CHAPTER 5. PESTICIDES

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A pesticide is any substance or mixture of substances intended to repel, destroy or control any pest or prevent plant growth Pesticides may include chemical and biological ingredients and may be further characterized as insecticides, herbicides, fungicides, bactericides, rodenticides, and plant growth regulators, as well as public health insecticides. The use of pesticides can protect crops and prevent post-harvest losses, thus contributing to food security. Pesticides also help to avoid the spread of pests and diseases in global trade and in stored agricultural commodities.

The development of pesticides was fundamental to the Green Revolution and transformation of modern agriculture and in many countries the use of pesticides, especially in monoculture areas, has been common practice for pest control (Ongley, 1996). Despite their importance in plant protection, more recently evidence of the serious impacts on the environment has emerged. Pesticide misuse and pesticides as water pollutants are increasingly serious global challenges resulting in heavy environmental pollution and high health risks for humans (FAO/WHO, 2016). This chapter briefly describes the global usage of pesticides, their characteristics, environmental loads and resulting concentration in water bodies and their impact on human health and the environment.

5.1 Pesticides and water pollution

5.1.1 Pesticide consumption and production

Fruit and vegetable crops account for most of the pesticides used worldwide, although in developed countries, pesticides (mainly herbicides) are used primarily for maize production (Zhang, Jiang and Ou, 2011).

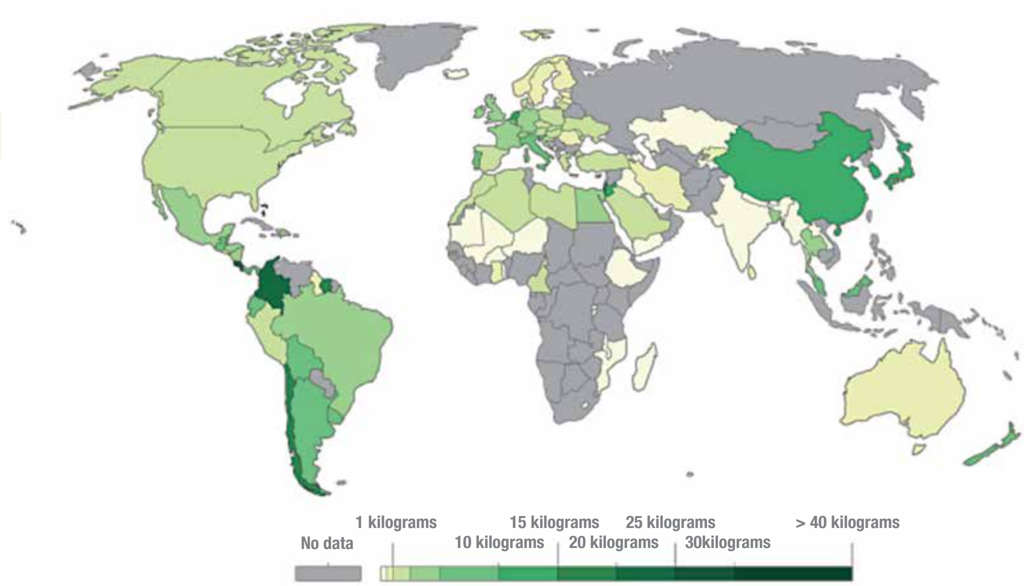
Pesticide production is a global industry worth more than USD 35 billion per year. About 500 pesticides are used for mass application, some of which are highly poisonous to the environment (Zhang, Jiang and Ou, 2011). Globally, 4.6 million tonnes of chemical pesticides are sprayed into the environment every year. Worldwide consumption of pesticides has undergone significant changes since the 1960s. The proportion of herbicides has increased and that of insecticides and fungicides and bactericides has declined (Zhang, Jiang and Ou, 2011). In terms of current global consumption, 47.5 percent of pesticides are herbicides, 29.5 percent are insecticides and 17.5 percent are fungicides, with all others accounting for 5.5 percent (De, 20.14).

