Dimensions of Climate variability and impact on Environment, Ecology and Agriculture – A step forward for implication in Climate-Smart Agricultural system for Sustainable Development

Shweta Padole, Sandeep Bodkhe

Climate change reshapes agricultural systems through interconnected processes operating at microclimatic, biological, and material levels. At the farm scale, altered canopy temperature, soil heat flux, and boundary-layer humidity modify field microclimates, with urban and peri-urban agriculture further exposed to heat island effects. These localized changes directly influence crop performance, water use efficiency, and stress tolerance. Climate stress also disrupts soil-climate-microbiome interactions by restructuring microbial communities, impairing nutrient cycling and carbon sequestration, and increasing the prevalence of pathogenic organisms under prolonged heat and drought conditions. The development of climate-resilient microbiomes and targeted bioinoculants is emerging as a promising adaptation strategy. Shifts in temperature and moisture regimes alter decomposition rates and modify lignocellulosic composition, resulting in increased lignin content and changes in cellulose crystallinity.

Keywords: *Climate change dimensions, Microclimate, Soil-microbiome interactions, Agro-waste valorisation, Climate change impacts, residue management, Climate resilient Agriculture*

Shweta Padole, Sandeep Bodkhe*
Academy of Scientific and Innovative Research, Kamla Nehru Marg, Ghaziabad, India; EIA Audit and Planning, CSIR-National Environmental Engineering Research Institute (NEERI), Nehru Marg, Nagpur, India.

*Email: sandeep.bodkhe@csir.res.in

Publisher: Cornous Publications LLP., Puducherry, India.
Advanced Researches in Agricultural Sciences (Volume 2)
Editors: Dr. Ashim Midya, Dr. Selvakumar Gurunathan
ISBN: 978-81-986832-0-5
DOI: https://doi.org/10.37446/vol2book092025/1-14

These transformations influence the quality and processability of agro-waste for bioenergy generation, bioplastics production, composting, and other resource recovery applications. Understanding these climate-driven material changes enables the design of climate-adaptive pathways for agro-waste valorisation. By integrating microclimate alteration, soil microbial resilience, and sustainable residue management, this chapter highlights underexplored dimensions of climate change critical for advancing climate-resilient and circular agricultural systems for sustainable development.

Introduction

Climate change is not a single-factor phenomenon limited to rising temperature or change in rainfall patterns; it is a multidimensional process that influences the natural system, human activities, and environmental management practices at multiple scales. The 6th Assessment Report of the Intergovernmental Panel on Climate Change, released on August 9, 2021, observed that climate change is widespread, rapid, and intensifying (O'Neill & Pidcock, 2021). During the past century, carbon dioxide (CO_2) concentration in the atmosphere has crossed 415 ppm. The global mean temperature has already risen by 1.1°C and could rise by 1.5°C by 2040 and up to 3.5°C by 2100 with the business-as-usual scenario. The last 7 years were the consecutive warmest years (2015 to 2021).

Climate change has emerged as one of the most formidable challenges in the 21st century, confronting humanity and capturing the unwavering attention of governments around the world (Afzali et al., 2025; Albitar et al., 2023). The complex global scenario that we face, especially when an increase in temperature will cause droughts, typhoons, wildfires, and floods (Mukherji, 2022) and bring worsening impacts of climate change, as shown in figure1 (Dafermos & Nikolaidi, 2018). These natural disasters induced by climate change negatively impact agricultural fields. According to (Rudrakar & Rughani, 2024) found that more than 27 % of the world population directly relies on agriculture for their livelihoods. Despite a lack of agricultural land, a severe global shortage of farm labour, rising agricultural input costs, the effects of climate change, and other pressing societal issues like social polarization and an ageing population, agricultural production needs a huge growth to meet this demand for food.

The uncertainty in the evolution of climate change, the occurrence of extreme climate events, and the formulation and implementation of relevant climate policies result in a highly complex interaction mechanism among climate change, economic growth and the financial market. To deal with such complex impacts of climate risks on the financial market is necessary to accurately measure climate risks, which have evolved with advancements in technology and data analytics. Innovative approaches, including the use of big data, machine learning, and complex network models, have emerged to quantify and evaluate climate risks more accurately (Wang et al., 2024; Xu et al., 2024).

According to NASA, climate change refers to significant changes in Earth's local, regional, and global climates over long periods. Droughts, temperatures, and floods are significantly affecting the development of agriculture and food supply by affecting land and crops. It may also affect global agricultural welfare, especially after 2050, when the consumer surplus loss in the agriculture sector is projected to exceed gains in producer surplus, resulting in an agricultural loss of 0.3% of the future GDP by the end of the century (Stevanovi et al., 2016). However, the degree to which humans around the world will effectively adapt their agricultural practices in reaction to these changes remains unknown (Auffhammer & Schlenker, 2014). Such challenges reflect broader dimensions of climate change, where atmospheric variability, soil-microbe interaction, and agro-waste dynamics collectively determine agricultural resilience.

This chapter contains a comprehensive discussion on the key dimensions of climate change, including agricultural microclimate alteration, soil-climate-microbiome interaction, and climate-driven agro-waste dynamics.

