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From application in the fields to dispersion in the atmosphere: A narrative review on airborne pesticides and their monitoring in France

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ABSTRACT

Pesticides, widely used to enhance agricultural productivity, are increasingly monitored and consequently detected in the atmosphere, raising concerns for environmental and human health. This narrative review summarizes current knowledge on the main pathways of atmospheric contamination, namely spray drift, volatilization, and wind erosion, and the key physicochemical, environmental, and operational factors that govern pesticide dispersion. It also evaluates modeling approaches and monitoring initiatives, with a particular focus on France, where recent studies have revealed regional patterns, persistence of banned substances, and the influence of agricultural practices. The review underscores the need for more comprehensive models, integrated monitoring frameworks, and targeted policies to better assess and mitigate airborne pesticide pollution.

1. Introduction

Pesticides are substances or mixtures used to prevent, destroy or control pests (insects, fungi, rodents or unwanted plants) that threaten human activities, such as crop production, food storage and infrastructure maintenance (Abubakar et al., 2020). The use of pesticides dates to Ancient Greece, but it expanded widespread starting from the world wars, particularly with the development of synthetic chemistry. Since the discovery of the insecticidal properties of DDT by Paul Muller in 1939, numerous families of synthetic chemicals have been marketed and applied to crops, often with limited regulation (Mnif et al., 2011).

The global production of synthetic active substances rose by 11 % annually between 1950 and 2005, from 0.2 million tons to over 5 million tons (Tudi et al., 2021). The distribution of global pesticide consumption between 1990 and 2018 shows a strong geographical imbalance. Asia was by far the largest consumer, accounting for about 53 % of the total, followed by the Americas (North and South) with nearly 30 % and Europe with around 14 %. In contrast, Africa, despite the central role of agriculture in many of its economies, represented only about 2 % of global use, while Oceania contributed roughly 1 %. At the national level, the ten leading consumers were China, the United States, Brazil, Argentina, Russia, France, Italy, Japan, Colombia, and Canada (Ponnuchamy et al., 2021). More recent Food and Agriculture

Organisation (FAO) statistics confirm both the overall intensification of pesticide reliance and the persistence of regional disparities (FAO, 2025). Global use rose from 2.66 million tonnes in 2020 to 3.13 in 2023. In the 27 European Union (EU) countries, pesticide sales consistently exceeded 350,000 tons per year between 2011 and 2020, although they declined to 322,000 tons in 2022 (McGinley et al., 2023). Fungicides and bactericides accounted for the largest share (43 %), followed by herbicides (35 %) and insecticides (14 %). France, Spain, Germany and Italy recorded the highest sales, reflecting their status as major agricultural producers.

Pesticides are essential for crop protection and public health, but they pose significant environmental and health risks due to their dispersion through air, soil and water. Beyond direct application, pesticides may reach non-target areas through various off-field contamination pathways, including spray drift, volatilization and atmospheric transport, as well as runoff and leaching. Agriculture is the primary source of pesticide pollution: 95–98 % of applied pesticides disperse in the environment (Mahmood et al., 2016). These processes can contribute to the exposure of nearby residential zones (Dereumeaux et al., 2020), natural habitats (Leenhardt et al., 2023), and peri-urban (Agost and Velázquez, 2020) and urban area (Md Meftaul et al., 2020). This widespread contamination affects livestock, natural fauna and flora and human health (Huang and Li, 2024) and has considerable economic consequences (for example, in

