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Climate Change Adaptation through Soil and Nutrient Management for Sustainable Crop Production in Bangladesh: A Review

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Abstract

Bangladesh's agriculture is highly vulnerable to climate change, with increasing temperatures, erratic rainfall, flooding, drought, and salinity intrusion affecting crop productivity, soil fertility, and nutrient dynamics. Soil and nutrient management practices provide essential tools for climate adaptation, improving crop resilience, nutrient use efficiency, and sustainability. This review synthesizes current knowledge on climate trends, soil degradation, nutrient dynamics, and crop-specific adaptation strategies in Bangladesh. It highlights integrated soil fertility management, organic amendments, conservation agriculture, and climate-smart nutrient practices as key interventions. Socio-economic and institutional constraints, environmental co-benefits, and trade-offs are also discussed. Finally, research gaps and policy recommendations are identified to guide future strategies for resilient and sustainable agriculture under changing climate conditions.

Keywords: *Climate change adaptation; Soil fertility; Nutrient management; Crop resilience; Bangladesh; Sustainable agriculture.*

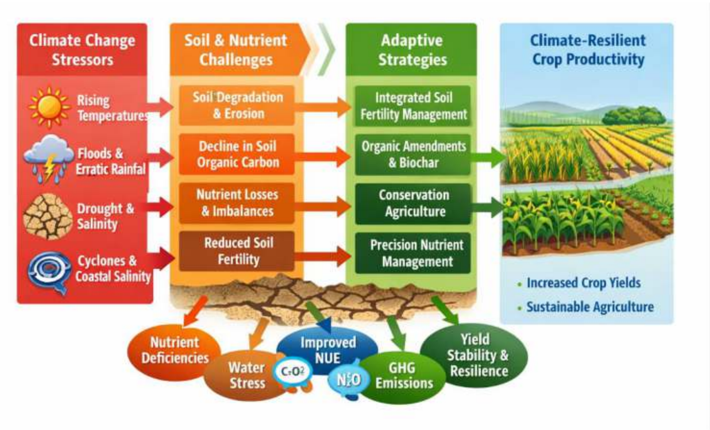

Figure 1: Graphical Abstract

Introduction

Climate change poses a substantial threat to global agricultural systems, with developing countries experiencing disproportionate impacts due to their high dependence on climate-sensitive livelihoods and limited adaptive capacity [1,2]. Bangladesh is recognized as one of the most climate-vulnerable countries in the world, where agriculture plays a central role in food security, employment, and rural livelihoods [1]. Increasing temperatures, erratic rainfall patterns, frequent floods, prolonged droughts, and accelerating salinity intrusion are already disrupting crop production systems across the country [2]. These climate-induced stresses are projected to intensify in the coming decades, posing serious challenges to sustaining crop productivity and national food security[1].

Soil health and nutrient availability constitute the foundation of sustainable crop production, yet they are highly sensitive to climate variability and extreme events [3, 4]. Rising temperatures accelerate organic matter decomposition, alter nutrient mineralization rates, and increase nitrogen losses through volatilization and leaching [5, 3]. Changes in precipitation regimes influence soil moisture dynamics, erosion processes, and nutrient transport, while floods and waterlogging modify redox conditions, affecting the availability of nitrogen, phosphorus, sulfur, and micronutrients [6]. In coastal regions of Bangladesh, sea-level rise and saline water intrusion further exacerbate soil degradation by increasing salinity and sodicity, leading to nutrient imbalance and reduced crop growth [7,8]. Consequently, climate change is not only a direct stressor on crops but also an indirect driver of declining soil fertility and nutrient use efficiency [9].

Bangladesh agriculture is predominantly characterized by intensive cropping systems, particularly rice-based rotations, which place continuous pressure on soil resources [10]. Decades of high-input fertilizer use, often imbalanced and inefficient, combined with limited organic matter recycling, have resulted in declining soil organic carbon and emerging micronutrient deficiencies in many agroecological zones [11]. Under changing climatic conditions, these existing soil fertility constraints are becoming more pronounced, increasing the vulnerability of cropping systems to yield instability. Therefore, enhancing soil resilience and optimizing nutrient management are increasingly viewed as central pillars of climate change adaptation in agriculture [12,3].

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Soil and nutrient management practices offer significant potential to buffer climate risks while supporting sustainable intensification [12,13]. Integrated soil fertility management, balanced and site-specific nutrient application, organic amendments, conservation agriculture, and climate-smart nutrient strategies can improve soil structure, water-holding capacity, nutrient retention, and crop nutrient uptake under variable climate conditions [14,9]. These practices not only enhance crop productivity and yield stability but also generate co-benefits such as soil carbon sequestration, reduced greenhouse gas emissions, and improved resource-use efficiency [15]. In the context of Bangladesh, where land availability is limited and production pressure is high, climate-adaptive soil and nutrient management approaches are particularly critical.

Despite a growing body of research on climate change impacts and agricultural adaptation in Bangladesh, existing studies are often fragmented, focusing on individual crops, nutrients, or stress factors. A comprehensive synthesis that explicitly links climate change, soil processes, nutrient dynamics, and adaptation strategies for sustainable crop production remains limited [9]. Moreover, the integration of biophysical evidence with socio-economic and institutional considerations relevant to the adoption of improved soil and nutrient management practices has not been adequately addressed in previous reviews [16].

This review aims to critically synthesize existing knowledge on climate change adaptation through soil and nutrient management in Bangladesh agriculture. Specifically, it examines (i) climate-induced changes in soil properties and nutrient dynamics, (ii) soil and nutrient management strategies that enhance crop resilience and sustainability under climate stress, and (iii) key research gaps, policy implications, and future directions for strengthening climate-resilient crop production systems [1]. By consolidating current evidence, this review seeks to inform researchers, policymakers, and practitioners on pathways to sustainable agricultural adaptation in Bangladesh under a changing climate.

