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A Review Paper on Evolution and Side-effects of Pesticides

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Abstract: ***Since their extensive usage in the middle of the 20th century, pesticides—essential chemical and biological agents employed worldwide to ensure food production and control disease vectors—have significantly increased crop yield and advanced public health. However, the detrimental effects of excessive and negligent use on the environment and human health outweigh this necessity. In order to summarize the current understanding of the health risks and long-term environmental effects of pesticide exposure, this systematic review synthesizes data from 2000 to 2024. Results consistently show that a range of non-communicable diseases, including neurodegenerative disorders (Alzheimer's and Parkinson's disease), different types of cancer, respiratory conditions, and metabolic disorders like Type 2 Diabetes and Non-alcoholic Fatty Liver Disease (NAFLD), are strongly associated with chronic exposure, mainly through dietary intake and occupational handling. Additionally, pesticide residues contaminate soil and water widely, reducing the diversity of beneficial microorganisms and building up through bioamplification in the food chain. In order to reduce risks and guarantee efficient, ecologically responsible pest management in the future, the review ends by emphasizing the critical need for sustainable strategies, concentrating on innovations like nanopesticides, RNAi-based technology, and precision agriculture (AI Spot Spraying and Drone Application).***
Keywords: Pesticides, Effects of pesticides on crops, soil and human health, climate change, genetic engineering

I. INTRODUCTION

The use of pesticides has been deeply entwined with the history of crop protection and public health. From the use of early inorganic compounds like arsenic in the 19th and early 20th centuries to the introduction of synthetic petrochemicals like DDT and BHC in the 1940s, these agents have been crucial in managing insect-borne human illnesses like typhus and malaria, controlling crop diseases, and eliminating pests like rats and grasshoppers. The use of pesticides starting in 1948 was crucial to agricultural modernization in emerging countries like India, where food grain production doubled between 1948 and 1997. Pesticides are an essential part in lowering losses from weeds, illnesses, and insect pests, and their widespread usage has resulted in significant increases in output.

The widespread, unchecked, and excessive use of pesticides since the mid-20th century has caused significant environmental harm and major public health emergencies worldwide, despite these indisputable advantages to food security and productivity. Pesticides are cytotoxic, mutagenic, and carcinogenic to non-target creatures, including humans, because they are made to target biological systems and are frequently not species-specific. Fruits, vegetables, processed meals, the air, water, and soil all contain remnants of contamination, which is now widespread. With over 50% of food items polluted with pesticide residues and 20% surpassing worldwide maximum limits, India, for instance, has a serious problem.

As a result, humans are exposed through a variety of routes, including ingestion, absorption, and inhalation. This can have both immediate, acute health impacts (such as skin irritation or breathing problems) and, more concerningly, long-term, chronic effects. Many chemicals, especially organochlorines, are persistent in the environment, which makes it easier for processes like bioaccumulation—the accumulation of chemicals in the body over time—and biomagnification—the amplification of chemicals along the food chain—to occur, leading to increased health effects at higher trophic levels. It is acknowledged that there is an urgent need to evaluate the entire range of these long-term risks as toxicology and environmental science become more well understood.

As a result, the purpose of this review paper is to give a complete, systematic synthesis of the evidence on the negative consequences of pesticide exposure on human health and the environment, with a special emphasis on chronic diseases and environmental persistence. It delves deeper into the dynamics of pesticide use and contamination, with a regional focus on India, and assesses the next generation of innovations—including nanopesticides and advanced digital pest management techniques—that are poised to redefine the crop protection market and guide the necessary transition to safer, more sustainable agricultural practices.

II. HISTORY

For many years, arsenic—which is extremely hazardous to both humans and animals—has been used as a component in herbicides and as a pesticide to eradicate rats and grasshoppers. "Agent Blue," which is a combination of sodium cacodylate and dimethylarsinic acid, has been used as an insecticide, fungicide, and herbicide. In an effort to starve the North Vietnamese, it was used to damage rice plants during the Vietnam War. It was sprayed by airplanes over Italy during World War II to eradicate malaria-carrying mosquitoes. In addition to its current industrial applications, sodium arsenite was once used as a pesticide. In addition to being poisonous, it causes cancer in people. It is noteworthy that Oregon was the only state to raise concerns about the use of arsenicals at the Western Weed Control Conference in 1942. A variety of additional pesticides were used prior to the advent of petrochemicals. These are:

1) Sinox (dinitro-cresol) was introduced into use in US agriculture in the 1940s. It was used as an herbicide and insecticide until banned by the EPA in 1991.. The chemical is highly toxic to humans and sheep in the field.
2) Diesel oil, fuel oil were petrochemical fuels used as pesticides.
3) Carbon bisulfide is still used today as a fumigant in grains and a soil disinfectant to kill insects and nematodes. It has various industrial uses, including use as a solvent. It is toxic to humans.
4) Sulfamic acid is no longer used in agriculture but is used in various industries. It is toxic to humans.
5) Sodium pentachlorophenate is still used as an herbicide and to kill invasive molluscs today.
6) Altacide (referenced in the 1942 minutes) (Sodium chlorate) is still used today as an insecticide to kill mosquito larvae.
7) Borax - In the 1945 minutes it was reported that Borax caused concern because it was expensive, and it causes soil sterility for three years. It has many uses today, including as an insecticide.
8) Copper sulfate (referenced in the 1945 minutes) is still used today as a fungicide and to kill aquatic plants and algae.
9) Ammate (ammonium sulphamate) is still used in herbicides today, and has various industrial uses. It is slightly toxic to animals and humans.