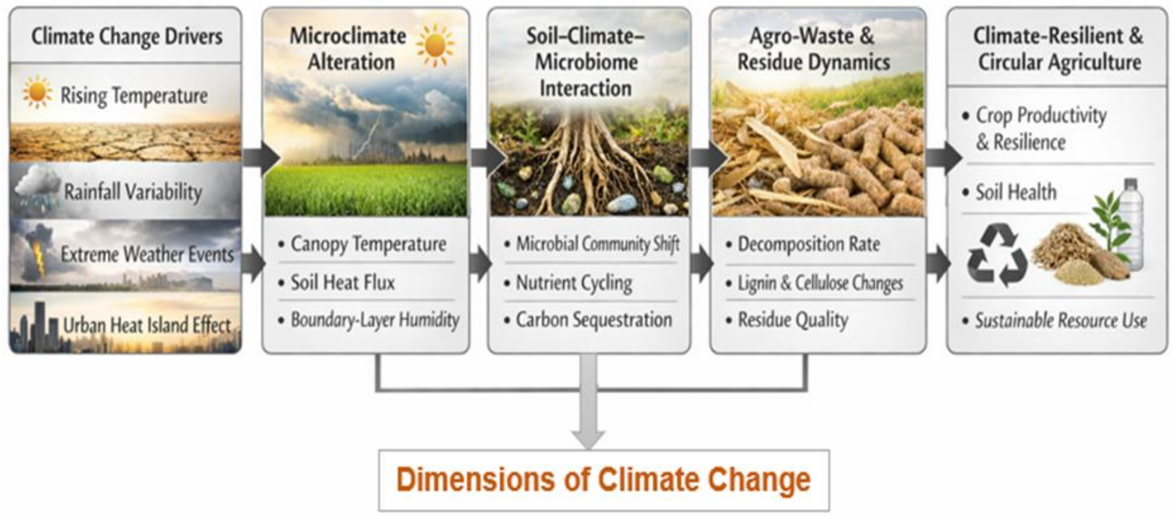

Figure 1. Different dimensions of climate change

Microclimate alteration

At the farm level, climate change alters localized microclimatic conditions within and immediately above the crop canopy, which can differ substantially from regional or macroclimate patterns. It is the vicinity of plants within a few meters above and below the soil and canopy surface that directly influences physiological processes in plants such as photosynthesis, transpiration, and heat stress responses. Singh et al., documented the significant diurnal variation in canopy and within-canopy temperatures compared to above-canopy air temperature, emphasizing the unique thermal environment plants experience at the farm scale (Singh et al., 2023). The primary microclimate factors, such as soil temperature, moisture content, soil properties, atmospheric temperature, atmospheric humidity, wind, etc., have a major impact on the agricultural production system. The various microclimate management strategies that can be readily implemented and impact the agricultural system in a changing climate scenario are reviewed in this chapter. Soil moisture is one from which thermal conductivity and heat capacity of soil. When the moisture occupied by the soil is roughly 60% of available soil moisture, optimal conditions are achieved. Plant growth is adversely affected when there is an excess of water because it hinders the flow of oxygen, which causes microbial activity to stall, stop, or become anaerobic. Cuartero et al., conducted an experimental study on how climate change (warming and rainfall reduction) alters soil microbial community structure, increasing the relative abundance of symbiotic and pathogenic fungi under warmer conditions (Cuartero et al., 2024).

Warmer temperatures expected with climate change, and the potential for more extreme temperature events will impact plant productivity (Hat & Prueger, 2015). Projected air temperature increases throughout the remainder of the 21st century suggest that grain yields will continue to decrease for the major crops because of the increased temperature stress on all major grain crops (Hat & Prueger, 2015). Beyond a certain point, higher air temperatures have an adverse effect on plant growth, pollination, and reproductive processes (Sacks & Kucharik, 2011). However, crop yield losses accelerate as air temperatures rise above the optimal level rather than decreasing at a pace that keeps pace with the temperature increase. For example, an analysis by (Schlenker & Roberts, 2009) indicated that yield growth for corn, soybeans, and cotton would gradually increase with temperatures up to 29°C to 32°C and then sharply decrease with further temperature increases beyond this threshold. The current evaluations of the impact of changing temperature have focused on the effect of average air temperature changes; however, increases in minimum air temperature may be more significant in their impact on growth and phenology (Ort et al., 2011). Additionally, windbreak agroforestry techniques have been proposed as climate-smart agricultural solutions to mitigate climate change and global climate variability. It is among the most crucial methods for mitigating and adapting to climate change. It is among the most crucial methods for mitigating and adapting to climate change. The function of windbreak technology at the landscape and farm levels, how windbreaks protect soil and lower wind speeds, and how windbreaks lessen climate change vulnerability. Windbreaks can improve the efficiency of ecological and ecosystem services provided by natural resources (Mume & Workalemahu, 2021).

