

4. PERSISTENCE, DEGRADATION AND METABOLITES

When a pesticide is introduced into the environment, it does not necessarily remain unchanged. It may be transported by water and air, adhere to soil particles, penetrate plant tissues, be absorbed by living organisms, or undergo chemical and biological transformations. Some substances degrade relatively quickly, while others may remain in the environment for very long periods. Under certain conditions, the original molecule may be transformed into other compounds known as degradation products or metabolites. These compounds may have chemical and toxicological properties different from those of the parent substance.

Transformation may reduce the hazard posed by the original molecule, but this does not automatically mean that the resulting products are harmless. It is also essential to distinguish the actual chemical degradation of a substance from a mere decline in its concentration at the sampling location. A pesticide may disappear from the soil being examined without necessarily having been destroyed: it could have moved into water, been transported with soil particles, or been converted into compounds that the analytical method does not target. Understanding these processes is essential to assessing pesticide persistence in the environment, their possible transfer into food, and the limitations of chemical testing.

4.1 What pesticide persistence means

Persistence is the ability of a substance to remain in the environment for a certain period without being completely degraded. Pesticides differ greatly in this respect. Some molecules are rapidly transformed through chemical or biological processes; others have more resistant structures and can persist for months, years or, in particular cases, even longer.

Their behaviour depends on the substance and its environmental conditions. Temperature, moisture, soil acidity, oxygen availability, microorganisms and the amount of organic matter can influence the rate of transformation. Persistence is therefore not always a fixed property independent of the environment. The same pesticide may degrade quickly in warm, well-aerated, biologically active soil and much more slowly under other conditions.

Moreover, the persistence of the parent molecule does not necessarily describe that of its transformation products. A pesticide may disappear relatively quickly while leaving metabolites that persist longer. The duration of contamination depends not only on the persistence of the original pesticide but also on the fate of the substances into which it may be transformed.

4.2 The difference between degradation and dissipation

To understand the environmental behaviour of pesticides, two frequently confused terms must be distinguished: degradation and dissipation. Degradation is a process that alters the chemical structure of a substance: the parent molecule can be converted into one or more different products. Dissipation, by contrast, is a decrease in the concentration of a substance in the environment or in the compartment being observed. Dissipation may result from degradation, but it may also result from physical transport.

Suppose a pesticide is applied to soil and, one week later, its concentration in the surface layer has halved. This does not necessarily demonstrate that half the substance has degraded. Some may have been carried deeper by infiltrating water, some removed by runoff or erosion, and certain compounds may have volatilised. Only appropriately designed studies can distinguish the contributions of these processes.

The distinction is also essential in interpreting scientific experiments. Laboratory studies may isolate particular degradation reactions, whereas field studies observe a more complex system in which chemical, biological and physical processes occur simultaneously. A reduction in pesticide concentration at a particular point does not necessarily mean that the total amount of the substance and its transformation products in the environment has decreased.