III. INDIA

Pesticide use in India started in 1948 with the importation of BHC for locust control and DDT for malaria prevention. In 1952, India began producing pesticides with a factory that produced DDT and benzene hexachloride (BHC) (HCH). India produced more than 5000 metric tons of insecticides in 1958. The manufacturing of pesticides has increased to over 85,000 metric tonnes, and there are currently about 145 pesticides registered for usage. Numerous short-term and long-term negative effects of these substances have resulted from their widespread use. In 1958, over 100 individuals in Kerala died after consuming wheat flour tainted with parathion, which was the first documented case of pesticide poisoning in India.

There have since been other reports of pesticide poisoning, notably the Bhopal tragedy. Even though India still uses very little pesticide—roughly 0.5 kg/ha compared to 6.60 and 12.0 kg/ha in Korea and Japan, respectively—food commodities have been widely contaminated with pesticide residues, primarily as a result of careless pesticide use. 51% of food commodities in India are polluted with pesticide residues, and 20% of these contain residues over the global maximum. Long-term, low-dose exposure to them has been found to be increasingly associated with negative consequences on human health, including cancer, immunological suppression, hormone disruption, reduced intellect, and reproductive problems. In this context, potential approaches to reducing human exposure to pesticides include addressing issues with pesticide safety, regulating the use of pesticides, using biotechnology and biopesticides, and using insecticides derived from natural plant sources like neem extracts.

A. Side Effects on Human Health

Pesticides are synthetic or natural substances used to control the populations of weeds and insects. These substances are categorized based on how they are used, the dangers they pose, and their chemical structures. Due mostly to commercial farming, the need for pesticides has increased dramatically and steadily since the mid-1940s. Food contamination as well as environmental, agricultural, and marine damage were caused by excessive and uncontrolled pesticide use. Pesticide residue can be found in foodstuffs, water, air, and soil. Particularly in developing nations, dietary exposure to agricultural pesticides and their acute and long-term health impacts are major public health problems. These can be mutagenic, cytotoxic, and carcinogenic to human health. Pesticides often kill or damage organisms other than pests, including humans, because their method of action is not species-specific.

Pesticides can be consumed, inhaled, and absorbed through a variety of pathways, which can have both immediate and long-term health effects. With an emphasis on epidemiological and toxicological research, this systematic review summarizes the data that is currently available about the health hazards and long-term effects of pesticide exposure. Between 2000 and 2024, a systematic

review was carried out by scanning scientific databases such as Web of Science and Scopus. Studies that focused on pesticide exposure, health hazards, and long-term impacts were chosen. When there was enough homogeneity of results, a meta-analysis was carried out. Chronic pesticide exposure has been consistently linked to non-communicable diseases such as cancer, neurological problems, and endocrine disorders, according to this research. Pesticide exposure at work has frequently been linked to an increased risk of respiratory problems and neurological disorders..(NATIONAL LIB OF MEDICINE.)

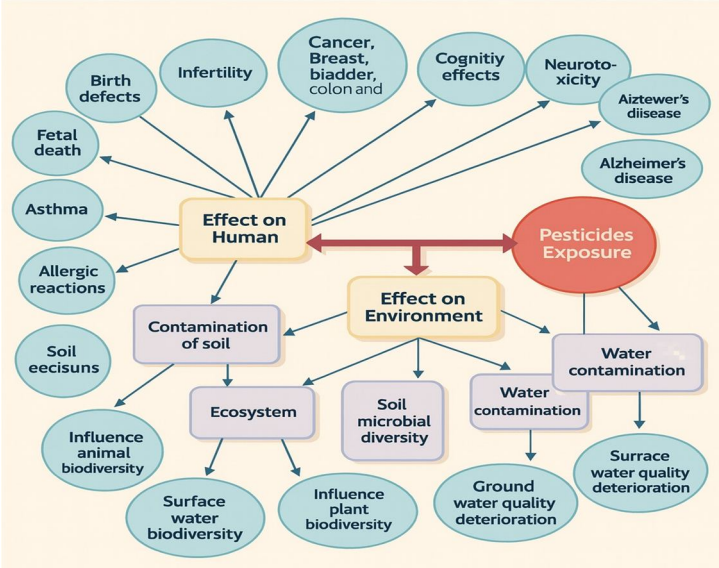

Fig 1: Effects of pesticides on soil, environment and human health

Both direct and indirect exposure are the main causes for worry. When pesticides are applied, there may be direct exposure, which could result in immediate health impacts like headaches, skin irritation, or breathing issues. When pesticide residues linger on food, seep into water sources, or build up in the environment, they might eventually impact human health through contact or ingestion. This is known as indirect exposure. Bioaccumulation, which occurs when chemicals accumulate in the body over time, particularly when exposure is frequent or protracted, is a major problem related to pesticide use. Because pesticides are persistent in the environment and can magnify via the food chain—a process known as biomagnification—this buildup may result in more serious health issues. Higher trophic levels, including people, may therefore be more affected in terms of health. Pesticide residues are almost always detected in conjunction with other chemicals. The toxicological effects of low-dose pesticide mixtures on human health have not received much attention, despite the risks they present.