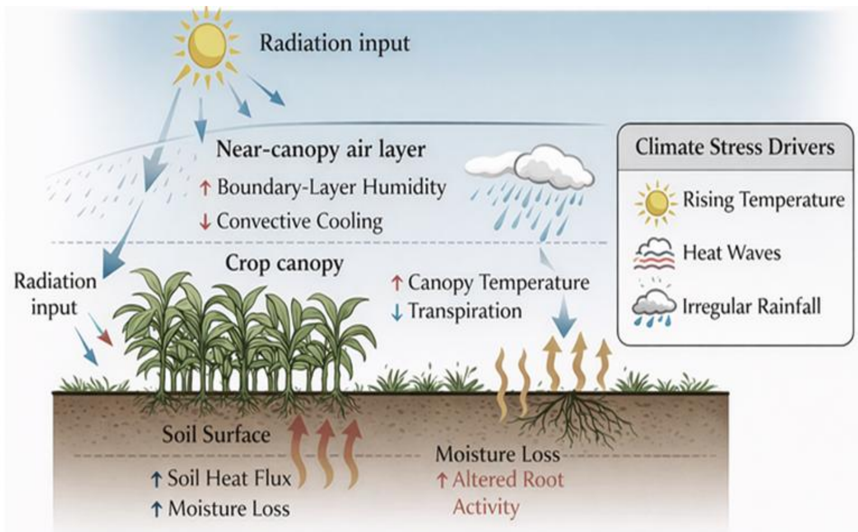

Figure 2. Soil- canopy interaction under climate stress

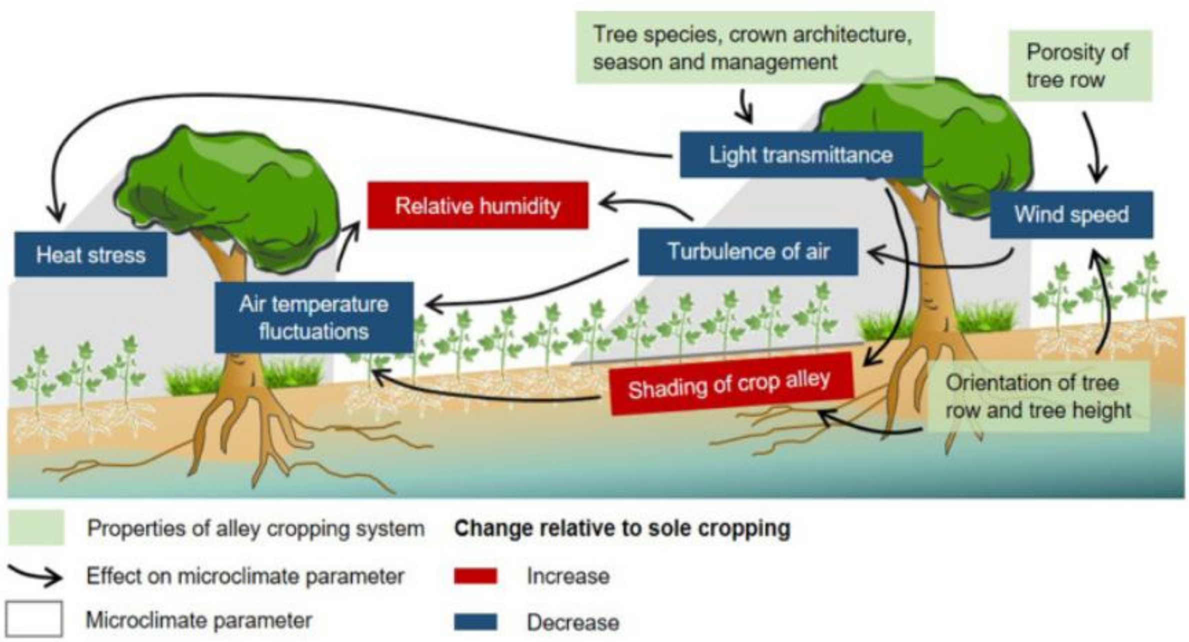

Figure 3. Effects of alley cropping on microclimate

Green boxes represent properties of alley cropping systems, and interactions between microclimate parameters are indicated with black arrows. The colour of the box with the microclimate parameter indicates an increase (red) or reduction (blue) relative to a sole cropping system (Jacobs et al., 2022). Photosynthesis is the key factor in crop productivity, competition for light due to the inclusion of trees on cropland is a major concern for agroforestry (Dufour et al., 2013). Wachendorf et al., studied a willow grassland alley cropping system in Germany, found a reduction of 10-25% of the photosynthetically active photon flux density close to the tree growing in the first two years after establishment, whereas no significant differences with the control site were observed for the centre of the 9 m crop alley (Wachendorf & Ru, 2018). Tree height likely plays a role as well figure 2, as trees in the agroforestry system studied by (Yang et al., 2021) were up to 5.1 m high, while trees in the systems studied by (Carrier et al., 2019) and (Wachendorf & Ru, 2018) were 3.5–12.7 m and 0.8–4.0 m high, respectively. A reduction in light intensity might be minimized through the use of trees with a beneficial crown architecture or by manipulation of the crown through pruning or pollarding (Dufour et al., 2020).

The effect of wind speed is determined by factors such as length, height, orientation of the tree row or hedgerow relative to predominant wind direction, and density (Dirk & Bo, 2014). The row of trees decreases the air velocity at the windward and leeward sides in proportion to their height. At the leeward side, wind reduction at a distance of up to 12 times the height of the windbreak has been reported (Foereid et al., 2002). Even relatively young tree rows (3 m height) were able to reduce wind speed across 48 m wide crop strips (Kanzler et al., 2019), suggesting that beneficial effects can be observed shortly after establishment of an agroforestry system. At the windward side, reductions in wind speed have been observed at distances of 0.5 to 3 times the height (Dirk & Bo, 2014; Kanzler et al., 2019). Therefore, it is advised to incorporate windbreak elements, like shrubs, within such tree lines. Turbulences are also related to the length of the windbreak, whereby a length of at least 10 times the height of the windbreak is recommended (Gordon et al., 2017). Other microclimatic factors, like crop evapotranspiration and vapour pressure deficit, can be impacted by windbreaks. Agroforestry is relevant for regions with a coarse soil texture, which dry out faster and thus will experience a stronger effect of the expected climate change.