Overall pesticide consumption in Europe has declined 50 percent compared to the average in the 1980s (Zhang, Jiang and Ou, 2011). As early as 1972, the use of DDT and related organochlorine insecticides, was banned in the United States and many other countries. Subsequently, pesticide consumption in the United States declined by 35 percent without reducing crop production (Zhang, Jiang and Ou, 2011). However, the United States is still the second largest consumer of pesticides in the world, accounting for 410 000 tonnes of active ingredients, followed by Brazil with 396 000 tonnes, Argentina with 208 000 tonnes, Mexico with 99 000 tonnes, Ukraine with 78 000 tonnes, Canada with 73 000 tonnes and France, Italy, Spain and India with around 60 000 tonnes each (FAO, 2017a). China is the world's biggest producer and exporter of pesticides, and annual pesticide use in China is about 1.8 million tonnes of active ingredients (FAO, 2017a), on approximately 300 million hectares of farmland and forests. However, official statistics indicate about seven percent of China's cropland has been polluted due to improper use of pesticides and fertilizers, and the use of high-toxicity pesticides has killed beneficial insects, leading to numerous pest disasters in China in recent years.

Figure 5.1 below shows the average pesticide application per unit of cropland.

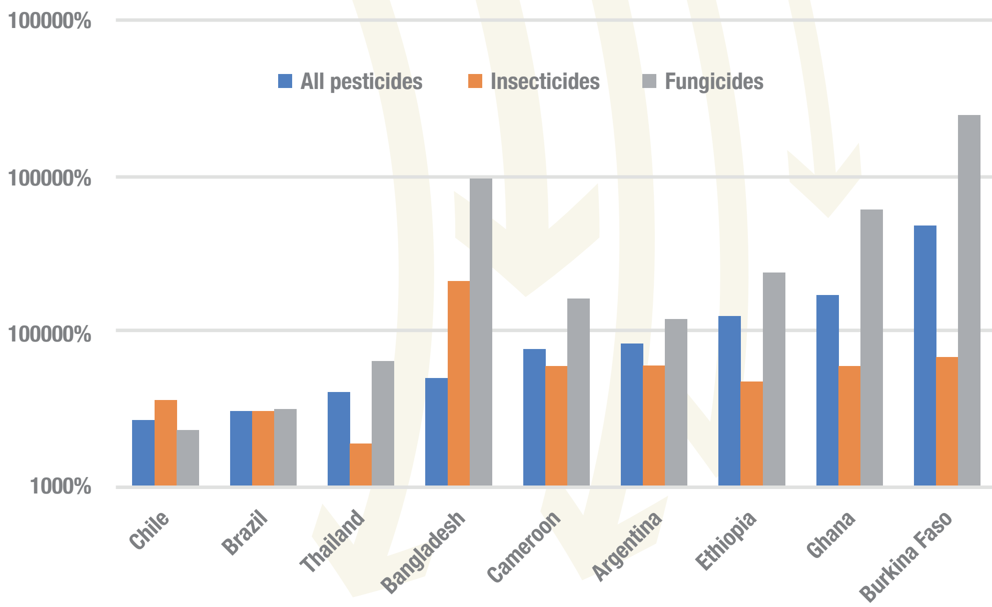
In terms of pesticide consumption in the developing world, sales are growing, even if from generally low levels (Figure 5.2). In Vietnam, pesticide consumption increased from 14 000 tonnes (under 837 trade names) in 1990 to 50 000 tonnes (under more than 3 000 trade names)

FIGURE 5.1 Pesticide use per hectare of cropland, 2007



Source: FAO, 2014.

FIGURE 5.2 Change in agricultural pesticide use (%) over an approximate 20-year period (1990 to latest data: 2007–2012) (countries with the highest increase)



Source: Adapted from Pretty and Bharucha, 2015; FAOStat, 2011; OECD, 2013.

