# CROP PRODUCTIVITY AND GLOBAL FOOD SECURITY NEXUS IN THE FACE OF CLIMATE CHANGE: SUSTAINABLE PATHWAYS TO A GREEN ECONOMY IN GHANA

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## Abstract—

*Climate change constitutes a substantial threat to food security globally, and Ghana, as a development nation, is not immune to this menace. Rising temperatures, changing precipitation patterns, and increased frequency of extreme weather events are impacting crop productivity, water availability, and food quality. This review synthesizes current studies on climate change impacts on crop productivity and food security in Ghana, identifying knowledge gaps and areas for further research. Ghana's agricultural sector is highly susceptible to climate change, with potential yield declines of 2.8%, 2.6%, and 2.4% for rice, maize, and wheat, respectively, for every 1°C temperature increase. The study projects significant economic losses, increased poverty, and food insecurity, emphasizing the need for urgent action to implement climate-resilient agriculture practices. The study explored adaptation strategies, including genome-based approaches, climate-smart agriculture practices, artificial intelligence, nanotechnology, and strategic irrigation management, which can be integrated to promote sustainable agriculture and enhance food security. Ghana faces challenges in addressing climate change, including limited funding and lack of comprehensive climate change law, but has committed to reducing greenhouse gas emissions by 30% by 2030 by presenting its updated Nationally Determined Contributions (NDCs). The findings inform evidence-based policymaking, aligning with the United Nations' Sustainable Development Goals (SDGs), particularly Goal 2 (Zero Hunger), Goal 6 (Clean Water and Sanitation), and Goal 13 (Climate Action). This study provides a foundation for further research and policy development to address the pressing issue of climate change and food security in Ghana.*

**Keywords—** *Climate change; Crop productivity; Temperature; Weather extremes; Food security*

## 1. INTRODUCTION

Climate change, a nationwide priority for its attenuation to achieve a green economy [1,2] has been progressing at a fast rate over the past decades, with profound effects on global food security [3,4,5], affecting crop productivity [6], water availability [7,8], and food quality [9,10]. The impacts of climate change on crop productivity vary across different regions, with some areas experiencing increased productivity and others facing decreased productivity, widely dependent on the latitude of the region [11,12,13]. Concurrently, atmospheric carbon dioxide ($CO_2$) and ozone ($O_3$) levels have been rising by leaps and bounds [14,15,16]. The certainty that climate change and $CO_2$ levels will follow their current trend in the coming years gives rise to vital questions concerning worldwide food security [17,18]. According to Mahato (19), a primary concern is the possibility of the effect on the overall productivity of world agriculture.

The world's most vulnerable populations are on the frontlines of a looming crisis: the devastating impact of climate change on crop productivity [20,21,22]. Rising temperatures, erratic rainfall, and intense weather events are already threatening the livelihoods of millions of small-scale farmers, the backbone of global food systems [23,24,25]. The consequences are dire: reduced crop yields, decreased water availability, and compromised food quality, leaving families without access to nutritious food [26,27,28]. The world's growing population, projected to reach 9.7 billion by 2050, will only exacerbate this crisis [29]. The fate of future generations hangs in the balance. Rhetorically, can we find a way to safeguard crop productivity, ensure global food security, and protect the most vulnerable among us from the ravages of climate change? The pressing necessity to act against the existential threat of climate change to global food security demands a collective and immediate response to comprehend the intricate relationships between climate variability, crop productivity, and sustainable food systems. As such, climate-resilient agriculture is pivotal, as climate change is already influencing the productivity of crops, with its effects expected to intensify in the coming decades [30,31,32,33,34,35]. The world stands at a crossroads, where the confluence of climate change, population growth, and crop productivity issues converge, necessitating extensive research. However, the existing knowledge disparity in this vital sector hinders the formulation of successful adaptation and mitigation mechanisms, particularly in countries like Ghana, which is highly vulnerable to climate change impacts [36,37,38], despite contributing only 0.07% of global greenhouse gas emissions (ranking 108 out of 180 countries for GHG emission per capita) [39].

Also, it ranks 101 out of 181 countries in terms of climate vulnerability and is ranked the 68th most vulnerable and 85th least ready country to fight the effects of climate change. Climate change projections for Ghana show large uncertainty regarding changes in rainfall, with estimations for future precipitation change predicted at a range between -3% to +7% [40]

This research synthesizes current studies on the impact of climate change on crop productivity and food security, focusing on yield variability, quality, and water use efficiency, while critically analyzing existing mitigation and adaptation strategies. By filling these knowledge gaps, the findings will help mitigate the adverse effects of climate change on agriculture and food security. The insights gained will inform policymakers, farmers, and stakeholders on best practices for managing climate change impacts, enabling evidence-based policymaking for climate-resilient agriculture. This is in line with the United Nations' Sustainable Development Goals (SDGs), namely, Goal 2 (Zero Hunger), Goal 6 (Clean Water and Sanitation), and Goal 13 (Climate Action) which advocate a green economy.

## 2. Impacts of climate change on global crop productivity

At a global scale climate change is significantly affecting crop productivity, thereby endangering food security and sustainability. The increasing temperatures (future projections predict that the average global temperature will rise by 2.0 to 6.4 °C and the increase in sea level will be 59 cm by the end of 21st century), precipitation pattern changes, rising frequency of extreme events, and changing growing seasons and phenology are all affecting crop growth and development [41,42,43,44,45,46].

Increasing temperatures according Yuan *et al.* [47], are disrupting the fine equilibrium of agricultural advancement, bringing about alterations in yield, quality, and geographical distribution. Temperatures can hasten the growth of crops; nonetheless, extreme temperatures can lead to heat stress and thereby lower productivity and impact the quality of crops [48,49,50,51,52]. The analysis of temperature for optimal growth of crops, heat stress effects, and geographical variations in temperature impacts on crop yield is an imperative topic of scholarly study. The increase in atmospheric $CO_2$ level and the predicted climate change could impact the future of agriculture worldwide by changing the plant growth and development, respiration, transpiration and photosynthesis rate [53,54,55].

Declining soil fertility, water quality, changes in groundwater table and increasing salinity in some parts of the world are now major concerns of existing agriculture. Short growing season, water scarcity, high temperature and heat stress at important reproductive phases of crops can cause massive yield reduction (6-18%) in arid and semi- arid regions of the world [56]. The pattern of precipitation and water resources is also influencing crop production considerably. Flood, drought, and changed rainfall patterns can retard the growth of crops, decrease production, and impact water quality. The effects of changed patterns of precipitation on the growth and development of crops, the effects of drought and water scarcity on crop production, and water resource management with the perspective of minimizing the impacts of drought are very pertinent areas of research.

Extreme weather conditions, such as hurricanes, wildfires, and heatwaves, are becoming more frequent and intense due to climate change [57]. Extreme weather conditions can devastate crops, leading to significant economic loss and food insecurity. Impacts of extreme weather conditions on crop production and food security, geographical variation in the frequency and intensity of extreme weather conditions, and mitigation and adaptation strategies for extreme weather conditions are critical areas of research.

Notably, climate change is modifying the timing of growing seasons and phenological events, including flowering and harvest. Such changes can be disruptive to plant development, decrease yields, and influence ecosystem function. The effects of shifting growing seasons and phenology on crop productivity, regional variation in the responses of growing seasons and phenological shifts, and adaptation strategies to such changes are significant areas of research.

## 3. Climate Change Trends in Ghana

A. Ghana’s climate profile

The effects of climate change are increasingly evident around the world, especially in developing nations such as Ghana, located in West Africa, bordered to the north by Burkina Faso, east to Togo, west to Ivory Coast, and south to the Gulf of Guinea. It is located between latitude 4.50º N and 11.50º N and longitude 3.50º W and 1.30º E. The country has an area of 239,567 km$^2$ (92,497 sq mi) [58], and a population of around 34.4 million (2024), with an annual growth rate of about 1.89% (2024) (Worldometer). Young people dominate this population.

