) is revolutionising other industries, the Indian government has begun to recognise the value of this technology and is now putting it towards the development of the agriculture sector. AI has also had an impact on soil science, which is a significant area of agriculture. It impacts a number of soil science domains, including soil testing and monitoring, soil/land cover/management monitoring, soil fertilisation assessment of soil quality, identifying nutrient deficiencies, carbon sequestration, and many other areas of interest. AI is arising as a great boon to the agricultural sector, AI and cognitive technologies can work irrespective of farm size. Evidently, dissemination of AI powered tools and technology will fetch a paradigm shift in Indian agriculture.

Keywords: Artificial Intelligence, Agriculture, Soil Testing, Carbon Sequestration, Cognitive

Introduction:

The term artificial intelligence was coined by the American scientist John McCarthy in 1956. He defined it as the science and engineering of making intelligent machines. Being one of the oldest sectors and the backbone of the country, developing the agriculture industry has been a huge concern for the Indian government. A lot of factors such as climate change, population growth, and food security concerns. Artificial intelligence (AI) being a game-changer in other industries, the Indian government has also realised its importance and started to hold this technology in developing the sector (Blanco & Lal, 2023).

Internet of Things (IoT)

Internet of things is an idea from computer science: connecting ordinary things like lights and doors to a computer network to make them "intelligent". An embedded system or a computer connects each thing together in a network and to the internet. It is also referred to as *Machine-to-Machine (M2M*), *Skynet* or *Internet of Everything*. Some technologies used for the internet of things are: RFID and meshnets. The connections allow each thing to collect and exchange data, and we can control them remotely or by setting rules or chains of actions.

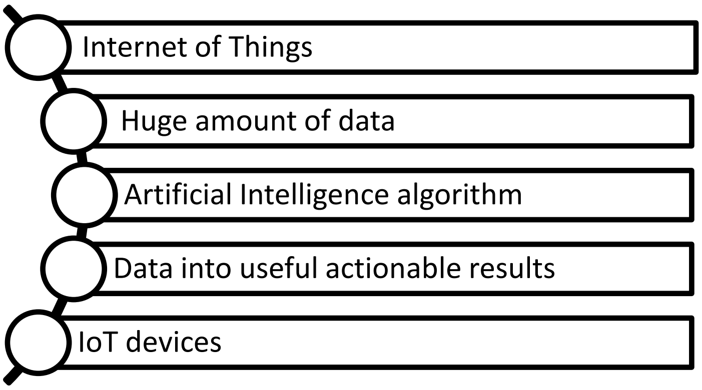
Importance of AI in IoT

"Artificial Intelligence and the Internet of Things is like a match made in Tech Heaven!!"

Maciej Kranz,

(Vice President of Corporate Strategic Innovation at Cisco)

"Without AI-powered analytics, IoT devices and the data they produce throughout the network would have limited value.



Example of IoT (Nikash Application)

An Ingenious automated irrigation system called Nikash which uses IoT (Internet of Things) technology to control irrigation in the fields.

Controller ⟶ Application ⟶ Wireless Sensor ⟶ Soil

Vijayeendra HS and Channabasappa Kolar's Bengaluru-based startup, Avanijal.

Applications of Artificial Intelligence in Agriculture

1. Autonomous Tractors/Drones/UAS

An automated farm vehicle known as a driverless tractor is designed to do tillage and other agricultural duties by applying a high tractive effort, or torque, at modest speeds. They are designed to autonomously track their location, choose their own pace, and steer clear of objects, people, and animals in the field when carrying out their assigned duties. Two categories exist for the different types of driverless tractors: fully autonomous and supervised autonomous. The tractors farm land without a driver by using GPS and other wireless technology. They just need a supervisor at a control station to keep an eye on things, or they can work with a manned tractor leading the way (Awais *et al.,* 2023).

