Research Article

Critical Analysis and Ameliorative Strategies in Combating the Impact of Climate Variability on Pesticide Dynamics and Efficacy

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The importance of pesticides in the economy especially in agriculture, cannot be over-emphasized. It is therefore very crucial to uphold and maintain the efficacy of these pest control agents. This study seeks to explore the effect of climate variables on the potency of pesticides. Climate change has emerged as one of the most significant global challenges, disrupting weather patterns and altering ecosystems. These changes pose serious implications for pest dynamics, distribution, and behavior, thereby directly influencing the performance of pesticides. This study analyzed relevant articles related to climate change and pesticides systematically sourced from credible reference databases for a period of 21 years from 2002 to 2023, using the most suitable keywords. Recent scientific research and empirical evidence, analyzing the effects of rising temperatures, altered precipitation patterns, and changing humidity levels on pests and their interactions with pesticide applications were studied. The relevant impact of these effects is seen in reduced agricultural yield, loss of livelihood and source of income, infestation and destruction of agricultural crops, and reduced living standard in the society amongst others. The projected changes include; the development of adaptive agricultural practices and integration of climate-resilient pest management strategies that could improve the efficacy of pesticides. This involves exploring the potential of eco-friendly and biologically-based pest control approaches to reduce the destructive impacts that arise from climate change. These sustainable practices and novel technologies aimed at improving pest control under changing climatic conditions must be encouraged and upheld tenaciously.

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1. Introduction

Climate Change may be defined as a total of all the activities and natural occurrences that disrupt otherwise stable weather conditions, especially over a prolonged period. Some of the activities that contribute to climate change are usually carried out by man and include the combustion of fossil fuels, excessive cutting of vegetation, and other unpopular activities from industries [1]. Due to the extended period of these natural events, as well as the intensity, some consequences arise such as; flood and drought, these destroy agricultural products [2][3]. These natural disastrous events also affect soil health and efficiency, which in turn affects agricultural productivity adversely, as nutrient-rich soil is necessary for improved agriculture [3]. Global warming resulting from greenhouse gas emission is usually increased when activities such as combustion of fossil fuels, felling of trees, and other agricultural practices that are ecosystem unfriendly are continuously carried out on the environment. Agriculture and its attendant activities have been reported as one of the commonest causes of deforestation globally. It is thus a cycle of feedback effect, where agriculture contributes adversely to climate change, and is in turn affected by climate change [4]. The burning of fossil fuels emits greenhouse gases like carbon dioxide (CO_2), methane, and nitrous oxide into the atmosphere. This results in the trapping of heat and a corresponding increase in temperature [5]. As evidenced by numerous literature reports, climate change is a serious challenge globally in recent times. Its effects on the economy and agriculture in particular are far-reaching, affecting various aspects of our environment and society. It has been reported by Olivier and Peters [6], that in 2017, 2018, and 2019 global CO_2 emissions increased by 1.4, 2.4, and 0.9%, respectively. The impact of increased temperature, erratic precipitation patterns, and unstable weather conditions obviously affects the performance of pesticides, potentially compromising pest control efforts and agricultural productivity. Understanding these interactions between climate change and pesticide efficacy is crucial for developing adaptation strategies and sustainable agricultural practices that can mitigate these adverse effects and ensure food security in a changing world. A study on the effect of climate change on pesticide efficacy is vital for improved economy, agriculture, and the general welfare of any nation. Many pesticides are equally useful in the control of disease vectors, such as the female anopheles' mosquito, which transmits the malaria parasite; one of the greatest causes of mortality in Africa [7]. It is therefore essential to comprehend the various ways by which climate change influences pesticide efficacy, in order to employ appropriate mitigation strategies to overcome these effects [8].

The effect of climate change on agricultural yield and especially insect pests is enormous. There are several ways by which climate change affects insect pests e.g. The geographical distribution due to migration of pests during climate change could be altered, survival of pests may increase, increase in reproduction and proliferation of pests may also ensue causing other effects including invasion of agricultural products by migrating pests, increased transmission of plant diseases by pests as well as reduced efficacy of biological pest control agents. If left unattended, these events could result in serious economic loss to any nation. Food security may be grossly threatened too. Adaptive and mitigative management strategies are very crucial to control or at least reduce the impact of climate change; a major driver of pest population. Some of the strategies that could be employed for adaptation and mitigation of climate change impacts include; the application of Integrated Pest Management (IPM) approach, monitoring climate indices and pest population, and applying modern prediction tools [9]. Again, climate change affects the growth of organisms present in an ecosystem. According to the Inter-Governmental Panel on Climate Change (IPCC) [8] the major indices for climate change impact measurement include; an increase in global temperature, increased atmospheric carbon dioxide concentration, unpredictable rainfall patterns, and unstable radiation. Climate change encourages differential growth patterns in crops and weeds, this could endanger plants and disrupt weed management strategies. It has been projected that a 2.4-6.4 °C increase in temperature may arise by the end of the twenty-first century as a result of climate change [10]. When the mean temperature increases from global warming, weeds may expand their range and conquer new habitats following evolutionary mechanisms. In higher temperatures, C_4 photosynthetic plants possess a more competitive advantage over C_3 plants and most weeds belong to the C_4 class. Also, climate change could cause an increased invasion of weeds from adjacent territories during unstable climatic conditions [11]. Due to their physiological plasticity and flexibility, weeds endure stress more than regular plants.