The country's predominantly tropical climate is significantly influenced by the West African monsoon winds, which is fairly variable coupled with the country's varied topography [59]. The rainfall in Ghana ranges between 1,100mm in the northern part to about 2,100 mm in the southwest annually. The country's northern region has a single rainy season that runs from May to September; the southern region, on the other hand, has two rainy seasons: the first one runs from April to July, and the second runs from September to November. The dry season, running from December to March, brings the arid and dusty harmattan winds that originate from The Sahara Desert has low humidity, high temperatures during the day in excess of 25°C, and lower temperatures at night below 20°C [60]. The average temperature is approximately 27°C, with high temperatures generally in the north and during the country's dry season. The area between the savanna to the north and the forest to the southwest is extremely significant in national food production, owing to its more predictable rainfall and longer growing season [61].

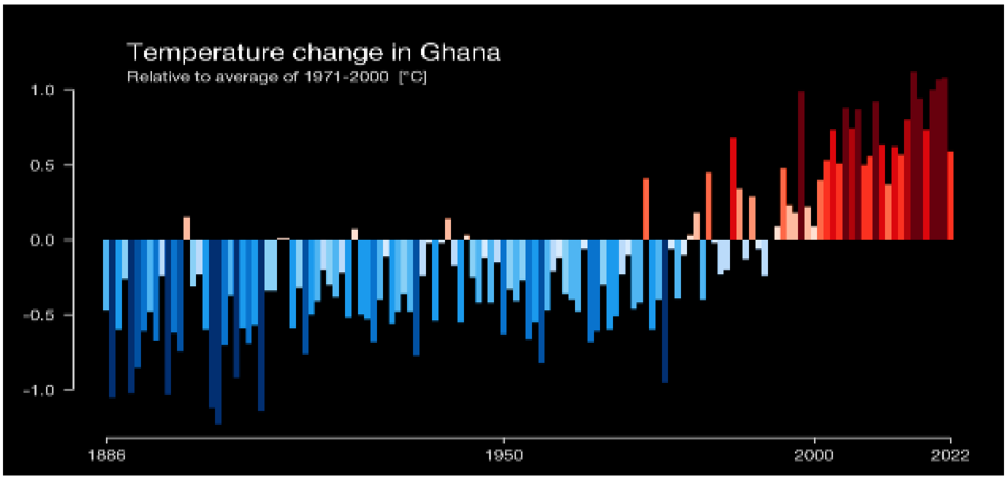
Ghana is extremely vulnerable to climate change and variability, which remains a critical risk to its future growth and development. Sea-level rise, drought, higher temperatures (with temperatures ranging from 18ºC and 40ºC and an average annual temperature between 24ºC and 30ºC, and erratic rainfall have adverse effects on infrastructure, hydropower production, food security, and agricultural and coastal livelihoods. Close to one-quarter of the population resides along the coastline in rapidly expanding urban areas such as Accra, which makes them particularly vulnerable to flooding and waterborne diseases. Drought and reduced rainfall threaten access to reliable sources of power, which is already unstable and low.

Semi-arid, coastal and wetland areas in Ghana are characterized by climatic and socio-economic conditions that open the communities to food insecurity and vulnerable livelihoods as well as unsustainable agroecological systems, crop loss and unproductive rangelands [62,63]. Analysis of historical data from the World Bank Group's Climate Change Knowledge Portal (CCKP) (Table 1) reveals data for 1901–2022. The mean annual mean temperature for Ghana is 27.3°C, with mean monthly temperatures of 25°C–26°C (June to September) and 28°C–29°C (February to April).

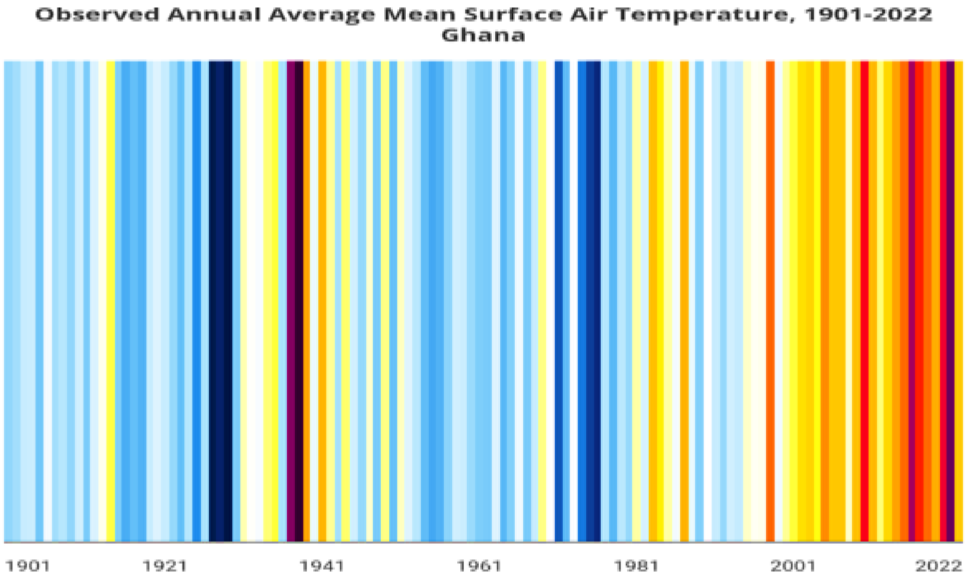
The mean yearly rainfall is recorded at 1,189.9 mm, with the most significant rainfall between May and September, and extremely low precipitation from November to January, based on the current climatological statistics from 1991 to 2022 (refer to Fig. 2). Fig. 1 illustrates the geographic pattern of mean yearly rainfall and temperature in Ghana.

**Table 1. Data snapshot: Summary statistics**

| Climate Variables | 1901–2022 |
|---|---|
| Mean Annual Temperature (°C) | 27.3°C |
| Mean Annual Precipitation (mm) | 1,189.9 mm |
| Mean Maximum Annual Temperature (°C) | 32.5°C |
| Mean Minimum Annual Temperature (°C) | 22.1°C |




(A)




(B)

**Fig. 1 Observed annual average mean surface air temperature trend, 1901-2022, Ghana (Source: Climate Change Knowledge Portal)**

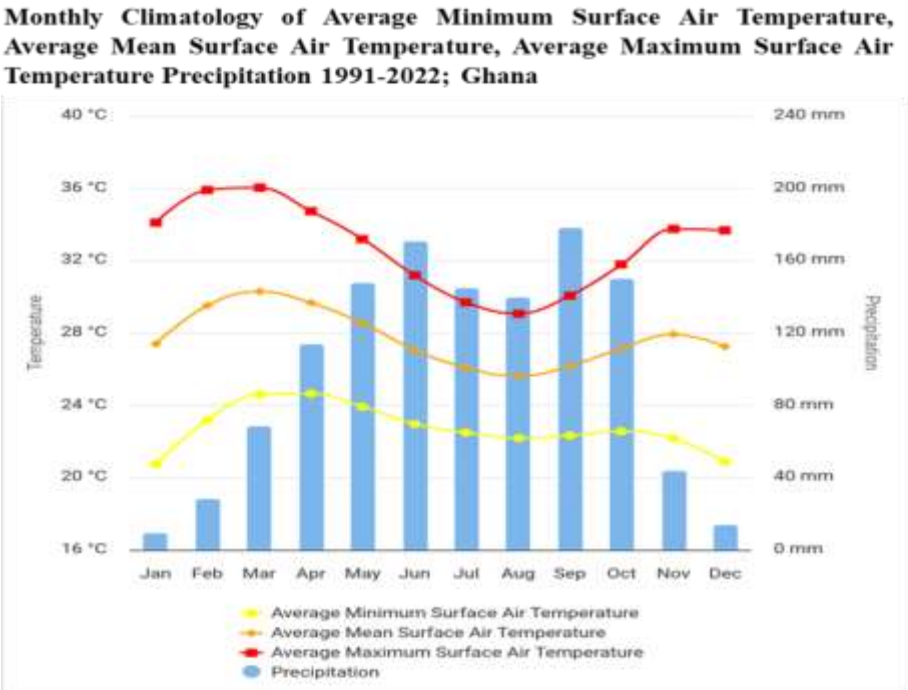



**Fig. 2 Average monthly temperature and precipitation trends in Ghana, 1991-2022 (Source: Climate Change Knowledge Portal)**

B. Current trends and projections in Ghana

Ghana is exposed to the consequences of higher sea levels, prolonged droughts, rising temperatures, and irregular rainfall. In order to face these threats, Ghana will have to depend on foreign donors to finance climate change interventions as the economic situation in the country will make Ghana unable to finance climate change mitigation efforts on its own [64].

