



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 10, Issue 7, July 2021

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 7.569

 9940 572 462

 6381 907 438

 ijirset@gmail.com

 www.ijirset.com



An Overview on Study of Effect of Pesticides on Human Health

DR. ROMILA KARNAWAT

SCRS GOVT. COLLEGE, SAWAI MADHOPUR, RAJASTHAN, India

ABSTRACT: Pesticides are substances that are meant to control pests.^[1] This includes herbicide, insecticide, nematocidal, molluscicide, piscicide, avicide, rodenticide, bactericide, insect repellent, animal repellent, microbicide, fungicide, and lampricide.^{[2][3]} The most common of these are herbicides, which account for approximately 50% of all pesticide use globally.^[4] Most pesticides are intended to serve as plant protection products (also known as crop protection products), which in general, protect plants from weeds, fungi, or insects. In general, a pesticide is a chemical (such as carbamate) or biological agent (such as a virus, bacterium, or fungus) that deters, incapacitates, kills, or otherwise discourages pests. Target pests can include insects, plant pathogens, weeds, molluscs, birds, mammals, fish, nematodes (roundworms), and microbes that destroy property, cause nuisance, or spread disease, or are disease vectors. Along with these benefits, pesticides also have drawbacks, such as potential toxicity to humans and other species.

KEYWORDS- pesticides, human, health, disease, toxicity, protection

I. INTRODUCTION

The Food and Agriculture Organization (FAO) has defined pesticide as: any substance or mixture of substances intended for preventing, destroying, or controlling any pest, including vectors of human or animal disease, unwanted species of plants or animals, causing harm during or otherwise interfering with the production, processing, storage, transport, or marketing of food, agricultural commodities, wood and wood products or animal feedstuffs, or substances that may be administered to animals for the control of insects, arachnids, or other pests in or on their bodies. The term includes substances intended for use as a plant growth regulator, defoliant, desiccant, or agent for thinning fruit or preventing the premature fall of fruit. Also used as substances applied to crops either before or after harvest to protect the commodity from deterioration during storage and transport.^[5]

Definition

Type of pesticide	Target pest group
Algicides or algaecides	Algae
Avicides	Birds
Bactericides	Bacteria
Fungicides	Fungi and oomycetes
Herbicides	Plant
Insecticides	Insects
Lampricides	Lampreys ^[3]
Miticides or acaricides	Mites
Molluscicides	Snails
Nematicides	Nematodes
Rodenticides	Rodents
Slimicides	Algae, Bacteria, Fungi, and Slime molds
Virucides	Viruses

Pesticides can be classified by target organism (e.g., herbicides, insecticides, fungicides, rodenticides, and pediculicides^[6] – see table), chemical structure (e.g., organic, inorganic, synthetic, or biological (biopesticide),^[7] although the distinction can sometimes blur), and physical state (e.g. gaseous (fumigant)).^[7] Biopesticides include microbial pesticides and biochemical pesticides.^[8] Plant-derived pesticides, or "botanicals", have been developing quickly. These include the pyrethroids, rotenoids, nicotinoids, and a fourth group that includes strychnine and scilliroside.^{[9]:15}

Many pesticides can be grouped into chemical families. Prominent insecticide families include organochlorines, organophosphates, and carbamates. Organochlorine hydrocarbons (e.g., DDT) could be separated into dichlorodiphenyl ethanes, cyclodiene compounds, and other related compounds. They operate by disrupting the sodium/potassium balance of the nerve fiber, forcing the nerve to transmit continuously. Their toxicities vary greatly, but they have been phased out because of their persistence and potential to bioaccumulate.^{[9]:239–240}

Organophosphate and carbamates largely replaced organochlorines. Both operate through inhibiting the enzyme acetylcholinesterase, allowing acetylcholine to transfer nerve impulses indefinitely and causing a variety of symptoms such as weakness or paralysis. Organophosphates are quite toxic to vertebrates and have in some cases been replaced by less toxic carbamates.^{[9]:136–137} Thiocarbamate and dithiocarbamates are subclasses of carbamates. Prominent families of herbicides include phenoxy and benzoic acid herbicides (e.g. 2,4-D), triazines (e.g., atrazine), ureas (e.g., diuron), and Chloroacetanilide (e.g., alachlor). Phenoxy compounds tend to selectively kill broad-leaf weeds rather than grasses. The phenoxy and benzoic acid herbicides function similar to plant growth hormones, and grow cells without normal cell division, crushing the plant's nutrient transport system.^{[9]:300} Triazines interfere with photosynthesis.^{[9]:335} Many commonly used pesticides are not included in these families, including glyphosate.

The application of pest control agents is usually carried out by dispersing the chemical in an (often hydrocarbon-based) solvent-surfactant system to give a homogeneous preparation. A virus lethality study performed in 1977 demonstrated that a particular pesticide did not increase the lethality of the virus. Combinations that included surfactants and the solvent clearly showed that pretreatment with them markedly increased the viral lethality in the test mice.^[10]

Pesticides can be classified based upon their biological mechanism function or application method. Most pesticides work by poisoning pests.^[11] A systemic pesticide moves inside a plant following absorption by the plant. With insecticides and most fungicides, this movement is usually upward (through the xylem) and outward. Increased efficiency may be a result. Systemic insecticides, which poison pollen and nectar in the flowers, may kill bees and other needed pollinators.^[12]

In 2010, the development of a new class of fungicides called paldoxins was announced. These work by taking advantage of natural defense chemicals released by plants called phytoalexins, which fungi then detoxify using enzymes. The paldoxins inhibit the fungi's detoxification enzymes. They are believed to be safer and greener.^[13]

History

Since before 2000 BC, humans have utilized pesticides to protect their crops. The first known pesticide was elemental sulfur dusting used in Sumer about 4,500 years ago in ancient Mesopotamia.^[14] By the 15th century, toxic chemicals such as arsenic, mercury, and lead were being applied to crops to kill pests. In the 17th century, nicotine sulfate was extracted from tobacco leaves for use as an insecticide. The 19th century saw the introduction of two more natural pesticides, pyrethrum, which is derived from chrysanthemums, and rotenone, which is derived from the roots of tropical vegetables.^[15] Until the 1950s, arsenic-based pesticides were dominant.^[16] Paul Müller discovered that DDT was a very effective insecticide. Chlorinates such as DDT were dominant, but they were replaced in the U.S. by organophosphates and carbamates by 1975. Since then, pyrethrin compounds have become the dominant insecticide.^[16] Herbicides became common in the 1960s, led by "triazine and other nitrogen-based compounds, carboxylic acids such as 2,4-dichlorophenoxyacetic acid, and glyphosate".^[16]

The first legislation providing federal authority for regulating pesticides was enacted in 1910.^[17] During the 1940s, manufacturers produced large amounts of synthetic pesticides and their use became widespread.^[18] Before the first World War, Germany was the world's leading chemical industry and exported most of the dyes and other chemicals that were used in the United States. War implemented tariffs that stimulated the growth of the chemical industry in the U.S., which made chemistry a prestigious occupation as this industry expanded and became profitable. Money and ideas flowed back from Europe after the U.S. entered WWI, changing the way Americans interacted with themselves and nature, and the industrialization of war hastened the industrialization of pest control.^[19] Some sources consider the 1940s and 1950s to have been the start of the "pesticide era."^[20] Although the U.S. Environmental Protection Agency was established in 1970 and amendments to the pesticide law in 1972,^[17] pesticide use has increased 50-fold since 1950 and 2.3 million tonnes (2.5 million short tons) of industrial pesticides are now^[when?] used each year.^[15] Seventy-five

percent of all pesticides in the world are used in developed countries, but use in developing countries is increasing.^[21] A study of USA pesticide use trends through 1997 was published in 2003 by the National Science Foundation's Center for Integrated Pest Management.^{[16][22]}

In the 1960s, it was discovered that DDT was preventing many fish-eating birds from reproducing, which was a serious threat to biodiversity. Rachel Carson wrote the best-selling book *Silent Spring* about biological magnification. The agricultural use of DDT is now banned under the Stockholm Convention on Persistent Organic Pollutants, but it is still used in some developing nations to prevent malaria and other tropical diseases by spraying on interior walls to kill or repel mosquitoes.^[23]

Development

Available pesticides are not sufficient and new developments are needed. Continued research into the basic biology of pests may identify new vulnerabilities and produce new pesticides; it may also yield pesticides with better financial and environmental characteristics than those presently used.^[24] Plant-derived pesticides, or "botanicals", have been developing quickly. These include the pyrethroids, rotenoids, nicotinoids, and a fourth group that includes strychnine and scilliroside.^[9]

Fungicide resistance is increasing the proportion of inactive enantiomers in fungicide applications: The evolution of resistance necessitates research and discovery of new active ingredients, which trends away from already-discovered classes and toward more complex chemical structures. These tend to have more chiral centers more often which means more off products during synthesis.^[25]

Insecticides with systemic activity against sucking pests, which are safe to pollinators, are sought after,^{[26][27][28]} particularly in view of the partial bans on neonicotinoids. Revised 2023 guidance by registration authorities describes the bee testing that is required for new insecticides to be approved for commercial use.^{[29][30][31][32]}

Uses

Pesticides are used to control organisms that are considered to be harmful, or pernicious to their surroundings.^[33] For example, they are used to kill mosquitoes that can transmit potentially deadly diseases like West Nile virus, yellow fever, and malaria. They can also kill bees, wasps or ants that can cause allergic reactions. Insecticides can protect animals from illnesses that can be caused by parasites such as fleas.^[33] Pesticides can prevent sickness in humans that could be caused by moldy food or diseased produce. Herbicides can be used to clear roadside weeds, trees, and brush. They can also kill invasive weeds that may cause environmental damage. Herbicides are commonly applied in ponds and lakes to control algae and plants such as water grasses that can interfere with activities like swimming and fishing and cause the water to look or smell unpleasant.^[34] Uncontrolled pests such as termites and mold can damage structures such as houses.^[33] Pesticides are used in grocery stores and food storage facilities to manage rodents and insects that infest food such as grain. Each use of a pesticide carries some associated risk. Proper pesticide use decreases these associated risks to a level deemed acceptable by pesticide regulatory agencies such as the United States Environmental Protection Agency (EPA) and the Pest Management Regulatory Agency (PMRA) of Canada.