Drones/UAS

These are the flying robots, no on-board pilot, remotely controlled, semi-autonomous or autonomous or combination

- **Unmanned Aircraft System (UAS)**

- UAV
- Ground control station
- Pilot
- Visual observer
- Launcher

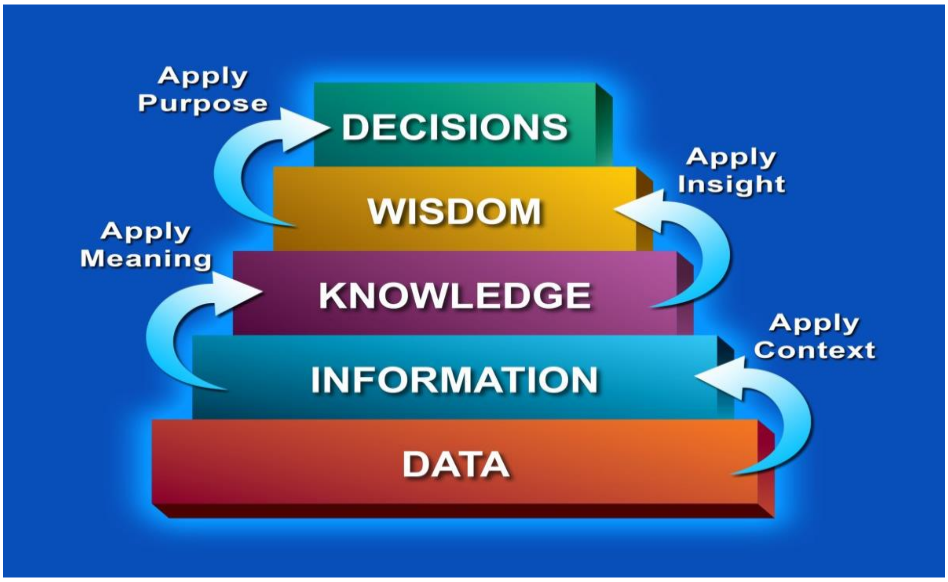
- **Unmanned Aircraft System (sUAS)-**

A system in which the UAV weight less than 55 Ibs.

Most common sensors are Thermal sensors, Visible light sensors (RGB), Multispectral sensors, Hyperspectral sensors. Software tools for image processing are QGIS, ArcGIS, Pix4D, ERDAS, MATLAB, Adobe photoshop, Agisoft Photoscan.

2. Decision Support System

Applications of these technologies have the potential to greatly increase agricultural productivity. They have concluded that computer programmes can produce rich recommendations and insights in real-time artificial intelligence, assisting farmers in making informed decisions.



3. Management of Crop and Soil Quality

An effective method of conducting or monitoring soil problems and nutrient deficits is to use artificial intelligence (AI). Using the image recognition method, artificial intelligence detects potential flaws in photos that are taken by the camera. Deep learning applications are being created to analyse flora patterns in agriculture with the use of AI.

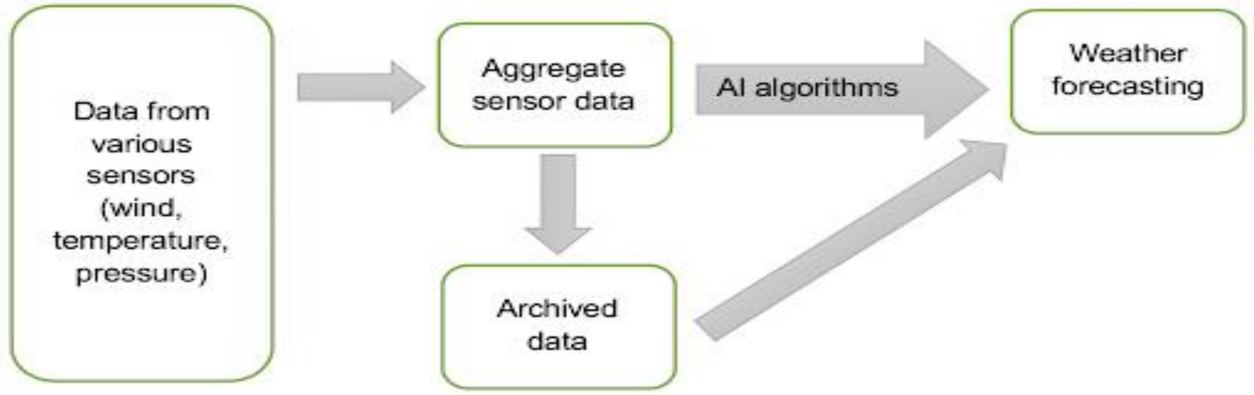
These AI-enabled applications aid in the knowledge of diseases, pests, and soil defects in the soil.

