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Climate Change and Soil Fertility: A Review of Strategies for a Sustainable Food Security in India

Niru Kumari [a++], Mukul Kumar [a++*], Ashutosh Singh [a++] and Amit Kumar Pandey [a++]

[a] *Bihar Agricultural University, Sabour, Bhagalpur, Bihar, 813210, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The long-term food security of humanity on Earth will be significantly influenced by the effects of climate change soils and then the agricultural production. In addition to being vulnerable to climate change, agriculture also contributes significantly to it. The article explores how soil fertility processes and qualities are impacted by climate change on a worldwide scale and adaptation and mitigation options for a sustainable food security. Due to the intricate relationship between soils and the climate system through nutrient and hydrologic cycles, it is anticipated that changes in the global climate may have an effect on soil fertility through changes in the physical, chemical, and biological characteristics of the soil as a result of rising temperatures, altered precipitation patterns, increased atmospheric concentrations of greenhouse gases, and other factors.

[++] *Assistant Professor Cum Junior Scientist;*
**Corresponding author: E-mail: kumarmukul93@gmail.com;*

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1. INTRODUCTION

"Climate change refers to any significant alteration in climatic phenomena that lasts for several decades or more" [1]. "These include variations in average climatic conditions, irregular rainfall events, the frequency and intensity of extreme weather events, and sea level rise, whether brought on by human activity or natural fluctuations. The process of global warming is commonly ascribed to greenhouse gases produced by burning fossil fuels such as coal, oil, natural gas, etc., which is a result of human activity" [2]. "Since the soil provides the majority of the food and fiber required by the world's growing population, climate change has an impact on the environment, including soil" [3]. "As a result, it may jeopardize global food security by altering soil processes and qualities" [4]. "According to the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report, human activity is most likely to blame for the estimated 1.0℃ rise in global temperature beyond preindustrial levels, with a likely range of 0.8 to 1.2℃. According to IPCC, if global warming keeps on its current pace, it might reach 1.5℃ between 2030 and 2052. This would alter other regional and global climate-related factors like rainfall, soil moisture, and sea level" [5].

"One inherent quality of a soil is its state of health. It is understood to be a set of traits that classify and characterize its health. In contrast, soil quality is an external feature of soils and is influenced by how humans choose to utilize them. It might have to do with the productivity of agriculture and its ability to sustain wildlife, safeguard watersheds, or provide goods for leisure. In order to maintain or improve water and air quality, support plant and animal health, and operate as a viable living system within ecological and land use constraints, a soil must possess certain qualities, which Doran and Zeiss characterize as soil health" [6].

"Despite the fact 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 many soil processes, especially those that are connected to soil fertility" [6]. The primary predicted consequences of climate change on soils include changes in soil moisture conditions, as well as increases in soil temperature and CO_2 levels. One strategy that may be used to successfully lessen the consequences of climate change is adapt-led mitigation, which also encourages a variety of stakeholders to use different adaptation and mitigation technologies. In the field, adaptation may be achieved by making adjustments to the present practice packages to address fluctuations and changes in the climate.

Agronomic interventions in agriculture incorporate a range of techniques enhancing soil carbon and health, soil conservation, tillage operation, system innovations for enhancing productivity and more. Agriculture and climate change are interdependent processes, and it is anticipated that global warming would have a major influence on agriculture through direct and indirect effects on crops, soils, animals, and pests. In addition to the likely decrease in food production, there may be a decrease in food's nutritional quality, which raises questions about nutritional security [7]. Concerned about how climate change may affect the soil health and ecosystem sustainability, attempts are being undertaken to create mitigation solutions for its adverse effects. The impact of climate change on soils, as well as mitigation and adaptation techniques, have been explored in light of these issues.

2. CLIMATE CHANGE'S EFFECTS ON THE ENVIRONMENT AND MITIGATION MEASURES

"Globally, people are currently very concerned about the speed and extent of climate change. Since the Industrial Revolution, greenhouse gas emissions from human activities such as increased energy consumption, industrialization, intensive agriculture, and urban and rural development have increased in the atmosphere. This has increased heat retention, raised global temperatures, and increased spatial and temporal variability. The atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were significantly raised by anthropogenic greenhouse gas (GHG) emissions prior to the preindustrial era" [8,9]. "It was noted that approximately half of the anthropogenic CO_2 emissions from the preindustrial era to 2011 have occurred in the last 40 years" [10]. Of this increase, about 81% was attributable to CO_2 concentration. The accumulation of greenhouse gases (GHG) has caused an increase in the global mean annual temperature of 0.4–0.7℃ at the end of the nineteenth century [11], and the IPCC [1] predicts that by the end of the twenty-first century, the temperature will have climbed by 1.1–6.4℃.