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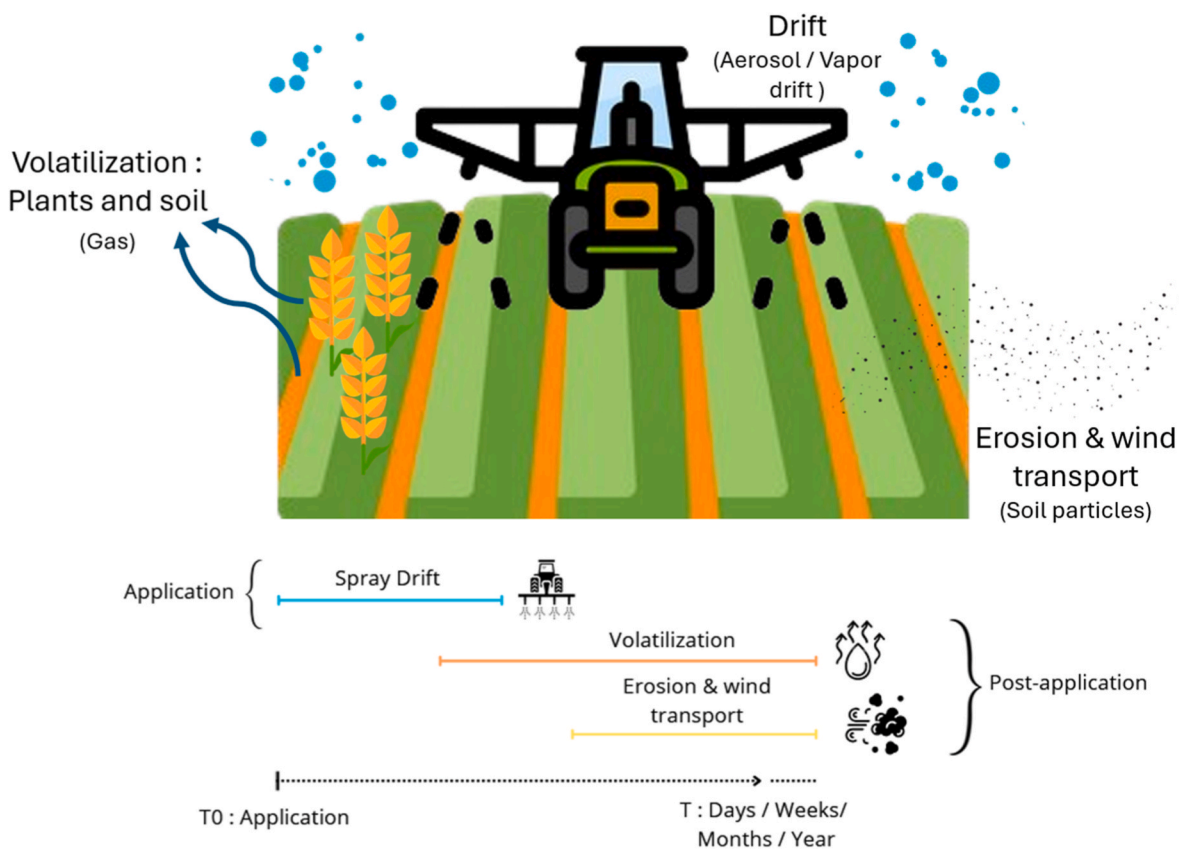


Fig. 1. Pesticide transport mechanisms (spray drift, volatilization, and erosion with wind transport) from the moment of application (T0) to days/years after application.

the USA, the annual losses due to non-target crop damage exceed \$10 billion) and regulatory costs (Reimer and Prokopy, 2012).

Modern agriculture relies heavily on chemical inputs, including pesticides that are applied through various techniques, such as sprayers with different nozzle types (Arvidsson et al., 2011).

To mitigate these risks, regulatory measures have been implemented. In the EU, Regulation (EC) No. 1107/2009 governs the approval of plant protection products to ensure their safety for human health, animal health, and the environment. Currently, 452 active substances are authorized in the EU, and 937 have been banned due to environmental or health concerns. However, some banned substances persist in the environment, posing long-term contamination risks (Roşca et al., 2023).

Since the publication of *Silent Spring* in 1962, concerns over the harmful effects of pesticides, particularly organochlorines, have grown (Carson et al., 2002; Stein, 2012). Pesticides can harm non-target organisms, including pollinators, earthworms, and birds, by affecting their survival, reproduction, and behavior, with cascading consequences for ecosystem health (Yadav and Devi, 2017). Humans may be exposed through occupational and environmental routes. Agricultural workers experience the highest levels of exposure, while the general population is exposed through domestic uses and through contaminated food, water and air (Baldi and Lebailly, 2024; Dhananjayan et al., 2020). Some contexts of pesticide exposure are associated to various health issues, including cancer, reproductive and neurocognitive impairment, asthma and allergies. This is particularly the case for : i) occupational exposure during adulthood or in early life (lymphoma, Parkinson disease, respiratory problems, pediatric cancers, malformations ...), ii) exposure due to residential use in early life (pregnant women) and childhood (leukemia, nervous central system tumor ...), and iii) exposure of residents in agricultural areas (neurological disorders) (Gangemi et al., 2016; INSERM, 2022). Except for occupational exposures, it is not clear what media and route of exposure contribute most to the health risk

(deposited dust, air, direct use, inhalation, oral or dermal routes).