DDT, sprayed on the walls of houses, is an organochlorine that has been used to fight malaria since the 1950s. Recent policy statements by the World Health Organization have given stronger support to this approach.^[35] It and other organochlorine pesticides have been banned in most countries worldwide because of their persistence in the environment and human toxicity. DDT use is not always effective, as resistance to DDT was identified in Africa as early as 1955, and by 1972 nineteen species of mosquito worldwide were resistant to DDT.^{[36][37]}

Amount used

In 2006 and 2007, the world used approximately 2.4 megatonnes (5.3×10^9 lb) of pesticides, with herbicides constituting the biggest part of the world pesticide use at 40%, followed by insecticides (17%) and fungicides (10%). In 2006 and 2007 the U.S. used approximately 0.5 megatonnes (1.1×10^9 lb) of pesticides, accounting for 22% of the world total, including 857 million pounds (389 kt) of conventional pesticides, which are used in the agricultural sector (80% of conventional pesticide use) as well as the industrial, commercial, governmental and home & garden sectors. The state of California alone used 117 million pounds. Pesticides are also found in majority of U.S. households with 88 million out of the 121.1 million households indicating that they use some form of pesticide in 2012.^{[38][39]} As of 2007, there were more than 1,055 active ingredients registered as pesticides,^[17] which yield over 20,000 pesticide products that are marketed in the United States.^[40]

The US used some 1 kg (2.2 pounds) per hectare of arable land compared with: 4.7 kg in China, 1.3 kg in the UK, 0.1 kg in Cameroon, 5.9 kg in Japan and 2.5 kg in Italy. Insecticide use in the US has declined by more than half since 1980 (0.6%/yr), mostly due to the near phase-out of organophosphates. In corn fields, the decline was even steeper, due to the switchover to transgenic Bt corn.^[41]

Benefits

Pesticides can save farmers' money by preventing crop losses to insects and other pests; in the U.S., farmers get an estimated fourfold return on money they spend on pesticides.^[42] One study found that not using pesticides reduced crop yields by about 10%.^[43] Another study, conducted in 1999, found that a ban on pesticides in the United States may result in a rise of food prices, loss of jobs, and an increase in world hunger.^[44]

There are two levels of benefits for pesticide use, primary and secondary. Primary benefits are direct gains from the use of pesticides and secondary benefits are effects that are more long-term.^[45]

Biological

Controlling pests and plant disease vectors

Improved crop yields

Improved crop/livestock quality

Invasive species controlled

Controlling human/livestock disease vectors and nuisance organisms

Human lives saved and disease reduced. Diseases controlled include malaria,^[45] with millions of lives having been saved or enhanced with the use of DDT alone.^[46]

Animal lives saved and disease reduced

Controlling organisms that harm other human activities and structures

Drivers view unobstructed

Tree/brush/leaf hazards prevented

Wooden structures protected^[45]

Monetary

In one study, it was estimated that for every dollar (\$1) that is spent on pesticides for crops can yield up to four dollars (\$4) in crops saved.^[47] This means based that, on the amount of money spent per year on pesticides, \$10 billion, there is an additional \$40 billion savings in crop that would be lost due to damage by insects and weeds. In general, farmers benefit from having an increase in crop yield and from being able to grow a variety of crops throughout the year. Consumers of agricultural products also benefit from being able to afford the vast quantities of produce available year-round.^[45]

Post- WWII conditions caused the pesticide industry to flourish for several reasons including the growing middle class and the invention of cheap tractor-drawn spraying equipment. By the 1980s the demand for pesticides had dropped due to farmers struggling financially and the market for chemicals becoming oversaturated. There were also new costs for producing pesticides due to the strict EPA laws surrounding the chemicals. The modern pesticide market is seven billion dollars and is growing 4% per year due to the invention of the lawn and the stigma surrounding the untamed yard.^[48]

Costs

On the cost side of pesticide use there can be costs to the environment, costs to human health,^[49] as well as costs of the development and research of new pesticides.

Health effects

A sign warning about potential pesticide exposure

Pesticides may cause acute and delayed health effects in people who are exposed.^[50] Pesticide exposure can cause a variety of adverse health effects, ranging from simple irritation of the skin and eyes to more severe effects such as affecting the nervous system, hearing,^[51] mimicking hormones causing reproductive problems, and also causing cancer.^[52] A 2007 systematic review found that "most studies on non-Hodgkin lymphoma and leukemia showed positive associations with pesticide exposure" and thus concluded that cosmetic use of pesticides should be decreased.^[53] There is substantial evidence of associations between organophosphate insecticide exposures and neurobehavioral alterations.^{[54][55][56][57]} Limited evidence also exists for other negative outcomes from pesticide exposure including neurological, birth defects, and fetal death.^[58]

The American Academy of Pediatrics recommends limiting exposure of children to pesticides and using safer alternatives.^[59]

Owing to inadequate regulation and safety precautions, 99% of pesticide-related deaths occur in developing countries that account for only 25% of pesticide usage.^[60]

One study found pesticide self-poisoning the method of choice in one third of suicides worldwide, and recommended, among other things, more restrictions on the types of pesticides that are most harmful to humans.^[61]

A 2014 epidemiological review found associations between autism and exposure to certain pesticides, but noted that the available evidence was insufficient to conclude that the relationship was causal.^[62]

Occupational exposure among agricultural workers

The World Health Organization and the UN Environment Programme estimate that 3 million agricultural workers in the developing world experience severe poisoning from pesticides each year, resulting in 18,000 deaths.^[63] According to one study, as many as 25 million workers in developing countries may suffer mild pesticide poisoning yearly.^[64] Other occupational exposures besides agricultural workers, including pet groomers, groundskeepers, and fumigators, may also put individuals at risk of health effects from pesticides.^[65]

Pesticide use is widespread in Latin America, as around US\$3 billion are spent each year in the region. Records indicate an increase in the frequency of pesticide poisonings over the past two decades. The most common incidents of pesticide poisoning is thought to result from exposure to organophosphate and carbamate insecticides.^[66] At-home pesticide use, use of unregulated products, and the role of undocumented workers within the agricultural industry makes characterizing true pesticide exposure a challenge. It is estimated that 50–80% of pesticide poisoning cases are unreported.

Underreporting of pesticide poisoning is especially common in areas where agricultural workers are less likely to seek care from a healthcare facility that may be monitoring or tracking the incidence of acute poisoning. The extent of unintentional pesticide poisoning may be much greater than available data suggest, particularly among developing countries. Globally, agriculture and food production remain one of the largest industries. In East Africa, the agricultural industry represents one of the largest sectors of the economy, with nearly 80% of its population relying on agriculture for income.^[67] Farmers in these communities rely on pesticide products to maintain high crop yields.

Some East Africa governments are shifting to corporate farming, and opportunities for foreign conglomerates to operate commercial farms have led to more accessible research on pesticide use and exposure among workers. In other areas where large proportions of the population rely on subsistence, small-scale farming, estimating pesticide use and exposure is more difficult.

Pesticide poisoning

The cholinergic synapse and the breakdown of acetylcholine into choline and acetate by acetylcholinesterase

Pesticides may exhibit toxic effects on humans and other non-target species, the severity of which depends on the frequency and magnitude of exposure. Toxicity also depends on the rate of absorption, distribution within the body, metabolism, and elimination of compounds from the body. Commonly used pesticides like organophosphates and carbamates act by inhibiting acetylcholinesterase activity, which prevents the breakdown of acetylcholine at the neural synapse. Excess acetylcholine can lead to symptoms like muscle cramps or tremors, confusion, dizziness and nausea. Studies show that farm workers in Ethiopia, Kenya, and Zimbabwe have decreased concentrations of plasma acetylcholinesterase, the enzyme responsible for breaking down acetylcholine acting on synapses throughout the nervous system.^{[68][69][70]} Other studies in Ethiopia have observed reduced respiratory function among farm workers who spray crops with pesticides.^[71] Numerous exposure pathways for farm workers increase the risk of pesticide poisoning, including dermal absorption walking through fields and applying products, as well as inhalation exposure.

Measuring exposure to pesticides

There are multiple approaches to measuring a person's exposure to pesticides, each of which provides an estimate of an individual's internal dose. Two broad approaches include measuring biomarkers and markers of biological effect.^[72] The former involves taking direct measurement of the parent compound or its metabolites in various types of media: urine, blood, serum. Biomarkers may include a direct measurement of the compound in the body before it's been biotransformed during metabolism. Other suitable biomarkers may include the metabolites of the parent compound after they've been biotransformed during metabolism.^[72] Toxicokinetic data can provide more detailed information on how quickly the compound is metabolized and eliminated from the body, and provide insights into the timing of exposure.

Markers of biological effect provide an estimation of exposure based on cellular activities related to the mechanism of action. For example, many studies investigating exposure to pesticides often involve the quantification of the acetylcholinesterase enzyme at the neural synapse to determine the magnitude of the inhibitory effect of organophosphate and carbamate pesticides.^{[72][68][69][70]}

Another method of quantifying exposure involves measuring, at the molecular level, the amount of pesticide interacting with the site of action. These methods are more commonly used for occupational exposures where the mechanism of action is better understood, as described by WHO guidelines published in "Biological Monitoring of Chemical Exposure in the Workplace".^[73] Better understanding of how pesticides elicit their toxic effects is needed before this method of exposure assessment can be applied to occupational exposure of agricultural workers.

Alternative methods to assess exposure include questionnaires to discern from participants whether they are experiencing symptoms associated with pesticide poisoning. Self-reported symptoms may include headaches, dizziness, nausea, joint pain, or respiratory symptoms.^[69]

Challenges in assessing pesticide exposure

Multiple challenges exist in assessing exposure to pesticides in the general population, and many others that are specific to occupational exposures of agricultural workers. Beyond farm workers, estimating exposure to family members and children presents additional challenges, and may occur through "take-home" exposure from pesticide residues collected on clothing or equipment belonging to parent farm workers and inadvertently brought into the home. Children may also be exposed to pesticides prenatally from mothers who are exposed to pesticides during pregnancy.^[74] Characterizing children's exposure resulting from drift of airborne and spray application of pesticides is similarly challenging, yet well documented in developing countries.^[75] Because of critical development periods of the fetus and newborn children, these non-working populations are more vulnerable to the effects of pesticides, and may be at increased risk of developing neurocognitive effects and impaired development.^{[76][74]}

While measuring biomarkers or markers of biological effects may provide more accurate estimates of exposure, collecting these data in the field is often impractical and many methods are not sensitive enough to detect low-level concentrations. Rapid cholinesterase test kits exist to collect blood samples in the field. Conducting large scale assessments of agricultural workers in remote regions of developing countries makes the implementation of these kits a challenge.^[72] The cholinesterase assay is a useful clinical tool to assess individual exposure and acute toxicity. Considerable variability in baseline enzyme activity among individuals makes it difficult to compare field measurements of cholinesterase activity to a reference dose to determine health risk associated with exposure.^[72] Another challenge researchers face in deriving a reference dose is identifying health endpoints that are relevant to exposure. More epidemiological research is needed to identify critical health endpoints, particularly among populations who are occupationally exposed.