B. Pesticide Classification Based on Application

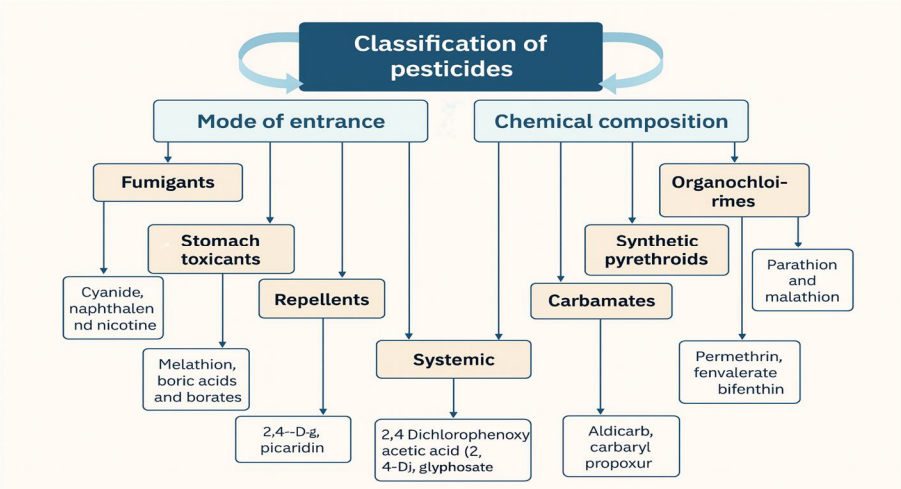

Fig 2: Classification of pesticides

How pesticides interact with or enter the target organism is described by their method of entry. For safe application and efficient pest control, it is essential to comprehend these techniques. Based on how they interact with pests, pesticides can be categorized as systemic, contact, stomach poisons, fumigants, or repellents. Systemic pesticides are pesticides that are absorbed by plants and transported throughout the entire plant. Following application, pesticides enter the circulation and digestive systems of various species, including people, as well as the leaves, trunks, and roots of plants. After being administered, non-systemic pesticides do not move or translocate within the plant. These insecticides do not penetrate or spread within the plant's tissues; instead, they stay on its surface. Non-systemic insecticides are determined by contact between pesticides and target organisms.

IV. EFFECTS OF PESTICIDES ON HUMAN HEALTH

Alzheimer's disease (AD) is the utmost frequent form of dementia among the elderly, and it's becoming more widespread around the world. Exposure to pesticides has been connected to neurological issues. Investigations into the relationship between pesticide exposure and Alzheimer's disease and its controls were carried out. Pesticides are dangerous, according to the initial investigation's conclusions. A second investigation discovered a connection between AD and high blood DDE levels. Early exposure to organophosphates has been shown to affect brain function in young children, especially in cases of neurodegenerative diseases. According to a different study, children who are exposed to pesticides (organochlorines) during pregnancy and after birth experience cognitive and autistic abnormalities. Exposure to pesticides affects the cholinergic neurons in the basal forebrain, causing memory and sensory issues. US military personnel exposed to sarin and cyclosarin during the Gulf War in 1991 experienced neurological issues.

1) Parkinson's disease: Parkinson's disease (PD) is a neurological disorder that makes people's everyday duties more difficult by producing stiffness, tremors, and balance problems. Although the exact etiology of Parkinson's disease (PD) is uncertain, environmental factors such as pesticides like rotenone have been connected to the disease's onset. Parkinson's disease risk has been associated with several pesticides, including organophosphates and carbamates.

2) Respiratory problems: A study found that 10.9% of agricultural workers have a higher severity of COPD and a loss in lung function. Red blood cell AChE levels are lower in agricultural laborers, and these levels are positively connected with COPD, lung function deterioration, and respiratory symptoms. In India, extended exposure to agricultural pesticides that block cholinesterase is linked to these health issues.

3) Asthma: A Spanish study found that exposure to pesticides, particularly DDE and polychlorobiphenyls, can worsen asthma symptoms and increase the risk of developing asthma. The study involved 405 children and 482 mothers and found a strong correlation between these chemicals and asthma. Pesticide aerosols have the potential to produce neurogenic inflammation by interacting with airway receptors or damaging bronchial mucosa cells. Inflammatory mediators are released by inflammatory cytokines and neuropeptides from sensory neurons, resulting in tissue damage and inflammation of the airways.