4. Identification of Pest Outbreak and Disease Management

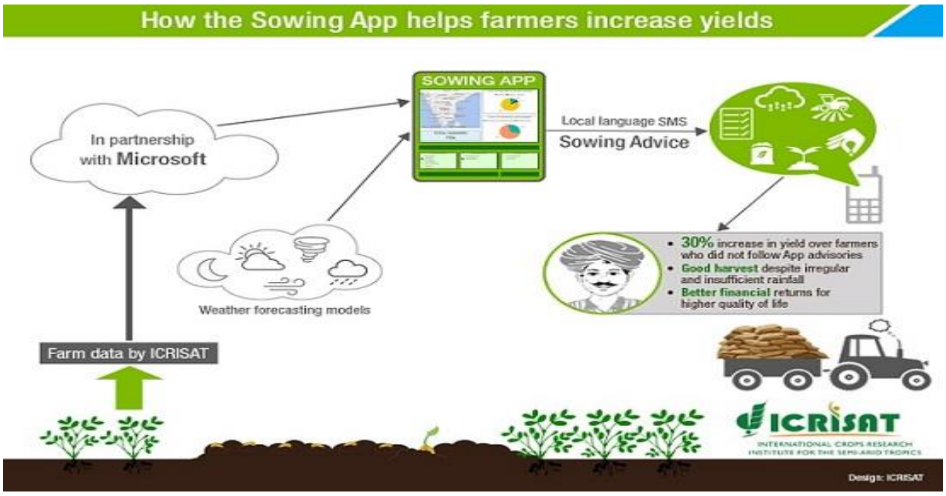
Image preprocessing makes sure that the backdrop, healthy portion, and diseased portion of the leaf images are separated. After that, the affected area is chopped and sent to distant labs for additional diagnosis. It also aids in the recognition of nutrient deficiencies and pests, among other things.

5. Abiotic Stress Management

A more sophisticated application of AI is assisting farmers in staying updated on weather forecasting data. Without endangering the crop, farmers can boost yields and earnings with the aid of anticipated or predicted data. The farmer can take preventative measures by using artificial intelligence (AI) to comprehend and learn from the data analysis. Implementing such practice facilitates timely and wise decision-making (Awais *et al.,* 2023).



6. Microsoft Sowing App



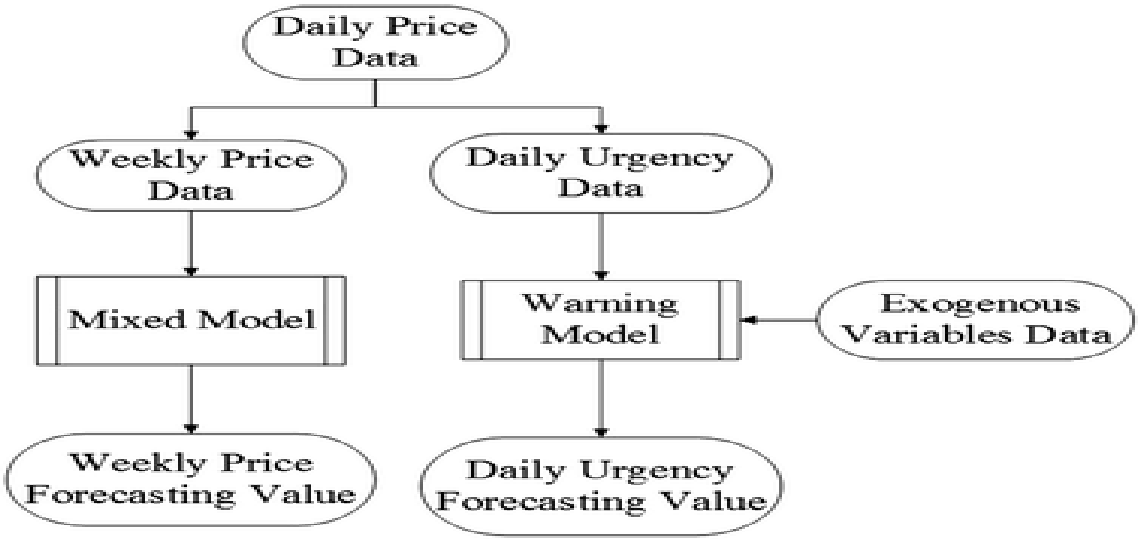
The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), a local non-profit, non-governmental agricultural research organisation, and Microsoft worked together to build the AI-sowing software. Microsoft Cortana Intelligence Suite and