Global warming has increased by 1°C above pre-industrial levels due to human activities [8]. There are predictions that this may increase to 1.5°C by 2052. The 1.5°C increase in global warming when compared to the changes in the pre-industrial levels, estimates extreme temperature rise, increased heavy rainfall and drought in many regions [8]. It has also been reported that climate change affects the toxicity of soil pollutants by altering natural cycles around the globe and weather patterns, this simply implies that the predicted changes may significantly affect the efficacy of pesticides too. Several reports have also shown that unstable temperatures and moisture affect the bioavailability of soil pollutants. Unfortunately, climate change indices are getting worse by the day with rainfall patterns, drought, and global temperatures becoming highly unpredictable and erratic. There is therefore the need for serious research to consider tenable and feasible ways of controlling these weather parameters. In 2019, the global temperature increased by 0.95°C, making it the second warmest in over a century. Leaching which increases soil acidification and run-off from agricultural areas is a serious cause for concern during flooding episodes. Drought on the other hand, is a major cause of poor vegetation and soil erosion globally [6]. An increase in pesticide use as a result of climate change has been reported by Shakhramanyan *et al* [12] to contribute to health and environmental costs. Climate change effects have also been observed on herbicides, fungicides and insecticides, as it affects their potency and persistence. It also affects pest and crop diseases and increases the susceptibility of plants to diseases as well as increases resistance to herbicides [13]. The food web is not spared in the myriad of effects resulting from climate change. Continuous pesticide application due to climate change increases the population of predator and prey species [14]. Again interaction of these pesticides with other atmospheric stressors could result in critical environmental pollution and toxicity [15]. Some authors already reported that climate change could influence the fate and toxicity of pesticides in the environment [16][17]. Other authors reported lower side-effects in water bodies resulting from bio-degradation [18]. Several studies have revealed that agricultural pests spread and migrate beyond their original distribution under certain climatic conditions instigated by climate change [19]. These pests attack more agricultural crops, and threaten food security [20]. The result is a corresponding increase in pesticide concentration per crop land used by farmers in order to considerably overcome the deleterious effects of climate change [21]. It is a known fact that as a result of climate changes, pesticide exposure rates become altered, affecting pest management as well as increasing the development of resistance by plants. In conducting this research, some of the questions to be answered include:

1. Does climate change affect the efficacy of pesticides?
2. How does climate change affect the efficacy of pesticides?
3. What can be done to mitigate the deleterious effects of climate change on pesticide efficacy?
4. Will these actions improve agricultural yield and food security?

At a time when food security has become a serious issue of global concern, partly due to the increase in human and wildlife population; this study is invaluable as it will help to understand how changing climatic conditions, can affect the potency of pesticides in controlling pests, diseases, and weeds in agricultural systems and also attempt to proffer solution(s) to this global threat on food security. After World War II, pesticides have typically been synthesized from petroleum or petroleum by-products [22]. ExxonMobil, Chevron, Phillips Chemical, and Shell all produce pesticides and their chemical components [23]. In the bid to mitigate the impact of climate change and develop a sustainable agricultural culture, it is very important to monitor and control the GHG emissions linked to pesticide use. Some of these emissions are released during production, transportation, and field application of these products, while others may result from interactions between pesticides and their environment after application. Currently, no studies have addressed the impact of climate change on pests and efficacy of pesticides, even when pesticide efficacy and by extension food security have been largely threatened by this ugly trend.

1.1. Pesticides and Pesticide Efficacy

Pesticides are chemical substances or mixtures used to control, prevent, destroy, or repel pests, including insects, weeds, fungi, and rodents. They are commonly employed in agricultural, industrial, and residential settings to protect crops, livestock, and human health from the negative impacts of pests [24]. Pesticides play a crucial role in modern agriculture, by aiding the control of pests, diseases, and weeds to enhance crop yield and protect agricultural investments. However, the effectiveness of these pesticides can be significantly affected by climate variabilities, e.g. global warming, unpredictable rainfall, and other critical weather conditions. The scope of pesticides extends beyond agricultural applications and also includes their use in public health programs, such as vector control to combat disease-carrying insects like the tsetse fly, which transmits the disease vector trypanosomes, causing trypanosomiasis in humans and animals. Moreover, pesticides are utilized in residential settings to manage pests that pose threats to human health or cause damage to structures and properties [24].