2. Climate Change Trends and Impacts on Bangladesh Agriculture

2.1 Observed and Projected Climate Trends in Bangladesh

Bangladesh has experienced clear and consistent signals of climate change over recent decades, characterized by rising temperatures, altered rainfall patterns, and an increased frequency of extreme weather events [1,2]. Observational records indicate a gradual increase in both mean annual and seasonal temperatures, with more pronounced warming during the pre-monsoon and post-monsoon periods [17]. This warming trend has important implications for crop phenology, evapotranspiration demand, and soil biological activity [3]. Concurrently, rainfall patterns have become increasingly erratic, marked by intense short-duration rainfall events interspersed with prolonged dry spells, rather than uniform seasonal distribution [17,1].

Climate projections suggest that these trends will intensify in the future. Model-based scenarios indicate further increases in temperature, heightened rainfall variability, and greater incidence of extreme events such as floods, droughts, and heatwaves [1,2]. Sea-level rise is projected to exacerbate saline water intrusion in coastal and deltaic regions, while upstream hydrological changes are likely to influence river flooding dynamics in floodplain areas [8]. Together, these changes are expected to increase climate uncertainty for agricultural systems, placing additional stress on soils and nutrient cycling processes that underpin crop production [9].

2.2 Impacts of Climate Variability on Soil Properties and Nutrient Dynamics

Climate variability directly influences soil physical, chemical, and biological properties, thereby altering nutrient availability and use efficiency in agricultural systems [3,4]. Rising temperatures accelerate soil organic matter decomposition, leading to declines in soil organic carbon stocks, which are critical for nutrient retention, aggregation, and moisture regulation [5]. Enhanced decomposition rates can initially increase nutrient mineralization but often result in long-term nutrient depletion and reduced soil resilience under intensive cropping systems [9].

Altered rainfall regimes further affect nutrient dynamics by influencing soil moisture status, erosion, and leaching losses [18]. Intense rainfall events increase surface runoff and soil erosion, leading to the loss of nutrient-rich topsoil and associated macro- and micronutrients [19,20]. Conversely, prolonged dry periods restrict nutrient diffusion and microbial activity, limiting nutrient uptake by crops [21]. Flooding and waterlogging, common in low-lying areas of Bangladesh, create anaerobic soil conditions that modify redox-sensitive nutrient transformations, particularly nitrogen and sulfur, resulting in gaseous losses and reduced fertilizer efficiency [6].

In coastal regions, salinity intrusion driven by sea-level rise and storm surges disrupts soil nutrient balance by increasing sodium concentrations, reducing calcium and potassium availability, and impairing root nutrient uptake [7,8]. Climate-induced changes in soil pH and redox potential also influence micronutrient availability, leading to deficiencies or toxicities that further constrain crop growth [22,23]. These interacting soil and nutrient stresses significantly reduce the effectiveness of conventional fertilizer practices under climate change conditions.

2.3 Effects on Crop Productivity, Yield Stability, and Food Security

The combined effects of rising temperatures, rainfall variability, and soil fertility degradation have already manifested in reduced yield stability of major crops in Bangladesh [24]. Heat stress during critical growth stages shortens crop duration, disrupts flowering and grain filling, and reduces biomass accumulation [25,26]. Increased climatic variability has heightened the risk of crop failure, particularly for rainfed systems that rely on predictable monsoon patterns.

Soil nutrient stress under changing climatic conditions further amplifies yield variability [3]. Declining nutrient use efficiency, increased nutrient losses, and imbalanced fertilization contribute to stagnating or declining yields despite increased fertilizer inputs [27]. This phenomenon is particularly evident in intensive rice-based systems, where continuous cropping and climate stress have reduced soil buffering capacity [10]. As yield instability increases, household-level food security and farmer livelihoods become more vulnerable, especially for smallholder farmers with limited adaptive capacity.

At the national scale, climate-induced reductions in crop productivity pose a direct threat to food availability and price stability [2]. Given the high population density and limited scope for horizontal expansion of agriculture in Bangladesh, sustaining yield growth through climate-adaptive soil and nutrient management is critical for ensuring long-term food security [1].

2.4 Regional Vulnerability: Coastal, Floodplain, Drought-Prone, and Hill Ecosystems

The impacts of climate change on agriculture in Bangladesh are spatially heterogeneous, reflecting variations in agroecological conditions and exposure to climate hazards [28,1]. Coastal regions are particularly vulnerable to salinity intrusion, tidal flooding, and cyclonic storm surges, which degrade soil structure, reduce nutrient availability, and limit crop choice [7,8]. In these areas, conventional fertilizer practices often fail to deliver expected yield responses due to saline stress and nutrient imbalance [12].

Floodplain ecosystems, which constitute a large proportion of Bangladesh's agricultural land, are increasingly exposed to unpredictable flooding regimes [29]. While seasonal flooding can replenish soil nutrients, excessive or untimely floods lead to nutrient losses, crop damage, and soil physical degradation [19]. Drought-prone regions, particularly in the northwestern part of the country, experience moisture stress and declining soil fertility, which restrict nutrient uptake and reduce crop productivity under rainfed conditions [17].

Hill ecosystems in southeastern and northeastern Bangladesh face distinct challenges related to soil erosion, shallow soil depth, and nutrient depletion, which are exacerbated by intense rainfall events linked to climate change [20]. In these fragile landscapes, inappropriate soil and nutrient management accelerates land degradation and undermines the sustainability of cropping systems [3]. Understanding these region-specific vulnerabilities is essential for designing targeted soil and nutrient management strategies that enhance climate resilience across diverse agricultural systems in Bangladesh.