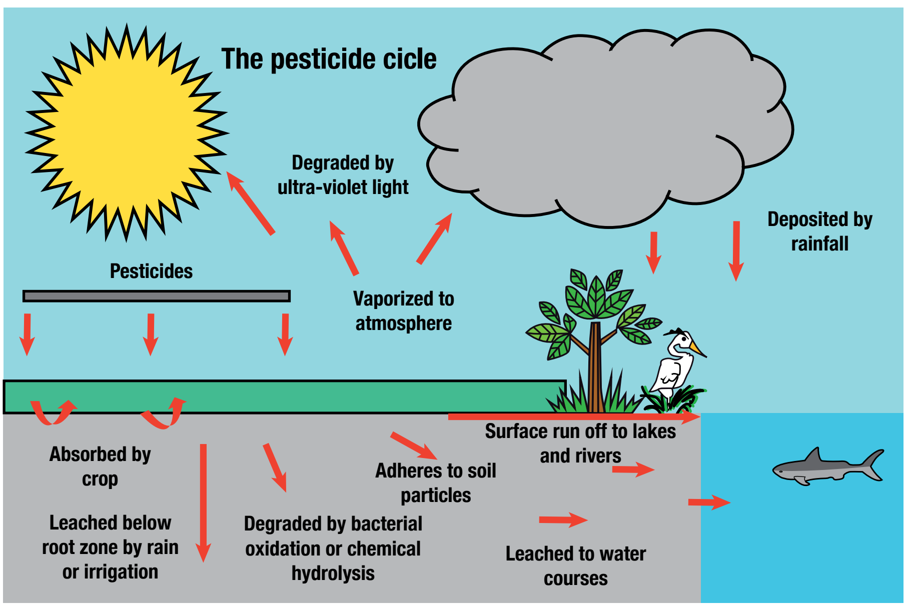
in 2008. Moreover, in the past decade pesticide sales increased even in Africa, which has the lowest consumption of any region. Several upper middle-income countries (e.g. Argentina, Brazil, Malaysia, South Africa and Uruguay) and lower middle-income countries (e.g. Cameroon, Cape Verde, Nicaragua, Pakistan and Ukraine) have experienced double-digit growth in the intensity of pesticide use, albeit from relatively low levels. Costa Rica, Colombia, Japan and Mexico have the highest intensity of pesticide use (kilogram of active ingredient per hectare and per crop output) worldwide (Schreinemachers and Tipraqsa, 2012).

5.1.2 Pesticide pollution of water

In terms of the risk of pesticide water pollution, each pesticide has unique properties and many variable factors affect this risk, such as the active ingredients, contaminants and additives as well as any degradate formed during chemical, microbial or photochemical degradation of active ingredients. The increased use of pesticides has been accompanied by the growing presence in soil of a large number of transformation products (TPs) for a wide variety of pesticides (Aktar *et al*., 2009) These compounds have proven to be highly toxic, persistent and accumulative in the food chain.

Figure 5. 3 below shows the pesticide cycle and how pesticides typically move throughout an ecosystem and may end up in other parts of the environment, such as in water and soil.

FIGURE 5.3 | The pesticide cycle



Source: University of Reading, 2018.

The persistence of agricultural toxins in ecosystems presents two primary concerns:

- bioaccumulation: an increase in concentration of a pollutant from the environment to the first organism in a food chain, and
- biomagnification: an increase in concentration of a pollutant from one link in a food chain to another. In order for biomagnification to occur, the pollutant must be long-lived, mobile, soluble in fats and biologically active.

Pesticides and TPs can be grouped into two classes: hydrophobic and polar. Hydrophobic pesticides are persistent, bioaccumulable and bind strongly to soil. They include organochlorines such as DDT, endosulfan, endrin, heptachlor, lindane and their TPs. Most of these have already been banned in agriculture but their residues are still present. Polar pesticides are mostly herbicides, but they also include carbamates, fungicides and some organophosphorus insecticide TPs. They are soluble, which means that runoff and leaching can transported them to surface water and groundwater from soil. The most researched pesticide TPs in soil are derived from herbicides and although most herbicides are not toxic to soil fauna, some are, including triazines (such as atrazine) and bipyridyl herbicides (such as paraquat). Newly developed pesticides, such as carbamate and organophosphate insecticides are considered 'safer' in that they are not persistent, one of the requirements to avoid biomagnification.

Other important properties relevant to pollution include the following:

- Pesticide half-life: The amount of time a pesticide takes to break down is measured in terms of its half-life. The more stable a pesticide, the longer it takes to break down and the higher its persistence. A pesticide's half-life also depends on specific environmental and application factors, but it is unique to each individual product.
- Mobility in soil: All pesticides have unique mobility properties through the soil structure, both vertically and horizontally. Even when pesticides have short half-lives, there are considerable risks from direct contamination of waterways through spray drift, runoff and leakage and seepage from improper storage.
- Solubility in water: Many pesticides are soluble in water so that they can be applied with water and absorbed by the target. The risk of leaching increases with higher solubility. Residual herbicides generally have lower solubility to aid soil binding but their persistence in soil can cause other problems (SDWF, 2017).