"Rising concentrations of greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O cause the global mean temperature to rise by 1.1 - 0.1℃ since the preindustrial era" [12]. "The rate of increase is 0.2℃ per decade (IPCC 2018), with an estimated 4 - 2℃ increase by the end of the twenty-first century" [13]. "Climate change has brought significant changes in land-use and natural vegetation, which in turn affects albedo, temperature, precipitation patterns, the heat and energy balance of the near-surface atmosphere, and other aspects of the climate. In addition to altering the characteristics of precipitation, rising temperatures also cause a significant portion of the polar ice caps, permafrost soil zones, and mountain glaciers to melt. This alters the dynamics of water flow, causing surface runoff and flood waves, and raises the eustatic sea level, endangering agricultural areas, low-lying areas, and settlements" [14]. "Additionally, the field water cycle and soil formation processes are significantly impacted by changes in vegetation" [15].

3. CLIMATE CHANGE'S EFFECT ON SOIL PROPERTIES AND ADAPTATION MEASURES

"Global climate change has a major impact on soils as well as the functions performed by the soils (Table 1). The main effects of climate

Table 1. Climate change effects on soil

Climatic Factors	Effects
Rise in temperature	• Salinization of soil • Soil organic matter decomposition increases • Loss of soil organic matter • Decreases soil porosity • Increases soil compactness • Reduction of soil CEC • Reduction of soil fertility • Deterioration of soil structure • Increases risk of soil erosion • Reduction of water retention capacity • Increases CO_2 release from soil • Reduction of soil organic C • Increases ammonia volatilization • Increases rhizospheric temperature • Stimulation of nutrient acquisition • Enhances soil microbial activity • Increases bioavailability of N and P from organic matter
Heavy and intensive rainfall	• Destruction of soil aggregate • Increases risk of soil erosion • Increases leaching of basic cations • Soil acidification • Reduces soil CEC • Loss of soil nutrients, especially N • Development of hypoxic condition in poorly drained soil • Toxicities of Fe, Mn, Al, and B • Loss of N through denitrification
Decreased rainfall	• Increases salt content • Soil moisture deficit • Decreases diffusion and mass flow of water-soluble nutrients • Possibility of occurring drought • Loss of nutrient from rooting zone through erosion • Reduces nutrient acquisition capacity of root system • Reduces N-fixation in legumes
Increase in atmospheric CO_2	• Increases soil C availability • Increases soil microbial activity • Increase soil fungal population

change that are expected to occur are elevated CO_2 levels, changes in soil moisture content, and temperature increases in the soil" [16]. The processes and characteristics of the soil that are in charge of restoring the soil's fertility and productivity are anticipated to be primarily impacted by temperature and CO_2 levels in the climate.

3.1 Soil Physical Properties

"The physical properties of soil are largely influence by the chemical and biological processes of soil, such as adsorption, water, heat and mass transport, nutrient supply, biological activity, etc., which have a significant impact on soil fertility and are strongly correlated with soil sensitivity to climate change" [17,18]. "Soil hydrophysical properties also play a significant role in influencing soil fertility" [19]. Increased temperatures, higher CO_2 concentrations, altered rainfall patterns, and their interactions as a result of climate change are predicted to have an impact on a number of soil physical processes, increasing the risk of salinization, reducing the availability of water and nutrients, changing the dynamics of C and N, and reducing soil biodiversity [20]. According to Mills et al. [21], soil moisture stress lowers soil functions, which in turn impacts plant yield. The following are significant soil physical characteristics that are impacted by soil fertility as a result of climate change.

Soil texture: Given that soil texture is a relatively stable soil feature, it has a significant impact on soil properties and controls how sensitive the soil is to changes in climate. According to Bormann [22], clay soils are the least responsive to climate change, whereas silt soils are the most. The primary contributing element affecting how soil reacts to local climatic change is soil texture.

Soil Structure: Significant variations in temperature and precipitation patterns brought on by climate change have a complex effect on the type, distribution, and aggregate stability of soil [14]. This process involves the slaking, dispersion, mechanical disturbance, and compaction processes [23]. Due to the aggregate-destructive nature of intense rainfall, surface runoff, and filtrating water during heavy downpours, thunderstorms have a direct effect on soil structure [24]. "Climate change may indirectly affect the land-use practices and also soil biological function (due to the sensitivity of soil macrofauna and microorganisms to climate change), which in turn affect the soil structure" [14,24].