Prevention

Minimizing harmful exposure to pesticides can be achieved by proper use of personal protective equipment, adequate reentry times into recently sprayed areas, and effective product labeling for hazardous substances as per FIFRA regulations. Training high-risk populations, including agricultural workers, on the proper use and storage of pesticides, can reduce the incidence of acute pesticide poisoning and potential chronic health effects associated with exposure. Continued research into the human toxic health effects of pesticides serves as a basis for relevant policies and enforceable standards that are health protective to all populations.

Environmental effects

Pesticide use raises a number of environmental concerns. Over 98% of sprayed insecticides and 95% of herbicides reach a destination other than their target species, including non-target species, air, water and soil.^[21] Pesticide drift occurs when pesticides suspended in the air as particles are carried by wind to other areas, potentially contaminating them. Pesticides are one of the causes of water pollution, and some pesticides are persistent organic pollutants and contribute to soil and flower (pollen, nectar) contamination.^[77] Furthermore, pesticide use can adversely impact neighboring agricultural activity, as pests themselves drift to and harm nearby crops that have no pesticide used on them.^[78]

In addition, pesticide use reduces biodiversity, contributes to pollinator decline,^{[79][80][81]} destroys habitat (especially for birds),^[82] and threatens endangered species.^[21] Pests can develop a resistance to the pesticide (pesticide resistance), necessitating a new pesticide. Alternatively a greater dose of the pesticide can be used to counteract the resistance, although this will cause a worsening of the ambient pollution problem.

The Stockholm Convention on Persistent Organic Pollutants, listed 9 of the 12 most dangerous and persistent organic chemicals that were (now mostly obsolete) organochlorine pesticides.^{[6][83]} Since chlorinated hydrocarbon pesticides dissolve in fats and are not excreted, organisms tend to retain them almost indefinitely. Biological magnification is the process whereby these chlorinated hydrocarbons (pesticides) are more concentrated at each level of the food chain. Among marine animals, pesticide concentrations are higher in carnivorous fishes, and even more so in the fish-eating birds and mammals at the top of the ecological pyramid.^[84] Global distillation is the process whereby pesticides are transported from warmer to colder regions of the Earth, in particular the Poles and mountain tops. Pesticides that evaporate into the atmosphere at relatively high temperature can be carried considerable distances (thousands of kilometers) by the wind to an area of lower temperature, where they condense and are carried back to the ground in rain or snow.^[85]

In order to reduce negative impacts, it is desirable that pesticides be degradable or at least quickly deactivated in the environment. Such loss of activity or toxicity of pesticides is due to both innate chemical properties of the compounds and environmental processes or conditions.^[86] For example, the presence of halogens within a chemical structure often



slows down degradation in an aerobic environment.^[87] Adsorption to soil may retard pesticide movement, but also may reduce bioavailability to microbial degraders.^[88]

Economics

Harm	Annual US cost
Public health	\$1.1 billion
Pesticide resistance in pest	\$1.5 billion
Crop losses caused by pesticides	\$1.4 billion
Bird losses due to pesticides	\$2.2 billion
Groundwater contamination	\$2.0 billion
Other costs	\$1.4 billion
Total costs	\$9.6 billion

In one study, the human health and environmental costs due to pesticides in the United States was estimated to be \$9.6 billion: offset by about \$40 billion in increased agricultural production.^[89]

Additional costs include the registration process and the cost of purchasing pesticides: which are typically borne by agrichemical companies and farmers respectively. The registration process can take several years to complete (there are 70 different types of field tests) and can cost \$50–70 million for a single pesticide.^[89] At the beginning of the 21st century, the United States spent approximately \$10 billion on pesticides annually.^[89]

Resistance

The use of pesticides inherently entails the risk of resistance developing. Various techniques and procedures of pesticide application can slow the development of resistance, as can some natural features of the target population and surrounding environment.^[3]

Alternatives

Alternatives to pesticides are available and include methods of cultivation, use of biological pest controls (such as pheromones and microbial pesticides), genetic engineering (mostly of crops), and methods of interfering with insect breeding.^[21] Application of composted yard waste has also been used as a way of controlling pests.^[90]

These methods are becoming increasingly popular and often are safer than traditional chemical pesticides. In addition, EPA is registering reduced-risk pesticides in increasing numbers.^[citation needed]

Cultivation practices

Cultivation practices include polyculture (growing multiple types of plants), crop rotation, planting crops in areas where the pests that damage them do not live, timing planting according to when pests will be least problematic, and use of trap crops that attract pests away from the real crop.^[21] Trap crops have successfully controlled pests in some commercial agricultural systems while reducing pesticide usage.^[91] In other systems, trap crops can fail to reduce pest densities at a commercial scale, even when the trap crop works in controlled experiments.^[92]

Use of other organisms

Release of other organisms that fight the pest is another example of an alternative to pesticide use. These organisms can include natural predators or parasites of the pests.^[21] Biological pesticides based on entomopathogenic fungi, bacteria and viruses causing disease in the pest species can also be used.^[21]

Biological control engineering

Interfering with insects' reproduction can be accomplished by sterilizing males of the target species and releasing them, so that they mate with females but do not produce offspring.^[21] This technique was first used on the screwworm fly in 1958 and has since been used with the medfly, the tsetse fly,^[93] and the gypsy moth.^[94] This is a costly and slow approach that only works on some types of insects.^[21]

Other alternatives

Other alternatives include "laserweeding" – the use of novel agricultural robots for weed control using lasers.^[95]

Push pull strategy

The term "push-pull" was established in 1987 as an approach for integrated pest management (IPM). This strategy uses a mixture of behavior-modifying stimuli to manipulate the distribution and abundance of insects. "Push" means the insects are repelled or deterred away from whatever resource is being protected. "Pull" means that certain stimuli (semiochemical stimuli, pheromones, food additives, visual stimuli, genetically altered plants, etc.) are used to attract pests to trap crops where they will be killed.^[96] There are numerous different components involved in order to implement a Push-Pull Strategy in IPM.

Many case studies testing the effectiveness of the push-pull approach have been done across the world. The most successful push-pull strategy was developed in Africa for subsistence farming. Another successful case study was performed on the control of *Helicoverpa* in cotton crops in Australia. In Europe, the Middle East, and the United States, push-pull strategies were successfully used in the controlling of *Sitona lineatus* in bean fields.^[96]

Some advantages of using the push-pull method are less use of chemical or biological materials and better protection against insect habituation to this control method. Some disadvantages of the push-pull strategy are that if there is a lack of appropriate knowledge of the behavioral and chemical ecology of the host-pest interactions then this method becomes unreliable. Furthermore, because the push-pull method is not a very popular method of IPM operational and registration costs are higher.

Effectiveness

Some evidence shows that alternatives to pesticides can be equally effective as the use of chemicals. A study of Maize fields in northern Florida found that the application of composted yard waste with high carbon to nitrogen ratio to agricultural fields was highly effective at reducing the population of plant-parasitic nematodes and increasing crop yield, with yield increases ranging from 10% to 212%; the observed effects were long-term, often not appearing until the third season of the study.^[90] Additional silicon nutrition protects some horticultural crops against fungal diseases almost completely, while insufficient silicon sometimes leads to severe infection even when fungicides are used.^[97]

Pesticide resistance is increasing and that may make alternatives more attractive.

Types

Pesticides are often referred to according to the type of pest they control. Pesticides can also be considered as either biodegradable pesticides, which will be broken down by microbes and other living beings into harmless compounds, or persistent pesticides, which may take months or years before they are broken down: it was the persistence of DDT, for example, which led to its accumulation in the food chain and its killing of birds of prey at the top of the food chain. Another way to think about pesticides is to consider those that are chemical pesticides are derived from a common source or production method.^[98]

Insecticides

Neonicotinoids are a class of neuro-active insecticides chemically similar to nicotine. Imidacloprid, of the neonicotinoid family, is the most widely used insecticide in the world.^[99] In the late 1990s neonicotinoids came under increasing scrutiny over their environmental impact and were linked in a range of studies to adverse ecological effects, including honey-bee colony collapse disorder (CCD) and loss of birds due to a reduction in insect populations. In 2013, the European Union and a few non EU countries restricted the use of certain neonicotinoids.^{[100][101][102][103][104][105][106]}

Organophosphate and carbamate insecticides have a similar mode of action. They affect the nervous system of target pests (and non-target organisms) by disrupting acetylcholinesterase activity, the enzyme that regulates acetylcholine, at nerve synapses. This inhibition causes an increase in synaptic acetylcholine and overstimulation of the parasympathetic nervous system.^[107] Many of these insecticides, first developed in the mid 20th century, are very poisonous. Although commonly used in the past, many older chemicals have been removed from the market due to their health and environmental effects (e.g. DDT, chlordane, and toxaphene).^{[108][109][110]} Many organophosphates do not persist in the environment.

Pyrethroid insecticides were developed as a synthetic version of the naturally occurring pesticide pyrethrin, which is found in chrysanthemums. They have been modified to increase their stability in the environment. Some synthetic pyrethroids are toxic to the nervous system.^[111]

Herbicides

A number of sulfonylureas have been commercialized for weed control, including: amidosulfuron, flazasulfuron, metsulfuron-methyl, rimsulfuron, sulfometuron-methyl, terbacil,^[112] nicosulfuron,^[113] and triflurosulfuron-methyl.^[114] These are broad-spectrum herbicides that kill plants weeds or pests by inhibiting the enzyme acetolactate synthase. In the 1960s, more than 1 kg/ha (0.89 lb/acre) crop protection chemical was typically applied, while sulfonylureates allow as little as 1% as much material to achieve the same effect.^[115]

Biopesticides

Biopesticides are certain types of pesticides derived from such natural materials as animals, plants, bacteria, and certain minerals. For example, canola oil and baking soda have pesticidal applications and are considered biopesticides. Biopesticides fall into three major classes:

Microbial pesticides which consist of bacteria, entomopathogenic fungi or viruses (and sometimes includes the metabolites that bacteria or fungi produce). Entomopathogenic nematodes are also often classed as microbial pesticides, even though they are multi-cellular.^{[116][117]}

Biochemical pesticides or herbal pesticides^[118] are naturally occurring substances that control (or monitor in the case of pheromones) pests and microbial diseases.