DEGRADATION

Chemical transformation

Parent compound → products

DISSIPATION

Measured concentration falls

Transformation OR transport

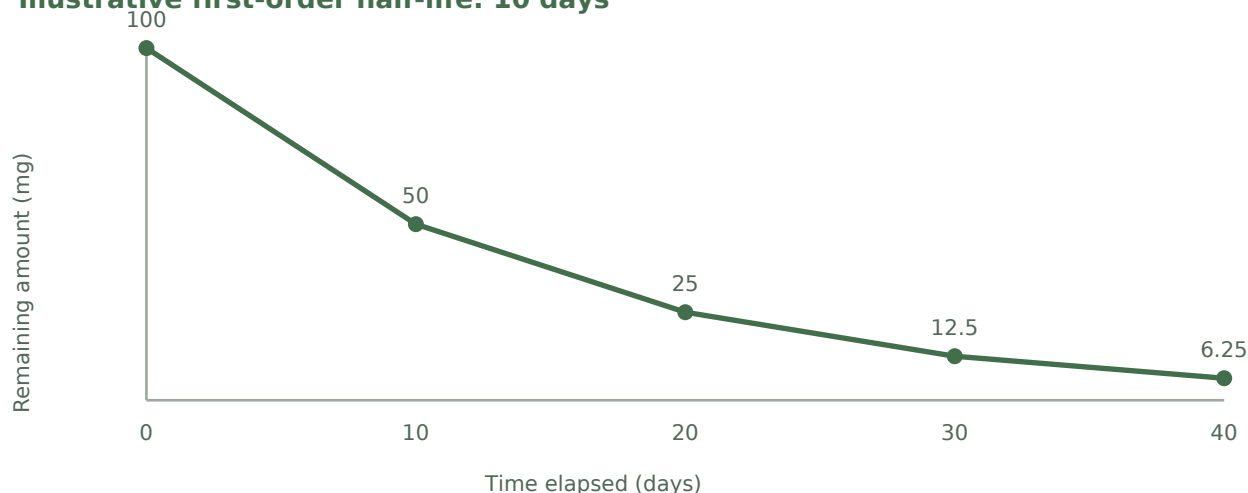
A lower measured concentration is not necessarily proof of degradation.

4.3 Half-life: how long does it take for a concentration to halve?

One of the most widely used measures of pesticide persistence is the time required for its concentration to fall by half, commonly called its half-life. Its meaning depends on the model used. Suppose there are initially 100 milligrams of a pesticide. If the process follows first-order kinetics and the half-life is ten days, 50 milligrams will remain after ten days, 25 after twenty days and 12.5 after thirty days.

Time elapsed	Remaining amount
Start	100 mg
10 days	50 mg
20 days	25 mg
30 days	12.5 mg
40 days	6.25 mg

Illustrative first-order half-life: 10 days



Example only: exponential decline in a simple first-order model; not measured data for a specific pesticide.

This is a theoretical model in which the degradation rate is proportional to the amount still present. Under those conditions, the amount declines along an exponential curve. This model is commonly used in environmental studies, but it does not perfectly describe every real process. A substance may, for example, degrade quickly at first and then much more slowly if part of it becomes strongly associated with soil particles and less accessible to degradation.

It is also important to distinguish half-lives describing degradation from those describing overall dissipation. Environmental studies frequently use parameters such as DT50 and DT90 to indicate the time required for a 50% and 90% reduction, respectively, in relation to the stated process and model. Half-life describes the rate of a process; it is not an expiry date after which a pesticide disappears completely.

4.4 Biological degradation: the role of microorganisms

Soil hosts extremely complex microbial communities. Bacteria, fungi and other organisms help transform organic matter and many chemicals found in the environment. Some microorganisms can transform specific pesticides through enzymatic reactions. Under certain conditions, a molecule may be used as a source of carbon, energy or other elements. In other cases, transformation occurs through metabolic processes that do not necessarily provide a direct energy benefit to the microorganism.

Biodegradation depends on the microbial community and soil conditions. Oxygen availability, moisture, pH and temperature can significantly influence these reactions. Biologically active soil may favour the transformation of certain substances, but this does not mean every pesticide will degrade rapidly in every soil. Some molecules are difficult for microorganisms to access; others have chemical structures that are not readily transformed. In some cases, microbial metabolism produces intermediate compounds that may persist in the environment. Biological degradation does not necessarily mean complete elimination: it may represent only one stage of transformation.

4.5 Chemical degradation and photodegradation

Pesticides can also be transformed through non-biological processes. One example is hydrolysis, a reaction in which water participates in changing a molecule's chemical structure. Hydrolysis rates often depend on pH and temperature. Some pesticides are relatively stable under certain acidity conditions and transform more rapidly under others.

Another process is photodegradation. A molecule that absorbs energy from light radiation may undergo chemical changes. Sunlight can therefore contribute to the transformation of pesticides on plant surfaces, in soil or in water. Its effectiveness depends on the substance, the intensity and spectrum of light, and environmental conditions. A molecule on a leaf surface may be exposed to sunlight, while that same molecule adsorbed deep in soil may receive much less light.