Power Business Intelligence powers the application. The technology included in the Cortana Intelligence Suite helps to make data more valuable by transforming it into formats that are easy to use.

In June 2016, a test pilot for the AI-sowing app was launched with 175 farmers in Andhra Pradesh.

7. Price Forecasting Model

In order to anticipate crop yields at every stage of the agricultural process, the model takes into account datasets on past sowing areas, production yields, weather patterns, and other pertinent information. It also employs remote sensing data from geostationary satellite photos. Microsoft claims that the model is now effective, scalable, and prepared for use with other crops and in different parts of India. The model was used for the first time during the summer 2018 harvest season.



8. Infosys Precision Crop Management

The rapidly expanding Indian population is putting more and more strain on the country's already meagre food supply. The agricultural industry is challenged to find new methods of producing more for less investment in light of the escalating effects of climate change and the scarcity of arable land. Using real-time data analysis from environmental sensors placed in commercial crop fields, the testbed's initial goal will be to increase crop yield.

AI Startups in Agriculture

1. Prospera: It was founded in 2014. To interpret everything, it combines it with an in-field tool. The Prospera device can be used in greenhouses and fields. It is powered by a variety of sensors and technologies, including computer vision. By finding a correlation between different data labels, the inputs from these sensors are used to make predictions.

2. Blue River technology: It was founded in 2011. It uses robotics to create cutting-edge, chemical- and cost-saving agricultural equipment. Robotics allows the intelligent robots to perform, while computer vision identifies each unique plant and machine learning determines how to treat it.

3. FarmBot: Formed in 2011. It assists the owner in handling end-to-end farming on his own. Using an open source software framework, this physical bot does everything from planting seeds to detecting weeds, testing the soil, and watering plants.

Applications of Artificial Intelligence in Soil Science

I. Soil testing and monitoring

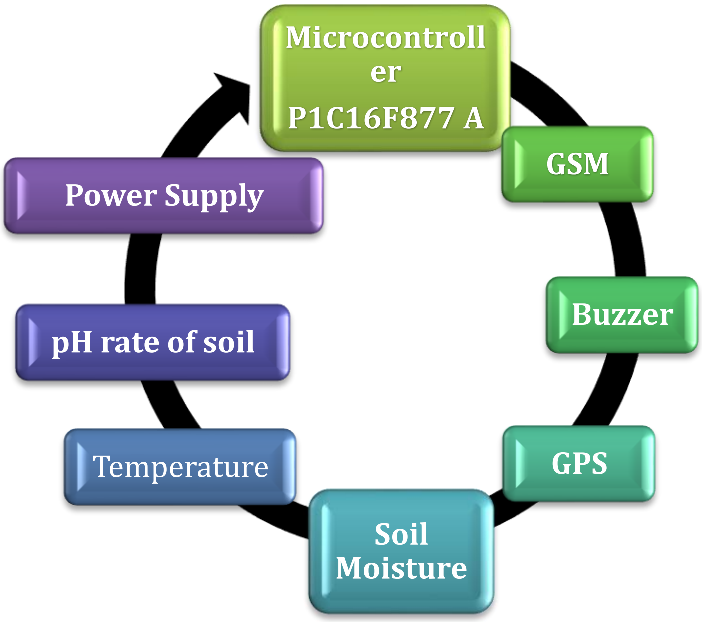
Agropad: Currently, farmers must send samples of their soil and water to a lab for analysis, for chemical and environmental testing. Smallholder farmers typically cannot afford this since it takes a lot of time and expenditure. A drop of water or soil is applied to the test strip by the farmer. Based on the concentrations of pH, nitrogen dioxide, aluminium, magnesium, and chlorine in the sample, the five indicators change colour. The farmer receives recommendations from the app regarding fertiliser adjustments that will best maximise crop establishment. The data is uploaded into the cloud along with all of the other local chemical readings as a last step. Interested parties are able to monitor larger soil patterns (IBM Technology, 2018).