Plant-incorporated protectants (PIPs) have genetic material from other species incorporated into their genetic material (i.e. GM crops). Their use is controversial, especially in many European countries.^[119]

By pest type

Pesticides that are related to the type of pests are:

Type	Action
Algicides	Control algae in lakes, canals, swimming pools, water tanks, and other sites
Antifouling agents	Kill or repel organisms that attach to underwater surfaces, such as boat bottoms
Antimicrobials	Kill microorganisms (such as bacteria and viruses)
Attractants	Attract pests (for example, to lure an insect or rodent to a trap).
Biopesticides	Biopesticides are certain types of pesticides derived from such natural materials as animals, plants, bacteria, and certain minerals
Biocides	Kill microorganisms
Disinfectants and sanitizers	Kill or inactivate disease-producing microorganisms on inanimate objects
Fungicides	Kill fungi (including blights, mildews, molds, and rusts)
Fumigants	Produce gas or vapor intended to destroy pests in buildings or soil
Herbicides	Kill weeds and other plants that grow where they are not wanted
Insecticides	Kill insects and other arthropods
Miticides	Kill mites that feed on plants and animals
Microbial pesticides	Microorganisms that kill, inhibit, or out compete pests, including insects or other microorganisms
Molluscicides	Kill snails and slugs
Nematicides	Kill nematodes (microscopic, worm-like organisms that feed on plant roots)
Ovicides	Kill eggs of insects and mites
Pheromones	Biochemicals used to disrupt the mating behavior of insects
Repellents	Repel pests, including insects (such as mosquitoes) and birds
Rodenticides	Control mice and other rodents
Slimicides	Kill slime-producing microorganisms such as algae, bacteria, fungi, and slime molds

Further types

The term pesticide also includes these substances:

Defoliants: Cause leaves or other foliage to drop from a plant, usually to facilitate harvest.

Desiccants: Promote drying of living tissues, such as unwanted plant tops.

Insect growth regulators: Disrupt the molting, maturity from pupal stage to adult, or other life processes of insects.

Plant growth regulators: Substances (excluding fertilizers or other plant nutrients) that alter the expected growth, flowering, or reproduction rate of plants.

Soil sterilant: a chemical that temporarily or permanently prevents the growth of all plants and animals, depending on the chemical. Soil sterilants must be registered as pesticides.^[120]

Wood preservatives: They are used to make wood resistant to insects, fungus, and other pests.

Gene drives, a complex genetic mechanism which can be embedded into the genetic material of the target species itself. Instead of killing the target individual it can, kill, eliminate the reproduction of, or suppress the reproductive rate of its descendants. This changes the target population in a more pervasive way and has few or no off-target effects.^[121]

Regulation International

In many countries, pesticides must be approved for sale and use by a government agency.^{[122][123]}

Worldwide, 85% of countries have pesticide legislation for the proper storage of pesticides and 51% include provisions to ensure proper disposal of all obsolete pesticides.^[124]

In Europe, EU legislation has been approved banning the use of highly toxic pesticides including those that are carcinogenic, mutagenic or toxic to reproduction, those that are endocrine-disrupting, and those that are persistent, bioaccumulative and toxic (PBT) or very persistent and very bioaccumulative (vPvB) and measures have been approved to improve the general safety of pesticides across all EU member states.^[125]

Though pesticide regulations differ from country to country, pesticides, and products on which they were used are traded across international borders. To deal with inconsistencies in regulations among countries, delegates to a conference of the United Nations Food and Agriculture Organization adopted an International Code of Conduct on the Distribution and Use of Pesticides in 1985 to create voluntary standards of pesticide regulation for different countries.^[122] The Code was updated in 1998 and 2002.^[126] The FAO claims that the code has raised awareness about pesticide hazards and decreased the number of countries without restrictions on pesticide use.^[5]

Three other efforts to improve regulation of international pesticide trade are the United Nations London Guidelines for the Exchange of Information on Chemicals in International Trade and the United Nations Codex Alimentarius Commission. The former seeks to implement procedures for ensuring that prior informed consent exists between countries buying and selling pesticides, while the latter seeks to create uniform standards for maximum levels of pesticide residues among participating countries.^[127]

Pesticides safety education and pesticide applicator regulation are designed to protect the public from pesticide misuse, but do not eliminate all misuse. Reducing the use of pesticides and choosing less toxic pesticides may reduce risks placed on society and the environment from pesticide use.^[34] Integrated pest management, the use of multiple approaches to control pests, is becoming widespread and has been used with success in countries such as Indonesia, China, Bangladesh, the U.S., Australia, and Mexico.^[21] IPM attempts to recognize the more widespread impacts of an action on an ecosystem, so that natural balances are not upset.^[18] New pesticides are being developed, including biological and botanical derivatives and alternatives that are thought to reduce health and environmental risks. In addition, applicators are being encouraged to consider alternative controls and adopt methods that reduce the use of chemical pesticides.

Pesticides can be created that are targeted to a specific pest's lifecycle, which can be environmentally more friendly.^[128] For example, potato cyst nematodes emerge from their protective cysts in response to a chemical excreted by potatoes; they feed on the potatoes and damage the crop.^[128] A similar chemical can be applied to fields early before the potatoes are planted, causing the nematodes to emerge early and starve in the absence of potatoes.^[128]

United States

Preparation for an application of hazardous herbicide in the US

In the United States, the Environmental Protection Agency (EPA) is responsible for regulating pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Food Quality Protection Act (FQPA).^[129]

Studies must be conducted to establish the conditions in which the material is safe to use and the effectiveness against the intended pest(s).^[130] The EPA regulates pesticides to ensure that these products do not pose adverse effects to humans or the environment, with an emphasis on the health and safety of children.^[131] Pesticides produced before November 1984 continue to be reassessed in order to meet the current scientific and regulatory standards. All registered pesticides are reviewed every 15 years to ensure they meet the proper standards.^[129] During the registration process, a label is created. The label contains directions for proper use of the material in addition to safety restrictions. Based on acute toxicity, pesticides are assigned to a Toxicity Class. Pesticides are the most thoroughly tested chemicals after drugs in the United States; those used on food require more than 100 tests to determine a range of potential impacts.^[131]

Some pesticides are considered too hazardous for sale to the general public and are designated restricted use pesticides.

Only certified applicators, who have passed an exam, may purchase or supervise the application of restricted use pesticides.^[122] Records of sales and use are required to be maintained and may be audited by government agencies charged with the enforcement of pesticide regulations.^{[132][133]} These records must be made available to employees and state or territorial environmental regulatory agencies.^{[134][135]}

In addition to the EPA, the United States Department of Agriculture (USDA) and the United States Food and Drug Administration (FDA) set standards for the level of pesticide residue that is allowed on or in crops.^[136] The EPA looks at what the potential human health and environmental effects might be associated with the use of the pesticide.^[137]

In addition, the U.S. EPA uses the National Research Council's four-step process for human health risk assessment: (1) Hazard Identification, (2) Dose-Response Assessment, (3) Exposure Assessment, and (4) Risk Characterization.^[138]

In 2013 Kaua'i County (Hawai'i) passed Bill No. 2491 to add an article to Chapter 22 of the county's code relating to pesticides and GMOs. The bill strengthens protections of local communities in Kaua'i where many large pesticide companies test their products.^[139]

Canada

EU

In 2023 The Environment Committee of European Parliament approved a decision aiming to reduce pesticide use by 50% (the most hazardous by 65%) by the year 2030 and ensure sustainable use of pesticides (for example use them only as a last resort). The decision also includes measures for providing farmers with alternatives.^[140]

Residue

Pesticide residue refers to the pesticides that may remain on or in food after they are applied to food crops.^[141] The maximum allowable levels of these residues in foods are often stipulated by regulatory bodies in many countries. Regulations such as pre-harvest intervals also often prevent harvest of crop or livestock products if recently treated in order to allow residue concentrations to decrease over time to safe levels before harvest. Exposure of the general population to these residues most commonly occurs through consumption of treated food sources, or being in close contact to areas treated with pesticides such as farms or lawns.^[142]

Many of these chemical residues, especially derivatives of chlorinated pesticides, exhibit bioaccumulation which could build up to harmful levels in the body as well as in the environment.^[143] The problem is most acute in China, the largest producer of chlorinated pesticides.^[144] Persistent chemicals can be magnified through the food chain and have been detected in products ranging from meat, poultry, and fish, to vegetable oils, nuts, and various fruits and vegetables.^[145]

Pesticide contamination in the environment can be monitored through bioindicators such as bee pollinators.^[77]

There is an ongoing research focused on pesticide residues in farming system.^[146]

II. DISCUSSION

^[1] Health effects of pesticides may be acute or delayed in those who are exposed.^[2] Acute effects can include pesticide poisoning, which may be a medical emergency.^[3] Strong evidence exists for other, long-term negative health outcomes from pesticide exposure including birth defects, fetal death,^[4] neurodevelopmental disorder,^[5] cancer, and neurologic illness including Parkinson's disease.^[6] Toxicity of pesticides depend on the type of chemical, route of exposure, dosage, and timing of exposure.^[6]

According to The Stockholm Convention on Persistent Organic Pollutants (2001), 9 of the 12 most dangerous and persistent chemicals were pesticides,^{[7][8]} so many have now been withdrawn from use.

Route of exposure

People can be exposed to pesticides, which include insecticides, herbicides, fungicides, by a number of different routes including: occupation, in the home, at school, in the air, water, soil, and in food. Almost all humans are exposed to some level of pesticides.^[6] For example, pesticide drift, may be a potentially significant source of exposure to the general public.^[9] Exposure can occur via ingestion, inhalation, or contact with skin.^[10] Some pesticides can remain in the environment for prolonged periods of time.