Pesticide monitoring in food and water is strictly regulated through the establishment of safe levels. Conversely, pesticide presence in the air is not subject to regulation yet. The aim of this narrative review was to summarize the existing knowledge on pesticide presence in the air in order to identify key findings, highlight knowledge gaps, and provide a comprehensive understanding of pesticide contamination in this environmental compartment. To achieve this, a literature search was carried out using Web of Science and Google Scholar. Web of Science was chosen for its rigorous indexing of peer-reviewed scientific articles that ensures high-quality sources (Falagas et al., 2008). Google Scholar was included to capture a wider range of relevant studies, including gray literature and reports that might not be indexed in traditional databases (Haddaway et al., 2015).

As an illustration, the French case was considered, given the implementation since 2021 of a national program to monitor pesticides in the air. Particular attention was paid to the Brittany region, both for its major agricultural activity and for its strong involvement in pesticide-related research.

2. How do pesticides get into the air?

In agriculture, pesticides are often applied by spraying on soil and plants (Langenbach et al., 2021). From the moment they are used, they can enter the atmosphere by different ways and in three different forms (Fig. 1): through drift in aerosol (liquid) form directly during the application; through erosion and wind transport attached on particles (solid form); and through evaporation from treated soil or plants in gaseous form (Galón et al., 2021; Gil and Sinfort, 2005; Mayer et al., 2024). The transfer may be immediate or continue for up to a few weeks after the product application, depending on the specific pesticide involved and the governing environmental conditions (Tudi et al., 2021). Although pollution levels are

generally higher in regions with intensive agriculture, pesticides have been detected also in remote areas. Currently used pesticides have been found in rural air (Coscollà et al., 2010; Degrendele et al., 2016) and ecosystems but have also been observed far from the sources (Tang et al., 2025), at high mountains (Feltracco et al., 2022), in the marine boundary layer and in the Arctic (Balmer et al., 2019; Mayer et al., 2024). For instance, pendimethalin has been detected in nearly 40 % of samples collected in Sweden, although its use is not authorized in this country. This suggests that it originated from neighbouring countries, such as Denmark, Germany and Poland (Kruse-Plab et al., 2021). Similarly, a recent French study on pesticides in clouds has highlighted the occurrence of substances that are banned in France, providing additional evidence for the long-range tropospheric transport of pesticides. This work also demonstrated a specific mechanism of dispersion, namely the transfer of pesticides within clouds, which can subsequently lead, through rainfall, to their deposition into soils and aquatic environments (Bianco et al., 2025).

2.1. Spray drift

Spray drift can be described as the amount of pesticide that is carried away from the treated/target area during its application (De Schampheleire et al., 2007; Gil and Sinfort, 2005; Zhang et al., 2024). Studies showed that significant amounts of pesticides drift to nearby non-target areas and are lost during application, although the estimates vary widely: from 20 to 30 % (Van den Berg et al., 1999) to 50 % (Woodrow et al., 2018) and even up to 90 % of the total quantity (Bedos et al., 2002a). At least four technical and environmental factors influence pesticide drift into the air during the application and could explain the observed differences in estimates (Gil and Sinfort, 2005): (a) spray characteristics, such as the formulation volatility and viscosity; (b) equipment and application techniques; (c) climate conditions during application (wind speed and direction, temperature, relative humidity, and air stability at the site); and (d) the operator's care and skills (De Schampheleire et al., 2009).

Table 1

Summary of main pesticide dispersion processes, influencing parameters and duration.