Oxidation and other chemical reactions may also occur. The resulting products may again differ from the original substance. Light, water and chemical reactions can transform pesticides, but they do not guarantee that the transformation products will be harmless.

4.6 Soil: adsorption, mobility and availability

Soil is a complex system containing minerals, organic matter, water, air and living organisms. When a pesticide reaches soil, it may become distributed among these components. Some substances remain mainly dissolved in pore water; others tend to adhere to mineral surfaces or organic matter. This phenomenon is called adsorption.

Adsorption must not be confused with absorption. Adsorption means adherence to the surface of a material, whereas absorption involves a substance entering another material or organism. A pesticide's ability to bind to soil influences its mobility.

A strongly adsorbed substance may be less available for transport in water, but it may also be less accessible to certain degradation processes. Adsorption does not necessarily immobilise a substance forever. Changes in chemical or physical conditions may promote desorption, returning the substance to the aqueous phase. Soil particles carrying pesticides may also be transported by erosion.

Mobility therefore depends on various factors, including solubility, adsorption, soil properties and water flow. A poorly mobile pesticide is not automatically harmless, just as a highly mobile pesticide is not necessarily persistent. Mobility, persistence and toxicity are different properties that must be evaluated separately.

4.7 Transfer to surface water and groundwater

Pesticides in agricultural soils can reach water through several pathways. Rainfall may cause surface runoff, carrying dissolved substances or compounds attached to eroded particles. More mobile pesticides may also infiltrate soil and reach greater depths. When chemical properties and hydrogeological conditions allow it, they may reach groundwater.

An aquifer's vulnerability depends on geological structure, soil and rock permeability, depth to the water table, and recharge conditions. Fractures and preferential infiltration pathways can also influence transport.

It is important to consider both the parent substance and its degradation products. A metabolite may be more soluble and mobile than the pesticide from which it derives. In such cases, transformation of the original molecule may favour the appearance of a compound capable of reaching water more readily.

Water contamination is particularly relevant when water is used to irrigate crops or to water livestock, creating a further potential exposure pathway. A substance applied to one crop may travel through soil and water to other environmental compartments and potentially come into contact with different crops.

4.8 What metabolites are

A metabolite is a substance derived from the metabolic transformation of another molecule. With pesticides, such transformations may occur in plants, animals, humans or through microbial activity. The broader term degradation product refers to compounds formed as the original molecule is transformed. The two terms may overlap but are not perfectly equivalent.

A pesticide may undergo several successive reactions. The initial molecule can produce a first metabolite, which may in turn form another compound. In some cases, transformation progressively yields simpler molecules. When degradation is complete, organic carbon in the substance may be converted into inorganic compounds, such as carbon dioxide, depending on process conditions. This complete transformation is called mineralisation.

Not all pesticides rapidly reach this end point. Intermediate products may be relatively stable, more mobile or toxicologically different from the parent substance. Disappearance of the original pesticide does not necessarily mean disappearance of all the chemicals derived from it.

4.9 Metabolites that are less toxic, more toxic or simply different

Chemical transformation does not always have the same toxicological consequence. In some cases metabolism yields compounds that are less active or easier to eliminate, helping organisms reduce the effects of certain foreign substances. In other cases, transformation produces biologically active compounds.

Some metabolites have their own toxicity and, for particular effects, may even be more toxic than the parent molecule. A transformation product may also be less toxic but more persistent or mobile in the environment. Knowing only the original pesticide's toxicity is therefore insufficient. We need to understand which products form, in what amounts, how long they persist and what effects they may have.

Scientific assessment must also consider the conditions of transformation. A metabolite formed mainly in soil may have different environmental significance from one formed in plants or animals. The hazard of a metabolite cannot be inferred solely from the hazard of the parent substance. Every relevant compound requires an appropriate assessment.