There are concerns that pesticides used to control pests on food crops are dangerous to people who consume those foods. Many food crops, including fruits and vegetables, contain pesticide residues even after being washed or peeled. Chemicals that are no longer used but that are resistant to breakdown for long periods may remain in soil and water and, thus, in food.^[11] For example, most people in the United States still have detectable levels of dichlorodiphenyltrichloroethane (DDT), an insecticide, despite its ban in the US in 1972.^[8] These concerns are one reason for the organic food movement. In California, 92% of farmworkers are Latino^[12] and exposure to pesticides in majority-Latino counties of the state to pesticides is 906% higher than counties in which the Latino population is fewer than 24%. This has raised concerns over environmental justice.^[13]

Because of the common use of pesticides in agriculture, the United Nations Codex Alimentarius Commission has recommended international standards for maximum residue limits (MRLs), for individual pesticides in food.^[14] In the United States, levels of residues permitted to remain on foods are limited based on tolerance levels considered to be

safe as established by the U.S. Environmental Protection Agency (EPA).^[15] The EPA sets the permitted levels of pesticide residues based on the toxicity of the pesticide, its breakdown products, the amount and frequency of pesticide application, and how much of the pesticide (i.e. the residue) remains in or on food by the time it is marketed and distributed.^[16] Tolerance levels are obtained using scientific risk assessments that pesticide manufacturers are required to conduct—assessments include toxicological studies, exposure modeling and residue studies before a particular pesticide can be registered. However, the effects are tested a single pesticide at a time and there is little information on the possible synergistic effects of exposure to multiple pesticide traces in the air, food and water on human health.^[17] While pesticide use is commonly associated with agriculture, pesticides are also used as part of public health interventions to control vector-borne diseases (e.g. malaria and Dengue fever) and unwanted plants in the landscaping of parks and gardens.^[6]

Mechanism of action

Pesticides are designed to kill living organisms and vary in their mechanisms of action, depending on their class. The major classes of pesticides are organochlorines (OCPs) or persistent organic pollutants (POPs), organophosphates, carbamates, pyrethroids, and triazines. While all pesticides have been shown to have effects on human health, OCPs are notable for significant risk for adverse effects as they dissolve in fatty tissues and can, thus, accumulate to harmful levels in these tissues. For example, some OCPs are structurally similar to estrogen and can mimic the effects of endogenous estrogen via binding to the estrogen receptors.^[6] These pesticides exhibit their toxic effects by interfering with hormonal homeostasis, resulting in hormonal dysregulation. This promotes abnormal growth and development of reproductive tissues and can lead to cancer or harmful effects on reproductive health.^[10] OCPs or POPs, which were used in agricultural practices in the 1950s, have now been banned in most countries. However, their breakdown products are persistent and can still be found in soil.^[18]

Pesticides can also exert their adverse effects on human health by acting on cell receptors and ion channels, suppressing key signal pathways in cells, and by affecting DNA methylation and histone modifications, thus resulting in changes in gene expression and cellular function.^[18]

Acute effects

Acute health problems may occur in workers that handle pesticides, such as abdominal pain, dizziness, headaches, nausea, vomiting, as well as skin and eye problems.^[19] In China, an estimated half-million people are poisoned by pesticides each year, 500 of whom die.^[20] Pyrethrins, insecticides commonly used in common bug killers, can cause a potentially deadly condition if breathed in.^[21]

Long-term effects

Cancer

Many studies have examined the effects of pesticide exposure on the risk of cancer. Associations have been found with: leukemia, lymphoma, brain, kidney, breast, prostate, pancreas, liver, lung, stomach, esophageal, and skin cancers.^{[8][22]} This increased risk occurs with both residential and occupational exposures.^[8] Increased rates of cancer have been found among farm workers who apply these chemicals.^[23] Studies suggest an association between carbamate exposure and glioma and meningioma, glyphosate exposure and diffuse large B-cell lymphoma, as well as alachlor exposure and laryngeal cancer.^[24] A mother's occupational exposure to pesticides during pregnancy is associated with an increase in her child's risk of leukemia, Wilms' tumor, and brain cancer.^{[8][25]} Exposure to insecticides within the home and herbicides outside is associated with blood cancers in children.^[26] A 2007 systematic review found that "most studies on non-Hodgkin lymphoma and leukemia showed positive associations with pesticide exposure" and thus concluded that cosmetic use of pesticides should be decreased.^[27]

The suggested molecular mechanism for association of pesticide exposure and cancer development is damage to genetic materials such as chromosomes, DNA, and histone proteins, or damage to cell organelles such as endoplasmic reticulum, mitochondria, endocrine networks, and nuclear receptors.^[22]

Neurological

There is accumulating evidence of neurological effects secondary to pesticide exposure. Acute exposure to high levels of pesticides that affect the central nervous system can cause neurotoxicity, including cognitive and motor changes.^{[28][4]} In-utero and early-childhood exposure to organophosphates can cause neurodevelopmental impairment,^{[4][29][30]} in particular because some pesticides and their metabolites cross the placenta and fetal blood-brain-barrier, which has not fully developed in a fetus.^[30] In addition, an accumulation of chronic exposure has been associated with an increased risk of developing neurodegenerative disease later in life.^{[4][29][22]} There is strong evidence that chronic exposure to pesticides increases risk of developing Parkinson's disease, potentially through direct toxic effects on dopaminergic neurons (which are depleted in Parkinson's disease).^[29] In addition, there is increasing

evidence that chronic exposure increases risk of Alzheimer's disease.^{[29][22]} A review of multiple studies that looked at high pesticide exposure, mainly organophosphates, among agricultural workers further suggested neurological consequences for such exposures.^[24] High pesticide exposure is associated with neurologic, neuropsychiatric, and neurodegenerative disorders among agricultural workers who apply the pesticides.^{[24][22]} The reported disorders are: ADHD, depression, anxiety, dizziness, headaches and olfactory impairment (which was used as an early indicator for neurodegenerative disorders).^[24]

The United States Environmental Protection Agency finished a 10-year review of the organophosphate pesticides following the 1996 Food Quality Protection Act, but did little to account for developmental neurotoxic effects, drawing strong criticism from within the agency and from outside researchers.^{[31][32]} Comparable studies have not been done with newer pesticides that are replacing organophosphates.^[33]

Reproductive effects

Many pesticides act as endocrine-disrupting chemicals (EDC) or substances that interfere with normal hormonal activity.^[34] As of 2013, 101 pesticides have been listed as proven or possible endocrine disruptors. As such, high levels of and/or long-term exposure to pesticides can impact reproductive health and is associated with decreased fertility, increased rates of miscarriage, and changes in pattern of maturity. Specifically, triazines, organochlorines, and carbamate insecticides have anti-androgenic effects impacting males, resulting in the lack of development of male characteristics including decreases in testicular size, sperm production, and androgen production.^[22] A number of pesticides including dibromochlorophane and 2,4-D has been associated with impaired fertility in males.^[35] Pesticide exposure resulted in reduced fertility in males, genetic alterations in sperm, a reduced number of sperm, damage to germinal epithelium and altered hormone function.^[36]

The effects of endocrine disruption is dependent on the timing of pesticide exposure (for example, during embryogenesis in early pregnancy or in infancy) as windows of varying susceptibility dictate disease manifestation.^[34] Several studies suggest that higher levels of pesticides in the blood of the mother is associated with longer time to pregnancy and greater infertility rates. For example, in mothers and/or their partners who reported pesticide exposure, there was an increased risk of miscarriage with the strongest association with exposure during the first three weeks of pregnancy. This is perhaps linked to the possible negative impact of pesticides on oocyte development and fertilization. Similarly, studies evaluating the short-term impact of occupational exposure to a variety of pesticides on reproductive health suggest that pesticides can have deleterious effects on sperm—pesticide exposure, associated with decreased sperm motility, defects in sperm morphology and semen volume. However, the long-term impacts of pesticide exposure on spermatogenesis and fertility are unknown.^[30]

Because some pesticides and their resulting metabolites can cross the placenta and, therefore, the blood-brain-barrier, they can also impact development of the fetus; strong evidence links pre- and post-natal exposures to pesticides to congenital disorders, including physical and/or mental disabilities, fetal death and altered fetal growth.^{[4][30][22]} Perhaps the more widely known health effect of pesticides is the elevated rate of birth defects in areas in Vietnam sprayed with defoliant or Agent Orange, a 50:50 mixture of 2,4,5-T and 2,4-D, which has been associated with bad health and genetic effects in Malaya and Vietnam.^{[37][38][22]} It was also found that offspring who were at some point exposed to pesticides had a low birth weight and had developmental defects.^[39] Maternal exposure to pesticides has also been linked to higher incidence of hypospadias in the newborn, which is the abnormal opening of the urethra in males.^[22]

Other

Some studies have found increased risks of dermatitis in those exposed.^[4]

Additionally, studies have indicated that pesticide exposure is associated with long-term respiratory problems.^[40] A significant association was found between exposure to pesticides and decreased lung function along with related airway symptoms.^[24] Studies have suggested an association between exposure to pesticides and airway symptoms such as wheezing, cough, shortness of breath, runny nose, sore or irritation of throat, and difficulty breathing.^{[24][41]} Decreased lung function was associated with occupational exposure to pesticides. Studies have suggested a correlation between inhibition of cholinesterase by pesticides like carbamate and organophosphate and reduction or impairment of lung function.^[41] In addition, exposure to pesticides was also reported to be linked with obstructive and restrictive lung conditions. Specifically, organophosphate exposure was associated with lung function decline driven by a restrictive process.^[41]

Summaries of peer-reviewed research have examined the link between pesticide exposure and neurologic outcomes and cancer, perhaps the two most significant things resulting in organophosphate-exposed workers.^{[42][43]}

There is increasing evidence that possibly suggests increased risk of development of type 2 diabetes with exposure to pesticides and their metabolites.^[10]

Prevention

Pesticides exposure cannot be studied in placebo controlled trials as this would be unethical.^[4] A definitive cause effect relationship therefore cannot be established.^[4] Consistent evidence can and has been gathered through other study designs.^[4] The precautionary principle is thus frequently used in environmental law such that absolute proof is not required before efforts to decrease exposure to potential toxins are enacted.^[44]

The American Medical Association recommend limiting exposure to pesticides.^[45] They came to this conclusion due to the fact that surveillance systems currently in place are inadequate to determine problems related to exposure.^[45] The utility of applicator certification and public notification programs are also of unknown value in their ability to prevent adverse outcomes.^[45]

Epidemiology

The World Health Organization and the UN Environment Programme estimate that each year, 3 million workers in agriculture in the developing world experience severe poisoning from pesticides, about 18,000 of whom die.^[46] According to one study, as many as 25 million workers in developing countries may suffer mild pesticide poisoning yearly.^[47] Detectable levels of 50 different pesticides were found in the blood of a representative sample of the U.S. population.^[8]

Research conflicts of interest

Concerns regarding conflict of interests regarding the research base have been raised for some research into toxicity of pesticides. For example, Richard Doll of the Imperial Cancer Research Fund in England was found to have undisclosed ties to industry funding.^{[48][49]}

Other animals

A number of pesticides including the neonicotinoids clothianidin, dinotefuran, imidacloprid are toxic to bees.^[50] Exposure to pesticides may be one of the contributory factors to colony collapse disorder.^[51] A study in North Carolina indicated that more than 30 percent of the quail tested were made sick by one aerial insecticide application. Once sick, wild birds may neglect their young, abandon their nests, and become more susceptible to predators or disease.^[52]

III. RESULTS

The environmental effects of pesticides describe the broad series of consequences of using pesticides. The unintended consequences of pesticides is one of the main drivers of the negative impact of modern industrial agriculture on the environment. Pesticides, because they are toxic chemicals meant to kill pest species, can affect non-target species, such as plants, animals and humans. Over 98% of sprayed insecticides and 95% of herbicides reach a destination other than their target species, because they are sprayed or spread across entire agricultural fields.^[1] Other agrochemicals, such as fertilizers, can also have negative effects on the environment.