Pesticide efficacy refers to the ability of a pesticide to effectively control or manage pests, such as insects, weeds, fungi, or other organisms that can damage crops, plants, structures or human health. It is a measure of how well a pesticide performs in achieving its intended purpose, which is to reduce or eliminate the target pests and/or mitigate the damages they cause. The scope of pesticide efficacy refers to the range of control that a particular pesticide has on target pests. This includes providing long-lasting protection against pests. The scope of efficacy can vary based on such factors as; the type

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of pest, the specific pesticide, application routes, environmental conditions, and compliance with label instructions [25]. Before now, certain school of thought believed that some pesticides are more toxic to pests when the temperature is higher [20][26], However, de Beeck *et al.* [27] reported on the contrary that higher temperature caused the degradation of chlorpyrifos more easily, thus reducing its potency on insect pests. This is not surprising because of the higher rate of hydrolysis of organophosphates at higher temperatures [28]. Pesticides that are hydrolyzed in aqueous phase e.g. organophosphates, carbamates, sulfonylureas are usually temperature dependent. Also, certain pesticides undergo photo-degradation under intense sunlight. The result of these breakdown products can be less toxic or in some cases more toxic than the initial product [29][30]. Also, soils that are lower in moisture have been associated with slower degradation of herbicides [31]. An increase in temperature can also facilitate the volatilization and therefore loss of pesticides [32]. Soil microbial activities are also increased when there is a rise in temperature and moisture; this aggravates the degradation of pesticides by soil microbes, and ensures repeated use of pesticides and increase in concentration applied [33]. Healthy soil organisms are ultimately affected by increased soil temperature and moisture, thus affecting their weight, maturity, reproduction and lifespan [34]. The efficacy of a pesticide is typically evaluated based on its ability to: kill or suppress the target pests. A pesticide should be able to directly kill the pests or significantly reduce their population to an acceptable level, provide residual or long-lasting effects. Pesticides with residual activity remain effective for an extended period, providing continued protection against pests, and being target-specific. Ideally, a pesticide should have selective toxicity, meaning it primarily affects the target pests while minimizing harm to beneficial organisms, including humans, non-target animals, and the environment, penetrating and reaching target site. Pesticides should be able to reach the target pests, whether they are peripheral, within plants, or deep into the soil, and adhere to the target surface. Pesticides need to adhere to the target surface, such as plant leaves or soil particles, to ensure their effectiveness prevent them from being easily washed away or degraded, and withstand environmental conditions. Pesticides should remain effective under various environmental conditions, including temperature, humidity, rainfall, or sunlight exposure, be compatible with application methods. Pesticides need to work effectively with different application techniques, such as spraying, dusting, seed treatment, or soil application.

1.2. Factors Affecting Pesticide Efficacy

Several factors can influence the efficacy or effectiveness of pesticides. These factors can vary depending on the specific pesticide, target pest, application method, and environmental conditions [35]. Some common factors that can affect pesticide efficacy include Pest Species and Life Stage; different pesticides may be more effective against specific pest species or life stages (e.g., eggs, larvae, adults). Understanding the target pest's biology and life cycle is crucial in selecting an appropriate pesticide [35], Application Timing; proper timing of pesticide application is important to deduce the best period for application as well as ensure that the target pest is vulnerable and susceptible to the pesticide at that particular time. For instance, some pesticides may be most effective when applied during a particular stage of the pest's development or at a specific time of the day [36]. Application Rate and Method; applying the correct amount of pesticide and using the appropriate application method is crucial for achieving effective pest control. Improper application rates can result in under-dosing or overdosing, both of which can reduce efficacy or cause other issues [25]. Environmental Conditions; various environmental factors can influence pesticide efficacy. Temperature, humidity, wind speed, and sunlight can affect pesticide stability, degradation, and movement. It is important to follow label instructions regarding environmental conditions for optimal efficacy [35]. Formulation and Compatibility; pesticides are available in different formulations (e.g., liquid concentrates, granules, and powders) and may require mixing or dilution. Proper preparation of pesticides according to the label instructions and ensuring compatibility with other substances (e.g., tank mixtures) is essential for achieving the desired efficacy [37]. Resistance Development; pests can develop resistance to pesticides over time, rendering them less effective. Overuse or misuse of pesticides can also accelerate the development of resistance. Rotating between different chemical classes or using IPM strategies can help mitigate resistance issues [25] Adjuvants: Adjuvants are substances that are usually added to pesticide formulations to improve their potency, such as spreaders, stickers, and surfactants. The use of appropriate adjuvants can improve pesticide coverage, absorption, and retention on target surfaces [35]. Crop or Site Conditions; the type of crop or site where the pesticide is applied can affect efficacy. Factors such as crop stage, density, canopy structure, soil type, and presence of weeds or other non-target plants can influence pesticide effectiveness [35]. Storage and Handling. Proper storage and handling of pesticides are crucial for maintaining their efficacy. Exposure to extreme temperatures, moisture, or sunlight can degrade pesticides. Following

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storage and handling guidelines provided by the manufacturer is essential [37]. Regulatory Compliance. Adhering to pesticide regulations and guidelines is important to ensure the efficacy and safety of pesticides. Failure to comply with regulations can result in legal consequences and may compromise the effectiveness of pest control [36].