4.10 DDT and its transformation products

DDT is one of the most important historical examples of pesticide persistence. Widely used as an insecticide in the past, it was subsequently banned or severely restricted in many countries because of its environmental and toxicological properties. DDT is an organochlorine compound characterised by high persistence and affinity for fats.

In the environment it may transform into compounds including DDE and DDD, which can themselves persist significantly. Under certain conditions these compounds may still be detected in soils, sediments and living organisms many years after use of the original substance has ceased. They demonstrate that environmental contamination can outlast the agricultural use of a chemical.

Their distribution in organisms' tissues is also influenced by their affinity for lipids. Certain contaminants of this type can bioaccumulate and biomagnify. These characteristics do not apply to all pesticides: DDT is noteworthy precisely because of its particular properties. Banning a substance may end a source of contamination, but it does not automatically erase contamination already present in the environment.

4.11 Glyphosate and AMPA

Another interesting example concerns glyphosate and one of its main transformation products, AMPA (aminomethylphosphonic acid). Environmental biological processes can transform glyphosate into AMPA, among other products. AMPA may behave differently from the parent molecule, and its persistence and mobility depend on soil properties and environmental conditions.

AMPA can also arise from the degradation of other substances, including certain phosphonates. Its presence in the environment is therefore not, on its own, unequivocal evidence of previous glyphosate use.

This example is especially relevant analytically. A test targeting only glyphosate does not necessarily reveal the concentration of AMPA. To assess both compounds, methods that include both analytes are needed. The principle also applies to other pesticides: testing only the parent substance can provide an incomplete picture of contamination when transformation products are relevant.

4.12 Metabolites in plants and foods

Plants are not passive recipients of the pesticides they absorb. They have enzymatic systems capable of transforming numerous foreign molecules. Certain substances are modified by oxidation, reduction, hydrolysis and other metabolic reactions. The resulting products may then bind to cell components or accumulate in particular plant compartments.

Some transformations reduce the biological activity of the parent molecule; others yield compounds that retain relevant properties. Metabolite distribution may also differ among leaves, roots, fruits and seeds. This matters because the edible part of a plant may contain transformation products different from those found in soil or on its surface.

Where relevant, pesticide regulatory assessments include studies of metabolism in crops. Such studies help identify the compounds that should be considered in residue definitions. However, it cannot be assumed that routine multiresidue protocols search for every possible transformation product of every pesticide. The presence or absence of a metabolite must be assessed against the

actual list of substances covered by the analytical method. A plant can transform a pesticide without necessarily eliminating every relevant chemical trace.

4.13 Metabolites in animals and humans

When an animal or person ingests a pesticide, it may be absorbed and distributed among tissues. The body has metabolic systems that help transform foreign substances; the liver plays a particularly important role. Numerous enzymes modify molecules and, in many cases, make them easier to eliminate.

Such transformations may nevertheless produce metabolites with their own properties. Some compounds are rapidly excreted in urine or faeces; others may remain temporarily in tissues or undergo further transformation. Toxicological studies therefore consider the behaviour of the substance in the body and, when relevant, its metabolites.

For livestock, this information helps assess whether residues could reach meat, milk or eggs. For humans, it informs exposure and health-effect assessments. Biomonitoring often involves testing for metabolites in urine or other biological samples. Not every metabolite, however, is specific to one parent substance; some may arise from different compounds or exposure sources. Interpretation therefore requires particular care. Measuring a metabolite in the body may provide information about exposure, but its meaning depends on the compound's specificity and on knowledge of its metabolism.

4.14 Environmental persistence is not the same as persistence in the body

A substance may persist in the environment without necessarily accumulating in the human body. Conversely, a compound that transforms quickly in the environment may still have important toxicological properties under certain exposure conditions.

Environmental persistence depends on degradation rates in natural compartments. Retention in the body depends instead on absorption, distribution, metabolism and elimination. These are different properties, and food risk assessment must consider both.