4) Diabetes: According to recent research, diabetes may be impacted by exposure to environmental pollutants. Numerous studies have demonstrated that certain insecticides may worsen glycemic control or increase the risk of diabetes. According to certain studies, long-term exposure to certain pesticides, like organophosphates and organochlorines, may disrupt the regular functioning of the endocrine system, which may cause diabetes. Insulin resistance and poor glycemic control may result from these pesticides' disruption of insulin signaling and glucose metabolism. It is believed that exposure to pesticides, particularly organochlorines (OC) and their metabolites, increases the risk of type 2 diabetes (T2DM) and its consequences.

5) Leukemia: Exposure to pesticides has been linked to a higher risk of developing leukemia, a disease marked by aberrant production of white blood cells that can weaken the body's ability to fight infections and other illnesses. Pesticide exposure has been linked to the development of leukemia in several studies. Leukemia is more common in farmers, farmworkers, and pesticide applicators than in the general population due to their frequent exposure to pesticides. One of the main causes of acute leukemia is exposure to pesticides.

6) Non-alcoholic fatty liver disease (NAFLD): The accumulation of excess fat in the liver is the hallmark of non-alcoholic fatty liver disease (NAFLD), which is unrelated to heavy alcohol consumption. While obesity, insulin resistance, and metabolic syndrome are the primary risk factors for non-alcoholic fatty liver disease (NAFLD), there is evidence that some pesticides may potentially contribute to the development or progression of NAFLD. The precise mechanism by which pesticides may cause NAFLD is unknown. However, it is thought that pesticide exposure may alter the gut microbiota's makeup, cause oxidative stress and inflammation, and disrupt lipid metabolism—all of which are connected to the development and progression of NAFLD. Moreover, reactive oxygen species produced by pesticide metabolism might cause oxidative stress and liver damage.

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A. Side Effects on Crop Yield

Pesticides have many advantages for agricultural productivity. They help to rise crop yields by decreasing losses caused by pests, diseases, and weeds. By preserving the amount and quality of harvested crops, they also help ensure food security. In order to prevent the spread of illnesses like dengue fever, malaria, and Lyme disease, pesticides are used in the field of public health to manage disease-carrying insects like ticks, mosquitoes, and fleas. The production and development of environmentally friendly pesticides with various formulations, such as powder, solution, and emulsifiable concentrates, has significantly increased in the advanced world's pesticide trade, despite the well-established role of agrochemicals in boosting agricultural production. However, in order to maintain sustainable and successful pest control tactics, the use of pesticides must be balanced with health and environmental concerns, and responsible pesticide practices, including integrated pest management, should be encouraged.

B. DDT

DDT is a synthetic insecticide that is very poisonous to a wide range of insects as a contact poison. It appears to work by disrupting the nervous system. DDT is a member of the family of organic halogen compounds. In the 1940s, DDT (dichloro-diphenyl-trichloroethane) was created as the first synthetic insecticide. Initially, both military and civilian populations benefited greatly from its usage in the fight against typhus, malaria, and other insect-borne human diseases. Additionally, it worked well for controlling insects in houses, gardens, institutions, and the production of crops and cattle. Many insect pest species developed resistance as a result of DDT's rapid success as a pesticide and widespread use in the US and other nations. Due to DDT's detrimental impacts on the environment, including those on wildlife, and possible hazards to human health, the EPA issued a cancellation order for the chemical in 1972. Since then, research has progressed, and based on animal studies, there may be a connection between human reproductive impacts and DDT exposure. Additionally, liver tumors were produced in several study animals who were exposed to DDT. Because of this, DDT is still used in India even though U.S. and international agencies now classify it as a probable human carcinogen. [4] These days, DDT is replaced with pyrethroids and neonicotinoids.