Africa is among the lowest emitters of greenhouse gases, but it is the most vulnerable to climate change. As global warming has a direct impact on temperature and precipitation, the agricultural sector in Africa is without a shadow of a doubt the most susceptible segment of the African economy in tackling this phenomenon. Most, if not all, nations on the continent have incurred massive losses and damages, like water shortages, low agricultural production, and lowered economic growth due to this common dilemma [65]. Consistent with the Intergovernmental Panel on Climate Change (IPCC), increasing global warming of 1.5 to 2.0 degrees Celsius (°C) will cause extreme environmental shocks in the continent that will, in turn, aggravate poverty, decrease food production, and escalate food insecurity.

The World Bank's new Country and Climate Development Report estimates at least an additional one million individuals likely to be pushed into poverty by climate disasters, and household incomes for the poor decreasing by up to 40 percent by 2050 [66,67]. West Africa has, specifically, been identified as a climate change hotspot because of the region's fast-growing population, which is growing at the rate of 2.8 percent annually, and an environment that is driven by declining natural resources. Also, it is expected that rises in temperature across the region will accelerate, and regions that lie within 15 degrees of the equator will experience an enhancement of the period and frequency of heat waves.

Climate variability and unpredictable weather patterns in most West African countries, particularly Ghana, are exacerbating food insecurity and impacting the rural economy at multiple points along the agricultural value chain, including both on-farm productivity and off-farm policy and trade issues. Ghana is experiencing temperature changes, rainfall patterns, and rising frequency and intensity of extreme weather events like floods, droughts, and storms [68,69]. These impacts have significant consequences on the economy of the country, food security, and livelihoods of the people. To surmount these challenges, appropriate action to implement an integrated approach to environmental and agriculture management, increase risk preparedness, promote sustainable energy production, make transport systems better, and build more resilient infrastructure systems will be needed [70].

The World Bank estimates that the annual expenditure needed to support and maintain interventions of a similar nature to those heretofore outlined will amount to approximately $2 billion annually. Currently, Ghana is experiencing an economic downturn and is seeking an International Monetary Fund financing program worth some $3 billion to help it escape its economic woes. The rising inflation phenomenon, which hit 52.8 percent in February, coupled with the rapid depreciation of the Ghanaian Cedi—put at 55 percent to the U.S. dollar in 2022—combined with worldwide supply chain bottlenecks and fiscal shortfalls, has severely weighed on Ghana's economic prospects. Russia's attack on Ukraine added to these pressures, leading to food and gas price hikes. The price of fertilizer, now in shortage, has also tripled [71,72].

After their passionate denial of even thinking of seeking the assistance of the IMF, the GOG announced that they would be obtaining assistance with a view to alleviating the economic suffering the country is currently going through. Ghanaian farming is dominated by smallholder family farms, which are mostly rain-fed and therefore climate-sensitive. Erratic rainfall patterns have extreme consequences on productivity as merely 2 percent of the country's irrigation potential is being exploited. Around 80 percent of farms are rain-fed with very few functional irrigation systems. The majority of these institutions are small-holder farms with an average size of below 1.2 hectares [73].

Some of the major agricultural food crops produced are cassava, corn, yam, peanuts, and sorghum, and the commercial crops are cocoa, palm oil, rubber, sugar cane, cotton, and tobacco. Ghana is the world's second-largest producer and exporter of cocoa, only behind its immediate neighbour, Côte d'Ivoire [74, 75]. These two countries together produce over two-thirds of the world's total supply of cocoa.

## 4. Impacts of Climate Change on Ghana's Agriculture

A. Impact on crop yields due to temperature rise

Climate change impact on crop yields is a key concern for global food security. Rising temperatures and changing precipitation patterns has substantially influenced crop productivity, leading to food shortages and economic losses. A study by Nilsson *et al.* [76] indicated that the United Nations Sustainable Development Goals (SDGs) aiming to end hunger and ensuring access to sufficient, nutritious food by 2030 for 850 million people classified as undernourished globally. Notably, climate change effects on agricultural productivity pose an immediate threat to food security around the globe. Thereby, increasing temperatures and erratic rainfall patterns are considerably affecting crop production, resulting in food deficiencies along with financial losses [77,78].

The response of different crops to rising temperatures are not the same. For instance, Agnolucci *et al.* [79], presented a study result that shows that an increase in temperature by 1°C can cause a decline in the yield of rice, maize, and wheat by 2.8%, 2.6%, and 2.4%, respectively. Conversely, the yield of soybeans and potatoes can experience a boost of 1.5% and 2.2%, respectively. Besides that, irrigation and crop management can go a long way in reducing the adverse effects of elevated temperatures on crop yields. Irrigation may counteract negative consequences of the temperature increase, while pesticides and fertilizers can boost agricultural yields. The impact of increased temperatures on yields has widespread consequences for food security and agronomic productivity. The nations with low yields and poor dietary quality will be worst affected. Accordingly, there must be an international effort to improve the yields of such nations through the implementation of improved agronomic practices and upgrading of the agricultural system.

$CO_2$ fertilization has the potential to influence crop yields, with C3 crops (that is, rice,
wheat, soybeans, rye, barley, cassava and potatoes) more responsive to $CO_2$ than C4 crops (that is, maize, sorghum and sugar cane). Nevertheless, the effects of $CO_2$ fertilization may decline or become insignificant under the conditions of

wetter, drier, or warmer climates. Notably, rising temperatures has significantly influence the yields of crops due to the fact that different crops respond differently to increases in temperatures (see Fig. 3).