3. Soil Degradation under Climate Change in Bangladesh

Climate change is intensifying multiple soil degradation processes in Bangladesh, undermining the capacity of soils to sustain crop productivity and nutrient supply [3,1]. The interaction between climatic stressors and long-standing management pressures has accelerated the decline of key soil functions, including carbon storage, nutrient retention, water regulation, and structural stability [12,9]. Understanding these degradation pathways is essential for designing effective soil- and nutrient-based climate adaptation strategies [15].

3.1 Soil Organic Carbon Decline and Carbon Cycling under Changing Climate

Soil organic carbon (SOC) is a critical determinant of soil fertility, nutrient availability, and resilience to climatic stress [30,23]. In Bangladesh, SOC levels are generally low due to intensive cropping, limited organic matter return, and warm, humid climatic conditions that favor rapid decomposition [10]. Climate change further exacerbates SOC depletion by increasing soil temperatures, which accelerate microbial activity and organic matter mineralization [4,5]. While short-term increases in nutrient availability may occur following enhanced mineralization, long-term SOC decline reduces soil buffering capacity and increases vulnerability to climate extremes [3].

Changes in rainfall patterns also influence SOC dynamics by altering residue decomposition, erosion losses, and carbon inputs [18]. Intense rainfall events promote surface runoff and the physical removal of carbon-rich topsoil, whereas prolonged dry periods limit biomass production and organic matter inputs to the soil [20,21]. Flooding and waterlogging, common in low-lying regions, modify carbon cycling by creating anaerobic conditions that slow decomposition but may enhance methane emissions and disrupt nutrient transformations [6]. The net effect of these interacting processes is a progressive reduction in stable SOC pools, compromising soil structure, nutrient retention, and water-holding capacity under changing climatic conditions [9].

3.2 Climate-Induced Soil Erosion and Land Degradation

Soil erosion is a major form of land degradation in Bangladesh, driven by monsoon rainfall, riverine flooding, and land use intensification [19,29]. Climate change has increased the frequency and intensity of extreme rainfall events, thereby intensifying water erosion in both lowland and upland areas [18,20]. The loss of fertile topsoil through erosion disproportionately removes organic matter and essential nutrients, resulting in reduced soil fertility and declining crop productivity [19, 12.

In floodplain and riverbank areas, accelerated river erosion linked to altered hydrological regimes leads to the permanent loss of agricultural land and soil resources. In hill ecosystems, intense rainfall combined with steep slopes and inadequate soil cover exacerbates surface erosion and landslides, rapidly depleting already shallow and nutrient-poor soils [20]. These erosion processes not only reduce on-site soil productivity but also contribute to downstream sedimentation and nutrient pollution, highlighting the broader environmental consequences of climate-induced land degradation [3].

3.3 Salinity Intrusion and Sodicity Development in Coastal Soils

Salinity intrusion represents one of the most severe climate-related soil degradation challenges in Bangladesh's coastal regions [7, 8. Sea-level rise, reduced freshwater flow during the dry season, and increased frequency of cyclonic storm surges have expanded the spatial extent and severity of saline soils [1]. Elevated salt concentrations impair soil physical properties, reduce osmotic potential, and limit the availability and uptake of essential nutrients by crops [39].

In addition to salinity, sodicity development has emerged as a growing concern in coastal and deltaic soils. High sodium concentrations displace calcium and magnesium on soil exchange sites, leading to clay dispersion, reduced aggregate stability, and impaired soil permeability[23]. These structural changes restrict root growth, water infiltration, and nutrient movement, (further constraining crop productivity) Nutrient imbalances, particularly deficiencies of potassium, calcium, and micronutrients, are commonly observed in saline–sodic soils, reducing the effectiveness of conventional fertilizer management under climate stress [7,22].

3.4 Waterlogging, Compaction, and Structural Degradation

Waterlogging is a recurrent problem in many agricultural areas of Bangladesh, particularly in flood-prone and poorly drained soils. Climate change has intensified waterlogging through increased rainfall intensity and prolonged inundation periods [1]. Saturated soil conditions reduce oxygen availability, inhibit root respiration, and disrupt microbial processes essential for nutrient cycling [6]. Under anaerobic conditions, nitrogen losses through denitrification increase, while the availability of phosphorus, sulfur, and micronutrients is altered by changes in redox potential [23].

Repeated wetting and drying cycles associated with climate variability also contribute to soil compaction and structural degradation [31]. Mechanized land preparation under suboptimal moisture conditions exacerbates compaction, reducing pore space and limiting root penetration and water movement. Structural degradation reduces soil resilience to both drought and flooding, amplifying the negative effects of climate extremes on nutrient uptake and crop performance [3].

3.5 Heavy Metal Mobilization and Nutrient Imbalance under Stressed Conditions

Climate change can indirectly influence the mobility and bioavailability of heavy metals in agricultural soils, particularly in areas affected by industrial pollution, wastewater irrigation, and intensive fertilizer use [32,33]. Changes in soil moisture, temperature, and redox conditions alter the chemical forms and solubility of metals such as cadmium, lead, and arsenic, increasing their uptake by crops under certain climate scenarios.

Flooding and waterlogging enhance the reduction of metal oxides, releasing previously immobilized metals into the soil solution, while drought conditions can concentrate metals in the root zone due to reduced dilution and increased evapotranspiration [6,32]. These processes not only pose risks to food safety but also interfere with nutrient uptake by competing with essential elements and disrupting plant physiological processes [33]. Climate-induced nutrient imbalance, combined with heavy metal stress, further constrains crop growth and underscores the need for integrated soil and nutrient management approaches that address both fertility and contamination risks.