C. Effects on Soil

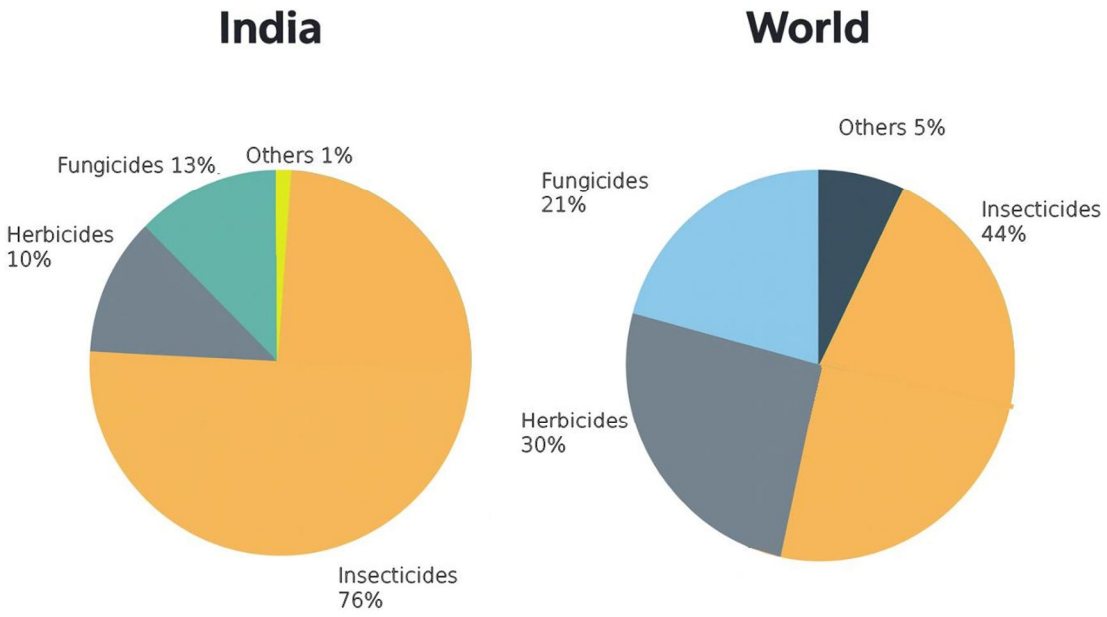
The environment itself can become contaminated by pesticides. They can kill weeds and insects, but they can also be poisonous to non-invasive wildlife. Although herbicides can also be harmful to non-target creatures, insecticides are typically the most acutely hazardous family of pesticides. Runoff from treated plants and soil can carry pesticides to surface water. Pesticide contamination of water is common. The U.S. Geological Survey (USGS) conducted extensive research on the nation's major river basins in the early to mid-1990s, and the findings were shocking. Over 90% of fish and water samples from every stream had one or more pesticides (Kole et al., 2001). Additionally, the USGS discovered that pesticide concentrations in urban streams frequently exceed recommendations for safeguarding aquatic species. There are numerous known transformation products (TPs) from a variety of pesticides (Barcelo and Hennion, 1997; Roberts, 1998; Roberts and Hutson, 1999). There is an urgent need for greater research in this area since few of all potential pesticide TPs have been observed in soil. The continuance and mobility of these pesticides and their TPs are determined based on their water solubility, soil-sorption constant (Koc), the octanol/water partition coefficient (Kow), and half-life in soil (DT50). Pesticides and TPs can be classified as follows: (a) Soil-bound pesticides that are hydrophobic, persistent, and bioaccumulable. The organochlorine DDT, endosulfan, endrin, heptachlor, lindane, and their TPs are among the pesticides that display similar behavior. Although their remnants are still present, most of them are currently prohibited in agriculture. (a) Herbicides make up the majority of polar pesticides, but they also include fungicides, carbamates, and certain organophosphorus insecticide TPs. They can be transported from the soil by leaching and runoff, which poses a challenge to the population's access to clean drinking water. Herbicide TPs are without a doubt the most studied pesticide TPs in soil. Numerous metabolic processes that result in the production of various hazardous phenolic compounds through hydrolysis, methylation, and ring cleavage have been proposed. Soils retain pesticides and their TPs to varying degrees, depending on how soil and pesticide characteristics interact; its most important feature being the amount of organic matter in the soil. The adsorption of pesticides and TPs increases with the amount of organic materials. When using paraquat and other positively charged herbicides, the soil's ability to retain positively charged ions in an exchangeable state is crucial. These compounds must be extracted using strong mineral acid; no recent research or analytical advancements have been reported. The pH of the soil is also quite significant. For ionizable herbicides (such as 2,4-D, 2,4,5-T, picloram, and atrazine), adsorption rises when soil pH decreases. Beneficial soil microbe populations may decrease as a result of extensive pesticide treatment. Dr. Elaine Ingham, a soil scientist, states that "the soil degrades if we lose both bacteria and fungi." The effects of overusing chemical pesticides and fertilizers on soil organisms are comparable to those of overusing antibiotics by humans.

Chemicals used carelessly may be effective for a few years, but eventually there won't be enough beneficial soil organisms to retain the nutrients (Savonen, 1997). For instance, a range of soil microbes are necessary for plants to convert atmospheric nitrogen into nitrates that they can utilize.

V. PRODUCTION AND USAGE OF PESTICIDES IN INDIA

India began producing pesticides in 1952 when a plant to produce BHC was established close to Calcutta. Today, India ranks twelfth in the world and is Asia's second-largest pesticide maker, after China (Mathur, 1999). India's production of technical-grade pesticides increased steadily from 5,000 metric tons in 1958 to 102,240 metric tons in 1998. The value of the demand for pesticides in 1996–1997 was expected to be around Rs. 22 billion (USD 0.5 billion), or roughly 2% of the global market.

India uses pesticides in a different way than the rest of the world. The pie figure illustrates that 76% of pesticides used in India are insecticides, compared to 44% worldwide (Mathur, 1999). As a result, fungicides and herbicides are used less frequently. In India, cotton crops account for 45% of pesticide use, with paddy and wheat coming in second and third.