Process	Description	Influencing parameters* (ranking)	Estimated loss	Duration
Spray drift	Pesticides carried away from the treated area during application	Environmental (1) Operational (2) Physicochemical properties (3)	20–90 %	Immediate
Volatilization	Transfer of pesticides from soil or plants	Environmental (2) Physicochemical properties (1)	Few % to >50 %	Few days to weeks
Wind erosion	Transport of pesticides via soil particles	Environmental (2) Operational (3) Physicochemical properties (1)	<5 %	Variable

The ranking (1–3) in the Influencing parameters column reflects the relative importance of each parameter category, from the most influential (1) to the least influential (3). Estimated values are literature-based ranges and should be interpreted with caution, as they are subject to significant variability depending on pesticide properties, environmental conditions, and application practices. *Environmental factors refer to external conditions, such as temperature, humidity, wind speed, and solar radiation. Operational factors are human-controlled or process-specific variables, such as application method, timing, and dose. Physicochemical properties describe the intrinsic characteristics of a substance, such as vapor pressure, solubility.

2.2. Volatilization

Pesticide volatilization can occur after its application to the target area (soil surface and/or plant surface) or its injection or incorporation into the soil (Guth et al., 2004; Van den Berg et al., 1999). Volatilization refers to the transfer of a substance into the gas phase through evaporation from a liquid, sublimation from a solid, or desorption from soil particles (Bedos et al., 2002a,b). Volatility losses can be very significant, reaching in some cases more than 50 % of the quantities applied (Guenzi and Beard, 1974).

2.2.1. Volatilization from soils

Pesticides accumulate in soils directly during their application or indirectly by deposition of airborne contaminants coming from different sites. Soil can act as a storage compartment for organic chemicals, and their retention is strongly influenced both by the amount of organic matter present and by the physicochemical properties of each pesticide. For some compounds, such as trifluralin and lindane, as much as 90 % of the application dose can be lost through volatilization within a week after their application. For others, such as atrazine, the cumulative losses after 24 days corresponded to ~2 % of the application dose. Quantitatively, pesticide volatilization rates range from few $\text{g}\cdot\text{ha}^{-1}\cdot\text{d}^{-1}$ to nearly $2000\text{g}\cdot\text{ha}^{-1}\cdot\text{d}^{-1}$, depending on the pesticide and the application dose (Bedos et al., 2002a). Several factors can influence volatilization: the soil moisture conditions and the soil surface temperature, which in turn depend on the soil nature and the weather conditions, and the pesticide physicochemical characteristics, such as vapor pressure or Henry's law constant (i.e., the partition coefficient between the gaseous and aqueous phases) (Bedos et al., 2002a).

2.2.2. Volatilization from plants

Compared to soil, pesticide volatilization from plant surfaces is generally higher and faster. This is mainly due to factors such as turbulence above and within the plant canopy, which enhances the convective exchange rate between leaves and the surrounding air. Furthermore, the interactions between pesticides and leaves differ from those with soil: pesticides generally are better adsorbed on soil than on plants. Variations in water evaporation from leaves and soil, influenced by differences in temperature and moisture levels, also play a role. Environmental conditions significantly affect this process, particularly rainfall within 24 h after pesticide application. Moreover, temperature affects the compound vapor pressure, and sunlight induces photochemical alterations of the substance. However, several processes occurring on the leaf surface, such as product penetration, chemical and photochemical degradation, and washing by rain, compete with volatilization. This makes it difficult to fully describe these dynamics (Galon et al., 2021; Van den Berg et al., 1999). Nevertheless, volatilization can be directly and indirectly influenced by physicochemical properties, environmental conditions, and agricultural practices (Bedos et al., 2002a; Van den Berg et al., 1999).