Table 1. Climate Stressors, Soil Impacts, Nutrient Implications, and Adaptation Strategies in Bangladesh Agriculture

Climate Stressor	Soil Impact	Nutrient Implications	Adaptation Strategies
Drought / Water Deficit	Reduced soil moisture, decreased microbial activity, compaction	Limited nutrient diffusion, reduced N, P, K uptake, micronutrient deficiencies	Mulching, organic amendments (compost, FYM, biochar), minimum tillage, split fertilizer application, drought-tolerant varieties
Flooding / Waterlogging	Anaerobic conditions, soil structure degradation, erosion	Denitrification, N and S loss, reduced P availability, micronutrient imbalances	Raised-bed planting, split N application, organic amendments, flood-tolerant crops, site-specific fertilization
Heat Stress / High Temperature	Accelerated SOM decomposition, reduced moisture retention	Increased N volatilization, reduced nutrient use efficiency	Split N application, biochar incorporation, conservation agriculture, residue retention
Salinity / Sodicity	Soil structural damage, osmotic stress, reduced infiltration	K deficiency, Ca/Mg imbalance, micronutrient limitations	Gypsum application, organic matter incorporation, K-rich fertilizers, salt-tolerant crop varieties
Erratic Rainfall / Extreme Events	Erosion, nutrient leaching, soil crusting	N and P losses, reduced NUE	Soil conservation (terracing, contour bunds), organic amendments, integrated nutrient management, cover cropping

4. Nutrient Dynamics and Climate Interactions

Climate change modifies nutrient cycling processes in agricultural soils by altering temperature regimes, soil moisture dynamics, redox conditions, and biological activity [3,1]. In Bangladesh, where intensive cropping systems already operate close to nutrient balance thresholds, climate-induced disruptions to nutrient availability and loss pathways significantly influence crop productivity and sustainability [10]. Understanding these interactions is essential for designing nutrient management strategies that enhance resilience under climate variability.

4.1 Climate Effects on Nutrient Availability and Loss Pathways (N, P, K, and S)

The availability and movement of essential plant nutrients in soil are strongly influenced by climatic factors, particularly temperature and rainfall variability [23,30]. Rising temperatures accelerate chemical and biological reactions, increasing nutrient mineralization rates while simultaneously enhancing loss processes [4]. Altered precipitation patterns influence nutrient transport through leaching, runoff, erosion, and gaseous emissions, often reducing the synchrony between nutrient supply and crop demand [18].

Nitrogen is particularly vulnerable to climate-induced losses through volatilization, leaching, and denitrification, while phosphorus losses are primarily associated with erosion and runoff during intense rainfall events [34]. Potassium, although less mobile in soil, can be depleted from surface layers through erosion and crop removal, especially in light-textured soils [19]. Sulfur availability is affected by changes in organic matter turnover and redox conditions, with waterlogged soils promoting sulfate reduction and associated nutrient losses. These climate-driven nutrient loss pathways collectively reduce fertilizer efficiency and increase production costs, posing challenges for sustainable crop production in Bangladesh [27].

4.2 Nitrogen Cycling, Volatilization, Leaching, and Greenhouse Gas Emissions

Nitrogen cycling is highly sensitive to climatic conditions, making it a critical component of climate-resilient nutrient management [3]. Elevated temperatures enhance microbial processes such as ammonification and nitrification, increasing the pool of plant-available nitrogen but also raising the risk of losses when crop uptake is limited [35]. Under warm and humid conditions common in Bangladesh, surface-applied nitrogen fertilizers are prone to ammonia volatilization, particularly in flooded or high-pH soils [36].

Increased rainfall intensity enhances nitrate leaching in well-drained soils and denitrification losses in waterlogged environments [6]. Flooded rice systems, which dominate Bangladesh agriculture, are especially susceptible to nitrogen losses through denitrification and associated emissions of nitrous oxide, a potent greenhouse gas [37]. These losses reduce nitrogen use efficiency and contribute to climate change, creating a feedback loop between nutrient management and greenhouse gas emissions [15]. Climate-adaptive nitrogen management must therefore balance productivity goals with the need to minimize environmental losses and emissions [9,12].

4.3 Phosphorus Fixation, Solubility, and Climate Sensitivity

Phosphorus dynamics in soil are governed by complex interactions among soil mineralogy, organic matter, and environmental conditions [23,38]. Climate change influences phosphorus availability indirectly by modifying soil moisture regimes, redox conditions, and biological activity. In flooded or waterlogged soils, reduction of iron and manganese oxides can temporarily increase phosphorus solubility, enhancing short-term availability to crops [6]. However, upon soil re-aeration, phosphorus may become re-fixed in less available forms, limiting its long-term effectiveness.

Intense rainfall events increase phosphorus losses through runoff and erosion, particularly in sloping or poorly managed soils [20]. In acid soils common in some regions of Bangladesh, increased weathering and leaching under high rainfall conditions may enhance phosphorus fixation by aluminum and iron compounds, reducing fertilizer efficiency [12,38]. These climate-sensitive phosphorus dynamics highlight the importance of management strategies that improve phosphorus availability while minimizing losses under variable climate conditions.

4.4 Micronutrient Deficiencies and Toxicities under Climate Stress

Micronutrient availability is highly sensitive to changes in soil moisture, temperature, and redox potential, all of which are influenced by climate variability [33,22]. Flooding and waterlogging can increase the solubility of certain micronutrients, such as iron and manganese, leading to potential toxicities, while simultaneously reducing the availability of zinc, copper, and boron. Conversely, drought conditions limit micronutrient diffusion and root uptake, exacerbating deficiencies in dryland systems [21].