II. Monitoring of Soil/Land Cover/ Land management

Smart System Monitoring on Soil Using Internet of Things

An electric tractor serves as the first autonomous vehicle in India, according to a Mumbai startup called AutoNxt. For agricultural tasks like tilling, pest management, ploughing, and seeding, AutoNxt's autonomous tractor is perfect. Since its founding in

2016, AutoNxt has collaborated with larger grape-growing farmers. It plans to create a platform for tractor sharing in order to reach more farmers and lower the cost of its tractor (Soni 2020).



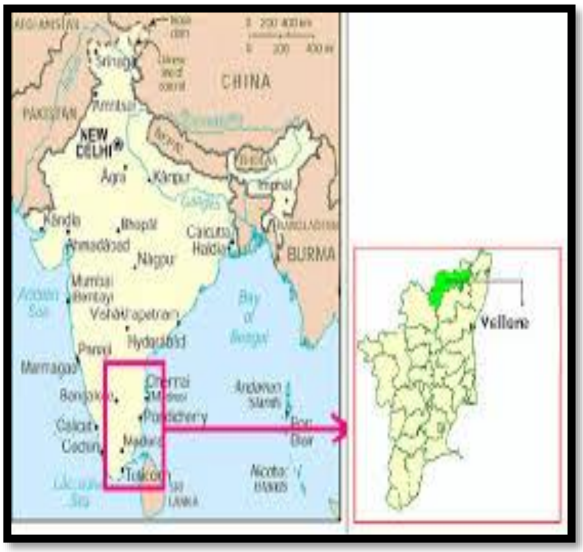
Sowmiya *et. al*, 2017

III. Assessment of Soil Quality

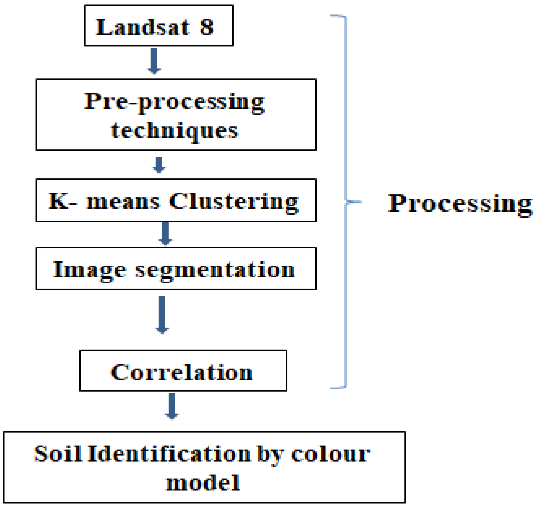
A work done by Kumar *et al.* (2013) is given example for assessment of soil quality**.** The main principle of the study is to inspect the possibilities of using remote sensing data for a common survey of the soil conditions and land use in the Vellore District area. This inspection has four processes. First process is the establishment of the associations between the ground truth and the images; it is based upon the reports and maps, and the Satellite Images. Second process is creating the correlation between the soil conditions and the present-day land use, vegetation and other factors of that area. Third process is the founding most appropriate augmentation techniques and best classification methods for the detection of different soil conditions of Vellore District. Final process is the mapping of different soils using satellite image classification methods.