2. Data Collection

Data was carefully sought from pre-existing peer-reviewed studies in reputable academic journals and books published in various databases (search engines) including Web of Science, Scopus, Google Scholar, and International System for Agricultural Science and Technology (AGRIS) amongst others. These search engines were selected among numerous others because of their broad coverage and up-to-date studies on the subject matter, as well as their inter-disciplinary approach and rich academic content [38]. This data covers the period from 2002 to 2023 representing the period of sporadic change in climate patterns especially an increase in global warming and greenhouse gas emissions in Africa and particularly in Nigeria [8]. Thus the review suitably provides reflection on significant trends in climate patterns and its effect on agriculture and pesticide efficacy in the past 21 years.

From available data, the study employed a systematic literature review (SLT) technique to assess historical trends in climate change especially global warming, and its implications for agriculture and pest management. SLR is usually applied to examine the state of knowledge on a particular topic of interest [39]. It is a common tool in climate change studies these days, to understand the latest trends and devise ways of improving them [40]. The study used the SLR standard to select and examine literature found in the selected database. Literature was identified using the following keywords: climate change, pesticides, efficacy, agriculture, sustainability, and impact amongst others for the selection of publications [41]. Selected studies were analyzed qualitatively and quantitatively (descriptive) to explore all possible responses to the research questions for this study. This approach has been used in a systematic review of meteorological drought in Africa by Ayugi et al [41].

3. Results and Discussion

3.1. Observed Indices of Climate Change on The Ecosystem, Agriculture and Pesticides.

3.1.1. Rising global temperatures

According to the Inter-Governmental Panel on Climate Change [8], global temperatures have been increasing at an unprecedented rate for some time now. Unfortunately, human influence is a major contributory factor to this increase. According to the report, it is unambiguous that the atmosphere, ocean, and land have been heated up by human activities [8]. It is a vicious cycle of effects where an increase in temperature causes a corresponding increase in precipitation, which in turn impacts soil texture and PH. When plants become vulnerable, insects can detect changes from afar and prepare for attack. These changes include higher plant surface temperatures, biochemical changes, and yellowing of leaves [42]. When temperatures increase, pesticide volatility is expected to increase, thus causing the accumulation of more pesticides in the air, rather than on the target species [20]. Volatilization which is aggravated by increased temperature is a key source of pesticide drift and could result in pesticide poisoning in anyone exposed to it [43]. Lowered temperature on the other hand, reduces nitrogen cycle which in turn affects the ecosystem's capacity to sequester nitrogen. The result is more acidification of the soil [44].

3.1.2. Erratic precipitation patterns and flooding

Since about 80% of the world's agricultural land is rain-fed, global crop yield is highly dependent on precipitation patterns and could be greatly affected by changes in precipitation and the attendant increase in pest pressure that arises thereafter [45]. This can result in increased pesticide use, economic losses, and potential environmental pollution. Increased precipitation can also cause flooding (figure 1) which reduces the population and activities of earthworms, thus decreasing crop resilience to diseases and pests, as earthworms are very beneficial for healthy soils [46]. According to Plum [47], the abundance, diversity, and biomass of various groups of soil organisms in grassland is reduced abundantly during flooding incidences. Also, high rainfall patterns accelerate the leaching of cations which further aggravates soil acidification [48].

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Figure 1. The impact of excessive flooding, on agricultural farmlands.

3.1.3. Melting ice caps and glaciers

The melting of ice caps and glaciers is a direct consequence of global warming (figure 2). This increases sea levels in coastal cities, as well as increases the risk of damage to life and properties from flooding.

Figure 2. Melting ice caps and glaciers resulting from global warming

3.1.4. Rising sea levels

Due to melting ice and expansion of sea water as a result of heat, sea levels continue to rise. The United Nations Framework Convention on Climate Change [49] warns that the global sea level has risen by about 20 cm since the start of the twentieth century. It also revealed that the rise in sea level has accelerated in recent years.

3.1.5. Extreme weather events

As a result of climate change, extreme weather events, such as hurricanes, droughts (figure 3), and heatwaves are grossly intensified. Also rising temperatures are causing regular and severe heat waves around the globe.

Figure 3. Fragmentation of agricultural farmlands due to excessive drought conditions.

3.2. Impact of Climate Change on Pesticides and Their Efficacy

3.2.1. Increased Metabolic and Reproductive Rates in Pests

Temperature is a fundamental factor that determines the performance of pesticides. Some pesticides are designed to work within specific temperature ranges. Higher temperatures may accelerate the rate of metabolism resulting in increased feeding and reproduction rates (figure 4). This could potentially require higher pesticide application rates or more frequent treatments to achieve effective pest control.