External factors are also important in determining the behavior of pesticides in the environment, including:

- Microbial activity, where pesticides in soil are primarily broken down by microbial activity and the greater the microbial activity, the faster the degradation.
- Soil temperature, where soil microbial activity and pesticide breakdown are closely linked to soil temperature.
- Treatment surface, where pesticides, such as residual herbicides, applied to hard surfaces (such as concrete or tarmac in garden pathways and driveways) cannot be absorbed and are particularly vulnerable to movement into water courses and non-target areas, especially after rainfall.
- Application rates, where the length of time that significant concentrations remain in the environment is directly related to the amount of pesticide that is applied (SDWF, 2017).

5.2 Pesticide accumulation in groundwater, surface water, lakes and reservoirs

Pesticides contaminate surface water, groundwater and soil. They can reach surface water by runoff from treated plants and soil and contamination of water by pesticides is widespread. The presence of pesticides as pollutants of water depends on their mobility, solubility and rate of degradation. Many modern pesticides break down quickly in soil or sunlight but are more likely to persist if they reach subsoil or groundwater because of reduced microbial activity, absence of light and lower temperatures (Kerle *et al*., 1994).

Pesticide residues are increasingly present in surface and groundwater (in OECD countries), with a significant number of samples above the legislated limits. In a survey of 3 500 sites in England and Wales, 100 of the 120 pesticides targeted were detected and five herbicides (Atrazine, diuron, bentazone, isoproturon and mecoprop) regularly exceeded EC Drinking Water Directive limits (Packman, 1995). In China, pesticides such as chlordane, Atrazine, carbofuran and many older pesticides, such as DDT, are banned outright but are used illegally and persist in the environment. Pesticides such as DDT, HCH, dieldrin and endrin have been detected in most bodies of water in China. Water bodies near croplands are generally polluted and the pesticide concentration in such water can reach tens of milligrams per litre. The levels of pesticide water pollution can be ranked from highest to lowest concentration as: cropland water > field ditch water > runoff > pond water > groundwater > river water > deep groundwater > sea water (Zhang, Jiang and Ou, 2011).

Most developed countries regularly monitor key pesticides, although high costs for sampling and analysis mean many datasets are not extensive. However, according to a recent meta-analysis, monitoring data is lacking for approximately 90 percent of global cropland (Stehle and Schulz, 2015). This study included 838 peer-reviewed scientific articles on surface water exposure to agricultural insecticides that between them covered more than 2 500 sites in 73 countries. The authors looked at whether measured insecticide concentrations (MICs) exceed regulatory threshold levels, as well as at the relationship between historical insecticide development, the level of environmental regulation and risks of exposure of surface waters to agricultural insecticides. The results showed that no MICs were present in 97.4 percent of the analyses and that newer insecticides, such as pyrethoids, have higher retention time locking (RTL) for surface water or sediment.

Another study, by the United States Geological Service (USGS), reported more than 143 different pesticides and 21 transformation products in groundwater, including pesticides from every major chemical class (Toccalino *et al.*, 2014). Over the past two decades, pesticides and TPs have been detected in the groundwater of more than 43 states. The United States of America Environmental Protection Agency (US EPA, 2017) reports widespread contamination of waterways (rivers, lakes) by Atrazine, the second most commonly used herbicide in the United States. In 1984, 12 kinds of high-concentration pesticides were measured in the groundwater in 18 states of the United States. By 1986, 17 kinds of pesticides had been detected in groundwater in 23 states. In Florida, concentration of dibromoethane in groundwater was 64 times higher than the maximum allowable amount, which resulted in more than 1 000 wells being closed (FAO, 2013). Moreover, the US EPA reports that many rural wells in the country contain at least one of 127 pesticides (Zhang, Jiang and Ou, 2011). Table 5.1 below shows the dominant pesticides used and typical compounds detected in groundwater selected regions.