Soil-Climate-Microbiome Interaction

Soil microbes play a crucial role in climate feedback, including the generation or consumption of greenhouse gases such as CO_2, CH_4 and N_2O, since they are primarily in charge of the cycling of soil organic carbon (SOC) and other nutrients. Due to unknown changes in soil carbon and nitrogen pools, as well as variations in microbial responses across soil locations, it has proven challenging to predict whether soil will become a source or sink of greenhouse gases under future climate scenarios. Thus, although the importance of soil microbial ecology for predicting future climate impacts has been recognised, it remains a challenge to integrate it with landscape-scale climate models (Wieder et al., 2013). In this chapter, give a summary of studies detailing how soil microbes react to the following predicted climate changes: higher atmospheric carbon dioxide (eCO_2) levels; higher temperatures; more drought; more precipitation and/or flooding; and more frequent fires, as illustrated in figure 4.

One of the most diverse ecosystems in plants is soil, which is located to an interacting community of bacteria, viruses, fungi, protozoa, and archaea known as the "soil microbiome." Soil contains abiotic and biotic properties, which is difficult to generalize the impact of climate change on soil microbiome across different soil ecosystems. Differences in biochemistry present in microorganisms, including pH (Fierer & Jackson, 2006), and salinity influences the creation of microbial habitats and niches (Schaeffer, 2012) with cascading effects on carbon and nutrient transformations. Therefore, understanding the fine-scale distribution and connectivity of soil microbial communities is essential to better comprehend how climate change affects species interactions and metabolism (Cordero & Datta, 2016). Also, different types of communities and physiological responses that soil microorganisms use to cope with changing environmental conditions, such as elevated CO_2, increased temperature, permafrost thaw, drought, increased precipitation and flooding, and fire frequency and its intensity.

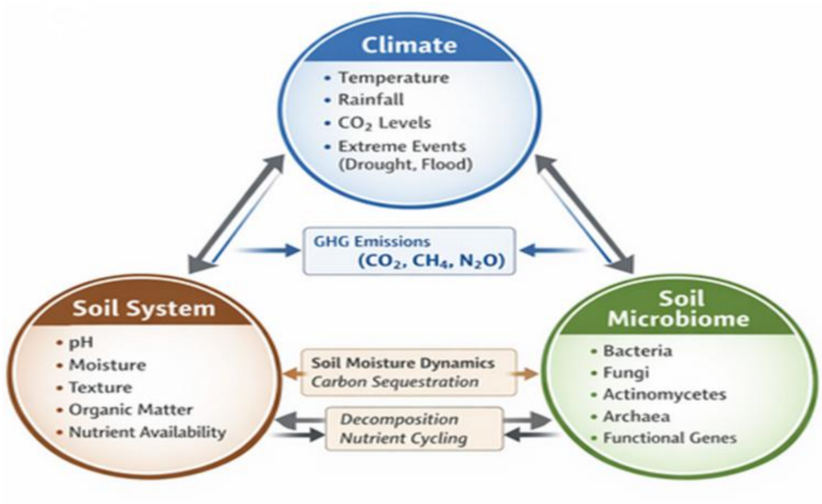

Figure 4. Soil-Climate-Microbiome Interaction

Residue Dynamics Under Climate Stress

Around 140 billion tons of crop residues are generated annually, which is approximately 40% of the total solid waste production (Greff & Lakatos, 2022). The five leading producers of crop residues are the United States, China, India, Brazil, and Russia, which produce 102.90, 84.90, 29.20, 21.60, and 15.90 million tons of residues per year, respectively. Only 30-75% of the total crop residues generated are recycled from these huge amounts in certain countries (Prasad et al., 2020). Figure 5 shows the climate stress drivers influence under residual climatic conditions.

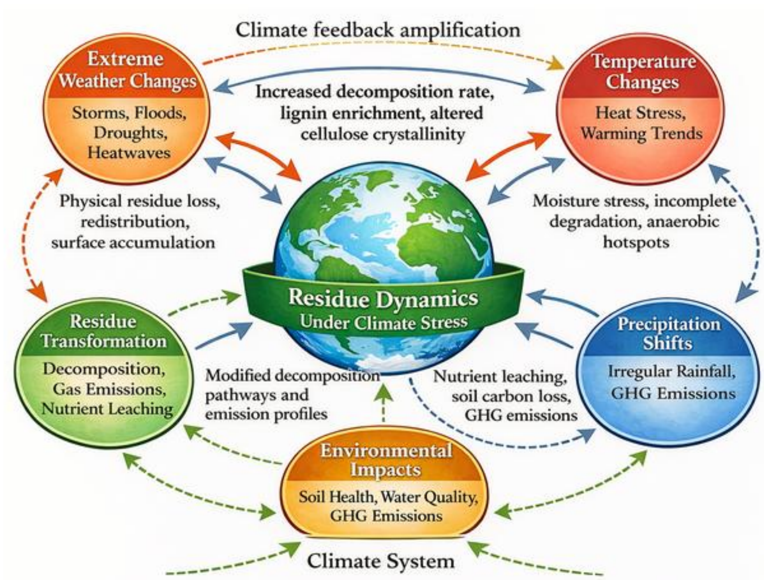

Figure 5. Residue dynamics under climate stress

Climate change is significantly influencing the transformation pathways for various residues by altering various environmental conditions. That transformation refers to physical, chemical, and biological processes through which residue decomposes, degrades, or changes after its generation. Previous studies have shown that the chemical composition of the plant residue directly and indirectly affects organic C fractions (Angst et al., 2021; Liu et al., 2022). Water-soluble residue compounds can directly add organic C to soil through leaching (Surey et al., 2020). The chemical structure of residues also impacts soil microbial activities responsible for decomposition, ultimately affecting organic C production. Physical transformation of residue due to changes in their size, structure, texture, and physical integrity without altering their chemical composition. Climatic stresses, such as high temperature fluctuations, irregular precipitation patterns, and intense weather events, play a crucial role in these physical changes.