Figure 4. Higher temperatures and humidity increase metabolic and reproductive rates in pests

The prevalence of agricultural pests increases pesticide dosage, this in turn poses ecological risks for aquatic life [50]. Also, the increase in global temperature apart from reducing crop resilience, may promote the rate of development of insect pests as well as encourage insect population growth in some regions [46]. The ability of insect pests to survive during winter is greatly influenced by rising temperatures and moisture conditions [51]. Scientists have proposed that insect pests' metabolic rate and consumption greatly depend on increased temperature and CO_2 emission, this will ultimately lead to reduced crop yield [52]. Increased temperature may also affect the incubation period of insects as well as extend the transmission period of vectors. Researchers have predicted that rising CO_2 and temperature will accelerate insect pests' metabolism and consumption, ultimately leading to declining crop yields.

3.2.2. Decline in Activity/Efficacy and Bioavailability

The presence and availability of pesticides in the soil is highly controlled by climate change variables, such as; temperature and soil moisture. Climate change can alter precipitation patterns, which can directly influence the effectiveness of pesticides.

Figure 5. Increased temperature and moisture increases pest infestation, while reducing pesticide efficacy

Excessive rainfall and increased humidity may lead to pesticide runoff and leaching, reducing their concentration and effectiveness in the target area. Similarly, these changes in rainfall patterns can alter the distribution and activity of pests, potentially reducing the effectiveness of pesticides, and increasing pest infestation (figure 5). Excessive heat and dry conditions can also lead to faster evaporation of sprays, reducing their effectiveness [53].

3.2.3. Altered Pest Dynamics

Climate change can change the life cycles and behavior of pests. Warmer temperatures can accelerate the development and reproduction of pests, leading to more rapid population growth. Changes in

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precipitation patterns can also impact the availability of food and water sources for pests. These alterations in pest dynamics (figure 6) can affect the timing and frequency of pesticide applications, making it more challenging to control pests effectively [37].

Figure 6. Increase in pest infestation due to altered dynamics

Climate change can affect the distribution and abundance of pests. Rising temperatures and changing rainfall patterns can create more favorable conditions for certain pests, leading to increased infestations. Conversely, some pests may decline in certain regions due to unsuitable conditions. Pesticides that were effective in the past may become less efficient or ineffective against new pest populations [53]. Climate change can also result in the expansion or contraction of pest and disease ranges. As a result, pests that were previously absent or less problematic in certain areas may become more prevalent. This can create new challenges for pest management, as different pest species may have varying susceptibilities to available pesticides [53]. Increased temperature and unstable precipitation patterns can affect the timing and intensity of pest outbreaks, making it challenging to apply pesticides effectively [54].

3.2.4. Development and Dominance of Resistant Species

Increased pest resistance refers to the ability of plants or crops to withstand and/or repel attacks from pests such as insects, pathogens, and weeds. It can be achieved through various methods, including traditional breeding techniques, genetic engineering, and the use of biotechnology [53]. Prolonged exposure of pests to certain pesticides can lead to the development of resistance. Climate change can exacerbate this issue by favoring the survival of resistant pests. For example, if a particular pest population has individuals with genetic resistance to a pesticide, and the climate becomes more favorable to their survival, those resistant individuals will have a higher chance of reproducing and passing on their resistance genes to future generations. This can reduce the efficacy of pesticides over time, as the resistant pest populations become more dominant [35].

3.2.5. Changes in Pesticide Degradation Rates

Climate change can influence pesticide degradation, especially at higher temperatures and increased UV radiation. This reduces their persistence and effectiveness. Conversely, in some cases, climate change may slow down degradation processes, leading to prolonged pesticide residues and potential environmental risks [25].

3.2.6. Inhibition of Pesticide Absorption and Increased Pest Infestation

Water stress in plants as a result of drought conditions can hinder pesticide absorption and translocation within the plant tissues, compromising their efficacy. Drought conditions can reduce the natural defense of plants against pests; also, alterations in the biology of plants as a result of drought could attract pests [51. Furthermore, drought conditions may lead to increased pest pressure as water-stressed plants become more susceptible to infestations. As a result of climate change, the frequency of extreme weather events like storms, floods, and hurricanes increases tremendously. These events can have severe implications for pesticide efficacy. Drought affects the soil's structure and profile significantly [55]. On the other hand, the absence or deficiency of rainfall reduces the water composition of the soil upper layer but does not immediately affect the deeper soil layers [56]. When there is reduced sol water, the mobility of healthy soil organisms is affected [57]. The frequency of occurrence of drought has become a cause for concern globally [58].