A pesticide that persists in soil may be a prolonged source of environmental exposure, but the dose actually consumed through food depends on transfer to crops and concentrations in consumed products. Likewise, the presence of a persistent metabolite does not automatically imply high health risk: toxicity and exposure must also be considered. Persistence, potential for accumulation and toxicological hazard are not synonyms. Confusing them turns different chemical properties into an undifferentiated judgement about risk.

4.15 The problem of metabolites not included in testing

Modern multiresidue analyses can screen foods for hundreds of pesticides simultaneously. This is a remarkable technological advance, yet even an extensive testing protocol has clearly defined limitations. Target substances are usually selected from lists of known analytes, using methods developed to identify them.

Some metabolites are included in routine methods, some require dedicated analyses, and others may be absent from the chosen panel. A negative result for the parent substance therefore does not automatically rule out the presence of its transformation products. For example, a food may contain a quantifiable metabolite even when the original molecule is not detected.

To understand the result, one must know exactly which substances were tested. This does not mean that every untested metabolite is dangerous. It simply means that a test which did not include it cannot establish its absence. The ability to look for hundreds of substances is not the same as knowing every chemical transformation that a food may have undergone.

4.16 How regulations assess transformation products

European pesticide assessment procedures require studies on the metabolism and environmental fate of active substances. They aim to identify relevant transformation products and assess their behaviour. Legislation on maximum residue levels may use a residue definition that includes several compounds.

In certain cases, the concentration used to check compliance is based on the sum of the parent substance and specified metabolites; in others, the definition covers only selected compounds. Decisions depend on the available scientific information and regulatory criteria. This system is a fundamental element of risk assessment, but it does not mean every conceivable transformation product has already been identified and assessed.

Knowledge evolves. New studies may reveal metabolites previously overlooked or provide new toxicological information. Regulatory assessment is therefore a scientific process requiring updates. Regulatory residue definitions reflect the knowledge and evaluations available at the time; they do not necessarily constitute a final list of all compounds that could form.

4.17 Historical contamination and subsequent generations of crops

Environmental persistence may have consequences years after the last pesticide application. Soil may retain residues of certain substances or their transformation products, associated with minerals or organic matter. Environmental changes may alter their availability, and crops grown later may sometimes absorb substances still present in the soil.

A residue found in a plant therefore does not automatically prove that the crop received a direct treatment. The history of the soil may also matter, particularly when agricultural management changes. Land previously cultivated under one set of practices may subsequently be used for a different production system, including organic farming. A change in practices reduces or stops certain contamination sources but does not necessarily erase pre-existing environmental residues.

This does not mean that every previously treated soil is significantly contaminated. The extent of any contamination depends on the chemicals used, amounts applied, elapsed time and environmental conditions. A soil's chemical history is not necessarily the same as the farming practices of the most recent season.

4.18 Persistence and food safety

Pesticide persistence is important in assessing the possibility of prolonged exposure, but it cannot, by itself, establish whether a food is dangerous. Health risk depends on the substance, its toxicity and the amounts actually consumed.

A highly persistent molecule may be present at extremely low concentrations, while a less persistent substance may be present at higher concentrations after a recent treatment. Meaningful comparisons require appropriate analytical and toxicological data. Metabolites must also be considered: some risks may be associated not only with the parent substance but also with the compounds into which it transforms.

Scientific assessment therefore integrates information on persistence, mobility, metabolite formation and dietary exposure. European and international scientific authorities undertake these complex assessments. However, the huge variety of substances and environmental conditions means complete knowledge of every scenario cannot be assumed. Proper risk assessment requires understanding not only what was used, but also what remains, where it moves and what it becomes.

4.19 Why testing the final product matters

Knowledge of farming practices and pesticides' environmental properties makes it possible to estimate which contaminants might occur, but prediction is not measurement. A pesticide may be used correctly and leave residues below the limit of quantification. Another, applied under different conditions, may leave measurable residues. A substance may even reach a crop through the environment without having been applied directly by the farmer. Degradation products create further possibilities.