International Conventions and Global Initiatives

The continuous rise in greenhouse gas emissions has intensified global warming, resulting in significant climate anomalies such as extreme heat waves, irregular precipitation patterns, melting glaciers, and rising sea levels (Physical & Basis, 2021). These changes pose serious threats to ecological balance, biodiversity conservation, water resources, and agricultural productivity across many regions of the world (IPCC, 2022). To address the growing climate crisis, several international conventions and global initiatives have been established to promote collective action. The United Nations Framework Convention on Climate Change (UNFCCC), adopted during the Rio Earth Summit in 1992, serves as the primary international treaty aimed at stabilizing greenhouse gas concentrations in the atmosphere (Murgan Murtala Ganiyu, 2021). The Kyoto Protocol, adopted in 1997 and enforced in 2005, introduced legally binding emission reduction commitments for developed countries under the principle of common but differentiated responsibilities (Grubb et al., 2022). More recently, the Paris Agreement (2015) represents a landmark global effort to limit the increase in global temperature to well below 2°C above pre-industrial levels while pursuing efforts to restrict warming to 1.5°C (Rogelj et al., 2018). Under this agreement, countries are required to submit Nationally Determined Contributions (NDCs) that outline their mitigation and adaptation strategies.

Several global initiatives also support climate mitigation and sustainable development. The Intergovernmental Panel on Climate Change (IPCC) provides comprehensive scientific assessments that guide international climate policy and environmental management (IPCC, 2023). Additionally, the United Nations Sustainable Development Goals (SDGs) integrate climate action into broader sustainability frameworks, particularly SDG 13, which focuses on urgent action to combat climate change and its impacts (United Nations, 2022). Other global initiatives, such as the Global Methane Pledge, Climate Action 100+, and international renewable energy programs, aim to reduce greenhouse gas emissions and accelerate the transition to low-carbon economies (IE Agency, 2023).

Advanced Tools for Ecosystem

In recent years, advanced analytical tools and technologies have significantly improved the understanding and prediction of global climate variability. Climate modelling approaches such as General Circulation Models (GCMs) and Earth System Models (ESMs) are widely used to simulate future climate scenarios under different greenhouse gas emission pathways (Eyring et al., 2016). Remote sensing technologies and satellite observations enable large-scale monitoring of atmospheric composition, land-use change, ocean temperature, and vegetation dynamics. Furthermore, emerging techniques such as machine learning, artificial intelligence, and big data analytics are increasingly being applied in climate science to enhance prediction accuracy and identify complex climate patterns (Reichstein et al., 2019). In addition, ecosystem-based analytical tools such as life cycle assessment (LCA), carbon footprint analysis, climate risk assessment, and ecosystem modelling are widely used to evaluate environmental impacts and develop sustainable mitigation strategies. These tools help researchers and policymakers assess ecosystem resilience, quantify greenhouse gas emissions, and design effective adaptation strategies that support long-term environmental sustainability and climate resilience (IPCC, 2023). Overall, strengthening international cooperation, implementing advanced analytical tools, and promoting sustainable environmental management are essential for addressing the global climate crisis. Collaborative efforts among governments, scientific communities, industries, and local stakeholders are crucial for reducing greenhouse gas emissions, enhancing climate resilience, and achieving global sustainable development goals.

Impacts of Climate Change

A)	**Physical impacts**		
Sr. No	**Variable**	**Impact**	**Source**
1	Elevated CO_2 concentration, crop growth and yield	1) Rise in photosynthetic efficiency and water-use efficiency 2) Decrease in transpiration and stomatal conductance 3) Growth in the biological and economic yield of crops	(Drake et al., 1997)
2	Elevated temperature, crop growth and yield	1) Early maturity of crop, shortened crop duration and improved respiration 2) Reduction in biomass and grain yields 3) Decrease in grain quality with increased night temperature	(Aggarwal & Singh, 2012)
3	Elevated temperature and soil fertility	1) Decline in soil organic carbon 2) Increased nitrogen mineralization in the short-term 3) Increased denitrification and volatilization losses of nitrogen 4) Negative impacts on soil fertility and mineral nutrition of crops	(Clair & Lynch, 2010)
4	Elevated temperature and water for irrigation	1) Irrigation water availability in the Indus, Ganges and Brahmaputra River basins may reduce 2) Increased predicted rainfall may increase runoff and flood in short-terms	(The World Bank, 2013)
5	Temperature, rainfall and CO_2, and agricultural biodiversity	1) Genetic erosion will increase	(Jarvis et al., 2008)
6	Temperature, rainfall, CO_2 and pest population	1) Increased pest severity 2) Declining production with increased losses	
7	Elevated CO_2 and temperature, and weed population	1) More growth of rhizomes in weeds 2) Higher seed production in annual weeds due to enhanced photosynthetic efficiency	