Graph 1: Types of pesticides used worldwide Vs in India

A. Benefits Of Pesticides

The primary benefits are the consequences of the pesticides' effects – the direct gains expected from their use. For instance, the main advantage of eliminating caterpillars that eat on the crop is increased cabbage yields and improved quality. There are 26 key benefits from the three main effects, which range from saving lives to protecting recreational grass. The less evident or immediate benefits that follow from the core benefits are known as secondary benefits. They could be long-term, subtle, or less immediately apparent. As a result, it is more challenging to prove cause and effect for secondary advantages, although they can still be strong arguments in favor of using pesticides. For instance, a larger yield of cabbage may result in more money that may be used for medical treatment or education for kids, making the population healthier and better educated. There are various secondary benefits identified, ranging from fitter people to conserved biodiversity.

B. The Impact of Climate Change On Pest Control

1) Rising temperatures and pest proliferation: The rise in global temperatures is one of the most obvious effects of climate change. In hot climates the reproductivity of pests can increase so they frequently procreate. For instance, insects like mosquitoes, which could survive in warmer regions can now also do the same in the colder regions. This ordeal presents a challenge for the people involved in bug extermination as they have to deal with a large number of pests.

2) Shifting habitats and migration patterns: Warming global temperatures are modifying the natural environments of many pests, resulting in altered migration routes. Pests that were historically confined to warmer regions (tropical or subtropical) are moving into cooler temperate areas. Consequently, pest control efforts need to adjust to these new geographic ranges, necessitating heightened monitoring and novel control techniques.
3) Greater Pest resistance: Climate-related changes often create environments where pests can thrive, leading to them building up tolerance for existing control methods. Species like ants and termites may become highly adaptive, allowing them to survive in new surroundings and making them more difficult to destroy. Consequently, pest control businesses must prioritize ongoing development of stronger, more successful alternatives to combat these tough pests.

C. *Adaptations In pest Control Strategies*

1) Integrated Pest Management (IPM): It represents an ecologically conscious method that brings together a variety of pest control tactics. Given the shifting climate, the importance of IPM has risen dramatically. Pest control businesses are increasingly implementing IPM protocols. This comprehensive strategy addresses not only the pests themselves but also takes into account the surrounding ecosystem, establishing it as both a sustainable and highly effective technique.
2) Advanced monitoring and surveillance: Effectively addressing the evolving pest situation requires upgraded monitoring and data collection. Companies in the pest control sector are investing in next-generation technology, like remote sensors, drones, and GIS, to follow pest movements and predict when outbreaks might occur. These systems enable firms to achieve a swifter and more precise reaction, thereby lessening the effect of pests on both city and rural areas.
3) Climate-adaptive pesticides: Pesticides developed to adapt to climate are another important improvement in pest control methods. These products are made to work well in various environmental settings, ensuring they remain reliable even as conditions change. Continued innovation and study in this area are critical, given that standard pesticides might lose their strength in changed climates. Climate-ready pesticides offer a reliable way to handle pests in an ever-changing ecosystem.
4) Community engagement and education: Public education and community involvement are essential elements of current pest control strategies. Pest management firms are working to actively inform communities regarding the impacts of climate change on pest populations and the necessity of taking proactive measures. By encouraging a cooperative approach, these companies can introduce pest management practices that are both more effective and sustainable. Community participation ensures that individuals are better equipped to handle pest problems, thereby reducing the total demand on professional services.

VI. IMPROVING PRODUCTIVITY IN INDIA

The use of pesticides has greatly benefited forests, public health, the home, and, of course, agriculture, which is a key component of the Indian economy. From an estimated 169 million hectares of permanently planted land, food grain output, which was just 50 million tons in 1948–49, nearly quadrupled to 198 million tons by the end of 1996–97. High-yield crop varieties, sophisticated irrigation systems, and agricultural pesticides have all contributed to this outcome (Employment Information: Indian Labour Statistics, 1994). Likewise, most nations have seen significant increases in productivity and outputs, such as the United Kingdom's wheat yields and the United States' maize yields. A number of variables, including the use of machinery, improved cultivars, and fertilizer, have contributed to increases in production. By lowering losses from weeds, illnesses, and insect pests that can significantly lower the amount of harvestable product, pesticides have been an essential component of the process. The remarkable gains in crop yields in the United States during the 20th century were also highlighted by Warren (1998). According to Webster et al. (1999), there would be "considerable economic losses" if pesticides weren't used. They also measured the notable increases in yield and economic margin that come from using pesticides.

A. *Consumption of Pesticides in India*

With 28 states, India is a large country with a variety of agro-ecological characteristics. The state with the most agricultural acreage in India, Uttar Pradesh, uses the most pesticides, followed by Maharashtra, Combined Andhra Pradesh, and Punjab. Punjab, Rajasthan, Karnataka, Odisha, Bihar, Madhya Pradesh, Kerala, Gujarat, and Jammu and Kashmir have seen a minor decrease in total pesticide consumption during the past ten years, whereas Uttar Pradesh and Maharashtra have seen an increase. This suggests that not every state has seen an increase in pesticide use; in fact, several have seen a decrease. Pesticide use has generally increased significantly, rising by 46% between the triennial ending (TE) of 2007 and TE 2023. Overall, the use of pesticides increased by 46% between the triennials that ended in 2007 and 2023.