Consequently, knowledge of the production process cannot fully replace analysis of raw materials or final food products. An appropriate analytical protocol may target not only active substances but also specified metabolites and transformation products regarded as relevant. The choice of analytes should be transparent; method sensitivity and sampling representativeness also matter.

A result below the limit of quantification does not mean absolute absence. It does, however, provide verifiable information that can be used to select products against predefined criteria. Supply-chain knowledge helps reconstruct what may have happened; chemical analysis helps verify some of what actually remains.

4.20 What we still do not know

Research on the environmental fate of pesticides has advanced enormously. Experimental methods and scientific models can now describe many degradation, transport and accumulation processes. Regulatory procedures require specific studies and assessments intended to identify major environmental and dietary risks. These tools are indispensable to chemical safety.

Real-world conditions, however, are extremely variable. A pesticide may encounter different temperatures, moisture levels, microbial communities and geological characteristics. It may interact with other substances, be transported and undergo successive transformations. The products formed may follow different pathways in turn. The ability to reconstruct every transformation and transfer is necessarily limited.

This does not make scientific assessments useless or unreliable. Rather, they describe known processes through experimental data and models that must be continuously improved. Modern analytical techniques detect an increasing number of metabolites and emerging contaminants, but the ability to identify new molecules may develop faster than comprehensive knowledge of their biological effects. Each analytical advance illuminates part of the problem, and sometimes reveals greater complexity than we had imagined.

Conclusion to Chapter 4

The persistence of pesticides in the environment depends on numerous chemical, physical and biological processes. Some substances transform quickly, whereas others can persist for very long periods. A decline in pesticide concentration does not necessarily show complete degradation: the substance may have moved to another environmental compartment or been converted into different compounds.

Metabolites and degradation products may differ from the parent molecule in persistence, mobility and toxicity. Testing only the original pesticide is therefore not always sufficient to describe the entire contamination. Organochlorine pesticides illustrate how certain chemicals and their transformation products can persist for decades. Glyphosate and AMPA demonstrate the importance of testing for specific metabolites and recognising that one compound may derive from several sources.

Scientific and regulatory assessments address many transformation processes, but knowledge continues to evolve. Disappearance of the parent molecule does not necessarily mean disappearance of contamination. This is one reason why understanding the chemistry of food may require testing not only for pesticides used but also for particular transformation products.

Regulatory compliance is essential. More extensive analyses can provide additional information. The objective is not to eliminate all uncertainty but to reduce it through appropriate scientific tools. Our understanding of a pesticide does not end when we stop using it: it continues until we know where it went, how much remains and what it has become. These phenomena are central to assessing pesticides' potential health effects, addressed in the next chapter.

Scientific and institutional sources

US EPA – Technical Overview of Ecological Risk Assessment: Exposure Characterization. Pesticide degradation, dissipation and environmental transport.

<https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/technical-overview-ecological-risk-assessment-1>

US EPA – Guidance to Calculate Representative Half-life Values and Characterizing Pesticide Degradation. Kinetic models, half-lives and environmental degradation.

<https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/guidance-calculate-representative-half-life-values>

US EPA – Guidance for Reviewing Pesticide Environmental Fate Studies. Methods for evaluating hydrolysis, photodegradation, soil metabolism, mobility and dissipation.

<https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/guidance-reviewing-pesticide-environmental-fate>

EFSA – Pesticides. Pesticide assessment and associated risks.

<https://www.efsa.europa.eu/en/topics/topic/pesticides>

Regulation (EC) No 1107/2009 – Placing plant protection products on the market.

<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009R1107>

Regulation (EC) No 396/2005 – Maximum residue levels of pesticides in food and feed.

<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32005R0396>

European Commission – EU Pesticides Database. Active substances and residue definitions.

https://food.ec.europa.eu/plants/pesticides/eu-pesticides-database_en

Stockholm Convention on Persistent Organic Pollutants. Persistent organochlorine pesticides.

<https://www.pops.int/>