Research from the USGS National Water-Quality Assessment (NAWQA) programme provides a comprehensive analysis of occurrence and decadal-scale changes in pesticide concentrations in groundwater of the United States for the period 1993-2011. Figure 5.4 below shows the twenty most frequently detected pesticides and their degradation products, as well as how the occurrences of individual pesticides in streams have changed between decades in the United States. The pesticides most frequently detected in the decadal comparisons include 11 herbicides (plus two degradates – deethylatrazine from atrazine and three 4-dichloroaniline from triclocarban, diuron, linuron, and other herbicides), four insecticides (plus two degradates – desulfinylfipronil and fipronil sulfide, both from fipronil), and one fungicide—metalaxyl (Stone, Gilliom and Ryberg, 2014). The results-based

Table 5.1 | Dominant pesticides used and typical compounds detected

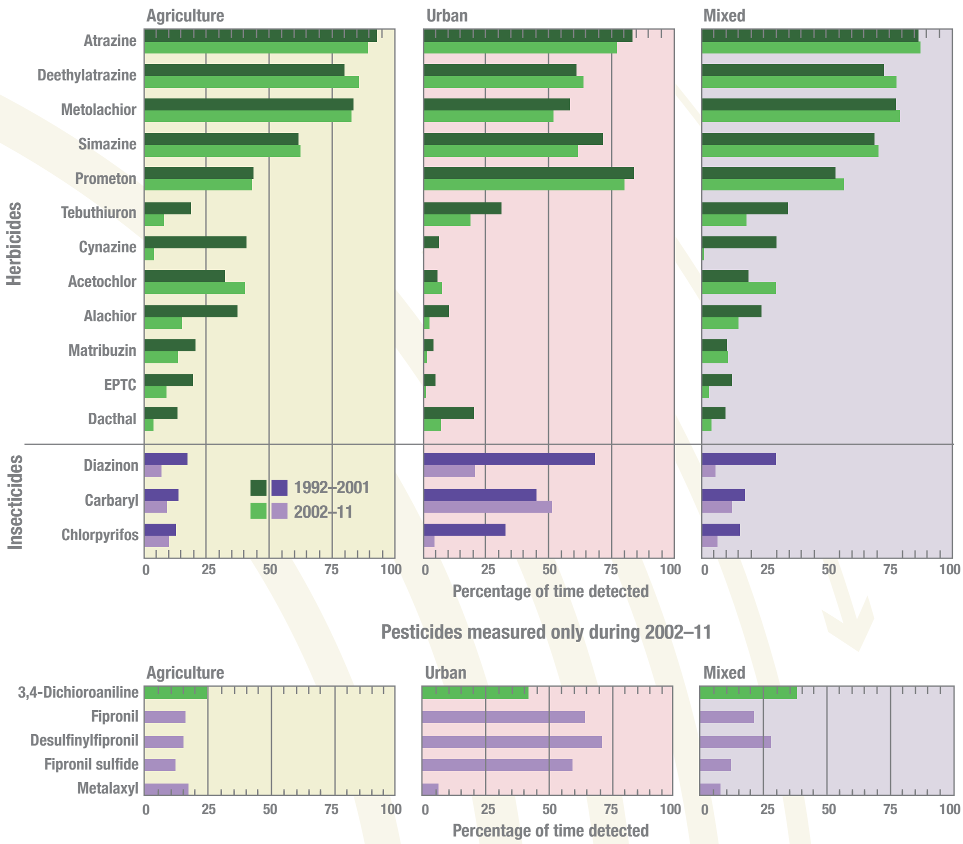
Region	Dominant pesticide use	Typical compounds detected
United Kingdom	Pre-and post-emergent herbicides on cereals, triazine herbicides on maize and in orchards	Isoproturon, mecoprop, atrazine, simazine
Northern Europe	Cereal herbicides and triazines as above	As above
Southern Europe	Carbamate and chloropropane soil insecticides for soft fruit, triazines for maize	Atrazine, alachlor
Northern United States	Triazines on maize and carbamates on vegetables e.g. potatoes	Atrazine, aldicarb, metolachlor, alachlor and their metabolites
Southern & Western United States	On citrus and horticulture, and fumigants for fruit and crop storage	Aldicarb, alachlor and their metabolites, ethylene dibromide
Central America & Caribbean	Fungicides for bananas, triazines for sugarcane, insecticides for cotton, and other plantation crops	Atrazine
South Asia	Organo-phosphorus & organo-chlorine insecticides in wide range of crops	Carbofuran, aldicarb, lindane
Africa	Insect control in houses and for disease vectors	Little monitoring as yet

Source: Morris *et al.*, 2003, as cited in FAO, 2012.