2.3. Wind erosion

Pesticides can enter the air through erosion and wind transport. This phenomenon allows pesticides to reach the atmosphere, but is considered less important than volatilization and spray drift (Galon et al., 2021). Wind erosion occurs in dry conditions when soil is exposed to wind and involves the detachment and transport of soil particles by wind forces (Zobeck and Scott Van Pelt, 2015). During this process, the finest particles, such as organic matter, clay and loam, are resuspended in the air. According to meteorological conditions this particles may carry over long distances before being redeposited elsewhere (Borrelli et al., 2017). This contributes to the release of sorbed pesticides into the troposphere where they can persist for several days or weeks after application (Coscollà et al., 2013; Galon et al., 2021). During wind erosion, soil particles move through three main mechanisms: surface creep, saltation, and suspension (Cessna et al., 2006). Surface creep occurs when large soil particles (1000–2000 μm in diameter) roll along the soil surface and

dislodge other particles. In saltation, particles from 100 to less than 1000 μm in diameter are briefly lifted into the air, typically reaching heights of less than 1 m. Suspension involves finer particles (<1–100 μm in diameter) that can remain airborne for extended periods and therefore, can be transported over long distances (Cessna et al., 2006). The height reached by particles carried by the wind decreases exponentially with their size. Moreover, the finest particles can travel over large distances, small particles can travel from 500 km to thousands of km. The largest amounts of pesticides are usually adsorbed onto fine particles (Csányi and Farsang, 2022). A study on trifluralin and triallate (two herbicides) found that $\sim 1.4\%$ of the total applied amount was lost through wind erosion. For other compounds, including 2,4-D, mecoprop, bromoxynil, and diclofop, wind erosion led to the loss of $\sim 4.5\%$ of the applied quantity (Cessna et al., 2006).

Several factors influence wind erosion: the presence and type of vegetation, including the type of crop, the pesticide physicochemical properties, mobility, persistence, and applied quantity. Mobility affects the pesticide distribution within the soil, and persistence determines its degradation rate. These two factors together dictate the pesticide amount that remains in the erodible surface layer over time and its potential for dispersal through wind erosion (Goossens and Riksen, 2004).

2.4. Summary

Table 1 provides a summary of the main processes (spray drift, volatilization, and wind erosion) responsible for pesticide dispersion in the environment following its application. For each process, the key influencing parameters, estimated loss ranges, and temporal dynamics are outlined. The next chapter discusses the individual roles and interactions of these parameters in influencing pesticide dispersion.

3. Parameters influencing pesticide presence in the air

This chapter presents a detailed analysis of the key parameters that influence the presence of pesticides in the air, focusing on their relationship with the sources of atmospheric contamination.

3.1. Pesticide physicochemical properties

3.1.1. Vapor pressure

Vapor pressure is a key chemical property that influences the environmental fate, transport, and distribution of compounds in environmental media. It is defined as the partial pressure of a chemical in the gas phase in equilibrium with its pure solid or liquid phase. Vapor pressure plays a critical role in determining how much of the pesticide will remain in the atmosphere as a gas and how much will settle onto the soil as a liquid or solid (Goodarzi et al., 2016). It also controls pesticide volatilization, with both positive and negative implications. A pesticide with high vapor pressure is more likely to volatilize, enhancing the penetrative action of fumigant pesticides, but leads to vapor drift. Experimental studies showed that volatile losses can be expected to remain below 10 % for soils and crops when the vapor pressure of the compound is below 10–3 and 10–4 Pa, respectively (Guth et al., 2004). Compounds with vapor pressure $>10\text{--}2$ Pa are mainly observed in the gas phase and those with vapor pressure $<10\text{--}5$ Pa are almost exclusively found in the atmospheric particulate phase (Nascimento et al., 2017). Most pesticides have a vapor pressure between these values and therefore, partition between gas and particulate phases (Yusà et al., 2014). The increased volatilization of components with a vapor pressure $>10\text{--}5$ Pa is in agreement with experimental data (Houbraken et al., 2016). Precisely, the volatilization flux during the first few hours after application often correlates with the compound vapor pressure (Bedos et al., 2002a). Compounds with higher vapor pressures (heptachlor, trifluralin and lindane) have initially high volatilization fluxes (>30 g $\text{ha}^{-1} \cdot \text{d}^{-1}$) that decrease rapidly. Conversely, the volatilization of

pesticides with lower vapor pressures (dieldrin, eldrin, DDT) is initially lower (<10 g $\text{ha}^{-1} \cdot \text{d}^{-1}$) and then decreases more slowly (Bedos et al., 2002a).