B)	**Spatial impacts**		
S. No	**Region**	**Impacts**	**Source**
1	North-West India	Under the altered climate, CO_2 fertilization effect for rice is insufficient to offset the adverse impact of rising temperatures	(Lal et al., 1998), (Kumar et al., 2019)
2	Central India	Significant impacts on central India's wheat productivity and rising temperatures	(Aggarwal, 2003), (Kumar et al., 2019)
3	Indo-Gangetic plains	Extreme weather events could have noticeable effects on agricultural productivity and production, but the short-term effects of climate change would not be severe.	(N. P. Singh et al., 2019)
4	Assam	Rural residents' forced relocation to urban areas because floods threaten farmland erosion	(Das, 2016)
5	North East	Northeast India's rice yield is generally negatively impacted by climate change.	(GOI, 2011)
6	Kerala	Rice yield may decline by 6% with a 1 °C rise in temperature.	(Saseendran et al., 2000), (Kumar et al., 2019)
7	Punjab	Rice and wheat yields have decreased in Punjab over the past few decades due to climate change and fluctuations.	
C)	**Socio-economic impacts**		
S. No	**Variable**	**Impacts**	**Source**
1	Farm income	1The average farm revenue in Kharif would decrease by 4.3 and 13.7%, and in Rabi by 4.1 and 5.5%, respectively, in a year with a temperature increase of 1°C and a rainfall deficit of 100 mm from the average rainfall. 2) According to IPCC climate change projections, farm income in India would be lost by 15–18% on average and 20–25% for unirrigated areas if policy responses are not made. At the current level of income, this would equate to more than Rs. 3600 per median farm household.	(GoI., 2017) (O'Neill & Pidcock, 2021)
2	Unemployment, rural migration, indebtedness, poverty and supply shocks	1) Climate change would lead to an increase in farm unemployment, rural migration and indebtedness among farmers 2) Food prices, poverty, rural–urban income parity and supply shock may increase 3) Consumer utility may decline as a result of climate change	

Source: Adopted from (Bisen et al., 2022)

Conclusion

Climate change is reshaping agricultural systems in complex and interconnected ways that extend beyond crop yield alone. Extreme climate variability resulted in ecological intensification and modification of insect pest population dynamics, loss of agricultural productivity and biodiversity. There should be a paradigm shift in planning for concerted, prudent crop management protocols, alleviating climate anomalies and fostering a global agricultural research perspective for climate-resilient, smart, sustainable agricultural production systems. Alterations in farm-scale microclimates, soil-microbiome interactions, and residue characteristics collectively influence crop resilience, nutrient cycling, and the quality of agro-waste. Climate-induced shifts in temperature and moisture not only disrupt microbial balance and carbon sequestration. Recognizing these material- and biology-driven changes is essential for designing climate-adaptive agro-waste management strategies. By linking microclimate dynamics, resilient soil microbiomes, and sustainable residue utilization, this chapter underscores critical yet underexplored pathways for advancing climate-resilient, resource-efficient, and circular agricultural systems for sustainable development.

Conflict of Interest Statement: The author has no conflict of interest.

References

Afzali, M., Colak, G., & Vähämaa, S. (2025). Climate change denial and corporate environmental responsibility. *Journal of Business Ethics*, *196*(1), 31–59. https://doi.org/10.1007/s10551-024-05625-y.

Aggarwal, P. K. (2003). Impact of climate change on Indian agriculture. *Journal of Plant Biology*, *30*(2), 189–198.

Aggarwal, P. K., & Singh, S. D. (2012). Climate change impact, adaptation and mitigation in agriculture: Methodology for editors.

Albitar, K., Al-Shaer, H., & Stephanie, Y. (2023). Corporate commitment to climate change: The effect of eco-innovation and climate governance. *Research Policy*, *52*(2), 104697. https://doi.org/10.1016/j.respol.2022.104697.

Angst, G., Mueller, K. E., Nierop, K. G. J., & Simpson, M. J. (2021). Plant- or microbial-derived? A review on the molecular composition of stabilized soil organic matter. *Soil Biology and Biochemistry, 156*, 108189. https://doi.org/10.1016/j.soilbio.2021.108189.

Auffhammer, M., & Schlenker, W. (2014). Empirical studies on agricultural impacts and adaptation. *Energy Economics, 46*, 555–561. https://doi.org/10.1016/j.eneco.2014.09.010.

Bisen, J., Priyadarsani, S., Pathak, H., Mondal, B., Tiwari, U., & colleagues. (2022). Socioeconomic implications of climate change on rice farming.

Carrier, M., Gonzalez, F. R., Cogliastro, A., Olivier, A., Vanasse, A., & Rivest, D. (2019). Light availability, weed cover and crop yields in second generation of temperate tree-based intercropping systems. *Field Crops Research*, *239*, 30–37. https://doi.org/10.1016/j.fcr.2019.05.004.

Clair, S. B. S., & Lynch, J. P. (2010). The opening of Pandora's box: Climate change impacts on soil fertility and crop nutrition in developing countries. *Plant and Soil, 335*, 101–115. https://doi.org/10.1007/s11104-010-0328-z.