Bulk Density and Porosity: The texture and organic matter content of the soil, as well as climate, have a significant impact on bulk density. Increased bulk density can result from soil erosion or the loss of organic matter in the soil due to an increased rate of decomposition brought on by an elevated temperature [25]. Compaction can then worsen the soil's porosity and cause a compact layer to form that prevents root growth [26,24]. Future climate change scenarios, such as rising temperatures and CO_2 levels as well as erratic and intense rainfall events, could have an unexpected impact on soil functions such as pore-size distribution and porosity, which could further change root development and soil biological activities.

3.2 Soil Chemical Properties

The chemical composition and/or fertility of the soil declined with rising soil temperature, even as several chemical processes in the soil quickened as a result of global warming [27]. The subsequent part discusses the direct effects of climate change on a few chemical characteristics of soil.

Soil pH: The direct consequences of climate change, such as higher temperature, varied precipitation, CO_2 fertilization, and atmospheric N deposition, are not likely to cause most soils' pH values to shift quickly [28]. But these climate change agents also alter the amount of organic matter in the soil, the cycle of carbon and nutrients, the amount of water accessible to plants, and therefore the productivity of plants, which can have an impact on the pH of the soil [29]. Rainfall increases have the potential to accelerate the leaching of basic cations, which results in acidified soil. Soil pH may also be impacted by changes in rainfall patterns brought on by seasonal and diurnal variations as a result of climate change.

Cation Exchange Capacity: One important factor influencing soil fertility is cation exchange capacity (CEC), particularly when it comes to the immobilization of potentially hazardous cations like Al and Mn and the retention of major cationic nutrients like Ca, Mg, and K. Because CEC is correlated with the amount of organic matter in the soil [30], coarse-textured soils and low-activity clay soils with a greater decomposition rate and declining SOM owing to rising temperatures [25] have lower CEC. High and frequent rainfall can cause more basic cation leaching, which can lead to low CEC in the soil.

Soil Salinization: The soil may naturally become weaker and more vulnerable to erosion by wind and water as a result of salinization and alkalization. Salt dynamics are the most susceptible to changes among the several indicators of climate change, which aggravates and causes soil salinization [31]. The two main factors that induce salinization, salt buildup and wind deposition, are predicted to be impacted by climate change [31]. Due to changes in the global climate, salinization has increased even more quickly, particularly in the last 20 to 30 years [32].

3.3 Soil Biological Properties

“Soil biological properties are also interlinked with other soil physical and chemical properties such as aeration, soil organic matter, or pH, influencing the soil microbial activity which in turn performs relevant activities in carbon and nutrients cycling” [33].

Soil Organic Matter: Soil organic matter (SOM) is a significant factor in determining soil fertility. It controls most soil activities, including cation exchange, water storage capacity, and pH. Compared to temperature rise, changes in soil moisture content brought on by climate change may have a greater impact on SOM breakdown in many ecosystems. The unsaturated zone has an oxic environment that speeds up the breakdown of organic materials and may be dominated by effective aerobic processes [34]. The optimal levels of microbial activity and SOM breakdown rates are observed at soil moisture contents between fifty and sixty percent. Excessive soil moisture in some habitats might impede the breakdown process [35].

Soil Microbial Biomass: “Elevated carbon dioxide levels over a longer period of time may have a little direct effect on soil microbial biomass (SMBC) and community structure” [36]. “Soil microbial biomass is responsive to short-term changes of environment and declines significantly with long-term simulated climate warming experiments” [37,38]. Thus, the living part of organic matter and the most labile C pool in soils, soil microbial biomass (SMB), represents microbial size and soil fertility status.

4. MITIGATION AND ADAPTATION THROUGH AGRONOMIC PRACTICES

Agricultural methods that reduce the negative effects of temperature fluctuations, fluctuating rainfall, and other extreme weather events can help agriculture adapt to climate change. In addition to broader agronomic management strategies (e.g., crop rotation, planting time [39], cover crop, organic farming, tillage practices etc. introduction of legume crop [40,41], there are many other management-level adaptation options available to mitigate the effects of climate change on crop production [42]. These options include zero tillage, retaining crop residues, extending fallows, increasing the diversity of production, and altering amounts and timing of external inputs (fertilizers, water). Through improved soil carbon sequestration and reduced greenhouse gas emissions (carbon dioxide, nitrous oxide, and methane), agriculture can help mitigate the effects of climate change. Carbon dioxide emissions can be decreased by burning less biomass and using energy more efficiently. Improved farm management techniques, such as better handling of animal waste and water in rice fields, can lower methane emissions. Improved N fertilizer management, which includes choosing the right kind, rate, and application technique, as well as soil management (prevention of soil compaction), can lower nitrous oxide emissions (Table 2).