3.1.2. Henry's law constant (HLC)

Henry's law constant is a measure ($\text{Pa} \cdot \text{m}^3 \cdot \text{mol}^{-1}$) of the concentration of a chemical in air over its concentration in water. It expresses the tendency of a material to volatilize from the aqueous solution to air. In the environment, a pesticide with a high Henry's law constant value will volatilize from water into air and will distribute over a large area. Conversely, a pesticide with a low HLC value will tend to persist in water and may be adsorbed into soil and sediments. The Henry's law constant value is also used to calculate the volatility of a chemical (Keshavarz et al., 2022; Stoytcheva, 2011). Indeed, a low vapor pressure is no guarantee of a low Henry's law constant and thus of a low volatilizing tendency. The Henry's law constant plays a critical role in determining the environmental dynamics of chemicals and particularly of pesticides (Suntio et al., 1988). Three pesticide categories can be defined based on their Henry's law constant: category I (highly volatile pesticides, with $\text{HLC} \gg 2.65 \times 10^{-5}$), category II (moderately volatile pesticides with intermediate HLC values), and category III (slightly volatile pesticides with $\text{HLC} \ll 2.65 \times 10^{-5}$). For pesticides with high Henry's law constant (category I), the volatilization rate is highest just after application (Bedos et al., 2002a), and then decreases over time, independently of water evaporation (Taylor and Spencer, 1990). Pesticides in category III often accumulate on the soil surface as water evaporates, leading to increased volatilization over time. However, if water evaporation stops, volatilization gradually decreases (Bedos et al., 2002a).

3.1.3. Solubility in water/soil adsorption

Water-soluble pesticides, typically characterized by low octanol-water partition coefficients (Kow), tend to remain in aqueous environments, reducing the risk of volatilization in the air. Conversely, pesticides with high Kow values are more lipophilic and exhibit greater tendency to evaporate, increasing their presence in the atmosphere (Boonupara et al., 2023).

The soil adsorption coefficient (Koc) also modulates this behavior. Pesticides with high Koc values bind strongly to soil particles, limiting their mobility and volatilization potential. However, environmental conditions, such as temperature, humidity and soil composition, can significantly alter these dynamics. For instance, Davie-Martin et al. emphasize that the soil-air partition coefficient (Ksoil-air) varies with the soil properties and climate factors, influencing the extent to which pesticides volatilize from soil into air (Davie-Martin et al., 2015). Pesticides with high Ksoil-air values are more prone to release in the air, increasing the risk of environmental contamination and human exposure. The soil Koc determines the extent to which pesticides bind to soil particles; however, this does not guarantee their permanent immobilization. Soil erosion, driven by wind or water, can remobilize pesticides adsorbed onto soil particles, leading to their redistribution into the environment. For instance, wind erosion can aerosolize pesticide-laden soil particles, contributing to their presence in the air and facilitating their long-range atmospheric transport (Cessna et al., 2006). Similarly, water erosion can lead to the transport of adsorbed pesticides into aquatic systems, where they may desorb and become bioavailable, posing risks to aquatic ecosystems. This phenomenon is particularly significant in agricultural areas with high erosion rates, where pesticides with high Koc values, and thus less prone to volatilization, can still become airborne or contaminate water bodies through physical soil movements.

3.1.4. Pesticide persistence and bioaccumulation

Persistence can be defined as the tendency of a given compound to conserve its molecular integrity and chemical, physical and functional characteristics in a medium through which it is transported and distributed after its release into the environment. Persistent compounds will then have long half-lives in the environment, and they can be found

in the environment long after their use has stopped. Persistent compounds that are resistant to biodegradation are called recalcitrant molecules. This property is commonly observed in many pesticides (Navarro et al., 2013). Bioaccumulable compounds accumulate in the tissues of living organisms over time, often faster than it is eliminated. These compounds have long biological half-lives and are detected in lipids of living organisms. This characteristic is related to their lipophilicity.