The negative effects of pesticides are not just in the area of application. Runoff and pesticide drift can carry pesticides into distant aquatic environments or other fields, grazing areas, human settlements and undeveloped areas. Other problems emerge from poor production, transport, storage and disposal practices.^[2] Over time, repeat application of pesticides increases pest resistance, while its effects on other species can facilitate the pest's resurgence.^[3] Alternatives to heavy use of pesticides, such as integrated pest management, and sustainable agriculture techniques such as polyculture mitigate these consequences, without the harmful toxic chemical application.

Environmental modelling indicates that globally over 60% of global agricultural land (~24.5 million km²) is "at risk of pesticide pollution by more than one active ingredient", and that over 30% is at "high risk" of which a third are in high-biodiversity regions.^{[4][5]} Each pesticide or pesticide class comes with a specific set of environmental concerns. Such undesirable effects have led many pesticides to be banned, while regulations have limited and/or reduced the use of others. The global spread of pesticide use, including the use of older/obsolete pesticides that have been banned in some jurisdictions, has increased overall.^{[6][7]}

History

After the end of World War I, the United States shifted its industries from the wartime production of chemicals to synthetic agriculturally used pesticide creation, using pyrethrum, rotenone, nicotine, sabadilla, and quassin as precursors to the expansive usage of pesticides in place today.^[8] Synthetic pesticides proved cheap and effective in killing insects, but garnered criticism from NGOs concerned about their effect on human health. In the years directly following World War II rose the creation and use of Aldrin (now banned in most countries), "dichlorodiphenyl



trichloroethane (DDT) in 1939, Dieldrin, β -Benzene Hexachloride (BHC), 2,4- Dichlorophenoxyacetic acid (2,4-D), Chlordane and Endrin".

While concern for ecotoxicology began with acute poisoning events in the late 19th century; public concern over the undesirable environmental effects of chemicals arose in the early 1960s with the publication of Rachel Carson's book, *Silent Spring*. Shortly thereafter, DDT, originally used to combat malaria, and its metabolites were shown to cause population-level effects in raptorial birds. Initial studies in industrialized countries focused on acute mortality effects mostly involving birds or fish.^[9]

Modern pesticide usage

However, true data on pesticide usage remain scattered and/or not publicly available, especially worldwide (3). Some scholars argue the common practice of incident registration is inadequate for understanding the entirety of effects.^[9]

Today, over 3.5 billion kilograms of synthetic pesticides are used for the world's agriculture in an over \$45 billion industry.^[10] Current lead agricultural producers include Syngenta (ChemChina), Bayer Crop Science, BASF, Dow AgroSciences, FMC, ADAMA, Nufarm, Corteva, Sumitomo Chemical, UPL, and Huapont Life Sciences. Bayer CropScience and its acquisition of Monsanto led it to record profits in 2019 of over \$10 billion in sales, which herbicide shares growing by 22%, followed closely by Syngenta.^[11]

In 2016, the United States consumed 322 million pounds [CONVERT] of pesticides banned in the EU, 26 million pounds [CONVERT] of pesticides banned in Brazil and 40 million pounds of pesticides banned in China, with most of banned pesticides banned staying constant or increasing in the United States over the past 25 years according to studies.^[12]

Scholarly research

Since 1990, research interest has shifted from documenting incidents and quantifying chemical exposure to studies aimed at linking laboratory, mesocosm and field experiments. The proportion of effect-related publications has increased. Animal studies mostly focus on fish, insects, birds, amphibians and arachnids.^[9]

Since 1993, the United States and the European Union have updated pesticide risk assessments, ending the use of acutely toxic organophosphate and carbamate insecticides. Newer pesticides aim at efficiency in target and minimum side effects in nontarget organisms. The phylogenetic proximity of beneficial and pest species complicates the project.^[9]

One of the major challenges is to link the results from cellular studies through many levels of increasing complexity to ecosystems.^[9]

The concept (borrowed from nuclear physics) of a half-life has been used for pesticides in plants,^[13] and certain authors maintain that pesticide risk and impact assessment models rely on and are sensitive to information describing dissipation from plants.^[14] Half-life for pesticides is explained in two NPIC fact sheets. Known degradation pathways are through: photolysis, chemical dissociation, sorption, bioaccumulation and plant or animal metabolism.^{[15][16]} A USDA fact sheet published in 1994 lists the soil adsorption coefficient and soil half-life for then-commonly used pesticides.^{[17][18]}

Specific pesticide effects

Pesticide environmental effects	
Pesticide/class	Effect(s)
Organochlorine DDT/DDE	Endocrine disruptor ^[19]
	Thyroid disruption properties in rodents, birds, amphibians and fish ^[20]
	Acute mortality attributed to inhibition of acetylcholinesterase activity ^[21]
DDT	Egg shell thinning in raptorial birds ^[20]
	Carcinogen ^[19]
	Endocrine disruptor ^[19]
DDT/Diclofol, Dieldrin and Toxaphene	Juvenile population decline and adult mortality in wildlife reptiles ^[22]
DDT/Toxaphene/Parathion	Susceptibility to fungal infection ^[23]
Triazine	Earthworms became infected with monocystid gregarines ^[9]
Chlordane	Interact with vertebrate immune systems ^[23]
Carbamates, the phenoxy herbicide 2,4-	Interact with vertebrate immune systems ^[23]

D, and atrazine	
Anticholinesterase	Bird poisoning ^[21]
	Animal infections, disease outbreaks and higher mortality. ^[24]
Organophosphate	Thyroid disruption properties in rodents, birds, amphibians and fish ^[20]
	Acute mortality attributed to inhibition of acetylcholine esterase activity ^[21]
	Immunotoxicity, primarily caused by the inhibition of serine hydrolases or esterases ^[25]
	Oxidative damage ^[25]
	Modulation of signal transduction pathways ^[25]
	Impaired metabolic functions such as thermoregulation, water and/or food intake and behavior, impaired development, reduced reproduction and hatching success in vertebrates. ^[26]
Carbamate	Thyroid disruption properties in rodents, birds, amphibians and fish ^[20]
	Impaired metabolic functions such as thermoregulation, water and/or food intake and behavior, impaired development, reduced reproduction and hatching success in vertebrates. ^[26]
	Interact with vertebrate immune systems ^[23]
	Acute mortality attributed to inhibition of acetylcholine esterase activity ^[21]
Phenoxy herbicide 2,4-D	Interact with vertebrate immune systems ^[23]
Atrazine	Interact with vertebrate immune systems ^[23]
	Reduced northern leopard frog (<i>Rana pipiens</i>) populations because atrazine killed phytoplankton, thus allowing light to penetrate the water column and periphyton to assimilate nutrients released from the plankton. Periphyton growth provided more food to grazers, increasing snail populations, which provide intermediate hosts for trematode. ^[27]
Pyrethroid	Thyroid disruption properties in rodents, birds, amphibians and fish ^[20]
Thiocarbamate	Thyroid disruption properties in rodents, birds, amphibians and fish ^[20]
Triazine	Thyroid disruption properties in rodents, birds, amphibians and fish ^[20]
Triazole	Thyroid disruption properties in rodents, birds, amphibians and fish ^[20]
	Impaired metabolic functions such as thermoregulation, water and/or food intake and behavior, impaired development, reduced reproduction and hatching success in vertebrates.
Neonicotinoic/Nicotinoid	respiratory, cardiovascular, neurological, and immunological toxicity in rats and humans ^[28]
	Disrupt biogenic amine signaling and cause subsequent olfactory dysfunction, as well as affecting foraging behavior, learning and memory.
Imidacloprid, Imidacloprid/pyrethroid λ -cyhalothrin	Impaired foraging, brood development, and colony success in terms of growth rate and new queen production. ^[29]
Thiamethoxam	High honey bee worker mortality due to homing failure ^[30] (risks for colony collapse remain controversial) ^[31]
Flupyradifurone	Lethal and sublethal adverse synergistic effects in bees. ^[32] Its toxicity depends on season and nutritional stress, and can reduce bee survival, food consumption, thermoregulation, flight success, and increase flight velocity. ^[33] It has the same mode of action of neonicotinoids. ^[34]



Spinosyns	Affect various physiological and behavioral traits of beneficial arthropods, particularly hymenopterans ^[35]
Bt corn/Cry	Reduced abundance of some insect taxa, predominantly susceptible Lepidopteran herbivores as well as their predators and parasitoids. ^[9]
Herbicide	Reduced food availability and adverse secondary effects on soil invertebrates and butterflies ^[36]
	Decreased species abundance and diversity in small mammals. ^[36]
Benomyl	Altered the patch-level floral display and later a two-thirds reduction of the total number of bee visits and in a shift in the visitors from large-bodied bees to small-bodied bees and flies ^[37]
Herbicide and planting cycles	Reduced survival and reproductive rates in seed-eating or carnivorous birds ^[38]

Persistent organic pollutants

Persistent organic pollutants (POPs) are compounds that resist degradation and thus remain in the environment for years. Some pesticides, including aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex and toxaphene, are considered POPs. Some POPs have the ability to volatilize and travel great distances through the atmosphere to become deposited in remote regions. Such chemicals may have the ability to bioaccumulate and biomagnify and can biomagnify (i.e. become more concentrated) up to 70,000 times their original concentrations.^[39] POPs can affect non-target organisms in the environment and increase risk to humans^[40] by disruption in the endocrine, reproductive, and respiratory systems.^[39]