4.1 Organic Farming

“Globally, organic farming is gaining momentum as the most sustainable agricultural system due to its ability to enhance physical, biological, and environmental resources like soil nutrient mineralization, microbial activity, diversity, abundance, and lower nitrate (NO_3-) concentrations in groundwater. It has been observed that legume crops, such as lucerne and *Sesbania spp.*, may enhance soil organic matter by about 50%, as well as boost soil N supply capacity and sequestration when compared to mineral fertilization” [43]. “In comparison to conventional systems, organic systems utilizing compost and peat sources demonstrated increased microbial populations and enzyme activity throughout the course of a 12-year research including rice (*Oryza sativa*) and maize (*Zea mays*) crops” [44]. “In comparison to traditional culture methods, organic farming has been shown to decrease soil pathogens, including *Fusarium wilt* in cucumber (*Cucumis sativus*) and plant parasitic nematodes

Pratylenchus and *Meloidogyne* in maize and beans” [45,46].

“The physical and chemical qualities of soil can be enhanced by organic farming. For instance, compared to conventional systems, organic systems in a clay soil increased soil water content (15%) and retention capacity (10%) and decreased soil bulk density (8%) in the top 20 cm soil layer” [47]. “Furthermore, organic farming provides an excellent supply of macronutrients. For instance, N storage of soil treated with organic manure was much greater (by 50%) in the 20 cm topsoil than that of standard chemical fertilizers in a long-term (18-year) research utilizing chemical and organic fertilization regimes” [48]. “Another long-term research (21 years) comparing conventional and organic farming found that whereas Ca^2+ and Mg^2+ were 30–50% greater in the conventional soil, nutrient input (N, P, and K) was 34–51% lower in the organic soil” [49].

Table 2. Adaptation measures to mitigate the effects of climate change on soil

Aspect	Adaptation Measure	Description
Physical Adaptations		
Erosion Control	Contour farming, terracing	Reduces soil erosion by slowing water runoff and increasing water infiltration
	Windbreaks, cover crops	Protects soil from wind erosion and improves soil structure
Soil Moisture Management	Mulching, irrigation improvements	Helps retain soil moisture and reduces evaporation
	Rainwater harvesting	Collects and stores rainwater for agricultural use, reducing dependency on irregular rainfall
Temperature Regulation	Agroforestry	Incorporates trees into agricultural systems to provide shade and reduce soil temperature
	Conservation tillage	Minimizes soil disturbance, preserving soil moisture and structure
Chemical Adaptations		
Nutrient Management	Organic amendments, crop rotation	Enhances soil fertility and nutrient cycling
	Precision agriculture	Utilizes technology to optimize fertilizer application and reduce chemical runoff
pH Regulation	Liming acidic soils	Increases soil pH to improve nutrient availability
	Gypsum application on sodic soils	Helps reclaim sodic soils by improving soil structure and reducing salinity
Biological Adaptations		
Enhancing Soil Biodiversity	Cover cropping, green manures	Improves soil health by increasing organic matter and supporting diverse microbial communities
	Reduced pesticide use	Protects beneficial soil organisms and promotes a healthy soil ecosystem
Promoting Soil Fauna	Habitat creation, reduced tillage	Supports earthworms and other beneficial soil fauna that enhance soil structure and fertility
Plant-Soil Interaction	Selecting climate-resilient crop varieties	Improves plant tolerance to changing soil conditions
	Mycorrhizal inoculation	Enhances plant nutrient uptake and soil health through beneficial fungal relationships

4.2 Tillage Practices

“Tillage techniques have been shown to impact crop productivity and fruit quality in watermelon and rice-maize cropping systems, as well as the chemical and physical characteristics of the soil” [50]. “Maintaining soil health and crop productivity requires the adoption of effective tillage practices” [51]. “Conservation tillage techniques (no-tillage, reduced, and strip) have been shown to drastically lower soil macro- and micro-aggregate stability while simultaneously increasing soil microbial activity, soil moisture, organic matter, aggregate stability, cation exchange capacity, and crop production” [52-54]. “In comparison to conventional tillage methods, conservation tillage techniques improved soil accessible P in the topsoil (0–20 cm) by 3.8%, K by 13.6%, and soil organic matter” by 0.17% [55]. “Reducing soil erosion and increasing soil moisture content can also be achieved by keeping crop residues on the top layer of the soil (complete cover, no till; partial cover, strip tillage)” [56]. “Compared to conventional methods, conservation tillage increases the quantity of nematodes, earthworms, gram-positive bacteria, and bacteria and fungus” [57,58].