When chemicals have both persistence and bioaccumulation properties, and are considered toxic to human health, ecosystems or wildlife, they are defined as persistent organic pollutants (POPs). Due to their properties, POPs are also capable of being transported across international boundaries through air, water, and migratory species, eventually being deposited far from their original source and accumulating in terrestrial and aquatic ecosystems (Gavrilescu, 2005). Numerous POPs were intentionally produced and applied as pesticides. For example, lindane (and more generally all isomers of hexachlorocyclohexane, HCH) as classified like a POPs since 2010 (Vijgen et al., 2019). Many countries are facing legacy issues related to lindane, particularly concerning manufacturing, agricultural use, and storage. Alongside this, lindane contaminates all environmental compartments worldwide, demonstrating its long-distance transport capability and its high lipophilicity (Vijgen et al., 2019). Other organochlorine pesticides largely used in the 1970s continue to contaminate the environment in certain area (ex. with the chlordecone in the Caribbean area). Although less or no bioaccumulable, and not classified as POPs, other molecules are also concerned by environmental persistence such as atrazine, an herbicide largely used until its ban in Europe in 2003. Due to its persistence but also its mobility, atrazine has caused extensive environmental contamination especially in groundwater.

3.1.5. Pesticide degradation

Certain pesticides are non-persistent and may degrade after entering the environment. Once released, they can undergo biological and chemical transformation processes, resulting in the formation of various compounds collectively known as “metabolites”, which include biological metabolites, transformation or degradation products, and reaction by-products. The degradation of pesticides is a critical process for reducing their persistence in soil, thus contributing to environmental protection (Galon et al., 2021). This process is influenced by various factors, such as agricultural practices (e.g., crop rotation, irrigation management, and pesticide application), soil properties, weathering, and meteorological conditions (wind speed, precipitation, and temperature) (Andreu and Picó, 2004; Galon et al., 2021). Like the parent compounds, metabolites and their transformation products can also be detected in the atmosphere. Their presence may result from the chemical degradation of pesticides in the air, as well as from the volatilization or wind erosion of metabolites formed in soil or water (López et al., 2016).

In the air, the main degradation pathways that are studied are the photolysis and the interactions with the main atmospheric oxidants such as ozone, nitrogen oxides (Mattei et al., 2019; Samia et al., 2024). Photolysis seems to be slower in particulate phase than in the gaseous phase, for certain molecule (Samia et al., 2024). In addition, pesticide degradation in soil occurs through chemical and microbiological mechanisms. Chemical degradation involves photolysis, hydrolysis, and oxidation-reduction reactions. Microbiological degradation takes place when soil microorganisms break down or consume pesticides (Andreu and Picó, 2004). Microbiological degradation is especially significant because the persistence of pesticides in the environment is closely linked to their chemical structures. Although many pesticides are synthetic and not naturally occurring, microorganisms have evolved and can produce specific enzymes capable of degrading both synthetic and naturally occurring compounds, including pesticides (Galon et al., 2021).

López et al. carried out a non-targeted screening with high resolution mass spectrometry. They identified 34 metabolites in the air equivalent to 22 parent compounds belonging to different families and usages (herbicides, insecticides and fungicides). Half of them are carbamates

and organophosphorus. Among these 34 metabolites, 11 were confirmed and quantified at concentrations from around 6 to 100 $\text{pg}\cdot\text{m}^{-3}$ for THPAM (captan metabolite) and 3-ketocarbocofuran (carbocofuran metabolite), respectively. Concentrations as high as 200 $\text{pg}\cdot\text{m}^{-3}$ were also found for omethoate and carbendazim which were both metabolites and parents compounds potentially forbidden at the time of the study (López et al., 2016). Altogether, this may result in a large number of compounds entering the atmosphere. However, unlike in water, soil, and food, only a limited fraction of possible metabolites has been monitored in air, and knowledge about their occurrence, fate, and impacts remains very limited, highlighting the need for further studies in these areas.