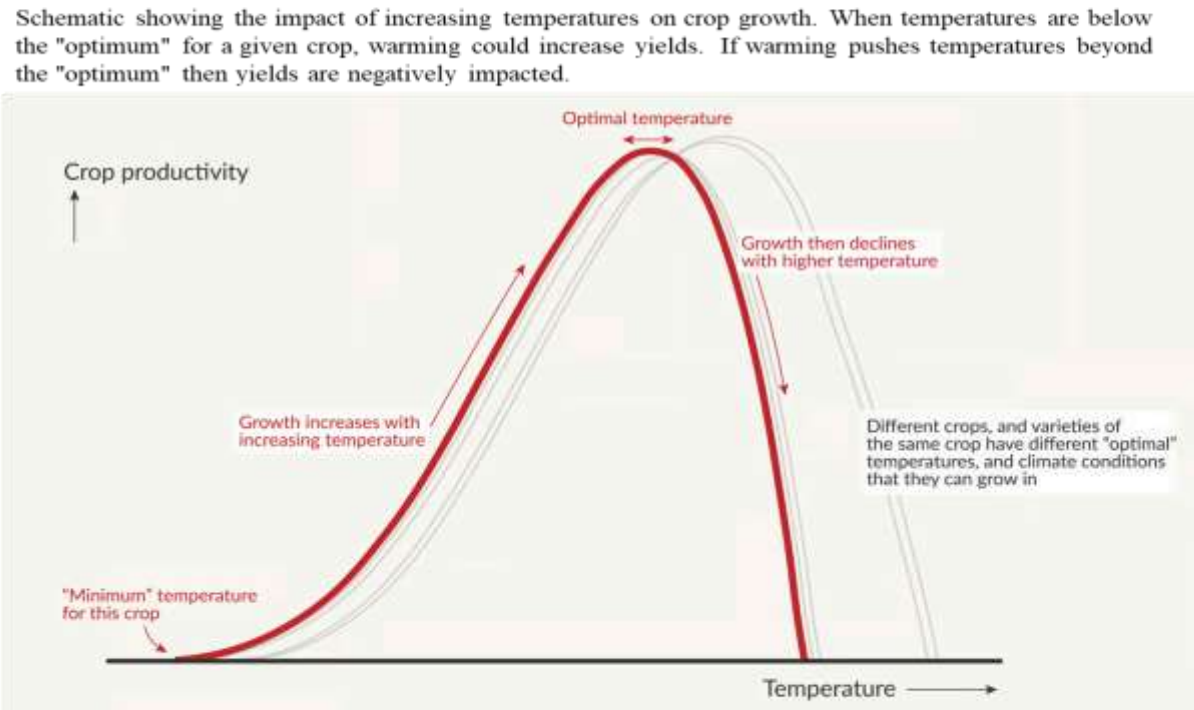



**Fig. 3 Schematic diagram showing the impact of rising temperatures on crop growth and yield, highlighting the optimal temperature range [80]**

4.1 Impact on rainfall patterns

Climate change increases the risk in agriculture through dry spells, pests and floods due to changing rainfall patterns. Farmers in Ghana continue living on a piece of land, depending upon how well they adjust to the risks of climate change [81]. Therefore, the total annual precipitation in 2100 is projected to range from -15% to +16% of current annual rainfall amounts. A standard illustration provided is a national decrease of 4% anticipated by 2040. For certain regions, an initial increase in rainfall, as projected by Panthou *et al.* [82], is succeeded by a decrease in the majority of regions over the long term. The impacts of climate change in Ghana mirror that which has been seen worldwide. There is evidence that not only are the intensity and patterns of rainfall in Ghana becoming more and more unpredictable, but they are overall declining in all the ecological regions [83]. The country's economy is set to withstand the consequences of climate change, given its reliance on agriculture, forestry, and energy sectors, all of which are prone to climatic changes.

According to a two-decade-long climate observation baseline, cereal crop yields such as maize are predicted to decrease by 7% by the year 2050. Furthermore, the observations of sea level rise over the past three decades have indicated a rise in sea level by 2.1 mm annually, which implies that by the years 2050 and 2080, sea level will be higher by 5.8 cm, 16.5 cm, and ultimately 34.5 cm, respectively [81]. The exposure to climate change in Ghana is very high; this is intensified by low adaptive capacity coupled with the interplay of a multiplicity of factors [60]. As such, Ghana's principal economic sectors are also very much exposed to the impacts of climate change, with such exposure being further exacerbated by underlying development challenges including poverty, low access to capital, weak governance, technological deficits, ecosystem degradation, and, in some instances, conflict [84].

Food security and agriculture production in Ghana are already negatively affected by climate change [85]. Climate change has converted the majority of the forest lands in Ghana into semi-arid land that is not suitable for farming crops [86]. Forest land loss due to its conversion to other uses has definitely increased and expanded $CO_2$ because the forest previously played the role of the basket for trapping $CO_2$. According to reports, climate change in some regions of East Africa has shortened the duration of conventional growing seasons as well as pushed some regions entirely out of production [87]. IPCC projection indicates a decrease in the yield of crops in some West African countries by as much as 50% by 2050 and as much as 90% by 2100, impacting net revenue of crops. This trend will definitely impact the food security of the continent and can actually trigger a huge worldwide migration of individuals.

B. Impact on soil salinity

Soil salinity is a major risk to food security and agricultural production in Ghana, largely because of climate change. High salt levels in the soil can result in low fertility, thereby making it hard for crops such as maize, rice, and cassava to grow. Such a phenomenon will add to the reduction in the production of crops, degradation of water quality, and a decline in biodiversity. Soil degradation, furthermore, will result in the loss of essential ecosystem services, hence ultimately affecting food nutritional value [88].

Changes in climatic regimes significantly affect the process of salinization. Salinization of the soil in the root zone may result from decreased water supply in irrigated semi-arid and arid agricultural regions, capillary rise of the salts from shallow water tables, recycling of degraded water, and intrusion of saltwater. If there is a limitation on water availability in the capillary zone of the soil, it can cause severe stress to the root system of crops, especially C4 crops like wheat,

leading to increased soil salinity, nutrient leaching in excess, and residual pollution due to the use of fertilizers and chemicals [89].
The etiological agents of soil degradation and salinity in Ghana are deforestation, slash-and-burn agriculture, land clearing, and the application of agrochemicals. Forest cover in Ghana has been lost at a rate of 20,000 hectares annually, and this promotes climate change and soil degradation [90]. Slash-and-burn agriculture is also 70% responsible for deforestation in Africa and results in soil erosion and loss of fertility. Economic impacts of soil degradation and salinity in Ghana are enormous. Environmental degradation costs more than 10% of the nation's GDP, which is around USD 850 million. Land degradation leads to a decrease in agricultural revenues by USD 4.2 billion over ten years, negatively affecting the economy of the nation [91,92]. Climate change and soil salinity can also lead to crop failure as well as lower levels of production and productivity, hence threatening food security and economic stability.

## 5. Climate Change Adaptation Strategies in Ghana

A. Ghana's response to climate change

It is not possible for Ghana to fund climate change mitigation interventions alone. For that matter, the nation is a member of the Green Climate Fund that finances climate change mitigation and adaptation projects, prioritizing the enhancement of resilience in vulnerable communities [93]. The Forestry Commission's Climate Change Unit is the national Reducing Emissions from Deforestation and Forest Degradation (REDD+) Secretariat, and climate change matters within the energy sector are managed by the Renewable Energy, Energy Efficiency, and Climate Change Divisions of the Energy Commission [94,95,96] (Miah, 2020; Bofin *et al.*, 2011; Kallies *et al.*, 2010).
However, Ghana faces significant gaps in addressing climate change. There is no comprehensive climate change law in Ghana but sectoral laws, regulations, and policies that are scattered. The Agriculture, Forestry, and Other Land Use (AFOLU) sector has the largest contribution to greenhouse gas emissions, emitting 54.4% of total emissions in 2016. Ghana receives financing from the Green Climate Fund to implement four projects in the North of Ghana. Despite this support, the funding sources available are not sufficient to cover all the climate change needs in the country. The financing has principally gone to mitigation actions and was distributed to 405 projects around the country.
The World Bank Group has also been supporting Ghana's efforts with regards to climate change through its Country Climate and Development Report (CCDR), which outlines the priority areas for a low-carbon and climate-resilient development pathway. Some of these areas involve adopting an integrated agriculture and environment management strategy, building sustainable cities and climate-resilient infrastructure systems, and promoting a clean energy transition [97].
Also, Government of Ghana has formulated a National Climate Change Policy (NCCP) and a Climate Change Master Plan that aim to integrate climate change into national development planning and decision-making. Notably, he has prepared several programs including the Renewable Energy Master Plan, the National Adaptation Strategy and Action Plan, and community-based adaptation initiatives all aimed at enhancing resilience to climate change. Ghana has committed to reducing greenhouse gas emissions by 30% by 2030 and has presented its updated Nationally Determined Contributions (NDCs). The implementation of the 47 NDC actions, however, will require an investment of between $9.3 billion and $15.5 billion. So far, the country has received financing from numerous global donors, such as the European Union (EU), the African Development Bank (AfDB), and the United States Government, but these funding sources are not sufficient to cover all the needs of climate change.
The key institutions engaged in combating climate change in Ghana are the Ministry of Environment, Science, Technology, and Innovation (MESTI), the Environmental Protection Agency (EPA), the Ministry of Finance (MoF), the National Development Planning Commission (NDPC), and the Ministry of Energy (MoE). The patterns of climate change in Ghana show that Ghana will keep on recording rising temperatures, with mean temperatures likely to increase by 1.0°C to 3.0°C by 2050 and by 2.3°C to 5.3°C by end of the century [98].
The climate change efforts and challenges of Ghana are intricate since the country participates proactively in global climate talks and has ratified key treaties, such as the Paris Agreement on Climate Change and the United Nations Framework Convention on Climate Change (UNFCC). Furthermore, Ghana has lodged its updated Nationally Determined Contributions (NDCs), thus committing to greenhouse gas emissions reduction by 30% by the year 2030 [99].