Climate-induced changes in soil organic matter and pH further influence micronutrient dynamics by affecting complexation, adsorption, and desorption processes [23,32]. In coastal and saline-affected soils, high sodium levels and osmotic stress interfere with micronutrient uptake, compounding nutrient stress under climate extremes [7,39]. These micronutrient imbalances reduce crop yield and quality, underscoring the need for integrated nutrient management approaches that address both macro- and micronutrient requirements under climate stress [27].

4.5 Nutrient Use Efficiency as a Climate Adaptation Indicator

Nutrient use efficiency (NUE) has emerged as a critical indicator of sustainable and climate-resilient agricultural systems [27]. Under climate change, improving NUE is essential for maintaining crop productivity while reducing nutrient losses, environmental pollution, and greenhouse gas emissions [9, 15]. Climate-induced stresses often reduce NUE by disrupting the timing and magnitude of nutrient supply relative to crop demand, leading to inefficient fertilizer use [26].

Adaptive nutrient management practices such as balanced fertilization, split application, soil test-based recommendations, and the integration of organic amendments can enhance NUE by improving nutrient synchronization and soil buffering capacity [12,14]. In the context of Bangladesh, where fertilizer inputs are increasing but yield responses are stagnating in some systems, NUE provides a valuable metric for assessing the effectiveness of climate adaptation strategies [10]. Enhancing NUE not only improves farm-level profitability but also contributes to broader sustainability goals by reducing the environmental footprint of agriculture under a changing climate [1].

5. Soil and Nutrient Management Strategies for Climate Change Adaptation

Sustainable crop production under climate change requires adaptive soil and nutrient management strategies that enhance resilience, maintain soil fertility, and improve nutrient use efficiency [3].

In Bangladesh, where diverse agroecological conditions and climate stressors challenge cropping systems, integrated approaches combining physical, chemical, and biological interventions are essential for mitigating the negative effects of climate variability on soils and nutrient dynamics [10].

5.1 Integrated Soil Fertility Management (ISFM)

Integrated Soil Fertility Management (ISFM) is a cornerstone approach for sustaining crop productivity under climate stress [12]. ISFM combines the judicious use of chemical fertilizers with organic amendments and improved agronomic practices to enhance nutrient availability and crop uptake. Balanced fertilizer application ensures that essential macro- and micronutrients are supplied in proportions that match crop demand, mitigating yield losses under temperature and moisture stress [27].

Integration of inorganic and organic nutrient sources, such as urea, TSP, and potash with farmyard manure or compost, improves soil structure, increases cation exchange capacity, and enhances microbial activity, which collectively support nutrient cycling under variable climate conditions [14,23]. Evidence from Bangladesh suggests that ISFM practices can reduce nutrient losses, improve yield stability in rice-based systems, and buffer crops against heat, drought, and flood-induced nutrient stress [10].

5.2 Organic Amendments and Carbon Sequestration

Organic amendments play a dual role in improving nutrient supply and enhancing soil resilience to climate extremes [30]. Farmyard manure, compost, and crop residues contribute to soil organic carbon, improve water-holding capacity, and support microbial populations that mediate nutrient mineralization [23,40]. These practices are particularly valuable under conditions of erratic rainfall, as they enhance soil moisture retention and reduce nutrient leaching during intense precipitation events [3].

Biochar, a carbon-rich product of biomass pyrolysis, has emerged as an effective strategy to improve nutrient retention and reduce losses under climate stress [44]. Biochar application enhances cation exchange capacity, stabilizes soil organic matter, and improves nitrogen and phosphorus availability in both upland and flooded rice systems . Additionally, biochar contributes to long-term carbon sequestration, offering co-benefits for climate mitigation while supporting sustainable crop production [9,15].

5.3 Conservation Agriculture Practices

Conservation agriculture (CA) practices, including minimum tillage, residue retention, and crop rotation, provide a climate-resilient framework for nutrient management [12,45]. Reduced tillage preserves soil structure, limits erosion, and maintains organic matter content, which stabilizes nutrient availability under extreme weather events [19,20]. Residue retention supplies additional organic inputs, moderates soil temperature, and promotes microbial activity essential for nutrient cycling [40,41].

Crop rotation, particularly the inclusion of legumes, enhances soil nitrogen through biological fixation, improves phosphorus mobilization, and disrupts pest and disease cycles [42,43]. In Bangladesh, CA practices have been shown to improve water-use efficiency and enhance nutrient-use efficiency, mitigating the adverse effects of droughts and floods on crop productivity [10].

5.4 Site-Specific and Climate-Smart Nutrient Management

Site-specific nutrient management (SSNM) aligns fertilizer application with spatial and temporal crop nutrient requirements, improving nutrient use efficiency and reducing environmental losses. Soil testing enables the identification of nutrient deficiencies and facilitates precise application rates, timing, and methods tailored to specific soil-crop combinations [27]. In Bangladesh, SSNM has been particularly effective in rice-based cropping systems, optimizing nitrogen and phosphorus inputs to enhance yield stability under variable rainfall and temperature regimes [10].

Climate-smart nutrient management integrates precision agriculture tools, decision support systems, and adaptive fertilization strategies to respond to climate variability [9,15]. Real-time monitoring of soil moisture, crop growth, and weather forecasts allows dynamic adjustment of nutrient inputs, improving synchronization between nutrient supply and crop demand [12]. Such approaches reduce nutrient losses, lower greenhouse gas emissions, and enhance the resilience of agricultural systems to climate extremes [1].

5.5 Managing Salinity, Flood, and Drought-Affected Soils

Soils affected by salinity, flooding, and drought require specialized management strategies to maintain nutrient availability and crop productivity [39]. In saline and sodic soils, the application of gypsum, organic matter, and potassium-enriched fertilizers mitigates sodium toxicity, improves soil structure, and enhances nutrient uptake [7]. Organic amendments increase water-holding capacity and microbial activity, supporting plant nutrition under osmotic stress.