The significant increase in historically lesser pesticide-using states like Jharkhand (an 833% increase), followed by Chhattisgarh (247%), Andhra Pradesh (265%), and Maharashtra (253%), is especially notable. On the other hand, developed states like Punjab, Haryana, West Bengal, Tamil Nadu, and West Bengal that already consume more pesticides per unit area have exhibited diminishing trends.

B. Impact Through Food Commodities

The first documented case of pesticide poisoning in India occurred in Kerala in 1958, when more than 100 individuals perished after eating parathion-contaminated wheat flour (Karunakaran, 1958). This led the ICAR's Special Committee on Harmful Effects of Pesticides to concentrate on the issue (Report of the Special Committee of ICAR, 1972). DDT residues were discovered in almost 82% of the 2205 samples of bovine milk collected from 12 states in a multicentric study to evaluate the pesticide residues in certain food commodities gathered from various states of the nation (Surveillance of Food Contaminants in India, 1993). DDT residues exceeding the threshold limit of 0.05 mg/kg (whole milk base) were found in almost 37% of the samples. Highest DDT residues found were approximately 2.2 milligram/kilogram. The highest percentage of samples with residues above the tolerance limit (74%) was found in Maharashtra. Gujarat (70%), Andhra Pradesh (57%), Himachal Pradesh (56%), and Punjab (51%) came next. This percentage was below 10% in the remaining states. DDT and HCH isomer residues were found in approximately 70 and 94% of 186 samples of 20 commercial brands of infant formula, respectively, with highest levels of 4.3 and 5.7 mg/kg (fat basis). The best estimates of human exposure and possible harm come from measuring the chemicals in the entire diet. After that, the risk to consumers can be assessed by comparing it to amounts of intake that are toxicologically acceptable .Adults ingested an average of 19.24 mg of DDT and 77.15 mg of BHC daily (Kashyap et al., 1994). The primary source of these pollutants was fatty meals.

VII. FUTURE OF PESTICIDES

A. Nanopesticides

Since nanopesticides are significantly more effective than current pesticides, numerous studies have predicted that they may soon completely replace traditional pesticides. Nanomaterials have distinct properties from their bulk counterparts because of an increase in their surface-to-volume ratio. These nanoparticles are used to create insecticides known as "nanopesticides," which have a high application efficiency and substantially fewer harmful environmental effects than chemically produced pesticides. Numerous formulation techniques, such as the use of nanoparticles to hold the active ingredient, have been proven to have positive impacts on pests. Notable features of these nanopesticides include target specificity, high stability, and controlled release of active ingredients (AIs). Encasing active ingredients in nanoparticles to improve stability, protect the active material from environmental degradation, and facilitate controlled, slow-release over time. Crop productivity may also be greatly enhanced by the creation of natural green nanopesticides with extremely low ecotoxicities and nanoscale characteristics. The primary benefit is from the particles' small size, which aids in effectively dispersing the chemicals on the pest's surface and, as a result, produces a better effect than traditional pesticides. Because of their increased effectiveness and lower dosage requirements, the usage of nanoparticles in nanopesticides, nanofertilizers, and nano delivery systems is growing daily. However, during or after the application, humans and other species are also exposed to the nano-entities. Thus yet, nothing is known about how these manufactured nano-entities interact with biological systems. Therefore, a greater knowledge of their interactions and any negative effects is therefore essential for a sustainable transition before they are used more widely in crop production and protection.

Pesticide innovations that are reshaping modern agriculture and redefining the global crop protection market:

1) RNAi Based Pesticides: Scientists can provide species-specific protection without endangering beneficial creatures by using RNA interference (RNAi) technology to silence critical genes in targeted pests. These insecticides are perfect for sustainable farming because they are highly precise and biodegradable. Although transport and stability have previously been obstacles, new developments in formulation are bringing RNAi pesticides closer to widespread use.

2) Drone Application Systems: The use of drones in agriculture has expanded rapidly. Drones with sophisticated spraying systems limit operator exposure, minimize chemical waste, and enable focused application. Drones offer affordable solutions for high-value crops and dispersed fields, allowing farmers to respond swiftly to insect outbreaks. In the pesticide industry, the emergence of drone-as-a-service models is also opening up new economic prospects.

3) Smart Sprayers and AI Spot Spraying: Ground and aerial spraying are becoming more precise thanks to artificial intelligence and computer vision. In order to administer pesticides only where necessary, smart sprayers with sensors and cameras can detect weeds or sick plants in real time. For farmers running large-scale operations, this increases returns on investment, minimizes the use of chemicals, and lessens the impact on the environment.

4) Semiochemicals and Pheromone-Based Control: Particularly in orchards and specialty crops, pheromone dispensers and lure-and-kill devices are becoming more and more common. These items greatly lessen the need for synthetic insecticides and interfere with pest mating cycles. Pheromone-based pest management is especially being adopted by export-driven markets, which demand low or zero pesticide residues.