B. Climate Change Adaptation Mechanisms for a Sustainable Green Economy

As Ghana grapples with the challenges of climate change, it is imperative to adopt various adaptation measures and actions to attenuate the vulnerabilities of crops and ensure sustainable agricultural production [100]. Adaptation measures encompass a range of activities and practices designed to reduce vulnerability and enhance the resilience of agricultural systems. Adaptation strategies offer a vital opportunity to address the challenges posed by climate change and maintain a sustainable agricultural production system. Some of the key adaptation techniques and practices being explored include the use of biotechnology, improved breeding and selection, artificial intelligence for climate action, development of climate-resilient crop varieties, and the adoption of climate-smart agriculture practices [101].

The use of biotechnology, for instance, can help develop climate-resilient crop varieties that can thrive in challenging environmental conditions. Improved breeding and selection practices can also enhance crop resilience, while climate-smart agriculture practices can help farmers adapt to changing weather patterns and increasing climate variability. Effective water and nutrient management practices are also critical for maintaining crop productivity and resilience in the face of climate change.

**6. Sustainable Agricultural Practices**

A. Water management

Projections on irrigation water demand for mid-21st century was 8–9% rise, whereas rainfall was expected to decline (11–18%) [102]. Contrary, the advancement of creative water management techniques such rain water harvesting, irrigation scheduling, ground water recharge, conservation, and Meter/Measure/Manage has assisted in mitigate the adverse effects of climate change. To prevent excessive or insufficient watering of plants, farmers keep an eye on the forecast for the weather. Farmers wisely utilize irrigation water for crops during their essential growth phases.

For instance, regarding wheat, if farmers possess two irrigation choices, then implement them at crown root initiation and booting phase of the crop; however, if three irrigation methods are available, then irrigate at crown root initiation and booting and the stages of wheat grain filling. Farmers irrigate crops during the cooler times of day (at night) or in the early morning), which reduces water loss even more. Utilization of the most effective irrigation technique, such as drip. The irrigation technique supplies water straight to the plant roots, reducing water loss via evaporation. Additionally, cultivating crops that are appropriate for the region's climate is another method to maximize yields per drop. Plant varieties that originate from semi-arid and arid regions are clearly more tolerant to drought and heat than those chosen from regions with irrigation.

For instance, sorghum, pearl millet (*Pennisetum glaucum*), and foxtail millet (*Setaria italica* L.), sweet potato (*Ipomoea batatas*), cassava (*Manihot esculenta*), sesame (*Sesamum indicum*), and black-eyed pea (*Vigna unguiculata*) (*unguilata*) are fairly resistant to drought conditions [103,104], and can thrive in regions susceptible to drought. Cultivating cover crops to prevent soil erosion and boost organic matter substance and soil productivity, while minimizing weeds. This will enable the irrigation or rainwater to penetrate the ground and enhance soil moisture-retaining ability (WHC). Similarly, the use of animal dung and decomposed material

B. Nutrients management

Nutrient management is an important aspect of enhancing plant strength and resilience to biotic and abiotic stresses. Plants require essential macronutrients (N, P, K, Ca, etc.) and micronutrients (B, Zn, Fe, Cu, Si, etc.) that play key roles in various physiological and metabolic processes, enabling them to withstand stresses.

Research has confirmed that proper nutrient management can mitigate the impact of drought stress and increase crop yields. For instance, foliar application of N fertilizer at later growth stages has been shown to effectively alleviate drought stress effects and improve grain filling in bread wheat [105]. Optimal N fertilizer rates have also been found to promote remobilization of plant stem reserves and increase grain-filling rates during drought stress. Furthermore, amino acid and potassium foliar sprays have been reported to enhance grain yield by inducing physiological and biochemical traits under both drought stress and well-watered conditions [106,107].

Similarly, additional foliar NPK fertilization can improve gas exchange characteristics, water relations, and nutrients status of wheat both in water-stressed and well-watered plants [108]. Exogenous Ca treatment can also increase drought tolerance by boosting endogenous polyamines content [109]. Moreover, silicon (Si) application has also been shown to alleviate stress-induced damage, improving the growth of shoots and chlorophyll content in leaves of wheat under water-limited conditions [110]. Besides, selenium (Se) application has also exhibited positive impacts on most crop plants when subjected to drought stress conditions [111,112]. Overall, strategic nutrient management can be a significant factor in the enhancement of crop resistance to abiotic stresses and increased productivity. These findings could be used by farmers and agricultural practitioners to come up with more feasible strategies for nutrient management and alleviation of drought stress in plants (see Fig. 4).


**Fig. 4 Advancements in soil management: Optimizing crop production through interdisciplinary approaches [113]**

C. Agronomic management practices

Agriculture production systems can be made more productive and resilient to changing climate by applying system-specific management measures [114]. Many options are available nutrient, water and soil management practices or technologies, which are helpful to mitigate and reduce adverse impacts of climate change. The important practices or technologies for rainwater harvesting, in situ moisture conservation, improvement in irrigation methods for efficient use of irrigation water, wastewater treatment, alternative land uses, reclamation of marginal lands, agroforestry on degraded lands, residue- and nutrient management [115]. Good agronomic management will not only improve the agricultural production but also help in combating climate change impacts [116].

Minimum soil disturbance and permanent organic soil cover reduces the soil erosion, evapotranspiration losses, weeds problem and increases soil infiltration rate [117]. Studies revealed that by adopting conservation practices, soil carbon sequestration can be achieved at 0.2–1.0 tones $ha^{-1}$ year-1depending on agroecological conditions [118], that would help to decrease greenhouse gas emission, further environmental damage improve and improve soil productivity [119]. The conservation agricultural (CA) practices are being adopted in 125 million hectares located in different countries, and are further rapidly increasing in subtropical, tropical and temperate areas of the world [120].

Many studies have indicated that CA can increase crops yields and improve soil health compared to conventional practices [121]. Furthermore, conservation practices can increase soil infiltration rate, water holding capacity, reduces water runoff, soil erosion, it can also decrease the incidence of pests and diseases [122]. Sowing of crops on permanent raised-bed with residue management, can decrease soil sodicity by 1.80 to 2.64 times in upper layer of soil compared to conventional beds [121].