3.3. Impacts on Human Health and Beneficial Organisms

The human health implication of industrial agriculture is often ignored or under estimated in most cases, as well as the degradation of ecosystem services like; healthy soil, clean air, and water [59]. Some of the health implications of hazardous pesticide exposure include; dermatological complications, gastrointestinal issues, respiratory ailments, and central nervous system complications [60][61]. Pesticide exposure is also linked to many long-term diseases like; cancers, neurological disorders, reproductive impediments, and stunted development [62]. Serious harm to honey bees has been reported from the use of neonicotinoids [63][64]. These honey bees are very important in the pollination of agricultural crops, thus their elimination by neonicotinoids is a great disservice to agriculture and food security as a whole [65]. Apart from pollinators, soil vertebrates also suffer greatly from the use of these pesticides thus reducing soil water retention and promoting the compaction of soils [66]. They play crucial roles in naturally regulating pest populations. Changes in temperature, rainfall, or other climate factors can disrupt the balance between pests and beneficial organisms, thus reducing the efficacy of natural pest management methods. In turn, this may increase the reliance on pesticides to manage pest populations. Sedimentation in streams and reservoirs results from excessive precipitation and flooding due to climate change, this leads to soil loss and subsequently erosion [67]. When soil is lost, beneficial organisms are also lost leading to poor soil function and compromised ecosystem. Favorable climatic conditions such as; moderate temperature and high soil moisture content increase earthworm abundance [68]. However, when the climate is cold and soil moisture content is low, earthworm population is decreased significantly [69]. This is quite unhealthy for crops.

3.4. Impact on Ecosystems and Biodiversity

Floods resulting from excessive and unpredicted rainfall patterns affect the soil profile tremendously [70], even though flood plains contain sediments which are rich in nutrients thus making them quite productive [71]. Hypoxia and diffusion in soil is reduced by flood, thus reducing soil nutrients and availability, and halting decomposition processes [3]. Because flooding gives rise to anaerobic conditions, soil composition, microbial biomass, and microbial community are greatly affected [47][72]. According to scientists, some natural enemies of insect pests which are beneficial to man and agriculture are negatively affected by climate change. This increases the susceptibility of

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crops to insect pests and damages. For instance, many insects migrate to new geographical areas where their predators may not be able to migrate, thus disrupting the synchronization between insect pests and their natural enemies [73]. Scientists have also predicted increased weed pressure in cultivated crops due to changing environmental conditions. Because of the diversity in their gene pool, as well as their physiological ability to acclimate to different environmental conditions, weeds are more adaptive and resilient than cultivated crops [74]. It is anticipated that climate change will introduce weeds to new regions, thus altering the composition of weed species in a particular region. The corresponding increase in herbicide use that follows will also promote herbicide resistant weeds [75]. For reasons stated above, weeds will automatically out-compete agricultural crops leading to lower yield and reduced availability of soil nutrients since weeds will also compete for nutrients. Thus, climate impacts in a particular region influences to a great extent what pests become dominant or more prevalent in that region.

As we already know, climate change could result in the movement of pesticides away from their intended target sites, thus moving into the environment and ecosystem, this causes environmental pollution and endangers public health and properties. Climate change impacts tend to promote insect pests as against crops. In most cases, wet condition is a prerequisite for many plant diseases because it promotes the growth and multiplication of microorganisms such as fungi and bacteria by germination and spore activity which are increased during wet conditions. On the other hand, a warm and dry environment can also influence plant resistance positively, resulting in reduced requirement for fungicide. However, an increased incidence of plant disease and physiological plant stress will promote host susceptibility and increased pesticide use [33]. Prolonged bouts of rainfall could also wash away small sized pests like; mites and whiteflies [29], while plant fungal and bacterial diseases also become more common [76].

3.4.1. Environmental Contamination and Unstable Environmental Conditions

Floods resulting from excessive and erratic rainfall patterns can also transport pesticides into non-target areas, leading to environmental contamination. Frequent rainfall patterns wash away pesticides applied on target sites to water ways and other non-target sites [77]. Increased wind speeds and erratic precipitation patterns can affect spray drift, causing pesticides to disperse away from the target area. The contribution of pesticides to greenhouse gas (GHG) emissions is often not considered, and eco-friendly solutions e.g. agro ecology which would reduce these impacts are hardly considered. Some climate smart practices e.g. the ‘no till’ system most of the time rely on synthetic herbicides for weed control, this could lead to increase in resistance to herbicides [78]. Climate change-induced weather events can disrupt the timing and scheduling of pesticide applications. Unpredictable weather patterns can make it challenging for farmers to determine the optimal timing for spraying pesticides, as the pests' life cycles and behavior may change due to shifting weather patterns [36]. Greenhouse gas emission from transportation and application of pesticides is most times overlooked, the distance that a pesticide travels to its target site and the frequency of the application determine the extent of the GHG emissions. When a pesticide is released into the environment, additional emissions follow, as the pesticide interacts with soil organisms as well as the atmosphere. Also, some pesticides are greenhouse gases on their own e.g. the fumigant sulfuryl fluoride used for fumigation of commodities during transport and storage. Furthermore, volatile organic compounds emitted during pesticide application, can result in GHG emission. Volatile organic compounds (VOCs) are majorly compounds which when released into the atmosphere, easily volatilize into gases that can react with nitrogen oxide and ultra violet (UV) rays to produce ground level ozone [79]. This ground level ozone is a greenhouse gas that can cause respiratory challenges in humans [62]. It causes more harm to plants than a combination of all the other air pollutants [80]. It has been reported that about 90% of pesticides may volatilize few days after application [81]. VOC emission is more common with fumigant pesticides than with others [82].