monitoring and assessment confirm previously reported findings: pesticides were frequently detected in groundwater (53 percent of all samples) and although concentrations seldom exceeded human-health benchmarks (1.8 percent of all samples) pesticides were found at concentrations that exceeded aquatic-life benchmarks in many rivers and streams that drain agricultural, urban, and mixed-land use watersheds. The frequent detection (>36 percent) of pesticides in samples from major aquifers used to supply drinking-water indicates the vulnerability of these aquifers to contamination from human activities at the land surface and emphasizes the importance of wellhead protection programmes and other strategies designed to reduce groundwater contamination from human sources (Toccalino *et al.*, 2014). In agricultural land, the proportion of assessed streams with one or more pesticides that exceeded an aquatic life benchmark, were very similar for the previous two decades, with 69 percent for 1992–2001 compared to 61 percent for 2002–2011 (Stone, Gilliom and Ryberg, 2014).

The result outlined in this section highlight the high risk to global water resources and the need for improved global regulation of agricultural pesticide practices. In addition, further research efforts are needed to better understand the presence and effects of

FIGURE 5.4 **Percentage of time detected for the periods of 1992-2001 and 2002-2011, for the most frequently detected pesticides in United States streams and rivers**



Source: Stone, Gilliom and Ryberg, 2014.

pesticide use, especially in developing countries, which often lack monitoring data and where chemical analyses are often not carried out because of a lack of facilities, low quality reagents or financial constraints (SDWF, 2017).

5. 3 Impacts on health and environment

Despite recent estimates that the economic impact of pesticides on non-target species (including humans) is approximately USD 8 billion annually in developing countries, the use of pesticides is increasing and millions of tonnes of active pesticide ingredients are used in agriculture (Aktar *et al.*, 2009). Understanding the potential effects of the resulting chemical mixtures on humans and the environment is one of the most complex problems facing scientists and regulatory agencies (SDWF, 2017). Pesticide accumulation in groundwater and surface water bodies, especially lakes and wetlands, is thus a growing concern.

Pesticide residues reach the aquatic environment through several non-point and point sources of pollution, including direct run-off, leaching, careless disposal of empty containers or the washing of equipment after pesticide application. All pesticides are designed to be sufficiently toxic and persistent to reduce populations of the pest they are designed to control, but most pesticides also poison fish and wildlife, contaminate food sources, destroy animal habitats and, moreover, are toxic to humans—representing a significant threat to human health when present in the water supply (Entry and Sojka, 2014). Contamination of surface water by pesticides usually depends on the farming season, whereas contamination of groundwater is more persistent and therefor may have continuous toxic effects on human health if used for public consumption (Herrero-Hernández *et al.*, 2013).

Prior to the 1980s, there was relatively little concern that water resources, especially groundwater, could be polluted by pesticides (Morris *et al.*, 2003). While significant advances have been made in controlling point-source pesticide pollution since then, little progress has been made regarding non-point-source pollution because of challenges related to the seasonality, inherent variability and multiplicity of origins of non-point-source pollution. At the same time, regulatory agencies have long agreed on the effects of pesticides in drinking water and limits to their. For instance, WHO water quality guidelines exist for some pesticides used in agriculture and public health—including for some highly hazardous pesticides—where there is a likelihood of drinking-water contamination (WHO, 2010). While there may be some increased vigilance about the probable negative impacts of using toxins to control pests and diseases in agriculture, a lack of understanding of the status of pesticides in ecosystems still poses a significant challenge. Some of the reasons for this knowledge gap includes: low detection limit requirements; costs of routine and area-wide monitoring; and poor understanding of the fate and processing of pesticides and their transformation products.

Pesticide poisoning in humans is a high-profile concern. Pesticide contaminated soil and water resources hamper development efforts in rural communities that are suffering from acute and likely chronic health effects related to pesticide poisoning (FAO, 2016). The health effects of pesticides depend on the type of pesticide. Some, such as the organophosphates and carbamates, affect the nervous system. Others may irritate the skin or eyes, cause cancer, or affect the hormone system. In any case, exposure to a sufficient amount of almost any pesticide can make a person ill, and the toxicity of some pesticides is so high that even very small quantities can kill a person.

Water degraded by pesticide runoff impacts human health in two ways; the consumption of food products contaminated by pesticides and the direct consumption of pesticide-contaminated water (FAO, 2013). Contaminated food, for example, mostly fruit and vegetables, is believed to be responsible for about 10 per cent of cancer cases in India (Aktar, Sengupta and Chowdhury, 2009). Furthermore, when pesticides come in contact with bodies of water, they can interfere with the food chain and cause that way. For example, if chemicals such as lead or copper from pesticides enter water bodies, fish can take them up and concentrate them. When people eat such contaminated fish, they can suffer damage to multiple systems including kidney disease (Ajia, 2017).