D. Genetic improvement

Breeding improved crop cultivars is crucial for increasing and sustaining yields under a changing climate. New crop varieties can perform well and enhance yields in extreme temperatures and drought stress [50]. According to studies by Mwadzingeni *et al.* [123] and Fita *et al.* [124], to breed drought and salt-tolerant cultivars, an integrated approach is necessary, combining the use of current genetic traits, exploitation of new and diverse sources, and historic breeding techniques. Selecting and breeding crops for climate resilience is a proven strategy for increasing yields in salt and drought-affected regions [125]. Mass screening and selection of genotypes for useful traits under water and salinity stress can improve yields in various cereal crops, including wheat, rice, maize, sorghum, and legume crops. By evaluating traits such as seedling emergence, fresh and dry weight of plants, and leaf $Ca^{2+}/Na^{+}$ ratio, researchers can identify salt-tolerant cultivars [126].

For drought tolerance, traits such as rooting depth, leaf area, dry weight of plant, number of grains per spike, and 1000-grains weight should be evaluated [127]. According to Zafar *et al.* [128], economic yield should be the final criteria for evaluating salt and drought tolerance, and therefore, the parameters that should be used for evaluating tolerance and resistance must be correlated with economic yields of crops. Direct selection of legume genotypes for salt tolerance can be carried out by conducting trials at multiple locations. Evaluating legume cultivars for salt tolerance by observing suitable traits during early growth stages can help identify salt-tolerant cultivars. Mass screening and selection can be carried out on the basis of plant dry and fresh biomass, osmotic adjustment, and other traits to identify salt and drought-tolerant cultivars [129,130] (Table 2).

**Table 2. Key indicators for drought tolerance**

| Category | Parameters |
|---|---|
| Morphological and Anatomica | Greater root length, root fresh and dry weight, root volume and thickness, leaf area of plant, canopy structure, stay-green character of leaves, fresh and dry weight of plant, number of grains per spike or pod, grain weight, harvest index and economic yield. |
| Phenological | Seedling vigor, early to flowering, anthesis and maturity, less silking interval, synchronization of silking and tasseling, weed competitiveness. |
| Physiological and Biochemical | Leaf water potential, stomatal conductance, osmotic adjustment, stay-green, carbon isotope discrimanation, stem reserves mobilization, specific leaf area, presence of awns, ABA content, heat-shock protein, wax coating, leaf rolling, electrolyte leakage, water use efficiency, nutrient use efficiency, osmoprotectants, auaporins and dehydrins. |

**Source:** [131,132]

E. Genome-based approaches

Genome-based approaches have revolutionized our understanding of crop biology and genetic information. Molecular plant breeding has emerged as a crucial technique for enhancing crop yields and resilience to abiotic and biotic stresses [133]. By leveraging molecular markers, researchers can identify novel genes that enable crops to thrive in specific environments. Recent progress in plant genomics has led to the development of various DNA markers, which are being utilized in marker-assisted breeding programs. This approach accelerates the breeding process, enabling scientists to develop crop varieties tailored to specific environmental conditions. For instance, researchers have successfully employed QTL mapping to develop drought-tolerant wheat varieties, such as "Ripper," which maintains grain yield despite water stress.

QTL mapping has been applied to various crops, including maize, durum wheat, and bread wheat, to identify traits associated with drought tolerance and heat stress [134,135]. Marker-assisted selection has enabled researchers to select specific wheat traits that confer drought tolerance. Furthermore, studies have identified key genomic regions and genes associated with cold and heat stress in Sorghum bicolor. The use of molecular markers and QTL mapping holds tremendous potential for enhancing crop resilience to abiotic and biotic stresses [136,137]. Further research should focus on exploiting these tools to identify distinctive variations in agricultural crops, ultimately leading to improved crop yields and sustainability.

**7. Innovative Solutions for Climate Resilience**

A. Climate-smart agriculture

Climate-smart agriculture (CSA) is being adopted in the world to cope with the negative impacts of climate change on crops. Climate-smart agriculture is technique or agricultural system, which transforms and reorients the agriculture sector under new realities of climate change [138]. Climate-smart agriculture enhances the productivity, increases resilience, reduces greenhouse gas emission where possible, and enhances food security and development goals [139,140].

The aim of CSA is to increase sustainability in agriculture and productivity or incomes from agricultural sector without imposing adverse effects on environment (Fig. 5). In CSA, sustainable farm-based agricultural practices such as highly efficient water management practices, conservation tillage, residue management and agroforestry [141]. In CSA, the focus is given on the implementation of these farm and field practices, and the ways that can further improve these practices with respect to changing climate. These farm-based practices deliver two or three climate-smart-benefits. For instance, agroforestry system in some regions of Kenya provide timbers for income generation, fire-woods for domestic use and sequester carbon (4.07 Mg C $ha^{-1}$) [142]. Likewise, different cropping practices in Zimbabwe and Tanzania considerably enhanced crop yield, income, and food security [143].

Moreover, diversified cropping system increases resilience against stresses, enhances yields and quality, soil fertility, and reduces the pests and diseases [144]. According to Kimaro *et al.* [145], in Tanzania, agroforestry and conservation agriculture not only increased the maize yield and but also improved resilience and mitigation benefits. In north-west Ethiopia, farmers who followed CSA practices between 2015 and 2017, according to [146], had higher farms productivity by 22% over non-adopters.

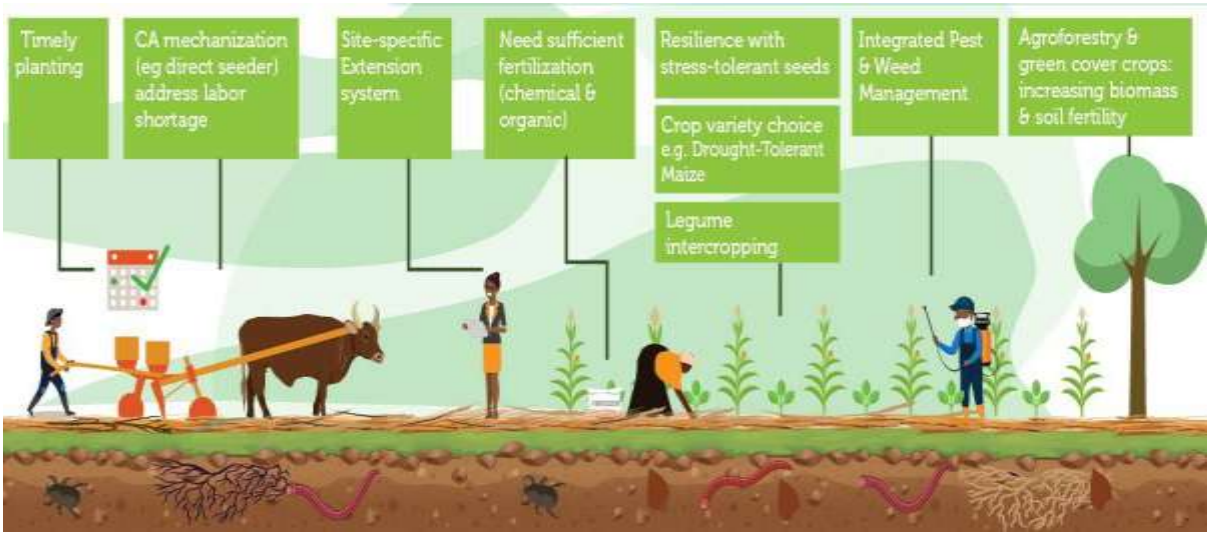



**Fig. 5 Scaling out climate-smart agriculture in Ghana**

B. Cultivation of climate resilient crops

Crops that resilient to climate change have been suggested to growers to cope with or adapt to climate change. Superior genotypes with better resilience to biotic and abiotic (water, heat, and salinity etc.) stresses will perform a significant role in adaptation to climate changes. Adoption of climate-resilient crops, such as short stature and early-maturing varieties in cereals, heat, drought and salinity tolerant cultivars, rice varieties with submergence tolerance, and drought tolerant tuber or legumes crops can help the growers to cope with climate change [147]. Stress tolerant crop varieties have high potential to resist against stresses and less economic yield losses. Thus, better understanding of relevant stress related parameters and their relationship to particular environment is crucial to variety development.