In flood-prone areas, timely nutrient application, incorporation of organic amendments, and selection of flood-tolerant crops reduce nutrient losses due to leaching and denitrification. Conversely, in drought-prone soils, moisture-conserving practices combined with slow-release fertilizers or fertigation enhance nutrient availability during critical growth stages [12, 21]. Understanding water–nutrient interactions under these stress conditions is essential for designing adaptive nutrient management strategies that stabilize yields and maintain soil health under climate extremes [9, 1].

6. Crop-Specific Adaptation through Soil and Nutrient Management

Crop-specific adaptation strategies are essential for maintaining productivity and nutrient use efficiency under climate change [1]. In Bangladesh, diverse cropping systems face distinct climate stressors—floods, droughts, salinity, and heat—which interact with soil nutrient dynamics to influence yield stability [10]. Tailored soil and nutrient management approaches can mitigate these stressors and support sustainable production across major crops [3, 15].

6.1 Rice-Based Systems (Aus, Aman, Boro)

Rice is the staple crop of Bangladesh, cultivated year-round in three main seasons: Aus (pre-monsoon), Aman (monsoon), and Boro (dry season) [28]. Each season faces unique climate-related challenges. Aus rice is often exposed to early-season drought, Aman to unpredictable monsoon flooding, and Boro to heat stress and water scarcity. These stresses reduce nutrient uptake, particularly nitrogen, and compromise grain yield .

Adaptive nutrient management in rice-based systems includes site-specific nitrogen application, split fertilization, and integration of organic amendments to improve nutrient retention and soil structure.

Flood-tolerant varieties combined with soil amendments that enhance potassium and sulfur availability improve resilience to submergence and salinity in coastal areas [7]. Biochar and compost have been shown to increase water-holding capacity, nutrient-use efficiency, and yield stability, especially in Boro rice under limited irrigation conditions.

6.2 Wheat, Maize, and Other Cereals

Cereal crops such as wheat and maize occupy a smaller but important portion of Bangladesh's cropping area, mainly in the northwestern and central regions [28]. These crops are sensitive to heat and moisture stress during critical growth stages, which reduces nutrient uptake and biomass accumulation [26]. Climate change exacerbates nitrogen and phosphorus losses through leaching and volatilization, leading to yield reductions [21].

Adaptive management strategies include precision nutrient application based on soil testing, use of slow-release fertilizers, and incorporation of organic amendments to enhance nutrient retention [27]. Conservation tillage and residue retention improve soil moisture and support nutrient availability during periods of water deficit [45,3]. Crop rotation with legumes enhances soil nitrogen availability and reduces dependence on synthetic fertilizers, supporting sustainable cereal production under climate stress [42, 43].

6.3 Pulses and Oilseeds

Pulses and oilseeds are critical for protein and edible oil production in Bangladesh, yet they are often cultivated on marginal lands prone to drought or low fertility. These crops are particularly sensitive to soil nutrient deficiencies, especially phosphorus and micronutrients, which are exacerbated under climate stress [22].

Integrated nutrient management, including inoculation with nitrogen-fixing rhizobia for pulses and combined organic–inorganic fertilization for oilseeds, enhances nutrient use efficiency and yield stability [43]. Mulching and residue retention conserve soil moisture, while site-specific phosphorus application addresses limitations in low-fertility soils [3,27]. Such practices improve resilience to drought and heat stress, ensuring stable production of pulses and oilseeds [1].

6.4 Vegetables and High-Value Crops

Vegetables and other high-value crops are grown in intensive systems and require careful nutrient management to maintain both yield and quality under variable climates [12]. These crops are particularly vulnerable to heat, water stress, and salinity, which can reduce nutrient uptake and lead to physiological disorders [39].

Adaptive strategies include fertigation, split nutrient applications, and organic amendments to improve nutrient availability and soil moisture. In coastal areas, soil amendments such as gypsum and organic matter help mitigate salinity stress, while raised-bed planting and mulching conserve moisture in drought-prone areas [7]. Site-specific micronutrient management ensures crop quality, supporting both food security and farm income [22,27].

6.5 Nutrient Management for Yield Stability under Climate Extremes

Yield stability under climate extremes depends on synchronizing nutrient supply with crop demand while mitigating losses caused by drought, flooding, or salinity [15].

Practices such as split nitrogen application, use of slow-release fertilizers, organic amendments, and conservation agriculture improve nutrient retention and uptake efficiency [45]. Biochar and compost enhance soil water-holding capacity, supporting nutrient availability during dry spells [3,44].

In flood-prone areas, incorporating organic amendments and optimizing fertilizer timing reduces nutrient leaching and denitrification losses [6]. Salinity management through gypsum and potassium application improves nutrient uptake in coastal soils. Overall, climate-adaptive nutrient management tailored to crop type, season, and local agroecological conditions is essential for maintaining both productivity and soil health under changing climatic conditions in Bangladesh [1].