Cordero, O. X., & Datta, M. S. (2016). Microbial interactions and community assembly at microscales. *Current Opinion in Microbiology, 31*, 227–234. https://doi.org/10.1016/j.mib.2016.03.015.

Cuartero, J., Querejeta, J. I., Prieto, I., Frey, B., & Alguacil, M. M. (2024). Warming and rainfall reduction alter soil microbial diversity and enhance pathogenic fungi in dryland soils. *Science of the Total Environment, 949*, 175006. https://doi.org/10.1016/j.scitotenv.2024.175006.

Dafermos, Y., & Nikolaidi, M. (2018). Climate change, financial stability and monetary policy. *Ecological Economics, 152*, 219–234. https://doi.org/10.1016/j.ecolecon.2018.05.011.

Das, D. (2016). Changing climate and its impacts on Assam, northeast India. *SpringerPlus, 5*, 1–12. https://doi.org/10.1186/s40728-015-0028-4.

Dirk, K., & Bo, C. (2014). Wind speed reductions as influenced by woody hedgerows grown for biomass in short rotation alley cropping systems in Germany. *Agroforestry Systems*, 579–591. https://doi.org/10.1007/s10457-014-9700-y.

Drake, B. G., Gonzàlez-Meler, M. A., & Long, S. P. (1997). More efficient plants: A consequence of rising atmospheric CO_2? *Annual Review of Plant Physiology and Plant Molecular Biology, 48*, 609–639.

Dufour, L., Gosme, M., Le, J., & Dupraz, C. (2020). Does pollarding trees improve crop yield in a mature alley-cropping agroforestry system? *Journal of Agronomy and Crop Science, 206*, 640–649. https://doi.org/10.1111/jac.12403.

Dufour, L., Metay, A., Talbot, G., & Dupraz, C. (2013). Assessing light competition for cereal production in temperate agroforestry systems using experimentation and crop modelling. *Journal of Agronomy and Crop Science, 199*, 217–227. https://doi.org/10.1111/jac.12008.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development, 9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016.

Fierer, N., & Jackson, R. B. (2006). The diversity and biogeography of soil bacterial communities. *Proceedings of the National Academy of Sciences, 103*(3), 626–631. https://doi.org/10.1073/pnas.0507535103.

Foereid, B., Bro, R., Overgaard, V., & Porter, J. R. (2002). Effects of windbreak strips of willow coppice Modelling and field experiment on barley in Denmark. *Agriculture, Ecosystems & Environment, 93*, 25–32.

Gordon, A. M., Newman, S. M., & Coleman, B. R. W. (2017). *Temperate agroforestry systems*. CABI.
Government of India. (2011). *Ministry of development of north eastern region*.

Government of India. (2017). *Economic survey 2017–18: Climate, climate change and agriculture*. https://mofapp.nic.in/economicsurvey/economicsurvey/pdf.

Greff, B., & Lakatos, E. (2022). Influence of microbial inoculants on co-composting of lignocellulosic crop residues with farm animal manure: A review. *Journal of Environmental Management, 302*, 114088. https://doi.org/10.1016/j.jenvman.2021.114088.

Grubb, M., Okereke, C., Arima, J., Bosetti, V., Chen, Y., Edmonds, J., Gupta, S., Köberle, A., Kverndokk, S., Malik, A., & Sulistiawati, L. Y. (2022). Introduction and framing. In *Climate change 2022: Mitigation of climate change* (pp. 151–214). Cambridge University Press. https://doi.org/10.1017/9781009157926.003.

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4–10. https://doi.org/10.1016/j.wace.2015.08.001.

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. https://doi.org/10.1017/9781009325844.

Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report*. https://www.unep.org/resources/report/climate-change-2023-synthesis-report.

International Energy Agency. (2023). *CO_2 emissions in 2023*. https://www.iea.org.

Jacobs, S. R., Webber, H., Niether, W., Grahmann, K., Lüttschwager, D., Schwartz, C., Breuer, L., & Bellingrath-Kimura, S. D. (2022). Modification of the microclimate and water balance through the integration of trees into temperate cropping systems. *Agricultural and Forest Meteorology*, *323*, 109065. https://doi.org/10.1016/j.agrformet.2022.109065.

Jarvis, A., Lane, A., & Hijmans, R. J. (2008). The effect of climate change on crop wild relatives. *Agriculture, Ecosystems & Environment*, *126*, 13–23. https://doi.org/10.1016/j.agee.2008.01.013.

Kanzler, M., Böhm, C., & Dieter, M. (2019). Microclimate effects on evaporation and winter wheat yield within a temperate agroforestry system. *Agroforestry Systems*, *93*, 1821–1841. https://doi.org/10.1007/s10457-018-0289-4.

Kumar, S. N., Islam, A., Rani, D. N. S., & Panjwani, S. (2019). Seasonal climate change scenarios for India: Impacts and adaptation strategies for wheat and rice.

Lal, M., Singh, K. K., Rathore, L. S., Srinivasan, G., & Saseendran, S. A. (1998). Vulnerability of rice and wheat yields in northwest India to future changes in climate. *Agricultural and Forest Meteorology*, *89*, 101–114.

Liu, S., Li, J., Liang, A., Duan, Y., Chen, H., Yu, Z., & Fan, R. (2022). Chemical composition of plant residues regulates soil organic carbon turnover in soils with contrasting textures. *Soil Biology and Biochemistry*.

Mukharji, A. (2022). Climate change: Put water at the heart of solutions.