Sorghum, foxtail millet, pearl millet, sweet potato, cassava, sesame and cowpea are comparatively drought and temperature resistant crops [148] compared to cotton, maize, rice, wheat, etc. In salt prone areas, sowing of salt tolerant crops can yield as compared to salt sensitive crops. Thus, the development of crop varieties demanding less water input to yield along with better site-specific production technology is very important to sustain crop production in drought prone regions. Similarly, advancement in the field of biotechnology and genomics seem viable to increase the crops performance under various stresses [149].

C. Artificial Intelligence for Climate Action

The increasing frequency and severity of extreme weather events, rising sea levels, and shifting precipitation patterns demand the development and deployment of new technologies that will enhance climatic adaptation and resilience. Artificial intelligence (AI) has emerged as a central force in this endeavor, providing disruptive potential for understanding and forecasting climatic events [150,151]. There are numerous applications of AI in climate change mitigation and adaptation. It enhances the accuracy and efficiency of weather event forecasting and climate change effects through methodologies like machine learning (ML) and deep learning (DL). Artificial intelligence models, satellite imaging, and IoT sensors detect and monitor deforestation, logging, and forest health to aid in sustainable forest management. AI-driven sensor data monitoring also tracks greenhouse gas emissions, predicting behavior at storage facilities and carbon foot printing cities and industries [152,153].

Artificial intelligence is at the core of sea level rise and coastal change research. Satellite imagery and AI models of advanced levels are utilized for monitoring sea level fluctuations, coastal erosion, and storm surges, thereby informing coastal management policy and mitigation planning. The advantages of AI applications in climate change mitigation and adaptation are many. It significantly improves forecasting accuracy, thereby enabling preparatory measures for reducing the impact of extreme weather phenomena. AI optimizes the use of resources in disaster response and preparedness to reduce potential damage and enhance resilience.

Moreover, AI's ability in processing and analyzing big data sets assists in identifying long-term climate trends, informing policy action for GHG emissions reduction and sustainability. AI aids policymakers in making more effective climate action plans that address mitigation as well as adaptation needs. For instance, in hurricane season, these models can generate updated forecasts that help governments and communities make informed decisions on evacuation, deployment of resources, and emergency response interventions. Similarly, for flood prediction, ML models can analyze rainfall data, river levels, and soil moisture content to predict floods and enable anticipatory action [154].

Jiang *et al.* [155] leveraged artificial intelligence for improving the early warning and detection function in relation to solar activity, which has an important impact on climate change, particularly in the context of droughts and floods. The authors utilized three-dimensional recognition techniques to identify instances of meteorological and ecological drought events and subsequently extracted propagating drought events based on spatiotemporal overlap rules. Overall, the application of machine learning algorithms in meteorology forecasting improves the accuracy of predictions and serves a critical purpose in reducing the effects of severe weather conditions by enabling timely and efficient response initiatives.

Overall, artificial intelligence enhances climate resilience through predicting and controlling emissions, deforestation monitoring, and optimizing resource management, hence working towards a better future.

It is possible to accelerate climate action, enhance climate resilience, and promote sustainable development using artificial intelligence technologies. Table 3 presents a systematic overview for understanding the complex contribution of Artificial Intelligence (AI) in promoting climate adaptation actions. The elaborate table explains the thematic applications, particular aims, and results of various studies focusing on AI-based climate adaptation initiatives. With a broad spectrum of applications and contexts, Table 3 highlights the revolutionary role of AI in tackling climate action.

Artificial intelligence is now a transformative technology for the assessment and enhancement of climate adaptation strategies. Through simulating various scenarios, AI models offer actionable insights on the performance of adaptation measures, forecast outcomes, optimize resource allocation, and identify the most appropriate strategies to manage climate variability and extremes. Through Machine Learning (ML) and Deep Learning (DL) approaches, societies can create more powerful and robust responses to the evolving environmental conditions [156,157,158]. The incorporation of Artificial Intelligence (AI) in climate change adaptation policies improves prediction accuracy, facilitates anticipatory decision-making, and promotes climate resilience.

**Table 3. AI-Enabled Adaptation Solutions for Policymakers: Evaluating and Comparing Promising Options to Mitigate Climate Change Impacts in LDCs and SIDS**

| Theme | AI Applications | Objectives | Key Contributions | Citations |
|---|---|---|---|---|
| Climate change impact on crop productivity | Statistical Downscaling, GA | To predict climate change effects on pearl millet production utilizing genetic Algorithms. | Shown potential for energy-efficient. renovations in urban settings utilizing neural Networks. | [159] |
| Flood analytics | AIoT, CNN | To advance flood analytics through AIoT During flood conditions. Awareness and risk. evaluation. | AIoT prototype Better flood warning. and contextual awareness; successfully tested by hurricane-driven floods. | [154] |
| Drought forecasting | ANN, ANFIS, SVM | To compare ANN, ANFIS and SVM. models during droughts forecasting. | SVM model provided the most precision in Drought forecasting. compared to ANN and ANFIS. | [160] |
| Urbanization and climate impact | Dynamic Simulation, Weather Research and Forecasting Model (WRF) | To explore the impact of future urbanization on local climate under varied climate Alter circumstances. | WRF simulations recorded significant warming and public health hazards associated with Urbanization and climate. shift by 2030. | Yeung *et al.* (2020) [161] |
| Groundwater table forecasting | LSTM Networks, RNN | To simulate and predict groundwater table Response to Storm. | To model and predict crop production below varied climate Modify circumstances. | Bowes *et al.* (2019) [162] |

| | | | | |
|---|---|---|---|---|
| | | | utilizing ML methods. | |
| Crop productivity prediction | DNN, Semiparametric | ML method exhibited less serious adverse Impacts on maize production. than traditional ways, especially in warmest scenarios. events in a coastal city. | LSTM networks outperformed RNNs at predictive accuracy; effective in real-time forecasting of groundwater table levels. | Crane-Droesch (2018) [163] |
| Best management practices (BMP) performance in agricultural watershed | Deterministic Models (SWAT), Decision Support Models (NSGA-II) | To measure changes in BMPs on total Phosphorus loads under climate change Situation. | SWAT and NSGA-II helped refine BMPs for Future climate scenarios. emphasized the necessity of adaptive BMPs. | Jeon *et al.* (2018) [164] |

**D. Use of nanotechnology**

Nanotechnology has emerged as a prospective contributor to enhancing crop resilience and productivity against climate change. It can be utilized to develop innovative solutions that fight the impact of climate change, making crops more productive while reducing the environmental impact associated with traditional farming [165,166]. Nanofertilizers and nanopesticides have great potential in boosting crop production while, in the process, lessening the environmental issue associated with conventional agriculture [167]. These nanoparticles can be engineered to release pesticides and nutrients in a specific and controlled way and hence minimize wastage and the possibility of water and soil contamination. Nanoparticles can also be utilized to deliver drought-resistant genes to plants, thereby enabling the plants to survive even when there is low water availability [168].

Nanotechnology can also be employed in the designing of more efficient irrigation systems, thus minimizing water loss and optimizing water use. This is more so in areas where water scarcity is a great challenge. Nanotechnology can also be utilized in the formulation of more efficient crop protection and disease management. For instance, nanoparticles have the potential to deliver fungicides and pesticides directly to the infection site, with less risk of chemical runoff and less damage to helpful insects. Agricultural nanotechnology can support climate-smart agriculture that involves creating and applying agricultural techniques and technology that reduce greenhouse gas emissions, increase soil fertility, and make crops more adaptable [169,170]. Farmers are able to adopt more sustainable and resilient agricultural systems through the application of nanotechnology, reducing their ecological footprint and elevating crop productivity.