Table 2. Crop-Specific Soil and Nutrient Management Strategies for Climate Adaptation in Bangladesh

Crop/Crop Group	Climate Risks	Key Nutrient Challenges	Adaptive Soil & Nutrient Management
Rice (Aus, Aman, Boro)	Drought (Aus), flood (Aman), heat/water stress (Boro)	N losses, P fixation, K and S imbalance	Split N application, organic amendments, biochar, flood/drought-tolerant varieties, raised-bed planting
Wheat and Maize	Heat stress, drought	N and P deficiency, micronutrient limitation	Precision fertilization, conservation tillage, crop rotation with legumes, organic amendments, slow-release fertilizers
Pulses	Drought, low fertility	P limitation, N deficiency in poor soils	Rhizobia inoculation, integrated organic–inorganic fertilization, mulching, moisture-conserving practices
Oilseeds	Drought, soil degradation	P and K deficiency	Organic amendments, site-specific P and K application, residue retention, water-saving techniques
Vegetables & High-Value Crops	Heat, water stress, salinity	N, P, K and micronutrient deficiencies	Fertigation, organic amendments, micronutrient application, raised beds, gypsum for salinity, residue mulch
General Adaptive Practices	Multi-stress environments	N, P, K, S, micronutrients	Integrated Soil Fertility Management (ISFM), conservation agriculture, biochar, site-specific nutrient management, organic amendments

7. Socio-Economic and Institutional Dimensions

Adapting soil and nutrient management practices to climate change in Bangladesh depends not only on biophysical solutions but also on socio-economic conditions, institutional support, and farmer behavior [1]. While technical solutions such as integrated soil fertility management, organic amendments, and conservation agriculture are well-documented, their adoption is constrained by multiple social, economic, and institutional factors that influence the effectiveness of climate adaptation strategies.

7.1 Adoption Constraints of Improved Soil and Nutrient Management Practices

Despite the demonstrated benefits of adaptive soil and nutrient management, adoption among Bangladeshi farmers remains limited [10]. Constraints include high initial costs of inputs such as organic amendments, biochar, and slow-release fertilizers; limited access to credit; labor requirements for implementing conservation practices; and uncertainty about benefits under variable climate conditions [46]. Additionally, smallholder farmers often operate on marginal lands with low resource endowment, which restricts the feasibility of adopting technically complex practices . Risk aversion, combined with short-term survival priorities, often leads farmers to continue conventional, less sustainable nutrient management strategies, even when long-term gains are apparent [47].

7.2 Farmer Perceptions and Indigenous Soil Management Knowledge

Local knowledge and perceptions play a crucial role in shaping soil and nutrient management decisions [16]. Farmers in Bangladesh possess indigenous strategies for coping with soil fertility and climate stress, including the use of traditional organic amendments, crop rotation, intercropping, and flood-tolerant crop varieties- Integrating these locally adapted practices with modern soil and nutrient management strategies can enhance adoption and effectiveness [12,48]. Understanding farmer perceptions of climate risks and nutrient needs is essential for designing interventions that are context-specific, culturally acceptable, and resilient to extreme events [49].

7.3 Role of Extension Services and Policy Support

Extension services are critical in bridging knowledge gaps and promoting climate-adaptive soil and nutrient management practices [50]. Government agencies, research institutions, and NGOs provide technical guidance, training, and demonstration plots; however, coverage and effectiveness remain uneven across regions. Policy frameworks that incentivize balanced fertilizer use, organic amendments, and soil testing can accelerate adoption [27]. In Bangladesh, existing policies such as subsidized fertilizer distribution often favor conventional fertilizers over integrated or climate-smart approaches, limiting the scalability of sustainable practices [2,7]. Strengthening extension networks, providing farmer education, and aligning policy incentives with adaptive management goals are essential for improving soil health and crop resilience [1,9].

7.4 Economic Feasibility and Input Accessibility

Economic considerations strongly influence farmers' ability to implement adaptive nutrient management practices. Input costs for organic amendments, biochar, or micronutrients can be prohibitive, particularly for smallholders. Accessibility of quality inputs, coupled with market linkages for high-value crops, determines whether adoption is financially viable. Cost–benefit analyses indicate that while adaptive soil management can increase long-term productivity and resilience, short-term labor and input costs often deter adoption [46]. Supporting farmers through credit schemes, subsidized inputs, and market integration is essential to make climate-adaptive soil and nutrient management economically feasible and widely accessible [1,12].

8. Environmental Co-Benefits and Trade-Offs *(with in-text citations)*

Adaptive soil and nutrient management not only enhances crop resilience but also generates environmental co-benefits for climate mitigation and ecosystem health [1, 3]. However, improper nutrient management may create environmental trade-offs under intensive farming systems.

8.1 Soil Carbon Sequestration and Climate Mitigation

Soil carbon sequestration is a major co-benefit of climate-adaptive soil management. Practices such as residue retention, organic amendments, conservation tillage, and biochar application increase soil organic carbon stocks, improving soil structure, water retention, and nutrient cycling [3].

In Bangladesh, where SOC levels are declining, these practices simultaneously enhance yield stability and contribute to climate mitigation [1].

8.2 Nutrient Management and Greenhouse Gas Emissions

Nitrogen fertilizer use is a major source of nitrous oxide emissions, particularly under warm and waterlogged rice systems. Flooded rice fields also emit methane, influenced by fertilizer type and organic matter management [1]. Adaptive practices such as split nitrogen application, precision fertilization, and biochar incorporation reduce greenhouse gas emissions while maintaining productivity [3].

8.3 Risks of Nutrient Mismanagement

Excessive or poorly timed fertilizer application under climate stress increases nutrient losses, water pollution, and greenhouse gas emissions. In saline and flood-prone soils, inefficient nutrient uptake may prompt over-application, exacerbating environmental degradation. These risks underscore the importance of site-specific and climate-responsive nutrient management.

8.4 Sustainability Trade-Offs in Intensive Systems

Intensive farming systems often face trade-offs between short-term yield maximization and long-term sustainability. High input use and monocropping degrade soil health and increase climate vulnerability [16]. Integrated nutrient management and conservation practices can reduce these trade-offs, but require supportive policies, farmer training, and economic incentives to ensure widespread adoption.

9. Research Gaps and Future Directions

Despite growing recognition of the role of soil and nutrient management in climate change adaptation, substantial knowledge gaps remain in Bangladesh. Addressing these gaps is essential to designing resilient cropping systems that sustain productivity, improve nutrient use efficiency, and ensure long-term food security under variable climate conditions.