Mume, I. D., & Workalemahu, S. (2021). Review on windbreaks agroforestry as climate-smart agriculture practices. *American Journal of Agriculture and Forestry, 9*(6), 342–347. https://doi.org/10.11648/j.ajaf.20210906.12.

Murtala Ganiyu, M. (2021). Revisiting the role of UNFCCC and the Kyoto Protocol in the fight against emissions from international civil aviation. *Nnamdi Azikiwe University Journal of International Law and Jurisprudence, 12*(1), 112–126.

O'Neill, S., & Pidcock, R. (2021). Introducing the topical collection: Climate change communication and the IPCC. *Climatic Change, 169*(3–4). https://doi.org/10.1007/s10584-021-03253-3.

Ort, D., Thomson, A. M., & Wolfe, D. (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, *103*, 351–370.

Physical, T., & Basis, S. (2021). *Climate Change 2021 The Physical Science Basis Summary for Policymakers*.

Prasad, S., Singh, A., Korres, N. E., Rathore, D., & Sevda, S. (2020). Sustainable utilization of crop residues for energy generation: A life cycle assessment perspective. *Bioresource Technology*, *303*, 122964. https://doi.org/10.1016/j.biortech.2020.122964.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., & Prabhat. (2019). Deep learning and process understanding for data-driven Earth system science. *Nature, 566*(7743), 195–204. https://doi.org/10.1038/s41586-019-0912-1.

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., Van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., & Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change, 8*(4), 325–332. https://doi.org/10.1038/s41558-018-0091-3.

Rudrakar, S., & Rughani, P. (2024). IoT-based agriculture (Ag-IoT): Architecture, security and forensics. *Information Processing in Agriculture, 11*(4), 524–541. https://doi.org/10.1016/j.inpa.2023.09.002.

Sacks, W. J., & Kucharik, C. J. (2011). Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance. *Agricultural and Forest Meteorology, 151*(7), 882–894. https://doi.org/10.1016/j.agrformet.2011.02.010.

Saseendran, S. A., Singh, K. K., Rathore, L. S., Singh, S. V., & Sinha, S. K. (2000). Effects of climate change on rice production in India. *Climate Research, 14,* 495–514.

Schaeffer, S. M. (2012). Microbial control over carbon cycling in soil. *Frontiers in Microbiology, 3,* 348. https://doi.org/10.3389/fmicb.2012.00348.

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences, 106*(37), 15594–15598. https://doi.org/10.1073/pnas.0906865106.

Singh, A., Khichar, M. L., Singh, J., & Ram, B. (2023). Diurnal temperature variation inside crop canopy of pearl millet under different sowing environments. *International Journal of Environment and Climate Change, 13*(4), 118–131. https://doi.org/10.9734/IJECC/2023/v13i41718.

Singh, N. P., Anand, B., Singh, S., & Khan, A. (2019). Mainstreaming climate adaptation in Indian rural developmental agenda: A micro-macro convergence. *Climate Risk Management, 24*, 30–41. https://doi.org/10.1016/j.crm.2019.04.003.

Stevanović, M., Popp, A., Lotze-Campen, H., Dietrich, J. P., Müller, C., Bönsch, M., Schmitz, C., Bodirsky, B. L., Humpenöder, F., & Weindl, I. (2016). The impact of high-end climate change on agricultural welfare. *Science Advances, 2*(8), e1501452.

Surey, R., Schimpf, C. M., Sauheitl, L., Mueller, C. W., Mikutta, R., Rummel, P. S., Dittert, K., Kaiser, K., & Böttcher, J. (2020). Potential denitrification stimulated by water-soluble organic carbon from plant residues during initial decomposition. *Soil Biology and Biochemistry, 147*, 107841. https://doi.org/10.1016/j.soilbio.2020.107841.

United Nations Department of Economic and Social Affairs. (2022). *The sustainable development goals report 2022*. https://unstats.un.org/sdgs/report/2022/.

Wachendorf, M., & Ru, M. E. (2018). Productivity at the tree-crop interface of a young willow-grassland alley cropping system. *Agroforestry Systems, 92*, 71–83. https://doi.org/10.1007/s10457-016-0015-z.

Wang, Z., Liang, G., Jiang, S., Wang, F., Li, H., Li, B., Zhu, H., Lu, A., & Gong, W. (2024). Environmental impacts and risks of organic additives in plastics. *Emerging Contaminants, 10*(4), 100388. https://doi.org/10.1016/j.emcon.2024.100388.

Wieder, W. R., Bonan, G. B., & Allison, S. D. (2013). Global soil carbon projections improved by modelling microbial processes. *Nature Climate Change, 3*, 909–912. https://doi.org/10.1038/nclimate1951.

World Bank. (2013). *Warming climate in India to pose significant risk to agriculture*. https://www.worldbank.org.

Xu, X., An, H., Huang, S., Jia, N., & Qi, Y. (2024). Measurement of daily climate physical risks and transition risks faced by China's energy sector stocks. *International Review of Economics and Finance, 93*, 625–640. https://doi.org/10.1016/j.iref.2024.05.006.

Yang, T., Ma, C., Lu, W., Wan, S., Li, L., & Zhang, W. (2021). Microclimate, crop quality, productivity, and revenue in agroforestry systems in drylands of Xinjiang, China. *European Journal of Agronomy, 124*, 126245. https://doi.org/10.1016/j.eja.2021.126245.