While there are no reliable figures on how many people suffer from pesticide-related health effects annually, acute pesticide poisoning causes significant human morbidity and mortality worldwide, especially in developing countries, where poor farmers often use very hazardous pesticide formulations. The lack of data on pesticide-related health issues is the result of several factors, including a lack of standardized case definitions. Studies in developed countries estimate that the annual incidence rates of acute pesticide poisoning in agricultural workers is around 182 per million, and 7.4 per million for full-time workers, and schoolchildren. In developing countries, where there may be insufficient regulation, lack of surveillance systems and training, poorly maintained or non-existent personal protective equipment and larger agriculturally-based populations, incidences are expected to be higher (Thundiyil *et al.*, 2008).

According to WHO and UNEP, worldwide there were more than 26 million human pesticide poisonings and about 220,000 deaths per year (Richter, 2002). In the United States alone, there are 67 000 human pesticide poisonings per year, compared to 500 000 in China, where such incidents result in 100 000 deaths per year (Zhang, Jiang and Ou, 2011). Pesticides can also induce various diseases. In China, as in India, it is estimated that 10 percent of all cancer cases are related to pesticide poisoning. Chen (2004) found that the incidence of breast cancer was linearly correlated with the frequency of pesticide use and that the organochlorine pesticide DDT, and its derivative DDE, were likely responsible for breast cancer (Zhang, Jiang and Ou, 2011).

Pesticides may also affect biodiversity by killing weeds and insects, with negative impacts up the food chain. Recent studies have shown that some pesticides that mimic natural hormones interfere not only with the normal functioning of the endocrine system, but also the immune, reproductive and nervous systems of non-target animals. The widely used pesticide atrazine causes male frogs to develop female characteristics at very low concentrations in water, which causes problems for frog reproduction. Glyphosate, another of the world's most common herbicides, is especially toxic to amphibians (e.g. frogs) and causes impaired growth and development and mortality. This is a particular problem for wetlands near farms. Organophosphate and carbamate pesticides are highly toxic to target organisms, but can also seriously impact birds (FAO, 2013).

Pesticide accumulation in the food chain, with the potential to poison humans and livestock, led to the ban of organochlorine pesticides such as DDT. The adverse health impact of pesticides, among other reasons, led pesticide designers to focus on developing products that do not harm non-target organisms and that are rapidly detoxified. In developed countries, although considerable use of older broad-spectrum pesticides persists, the trend is towards newer pesticides that are more selective and less toxic to humans and the environment and that are effective at lower doses. However, as better knowledge and understanding of the complexity of ecosystems is gained, expectations for true specificity and targeting of pesticides seems increasingly challenging and harder to achieve.

Overall, the four main issues that concern pesticide production and application worldwide can be summarized as follows:

- Some countries still produce or use highly toxic pesticides.
- Pesticides are overused on a variety of crops, such as cotton, vegetables and rice.
- The quality of pesticides is sometimes poor; some countries do not regulate pesticides effectively and thus counterfeit and illegal pesticides are in use.
- Pesticide residue standards are not implemented effectively (Vaagt, 2008, as cited in Zhang, Jiang and Ou, 2100).

The continued use of obsolete pesticides[6] also poses a significant risk in the developing world, where many older, non-patented, more toxic, environmentally persistent and inexpensive chemicals are still extensively used, creating serious acute health problems. Additionally, it is estimated that approximately half a million tonnes of toxic chemicals are contaminating soil and water resources as they slowly leak from outdoor containers, and eliminating dangerous stocks of pesticides is a development priority. Few developing countries have a clear policy concerning pesticides. There is a lack of rigorous legislation and regulations to control pesticides and few training programmes for personnel to inspect and monitor use and initiate training programs for pesticide consumption. Furthermore, there is growing concern in these countries that few farmers or consumers are aware of the extent of pesticide residue contamination of local fresh produce purchased daily or the potential, long-term, adverse health effects on consumers (FAO, 2011).

[6] Obsolete pesticides are defined as stocked pesticides that can no longer be used for their original purpose or any other purpose and therefore require disposal (FAO, 2017b).

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