9.1 Limitations of Existing Soil and Nutrient Adaptation Studies

Most existing studies in Bangladesh have focused on short-term experiments, single crops, or isolated soil fertility interventions, limiting the generalizability of findings across agroecological zones. There is a paucity of research on integrated approaches that simultaneously consider soil health, nutrient dynamics, crop performance, and climate variability. Additionally, the socio-economic dimensions of adoption, such as farmer behavior, cost–benefit trade-offs, and policy barriers, are underrepresented in the literature. This fragmented evidence base hinders the development of comprehensive strategies for climate-adaptive nutrient management.

9.2 Need for Long-Term Field Experiments under Climate Variability

Long-term experiments are critical to capture the cumulative effects of climate variability on soil properties, nutrient cycling, and crop yield. Short-term studies often fail to reflect real-world climate fluctuations, seasonal extremes, and soil degradation processes, leading to overestimation or underestimation of adaptation benefits. In Bangladesh, multi-year trials that monitor both soil health and crop performance across different seasons and climate scenarios are needed to evaluate the effectiveness of integrated nutrient and soil management practices under changing conditions.

9.3 Integration of Soil, Climate, Crop Modeling, and Remote Sensing

Advances in modeling and remote sensing offer opportunities to better understand soil–nutrient–climate interactions and optimize management strategies. Crop models combined with soil and climate data can simulate nutrient dynamics, yield responses, and risk under future climate scenarios, providing actionable insights for farmers and policymakers. Remote sensing and geospatial tools can support site-specific interventions, monitor soil moisture and nutrient status, and identify areas most vulnerable to climate stress. Integrating these tools with field-based data will improve decision-making and facilitate the design of climate-resilient cropping systems at regional and national scales.

9.4 Scaling Up Climate-Adaptive Soil Management Practices

The adoption of climate-adaptive soil and nutrient management practices at scale remains a major challenge. Socio-economic constraints, limited extension services, and policy gaps impede widespread uptake. Future research should focus on strategies to enhance scalability, including participatory approaches with farmers, incentive mechanisms, capacity-building programs, and public–private partnerships. Demonstrating the economic, agronomic, and environmental benefits of adaptive practices in diverse agroecological contexts will be crucial to promote adoption and ensure that climate adaptation strategies translate into tangible improvements in food security and soil sustainability across Bangladesh.

10. Policy Implications and Recommendations

Effective climate adaptation in agriculture requires not only technical solutions but also supportive policies, institutional frameworks, and incentive structures that enable farmers to adopt sustainable soil and nutrient management practices.

10.1 Aligning Soil Fertility Policies with Climate Adaptation Strategies

National soil fertility policies and fertilizer subsidy programs should be aligned with climate adaptation objectives. Emphasizing balanced fertilization, organic amendments, and integrated nutrient management within policy frameworks can enhance soil resilience, reduce nutrient losses, and stabilize crop yields under climate variability. Policies should encourage region-specific interventions, taking into account local soil conditions, crop types, and climate vulnerabilities.

10.2 Strengthening Soil Testing and Advisory Systems

Access to accurate soil testing and advisory services is critical for site-specific and climate-smart nutrient management. Strengthening government and private sector soil laboratories, promoting mobile and digital advisory platforms, and integrating climate forecasts into fertilization recommendations can improve decision-making at the farm level. Extension services should focus on educating farmers about adaptive nutrient practices, efficient fertilizer use, and soil health monitoring.

10.3 Incentives for Sustainable Nutrient Management

Incentive mechanisms can accelerate the adoption of climate-adaptive practices. Financial support for organic amendments, biochar, or slow-release fertilizers, combined with training and technical assistance, can reduce initial adoption costs.

Recognition of climate-smart practices through certification, carbon credit schemes, or preferential market access can further encourage sustainable nutrient management while enhancing farmer livelihoods.

10.4 Pathways toward Climate-Resilient Agriculture in Bangladesh

Developing climate-resilient agriculture requires integrated approaches that combine technical innovation, policy support, and socio-economic incentives. This includes promoting adaptive soil and nutrient management, investing in long-term research and monitoring, enhancing extension and advisory networks, and fostering participatory approaches with farmers. By implementing these strategies, Bangladesh can improve crop resilience, maintain soil fertility, reduce environmental impacts, and secure food production under changing climate conditions.

11. Conclusions

11.1 Synthesis of Key Findings

Climate change poses significant threats to agriculture in Bangladesh, affecting soil properties, nutrient dynamics, and crop productivity across diverse agroecological zones. Evidence suggests that integrated, site-specific, and climate-adaptive soil and nutrient management practices—including organic amendments, conservation agriculture, biochar application, and precision fertilization—can mitigate these impacts and improve yield stability.

11.2 Role of Soil and Nutrient Management in Sustainable Climate Adaptation

Soil and nutrient management are central to climate adaptation, serving both as a buffer against climate-induced stresses and a driver of sustainable crop productivity. Practices that enhance soil organic carbon, improve nutrient use efficiency, and maintain soil structure contribute to resilient cropping systems while generating environmental co-benefits, including reduced greenhouse gas emissions and improved ecosystem services.

11.3 Final Remarks on Ensuring Food Security under a Changing Climate

Ensuring food security in Bangladesh under climate change requires a multi-dimensional approach that integrates technical interventions, socio-economic support, and policy alignment. By scaling up climate-adaptive soil and nutrient management, strengthening research and extension systems, and providing incentives for sustainable practices, Bangladesh can build resilient agricultural systems capable of sustaining productivity, improving soil health, and safeguarding livelihoods under increasingly variable climatic conditions.

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