4.3 Cover Crop

“The purpose of growing cover crops is to increase soil fertility, reduce soil erosion, protect and enrich the soil, and improve the soil's quality, availability of nutrients, and water retention. The growth and maintenance of soil microbial biodiversity can be facilitated by cover crops [59]. The main purpose of planting cover crops is to reduce soil erosion. Certain crop species, such ryegrass, rye, and oats, have a strong capacity to reduce soil erosion, whereas cover crops with deep roots, like white mustard and fodder radish, are less successful in doing so” [59]. In a maize-soybean cropping system, it was discovered that using cereal rye (*Secale cereale* L.) as a cover crop improved soil water [60]. At water potentials relevant to field capacity and plant accessible water, cover crops enhanced soil water retention by 10%–11% and 21%–22%, respectively [61]. According to University of California study, cover crops such as brome grass, resident vegetation, and strawberry clover can reduce the strength of the surface soil by 38–41 percent. They can also increase the rate of soil infiltration by 37–41 percent and the cumulative water uptake by 20–101 percent [61]. Compared to the other management techniques that raised SOC, cover crops offer an advantage. A meta-analysis was carried out on 139 plots located at 37 distinct locations in order to assess the carbon response function, which describes the variations in SOC over time. At a soil depth of 22 cm, the cover crops in rotation that were studied for up to 54 years showed a linear correlation with the yearly change in SOC at a rate of 0.32 ± 0.08 Mg ha^{-1} yr^{-1} (R2 = 0.19). The premise that the observed linear SOC accumulation will not continue to rise indefinitely informed the modelling of the average SOC stock change. After 155 years of employing cover crops, the newly estimated steady state data would have a SOC buildup of 16.7 ± 1.5 Mg ha^{-1} yr^{-1} [62].

4.4 Crop Rotation

Crop rotation has several ecological and financial advantages. More precisely, it helps with long-term agriculture and soil management. Different plant species have different interactions with the nutrients in the soil, releasing and absorbing different nutritional components in different amounts [63]. In order to balance the soil's nutrient levels, a well-planned rotation strategy either replenishes deficient nutrients or uses surplus minerals [64]. Additionally, the organic matter levels in the soil are increased by the beneficial microbial leftovers left by different plants. Animal faeces from grazing areas naturally fertilizes fallow land. Pure green manure, or leftover biomass from harvesting, increases soil fertility and lessens the demand for commercial fertilizers.

Crop rotation influences the growth of beneficial bacteria in different types of soil, as well as the generation and dispersion of biopores and the cycling of nutrients in the soil. These procedures strengthen the health of the soil and lessen compaction. Root systems can be deep or shallow, entering the soil at varying depths and increasing the soil's porosity depending on the type of crop. Since the residue left by legume and high-residue plants works as a barrier to prevent topsoil erosion, rotation of these plants can help reduce soil erosion [64]. Perennial grasses with a long lifespan also successfully prevent soil nutrient loss and water erosion. Planning crop rotation and using a variety of perennial grass types can help reduce erosion even in highland locations.

4.5 Optimizing Nutrient Application

Site-specific nutrient management (SSNM), soil test-based nutrient delivery, integrated nutrient management (INM), green manure, and balanced fertilization methods are significant nutrient-application approaches that increase nutrient efficiency. Plant nutrients must be recycled by using compost, manure, mulch, sludge, biological N fixation through rotational or mixed cropping with legumes, and further use of synthetic fertilizers in order to increase soil fertility utilizing INM. Long-term manure experiments carried out as part of the All India Coordinated Research Project on Dry Land Agriculture (AICRPDA) demonstrated that adding green-leaf manure along with other crop residues and groundnut (*Arachis hypogaea* L.) shells enhanced soil infiltration and water retention [65].

5. CONCLUSION

Global climate change is predicted to alter soil physical parameters such as bulk density, porosity, texture, structure, and nutrient retention. These changes will likely affect soil fertility and may lead to salinization of the soil, decreased availability of nutrients and water, altered C and N dynamics, and decreased biodiversity of the soil. Given that most soil functions, including pH, cation exchange capacity, water and nutrient retention, and soil structure, depend on soil organic matter, and that this matter's variation in decomposition rate as a result of global warming has a negative impact on soil fertility, soil fertility is determined by the amount of organic matter present in the soil. Different farm management techniques can promote soil functional stability and increase soil carbon stocks. However, because many agronomic activities increase the overall sustainability of the ecosystem, it is necessary to assess the effect of these practices from the perspectives of adaptation and mitigation and to analyses their performance via a climatic lens. Effective adaptation and mitigation strategies must be widely disseminated in order to improve the ecology and soil health of the environment and stop the impending negative consequences of climate change and variability.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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