Notably, nanotechnology can transform our approach to crop productivity and climate change worldwide. Through the development and application of nanotechnology-based solutions, farmers can boost crop yields, minimize their environmental impact, and enhance their resilience to climate change [171,172]. As the globe struggles to find solutions to the impacts of climate change, nanotechnology can be a critical enabler of sustainable and resilient agriculture (see Fig. 6).

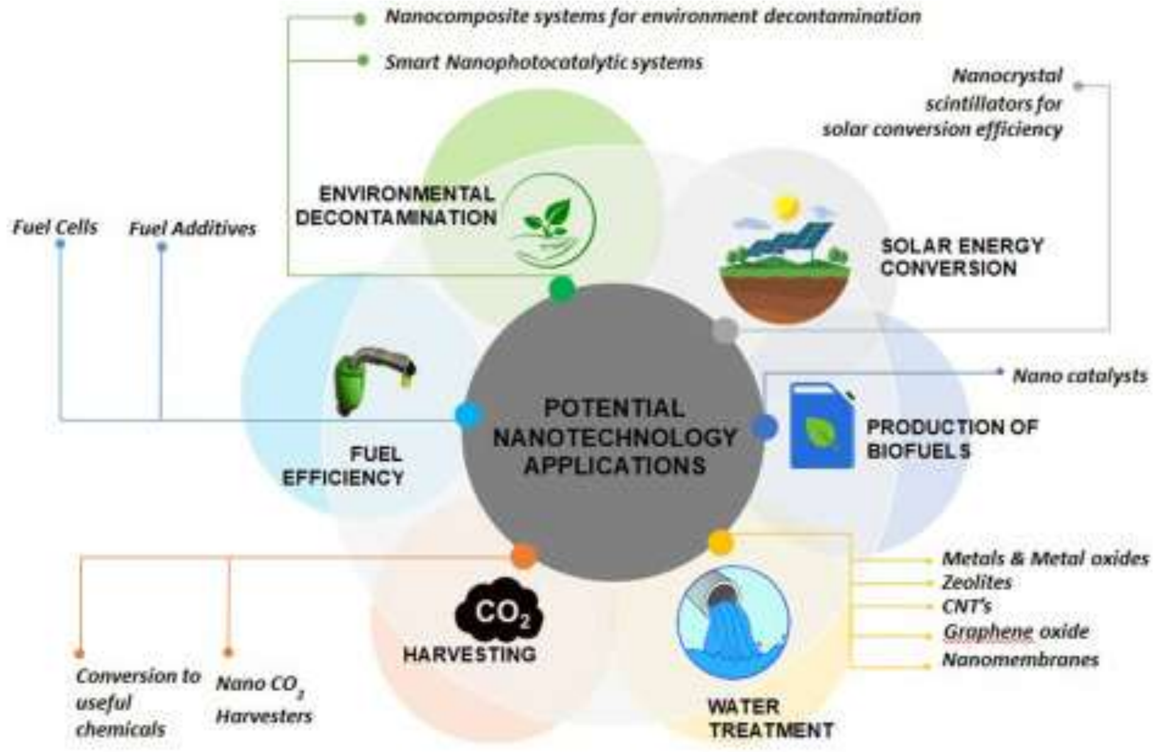



**Fig. 6. Combating climate change with nanoparticles [173]**

**E. Monitoring deforestation and forest degradation**

Deforestation is a significant global environmental risk with cross-cutting consequences for biodiversity, climate change, and livelihood [174]. Satellite and IoT sensor data, combined with sophisticated AI algorithms, can be utilized in detecting and monitoring deforestation and forest degradation. AI algorithms analyze high-resolution optical and laser-based satellite imagery, typically in conjunction with ground-truth biomass measurements, to map forest cover changes, identify illegal logging activities, and monitor forest health over time [175,176]. AI can help mitigate climate change by implementing effective and efficient sustainable forest management strategies to prevent deforestation [177].

They can differentiate between various land cover and vegetation types, thereby enabling accurate monitoring of the deforestation rate and area. Haq *et al.* [178] considered how artificial intelligence, the Internet of Things, and remote sensing can be utilized in combating deforestation. These technologies enable real-time monitoring, early warning, and intervention in processes such as illegal logging, plant disease, and forest fire (Fig. 7).

**Fig. 7 Ghana pushes ahead with efforts to reduce emissions from deforestation (Source: Forest Carbon Partnership Facility)**

F. Innovative Water Management Practices

The increasing demand for irrigation water, coupled with decreasing rainfall, necessitates the development of innovative water management practices [179]. To mitigate the negative impacts of climate change, growers must adopt efficient irrigation (methods. Strategic irrigation management is crucial, where farmers monitor weather forecasts and apply water judiciously during critical crop growth stages. Climate-smart crop selection is also vital for efficient water use. Planting crops suitable to the region's climate is crucial. Native crops, such as sorghum, pearl millet, and cowpea, are naturally drought- and heat-tolerant, making them ideal for drought-prone areas. Growing cover crops protects soil from erosion, enhances organic matter, and increases soil fertility [180].

Conservation tillage practices or partial ploughing, leaving at least 30% crop residues on the soil surface, reduces erosion, evaporation, and soil compaction. Furthermore, flooded rice cultivation should be discouraged, and instead, direct seeded rice or alternate wetting and drying methods should be adopted to reduce methane gas emissions and improve water use efficiency [181,182]. Planting crops on permanent raised beds is an effective soil and water management strategy, increasing water use efficiency, nutrient use efficiency, and soil structure. This method also reduces pesticide application due to improved aeration and reduced humidity. By adopting these innovative water management practices, farmers can enhance crop resilience to climate change while minimizing water waste.

## 8. Conclusion

This research identifies the critical issue of climate change and its far-reaching implications towards ensuring food security in Ghana. The research reveals that the agricultural sector of Ghana is highly vulnerable to climate change and its implications of possible yield declines, economic losses, and increased poverty levels. Climate change poses a significant risk to the country's efforts towards achieving sustainable development, particularly in the context of the United Nations' Sustainable Development Goals (SDGs). Despite these challenges, Ghana has demonstrated its commitment to addressing climate change by pledging to reduce greenhouse gas emissions and implement climate-resilient agriculture.

The findings of the study highlight the pressing need for intervention strategies to reduce the effects of climate change on food security in Ghana. The use of climate-resilient agriculture, such as climate-smart agriculture, has the potential to enhance food security and build resilience. Furthermore, genome-based technologies, artificial intelligence, and nanotechnology can be used to develop climate-resilient crops and boost agricultural productivity. The implications of the findings of this research are far-reaching and of great importance to policymakers, researchers, and stakeholders within Ghana's agricultural industry. The research emphasizes the relevance of evidence-based policymaking and calls for sustained research and development to face the intricate challenges of climate change. Through prioritizing climate-resilient agriculture practices and sustainable development, Ghana can evade the vulnerabilities of climate change and ensure food security among its populace.

Finally, this study lays the groundwork for subsequent research and policy-making aimed at addressing the issues of climate change and food security in Ghana. The conclusions and recommendations of this study have the potential to inform the formulation of appropriate strategies aimed at mitigating the impacts of climate change and promoting sustainable agriculture in Ghana.

**Recommendations**

1. Sustainable agriculture practices, such as climate-smart agriculture should be promoted in Ghana, to enhance food security and resilience.
2. Adequate funding to support climate change adaptation and mitigation efforts in Ghana's agricultural sector should be made available.
3. A comprehensive climate change laws should be enacted to guide climate change adaptation and mitigation efforts in Ghana.
4. Genome-based approaches, such as molecular plant breeding should be leveraged, to develop climate-resilient crop varieties.
5. The use of artificial intelligence and nanotechnology should be explored to support climate-resilient agriculture practices and enhance food security.
6. Research findings should be used to inform policymaking and decision-making processes related to climate change and food security in Ghana.

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