Environmental effects

Air

Pesticides can contribute to air pollution. Pesticide drift occurs when pesticides suspended in the air as particles are carried by wind to other areas, potentially contaminating them.^[41] Pesticides that are applied to crops can volatilize and may be blown by winds into nearby areas, potentially posing a threat to wildlife.^[42] Weather conditions at the time of application as well as temperature and relative humidity change the spread of the pesticide in the air. As wind velocity increases so does the spray drift and exposure. Low relative humidity and high temperature result in more spray evaporating. The amount of inhalable pesticides in the outdoor environment is therefore often dependent on the season.^[3] Also, droplets of sprayed pesticides or particles from pesticides applied as dusts may travel on the wind to other areas,^[43] or pesticides may adhere to particles that blow in the wind, such as dust particles.^[44] Ground spraying produces less pesticide drift than aerial spraying does.^[45] Farmers can employ a buffer zone around their crop, consisting of empty land or non-crop plants such as Evergreen trees to serve as windbreaks and absorb the pesticides, preventing drift into other areas.^[46] Such windbreaks are legally required in the Netherlands.^[46]

Pesticides that are sprayed on to fields and used to fumigate soil can give off chemicals called volatile organic compounds, which can react with other chemicals and form a pollutant called ground level ozone. Pesticide use accounts for about 6 percent of total ground level ozone levels.^[47]

Water

In the United States, pesticides were found to pollute every stream and over 90% of wells sampled in a study by the US Geological Survey.^[48] Pesticide residues have also been found in rain and groundwater.^[49] Studies by the UK government showed that pesticide concentrations exceeded those allowable for drinking water in some samples of river water and groundwater.^[50]

Pesticide impacts on aquatic systems are often studied using a hydrology transport model to study movement and fate of chemicals in rivers and streams. As early as the 1970s quantitative analysis of pesticide runoff was conducted to predict amounts of pesticide that would reach surface waters.^[51]

There are four major routes through which pesticides reach the water: it may drift outside of the intended area when it is sprayed, it may percolate, or leach through the soil, it may be carried to the water as runoff, or it may be spilled, for example accidentally or through neglect.^[52] They may also be carried to water by eroding soil.^[53] Factors that affect a pesticide's ability to contaminate water include its water solubility, the distance from an application site to a body of water, weather, soil type, presence of a growing crop, and the method used to apply the chemical.^[54]

Water-focused regulations

In United States regulation, maximum limits of allowable concentrations^[55] for individual pesticides in drinking water are set by the Environmental Protection Agency (EPA) for public water systems.^{[49][54]} (There are no federal standards for private wells.) Ambient water quality standards for pesticide concentrations in water bodies are principally developed by state environmental agencies, with EPA oversight. These standards may be issued for individual water bodies, or may apply statewide.^{[56][57]}

The United Kingdom sets Environmental Quality Standards (EQS), or maximum allowable concentrations of some pesticides in bodies of water above which toxicity may occur.^[58]

The European Union regulates maximum concentrations of pesticides in water.^[58]

Soil

The extensive use of pesticides in agricultural production can degrade and damage the community of microorganisms living in the soil, particularly when these chemicals are overused or misused as chemical compounds build up in the soil.^[59] The full impact of pesticides on soil microorganisms is still not entirely understood; many studies have found deleterious effects of pesticides on soil microorganisms and biochemical processes, while others have found that the residue of some pesticides can be degraded and assimilated by microorganisms.^[60] The effect of pesticides on soil microorganisms is impacted by the persistence, concentration, and toxicity of the applied pesticide, in addition to various environmental factors.^[61] This complex interaction of factors makes it difficult to draw definitive conclusions about the interaction of pesticides with the soil ecosystem. In general, long-term pesticide application can disturb the biochemical processes of nutrient cycling.^[60]

Many of the chemicals used in pesticides are persistent soil contaminants, whose impact may endure for decades and adversely affect soil conservation.^[62]

The use of pesticides decreases the general biodiversity in the soil. Not using the chemicals results in higher soil quality,^[63] with the additional effect that more organic matter in the soil allows for higher water retention.^[49] This helps increase yields for farms in drought years, when organic farms have had yields 20-40% higher than their conventional counterparts.^[64] A smaller content of organic matter in the soil increases the amount of pesticide that will leave the area of application, because organic matter binds to and helps break down pesticides.^[49]

Degradation and sorption are both factors which influence the persistence of pesticides in soil. Depending on the chemical nature of the pesticide, such processes control directly the transportation from soil to water, and in turn to air and our food. Breaking down organic substances, degradation, involves interactions among microorganisms in the soil. Sorption affects bioaccumulation of pesticides which are dependent on organic matter in the soil. Weak organic acids have been shown to be weakly sorbed by soil, because of pH and mostly acidic structure. Sorbed chemicals have been shown to be less accessible to microorganisms. Aging mechanisms are poorly understood but as residence times in soil increase, pesticide residues become more resistant to degradation and extraction as they lose biological activity.^[65]

Impact on living beings

The impact on living beings also affects the non-living environment and humans indirectly.

Plants

Nitrogen fixation, which is required for the growth of vascular ("higher") plants, is hindered by pesticides in soil.^[66] The insecticides DDT, methyl parathion, and especially pentachlorophenol have been shown to interfere with legume-rhizobium chemical signaling.^[66] Reduction of this symbiotic chemical signaling results in reduced nitrogen fixation and thus reduced crop yields.^[66] Root nodule formation in these plants saves the world economy \$10 billion in synthetic nitrogen fertilizer every year.^[67]

On the other side, pesticides have some direct harmful effect on plant including poor root hair development, shoot yellowing and reduced plant growth.^[68]

Pollinators

Pesticides can kill bees and are strongly implicated in pollinator decline,^[69] the loss of species that pollinate plants, including through the mechanism of Colony Collapse Disorder,^{[70][71][72][73][unreliable source?]} in which worker bees from a beehive or western honey bee colony abruptly disappear. Application of pesticides to crops that are in bloom can kill honeybees,^[41] which act as pollinators. The USDA and USFWS estimate that US farmers lose at least \$200 million a year from reduced crop pollination because pesticides applied to fields eliminate about a fifth of honeybee colonies in the US and harm an additional 15%.^[1]

Animals

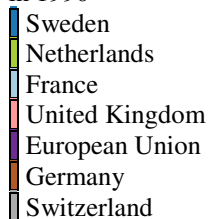
Many kinds of animals are harmed by pesticides, leading many countries to regulate pesticide usage through Biodiversity Action Plans.

Animals including humans may be poisoned by pesticide residues that remain on food, for example when wild animals enter sprayed fields or nearby areas shortly after spraying.^[45]

Pesticides can eliminate some animals' essential food sources, causing the animals to relocate, change their diet or starve. Residues can travel up the food chain; for example, birds can be harmed when they eat insects and worms that have consumed pesticides.^[41] Earthworms digest organic matter and increase nutrient content in the top layer of soil. They protect human health by ingesting decomposing litter and serving as bioindicators of soil activity. Pesticides have had harmful effects on growth and reproduction on earthworms.^[74] Some pesticides can bioaccumulate, or build up to toxic levels in the bodies of organisms that consume them over time, a phenomenon that impacts species high on the food chain especially hard.^[41]

Birds

Index of number of common farmland birds in the European Union and selected European countries, base equal to 100 in 1990^[75]



The US Fish and Wildlife Service estimates that 72 million birds are killed by pesticides in the United States each year.^[76] Bald eagles are common examples of nontarget organisms that are impacted by pesticide use. Rachel Carson's book *Silent Spring* uncovered the effects of bioaccumulation of the pesticide DDT in 1962.

Farmland birds are declining more rapidly than birds of any other biome in North America, a decline that is correlated with intensification and expansion of pesticide usage.^[77] In the farmland of the United Kingdom, populations of ten different bird species declined by 10 million breeding individuals between 1979 and 1999, allegedly from loss of plant and invertebrate species on which the birds feed. Throughout Europe, 116 species of birds were threatened as of 1999. Reductions in bird populations have been found to be associated with times and areas in which pesticides are used.^[78] DDE-induced egg shell thinning has especially affected European and North American bird populations.^[79] From 1990 to 2014 the number of common farmland birds has declined in the European Union as a whole and in France, Belgium and Sweden; in Germany, which relies more on organic farming and less on pesticides the decline has been slower; in Switzerland, which does not rely much on intensive agriculture, after a decline in the early 2000s the level has returned to the one of 1990.^[75]

In another example, some types of fungicides used in peanut farming are only slightly toxic to birds and mammals, but may kill earthworms, which can in turn reduce populations of the birds and mammals that feed on them.^[45]

Some pesticides come in granular form. Wildlife may eat the granules, mistaking them for grains of food. A few granules of a pesticide may be enough to kill a small bird.^[45] Herbicides may endanger bird populations by reducing their habitat.^[45] Furthermore, destruction of native habitat and conversion into other land-use types (e.g. agricultural, residential) contributes to the decline of these birds. Avicides poses a huge threat of direct poisoning of non-target birds. As poisoned birds can fly long distances before they die, death of non-target birds often remains unnoticed. Many countries have no registered pesticides of this group at all. In USA registered avicides belong to restricted use pesticides and can be used only by certified pest control operations.

Aquatic life

Fish and other aquatic biota may be harmed by pesticide-contaminated water.^[80] Pesticide surface runoff into rivers and streams can be highly lethal to aquatic life, sometimes killing all the fish in a particular stream.^[81]

Application of herbicides to bodies of water can cause fish kills when the dead plants decay and consume the water's oxygen, suffocating the fish. Herbicides such as copper sulfate that are applied to water to kill plants are toxic to fish and other water animals at concentrations similar to those used to kill the plants. Repeated exposure to sublethal doses of some pesticides can cause physiological and behavioral changes that reduce fish populations, such as abandonment of nests and broods, decreased immunity to disease and decreased predator avoidance.^[80]

Application of herbicides to bodies of water can kill plants on which fish depend for their habitat.^[80]

Pesticides can accumulate in bodies of water to levels that kill off zooplankton, the main source of food for young fish.^[82] Pesticides can also kill off insects on which some fish feed, causing the fish to travel farther in search of food and exposing them to greater risk from predators.^[80]

The faster a given pesticide breaks down in the environment, the less threat it poses to aquatic life. Insecticides are typically more toxic to aquatic life than herbicides and fungicides.^[80]

Amphibians

In the past several decades, amphibian populations have declined across the world, for unexplained reasons which are thought to be varied but of which pesticides may be a part.^[83]

Pesticide mixtures appear to have a cumulative toxic effect on frogs. Tadpoles from ponds containing multiple pesticides take longer to metamorphose and are smaller when they do, decreasing their ability to catch prey and avoid predators.^[84] Exposing tadpoles to the organochloride endosulfan at levels likely to be found in habitats near fields sprayed with the chemical kills the tadpoles and causes behavioral and growth abnormalities.^[85]

The herbicide atrazine can turn male frogs into hermaphrodites, decreasing their ability to reproduce.^[84] Both reproductive and nonreproductive effects in aquatic reptiles and amphibians have been reported. Crocodiles, many turtle species and some lizards lack sex-distinct chromosomes until after fertilization during organogenesis, depending on temperature. Embryonic exposure in turtles to various PCBs causes a sex reversal. Across the United States and Canada disorders such as decreased hatching success, feminization, skin lesions, and other developmental abnormalities have been reported.^[79]

Humans

Pesticides can enter the body through inhalation of aerosols, dust and vapor that contain pesticides; through oral exposure by consuming food/water; and through skin exposure by direct contact.^[86] Pesticides secrete into soils and groundwater which can end up in drinking water, and pesticide spray can drift and pollute the air.