5) Gene Editing and Sterile Insect Techniques: Sterile insect technique (SIT) initiatives, which release sterile bugs to naturally reduce populations, are being advanced by gene-editing methods like CRISPR. This strategy offers long-term ecological advantages and uses fewer chemicals. Pilot programs in regulated areas are showing promise for future market expansion, even if commercialization faces obstacles related to societal acceptance and regulations.

6) Digital Pest Forecasting and Decision Support: Digital agriculture platforms are transforming pest management decisions. By combining weather data, satellite imagery, and pest population models, farmers can predict outbreaks and spray at the optimal time. These decision support tools reduce unnecessary pesticide use, improve yields, and open new revenue streams through subscription-based platforms.

7) Resistance Management and Synergistic Chemistries: Resistance to pesticides is a major global challenge. New molecules with novel modes of action and synergistic additives are being developed to enhance effectiveness while slowing resistance development. Stewardship programs, backed by strict resistance management guidelines, are ensuring the long-term sustainability of these innovations.

VIII. RESULT AND CONCLUSION

To conclude, though pesticides are immensely beneficial to humans in the short term, their long-term effects cannot be ignored. Hence, their use should be deliberate, and advertised, so as to not cause harm to the layman. After some developments in the field, nanopesticides will allow for their downsides to be minimized, without affecting their strengths.

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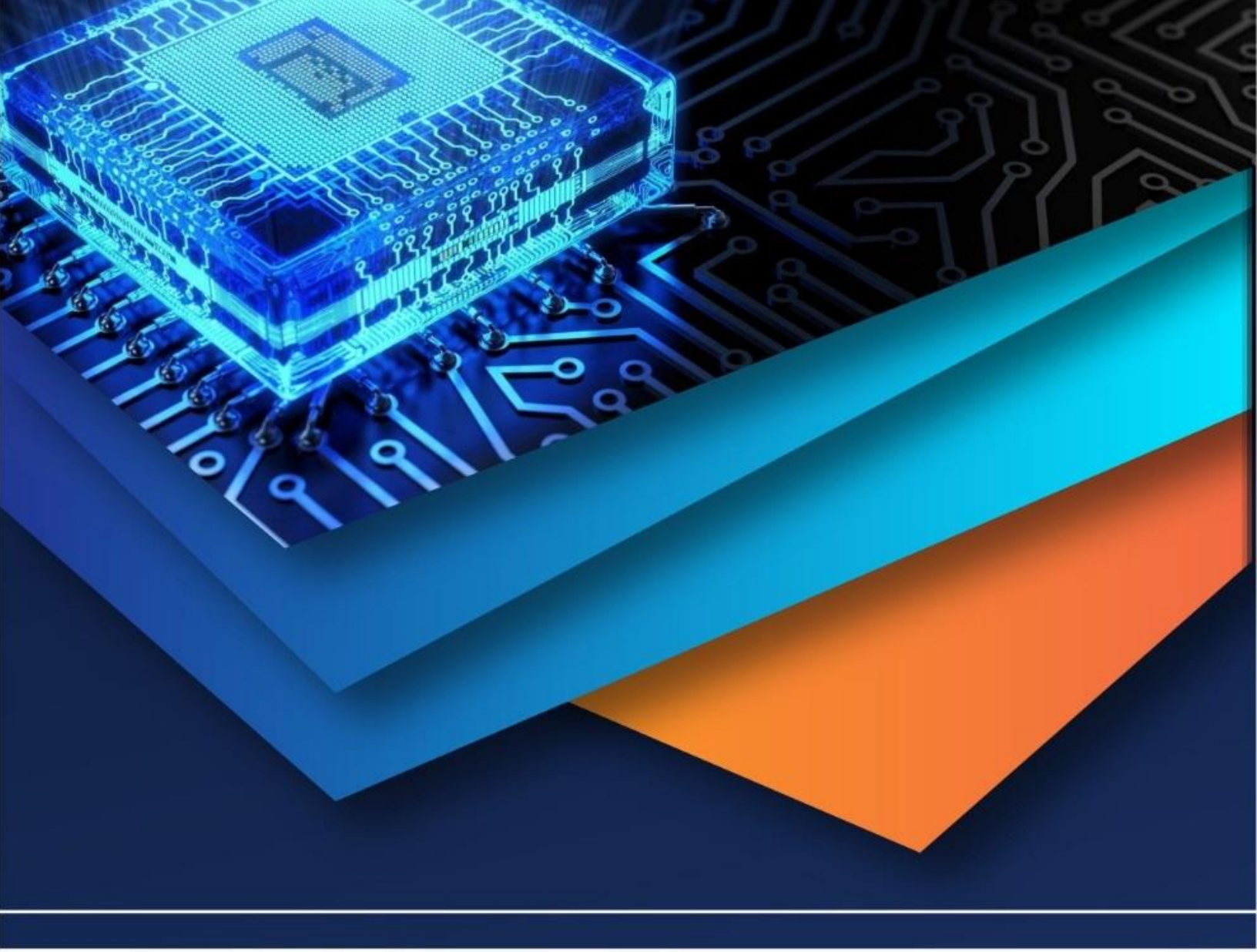

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