4. Future Directions

It is no news that climate change has become a constant issue of concern globally. The study of the effect of climate variability on the potency and effectiveness of pesticides is crucial to ensure effective pest management strategies in agriculture [25]. Agricultural systems based on agro ecological techniques and diversification, as well as organic farming practices, can reduce the emission of GHG as well as increase carbon sequestration [83]. These organic practices also increase farm resilience to climate change by improving many ecosystem services [84]. Utilizing ecological pest control techniques, reduces the need for synthetically made pesticides and fertilizers [85], thus minimizing greenhouse gas emissions.

However, instead of appreciating the role of synthetic pesticides in climate change, it has ignorantly been presented as a mitigation strategy for climate change especially by industrial agriculturists [23].

Scientific evidence has shown that pesticide application significantly promotes greenhouse gas emissions (figure 7) while exposing our agricultural systems to more danger and vulnerability. Several oil and gas industries are key players in the development of pesticides and their ingredients [23]. Research has also revealed that it takes 10 times more energy to manufacture 1kg of pesticide than it takes for 1kg of nitrogen fertilizer [86]. Some pesticides are powerful greenhouse gases; an example is sulfuryl fluoride, which is 5,000 times more potent than carbon dioxide [87]. Diversification of agricultural systems in a way that increases ecosystem resilience may be useful in achieving sustainability and reducing climate impact on the ecosystem regardless of region [88].

Figure 7. The application of synthetic pesticides, greatly contribute to greenhouse gas emission.

Research has revealed an increased use of synthetic pesticides in conventional agriculture resulting from climate change. This increase in pesticide use is as a result of decreased pesticide efficacy and increased pest pressure due to climate change effects [33]. Also, weeds are likely to develop resistance to herbicides while insect pests' resistance to insecticides is also promoted. This is dangerous to public health and the environment. Populations that are already under stress from climate change will be highly impacted, thus agro ecological practices are highly encouraged as they minimize the use of synthetic pesticides and increase resilience [89][90]. Agro ecology encourages working with nature, and not against nature. It encourages social justice, and protects the environment. It also prioritizes the power to make decisions by farmers and agriculturists. With a combination of agro ecology, social justice and diversified organic farming, many effects of climate change would be mitigated, while human health and the environment would receive maximum protection.

It is very timely to take decisive actions concerning the use of agrochemicals with the view to reduce their contribution to greenhouse gas emission, as well as improve resilience to climate change impacts. Policy makers must establish goals and climate policies that will reduce synthetic pesticide use and promote agro ecology and diversified organic farming by providing funds for research and implementation of relevant policies for agricultural sustainability as well as a safe environment. Farmers must be encouraged at all levels to embrace agro ecological practices. This will reduce the negative health impacts of synthetic pesticide use and mitigate the impact of climate change to a very large extent.

4.1. Proposed Ways of Mitigating Climate Change Effects

4.1.1. Integrated Pest Management (IPM) Approach

Adopting IPM approach can help reduce reliance on pesticides. IPM involves combining multiple approaches, such as biological controls (e.g., natural enemies), cultural practices (e.g., crop rotation), and mechanical methods (e.g., traps) to manage pests effectively. By utilizing a variety of strategies, farmers can reduce their dependence on synthetic pesticides and thus minimize the impact of climate change on their efficacy. Since its inception in the 1950s, Integrated Pest Management (IPM) model of crop cultivation has prevailed [91]. It engages appropriate pest control strategies and integration of measures that discourage the development of pest populations, thus controlling pests and reducing the use of synthetic pesticides to the barest minimum, this reduces risk to human life and the environment. It also promotes the growth and development of healthy crops thus ensuring food security and preventing disruption to agroecosystems.

4.1.2. Improved monitoring and forecasting

Climate change can alter pest populations, their behavior, and geographical distribution. Enhancing monitoring and forecasting systems can provide early warnings and enable farmers to respond promptly. Advanced technologies like remote sensing, weather data, and pest modeling can assist in predicting pest outbreaks, helping farmers make informed decisions about pesticide application timing and dosage, to avoid huge agricultural losses [92].