Vellore District

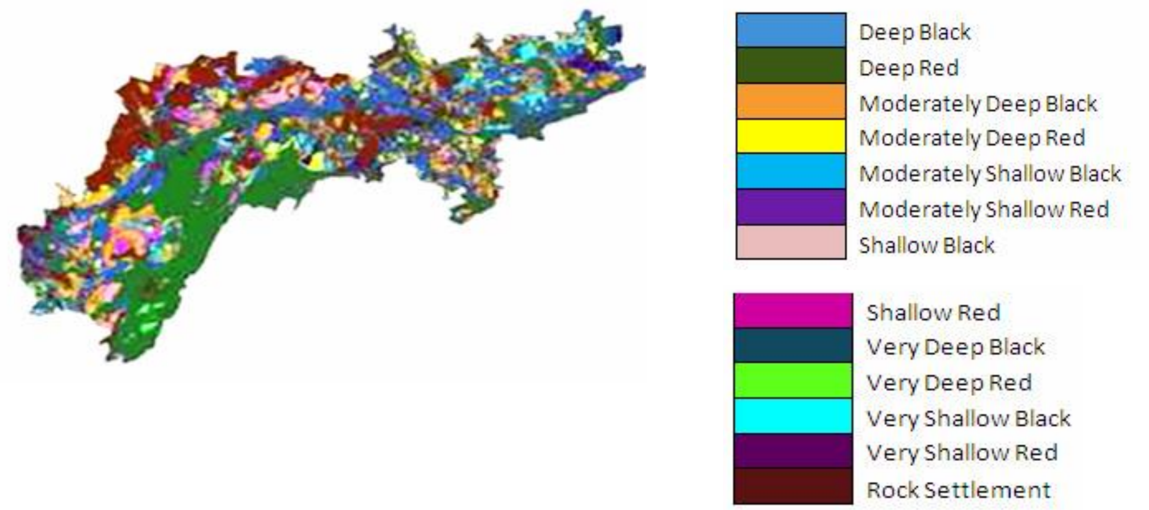
Satellite Data	**Landsat 8**
Lattitute	**12° 20’ to 13° 20’**
Longitude	**78° 10’ to 79° 40’**

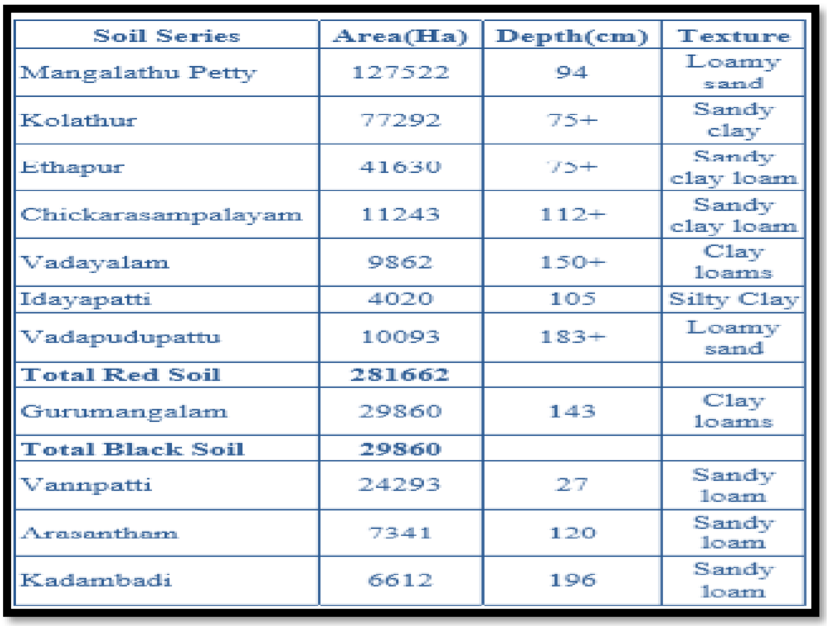


Location of Study Area (Vellore District)