The effects of pesticides on human health depend on the toxicity of the chemical and the length and magnitude of exposure.^[87] Farm workers and their families experience the greatest exposure to agricultural pesticides through direct contact. Every human contains pesticides in their fat cells.

Children are more susceptible and sensitive to pesticides,^[86] because they are still developing and have a weaker immune system than adults. Children may be more exposed due to their closer proximity to the ground and tendency to put unfamiliar objects in their mouth. Hand to mouth contact depends on the child's age, much like lead exposure. Children under the age of six months are more apt to experience exposure from breast milk and inhalation of small particles. Pesticides tracked into the home from family members increase the risk of exposure. Toxic residue in food may contribute to a child's exposure.^[88] Epidemiological studies have reported adverse effects of certain pesticides at current levels of exposure on children's cognitive development.^[89] The chemicals can bioaccumulate in the body over time.

Exposure effects can range from mild skin irritation to birth defects, tumors, genetic changes, blood and nerve disorders, endocrine disruption, coma or death.^[87] Developmental effects have been associated with pesticides. Recent increases in childhood cancers in throughout North America, such as leukemia, may be a result of somatic cell mutations.^[90] Insecticides targeted to disrupt insects can have harmful effects on mammalian nervous systems. Both chronic and acute alterations have been observed in exposures. DDT and its breakdown product DDE disturb estrogenic activity and possibly lead to breast cancer. Fetal DDT exposure reduces male penis size in animals and can produce undescended testicles. Pesticide can affect fetuses in early stages of development, in utero and even if a parent was exposed before conception. Reproductive disruption has the potential to occur by chemical reactivity and through structural changes.^[91]

Pest resistance

Pesticide application can artificially select for resistant pests. In this diagram, the first generation happens to have an insect with a heightened resistance to a pesticide (red) After pesticide application, its descendants represent a larger proportion of the population, because sensitive pests (white) have been selectively killed. After repeated applications, resistant pests may comprise the majority of the population.

Pesticide resistance describes the decreased susceptibility of a pest population to a pesticide that was previously effective at controlling the pest. Pest species evolve pesticide resistance via natural selection: the most resistant specimens survive and pass on their acquired heritable changes traits to their offspring.^[92] If a pest has resistance then that will reduce the pesticide's efficacy – efficacy and resistance are inversely related.^[93]

Cases of resistance have been reported in all classes of pests (i.e. crop diseases, weeds, rodents, etc.), with 'crises' in insect control occurring early-on after the introduction of pesticide use in the 20th century. The Insecticide Resistance Action Committee (IRAC) definition of insecticide resistance is 'a heritable change in the sensitivity of a pest

population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species'.^[94]

Pesticide resistance is increasing. Farmers in the US lost 7% of their crops to pests in the 1940s; over the 1980s and 1990s, the loss was 13%, even though more pesticides were being used.^[92] Over 500 species of pests have evolved a resistance to a pesticide.^[95] Other sources estimate the number to be around 1,000 species since 1945.^[96]

Although the evolution of pesticide resistance is usually discussed as a result of pesticide use, it is important to keep in mind that pest populations can also adapt to non-chemical methods of control. For example, the northern corn rootworm (*Diabrotica barberi*) became adapted to a corn-soybean crop rotation by spending the year when the field is planted with soybeans in a diapause.^[97]

As of 2014, few new weed killers are near commercialization, and none with a novel, resistance-free mode of action.^[98] Similarly, as of January 2019 discovery of new insecticides is more expensive and difficult than ever.^[99]

Pest rebound and secondary pest outbreaks

Non-target organisms can also be impacted by pesticides. In some cases, a pest insect that is controlled by a beneficial predator or parasite can flourish should an insecticide application kill both pest and beneficial populations. A study comparing biological pest control and pyrethroid insecticide for diamondback moths, a major cabbage family insect pest, showed that the pest population rebounded due to loss of insect predators, whereas the biocontrol did not show the same effect.^[100] Likewise, pesticides sprayed to control mosquitoes may temporarily depress mosquito populations, they may result in a larger population in the long run by damaging natural controls.^[41] This phenomenon, wherein the population of a pest species rebounds to equal or greater numbers than it had before pesticide use, is called pest resurgence and can be linked to elimination of its predators and other natural enemies.^[101]

Loss of predator species can also lead to a related phenomenon called secondary pest outbreaks, an increase in problems from species that were not originally a problem due to loss of their predators or parasites.^[101] An estimated third of the 300 most damaging insects in the US were originally secondary pests and only became a major problem after the use of pesticides.^[1] In both pest resurgence and secondary outbreaks, their natural enemies were more susceptible to the pesticides than the pests themselves, in some cases causing the pest population to be higher than it was before the use of pesticide.^[101]

Alternatives

Many alternatives are available to reduce the effects pesticides have on the environment. Alternatives to pesticides include manual removal, applying heat, covering weeds with plastic, placing traps and lures, removing pest breeding sites, maintaining healthy soils that breed healthy, more resistant plants, cropping native species that are naturally more resistant to native pests and supporting biocontrol agents such as birds and other pest predators.^[102] In the United States, conventional pesticide use peaked in 1979, and by 2007, had been reduced by 25 percent from the 1979 peak level,^[103] while US agricultural output increased by 43 percent over the same period.^[104]

Biological controls such as resistant plant varieties and the use of pheromones, have been successful and at times permanently resolve a pest problem.^[105] Integrated Pest Management (IPM) employs chemical use only when other alternatives are ineffective. IPM causes less harm to humans and the environment. The focus is broader than on a specific pest, considering a range of pest control alternatives.^[106] Biotechnology can also be an innovative way to control pests. Strains can be genetically modified (GM) to increase their resistance to pests.^[105]

Biopesticides such as canola oil and baking soda that contain certain active ingredients from natural substances are an environmentally friendly alternative for toxic pesticides.^[107] There are three categories of biopesticides; microbial pesticides, plant-incorporated protectants (PIPs), and biochemical biopesticides. The alternatives to pesticides include a range of genetic material introduction to plants that target a particular pest, and active ingredients that control the mating and reproduction of certain pests or kill target pests.^[107] Biopesticides are affective in small quantities and degrade quickly making them an eco-friendly alternative to pesticides.^[108] They are often used in Integrated Pest Management (IPM) as well and has been an important component to the UK IPM strategy for its crop protection.^[109]

Waste and disposal

In the United States, the Environmental Protection Agency (EPA) suggests proper use of pesticides and disposal that follows federal or individual state guidance for farmers or commercial users.^[110] Commercial users of pesticides are told to follow the disposal instructions on the labels of the pesticides while using necessary safety measures for the disposal of hazardous waste.^[110] They are also advised to call for assistance by their local agencies in the disposal of unwanted or unused pesticides.^[110]

Still are there environmental problems that emerge from runoff and other negative effects of pesticides. Runoff of pesticides into wastewater and pesticide drift into other ecosystems has led to research in the removal and remediation of pesticides in the environment. Research has been done on different methods to treat pesticide pollution including the use of activated carbon absorption and advanced oxidation processes. Different methods of pesticide removal require

different costs and can carry different removal outcomes. Some methods require low cost techniques but many result in byproducts that require an extra cost for removal or unwarranted environmental impacts.^[111]

There is an ongoing research focused on pesticide removal, a 2022 study for example demonstrated excellent removal efficiency of 80% for often used pesticide chlorpyrifos through usage magnetic plant biobots.^[112]

Activated carbon absorption

Due to the properties of activated carbon, different types have been researched as potential treatment for absorbing different pesticide species.^[113] Researchers found a use for activated carbon from tangerine seeds in the absorption of pesticides.^[114] Researches are utilizing this tangerine seed activated carbon in the removal process of carbamate pesticides that have been linked to an increased risk of cancer and other health risks.^[114] Absorption by activated carbon has been found to be a successful and cost-efficient way of removing pesticides.^[114]

IV. CONCLUSION

Advanced oxidation process (AOP)

Advanced oxidation processes have been used to combat against the problem of pesticide residue on fruits and vegetables. AOP and its technologies have been used in the removal efforts of pesticide pollutants in wastewater using different chemical reactions to target different pollutants.^[115] Researchers have found this method of pesticide removal using coupled free chlorine/ultrasound to be successful at removing pesticide residue from vegetables.^[116]

Activism

Pesticide Action Network

While dubbed economic and ecologically sound practices by suppliers, the effects of agricultural pesticides can include toxicity, bioaccumulation, persistence, and physiological responses in humans and wildlife,^[117] and several international NGOs, such as Pesticide Action Network, have risen in response to the economic activities of these larger transnational corporations. Historically, PAN's contributions targeting the Dirty Dozen have resulted in treaties and global environmental law banning persistent organic pollutants (POPs), such as endosulfan, and their campaign work on Prior Informed Consent (PIC) for countries in the Global South to know what hazardous and banned chemicals they might be importing have contributed to the culmination of the Rotterdam Convention on Prior Informed Consent, which went into effect in 2004.^[118] PAN's work, according to their website, involves "shifting global aid away from pesticides",^[119] in addition to community monitoring and serving as a watchdog for the World Bank policy failures.^[119] Additionally, Pesticide Action Network members helped co-author the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), working to center agroecological knowledge and farming techniques as crucial to the future of agriculture.^[119]

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