4.1.3. Research and development

Continued research and development are crucial to develop innovative and climate-resilient pesticides. These include exploring alternative pest control methods such as bio pesticides derived from natural sources, pheromone traps, and genetically resistant crop varieties. Investing in research can lead to the discovery of more effective and environmentally friendly options [93]. Farmer-centered participatory research should be funded by the governments, farmers should be provided with both financial and technical assistance that can enable them transit smoothly to agro ecological practices.

4.1.4. Optimized Pesticide Application Techniques

Proper application techniques can optimize pesticide efficacy and minimize environmental impacts. These include proper calibration of equipment, adequate measurement of the correct dosage, and adequate timing of applications to correspond to the pest’s life cycle. Using precision agricultural technologies may also be helpful to improve accuracy and reduce pesticide use in agriculture. Careful adherence to the manufacturer’s instruction during pesticide applications must be duly followed.

4.1.5. Education and Training

Providing education and training to farmers on climate change impacts and sustainable pest management practices is crucial. Farmers should be educated on the potential impacts of climate change on pests and pesticides, and the importance of implementing sustainable practices. Training programs can encourage farmers to adopt best farming practices and encourage the adoption of climate-smart pest management strategies. Knowledge sharing should be encouraged among farmers and agricultural workers, to enable them learn new agro ecological skills and techniques, as well as share expertise among themselves. This can be done via public funding and investments in lectures, seminars, town hall meetings and publication of relevant research findings in reputable and accessible academic journals. Small scale farmers should also be encouraged financially and otherwise to enable them adopt agro ecological farm management strategies, this could be done by making available agricultural loans and incentives to farmers as much as possible [94].

4.1.6. Policy, Regulation and Incentives

Governments and regulatory bodies are key players in reducing climate change impacts on pesticide efficacy. They can implement policies that promote sustainable agricultural practices, incentivize the application of environmentally friendly pesticides, as well as regulate the application of harmful chemicals. Supporting and enforcing these regulations can reduce the overall effect of climate change on pesticide efficacy. There must be measurable targets that must serve as guideposts to avoid government spending without achieving much. Also, government policies should be tailored to regional considerations since different countries have different agricultural systems and pest management methods. They must prioritize human health and well-being of farmers and agricultural workers to avoid a chemical-laden, industrial agricultural system like we have today [86]. The government must ensure secure land access and ownership for workers; policies that support this should be implemented and upheld.

4.1.7. Agro ecological and Diversified Organic Farming Methods

The benefits of agro ecological farming include the preservation of healthy soil organisms which promote plant health and increase crop resilience [95]. All barriers that discourage the transitioning of farmers to agro ecological diversified farming practices must be addressed squarely by the government via its policies which must ensure market incentives, secure land and better funding [96][97].

4.1.8. Climate Adaptation Strategies

Implementing climate adaptation strategies on farms can help promote the resilience of crops to pests and minimize the need for pesticides. This includes utilizing climate-resilient crop varieties, improving soil health, optimizing irrigation practices, and implementing agroforestry techniques. By building more resilient farming systems, farmers can better cope with the climate change conditions and reduce reliance on pesticides [93].

5. Conclusion

The effectiveness and persistence of herbicides, insecticides, and fungicides can be influenced by changes in climate conditions which can have very significant impacts on the efficacy of pesticides.

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Changes in temperature and precipitation patterns, as well as extreme climate events, can potentially affect the toxicity of pesticides. Additionally, climate change can lead to a decrease in environmental concentrations of pesticides due to increased volatilization and accelerated degradation. Therefore, it is important for policymakers and farmers to consider the potential impacts of climate change on pesticide use, and make useful policies that will promote proper adaptation and mitigation practices that will ensure the continued effectiveness of these pesticides. Government should adopt reasonable strategies to reduce pesticides as much as possible, in climate policies and provide improved technical assistance and incentives for farmers to minimize the use of synthetic pesticides. Climate action requires significant financial investments by governments and businesses. Industrialized countries, being major drivers of greenhouse gas emissions, should be seriously committed to assisting developing countries to adapt properly and move towards greener economies. Farmers should be encouraged to as much as possible use non-chemical management methods on their farms, such as introducing beneficial insects and wild, native plants, or using physical methods, including hand weeding, mulching, or setting traps, to reduce chemical use outdoors. Beneficial insects, like honey bees, which help to pollinate gardens, and ladybugs, which prey upon other nuisance pests such as aphids, can help to improve the health of a yard. The Kyoto Protocol, the signing of the Paris Agreement on climate change, and other initiatives set up to combat this effect globally should be effectively upheld [5]. Strategic practices like crop rotation, mixed cropping and varying cropping dates, can be engaged to moderate the impact of climate change on pesticides [98].

Statements and Declarations

Authors Contribution

Conceptualized and designed by Okonkwo, C.O, literature search and data acquisition by Essien, A.H, data analysis, manuscript preparation and review by Okonkwo, S.N. Submitted manuscript approved by all authors.

Conflicts of interest

The authors declare no conflict of interest.

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