Framework of soil identification method using remote sensing





Soil Series	Area(Ha)	Depth(cm)	Texture
Mangalathu Petty	127522	94	Loamy sand
Kolathur	77292	75+	Sandy clay
Ethapur	41630	75+	Sandy clay loam
Chickarasampalayam	11243	112+	Sandy clay loam
Vadayalam	9862	150+	Clay loams
Idayapatti	4020	105	Silty Clay
Vadapudupattu	10093	183+	Loamy sand
Total Red Soil	**281662**		
Gurumangalam	29860	143	Clay loams
Total Black Soil	**29860**		
Vannpatti	24293	27	Sandy loam
Arasantham	7341	120	Sandy loam
Kadambadi	6612	196	Sandy loam

Kumar *et. al.* (2013)

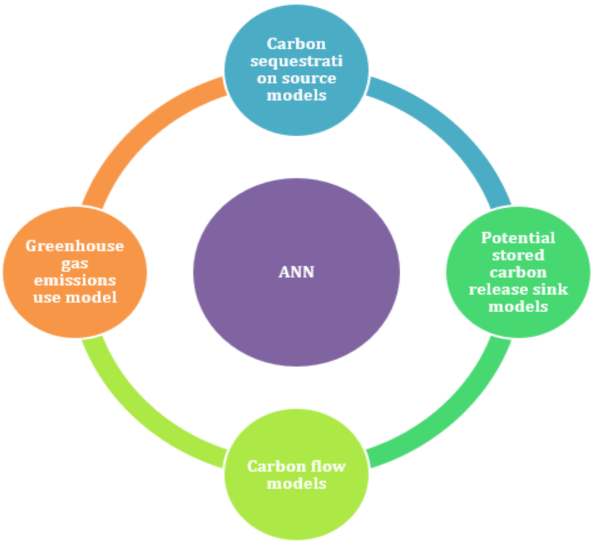
IV. Identification of Nutrient Deficiencies

The existing approaches are costly and slow. A comparison was made between bean plants grown in a medium that contained one of these elements and those grown on a complete nutrient solution (control). A mineral shortage in the nutrient solution was subsequently assessed by measuring the plants' photosynthetic activity in response to stress. Using the JIP-test method to analyse chlorophyll fluorescence, which represents the functional activity of Photosystems I and II and the electron transfer chain connecting them, the photosynthetic activity was estimated (Aleksandrov, 2019).

V. Carbon Sequestration

Model specifications for place-specific carbon sequestration and storage models (ARIES, 2018)

Sr.	Model	Input	Source
1	Carbon sequestration source models	The relationship between carbon sequestration and vegetation density and sequestration rate—two intermediary variables designed to maintain tractability in conditional probability tables—	Marcot *et al.*, 2006
2	Potential stored carbon release sink models	Data on past or projected land usage and fire Simulating carbon storage before and after changes in land usage	Lutes, 2013
3	Greenhouse gas emissions use model	For the country or sub-national region of interest, population density data are multiplied by per capita emissions.	Kirby & Potvin, 2007
4	Carbon flow models	The difference between the amount of carbon released by humans and the amount of carbon absorbed by ecosystems (sequestration less released stored carbon).	Liu *et al.*, 2010



Estimation of carbon sequestration (ARIES, 2018)

Conclusion:

Analysis and monitoring of soil health contributes to the sustainability of a particular area of arable land and saves farmers time and labour resources. AI in crop sowing has the potential to raise per acre crop output as well as reduce input costs for farmers. The Internet of Things (IoT) assists farmers in tracking and enhancing soil and agricultural productivity. The application of remote sensing technologies facilitates mapping, changes in vegetation indices, land use/cover changes, and crop yield prediction. As with mapping and vegetation indices, drones are crucial to precision farming. There is a great deal of promise for autonomous tractors to accurately and autonomously carry out the numerous cultural practises.

AI is the game changing tool as per as the modern agriculture is concerned. Thus, AI may have tremendous impact if used as a sustainable goal towards solution for food security in the future

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