3.1.6. Impact of co-formulants and adjuvants on the active substance volatilization

The effectiveness of pesticide applications in agriculture depends not only on the efficacy of the active ingredients, but also on how the inclusion of co-formulants and adjuvants modifies the physicochemical properties of the spray formulation. These additional components can significantly alter the spray properties, such as drift, adherence, penetration and volatilization (Mesnage, 2021). For instance, drift control adjuvants are designed to increase the coarse fraction and to reduce the fine fraction of the spray, thereby minimizing off-target movements. Although nozzle selection primarily governs droplet size distribution, adjuvants can modify the physicochemical properties of the spray solution, affecting atomization and breakup once the liquid exits the nozzle (Al Heidary et al., 2014; Katzman et al., 2021). Increasing droplet size with adjuvants is an effective strategy for reducing spray drift (Salyani et al., 2013).

Co-formulants and adjuvants also influence the volatilization of active substances. The formulation of a pesticide influences its uptake by plants and consequently, its volatilization (Houbraken et al., 2016). The inclusion of surfactants and other penetrants enhances the absorption of active ingredients into the plant tissues, influencing their effectiveness and their atmospheric release. Moreover, some formulation components can modify the photodegradation rate, which in turn affects the amount of active substance available for volatilization (Houbraken et al., 2016). A better understanding of how co-formulants and adjuvants influence these processes is crucial for optimizing pesticide efficacy and minimizing environmental risks.

3.2. Environmental parameters

Environmental conditions also influence the pesticide presence in the air. As they are beyond the operator's control, they must be carefully monitored before and during the pesticide application.

3.2.1. Weather conditions

3.2.1.1. Wind speed and direction. Among meteorological factors, wind speed and direction play a key role in spray drift. Wind speed is strongly and positively correlated with the extent of spray drift deposition (Arvidsson et al., 2011): higher wind speeds lead to increased drift over longer distances (Nuytens et al., 2009).

Wind speed and direction fluctuations can result in uneven spray distribution between the left and right sides of the sprayer (Al-Jumaili and Masoud, 2014). The risk of drift is lowest with wind speeds between 1.0 m/s and 4.5 m/s (Fishel and Ferrell, 2010). Similarly, in twenty tests carried out in different wind conditions, Gil and Sinfort (2005) found that the drift potential was not significantly affected when the average wind speeds remained below 1.0 m/s.

Wind speed also influences spray deposition on targets: when the sprayer moves against the wind (headwind), increasing the wind velocity from 1.0 to 3.0 m/s reduces deposition by 18 %, whereas deposition increases by 14 % when the sprayer travels with the wind (Al-Jumaili and Masoud, 2014). The same study reported that for wind speeds between 0.0 and 3.0 m/s, winds parallel to the sprayer direction

reduce the predicted deposition by 11 %, 16 %, and 48 % at sampling distances of 3 m, 6 m, and 9 m on both sides of the sprayer, respectively (Al-Jumaili and Masoud, 2014).

Large wind direction fluctuations increase the droplet movement unpredictability and contribute to dilution caused by atmospheric turbulence. As the position of droplet deposition depends on how long droplets remain in the atmosphere, meteorological conditions significantly influence spray drift.

Wind speed influences also pesticide volatilization by enhancing the pesticide transfer into the atmosphere. This effect applies to volatilization from plants and soils: higher wind speeds accelerate the process even when the atmospheric concentration of the pesticide is low (Bedos et al., 2002a).

3.2.1.2. Air temperature and humidity. Air temperature and relative humidity also influence spray drift during spraying operations. Low relative humidity and high temperatures can intensify evaporation, reducing droplet size, particularly for smaller droplets, thereby decreasing their sedimentation velocity and making them more susceptible to drift (AFSG Agrisystems & Environment et al., 2003; Maciel et al., 2018). Temperature also plays a critical role in pesticide volatilization because it directly affects the compound physicochemical properties. Higher air temperatures tend to enhance volatilization from plants and soils due to the exponential dependence of vapor pressure on temperature. For most pesticides, a 10 °C increase results in a 3- to 4-fold rise in vapor pressure (Bedos et al., 2002a). However, this effect is moderated by soil dryness that increases pesticide adsorption to the soil matrix and consequently, reduces its availability for volatilization. Volatilization is generally higher when soil moisture content is elevated, whereas dry soil conditions lead to minimal or negligible volatilization (Bedos et al., 2002a).

Air humidity affects volatilization differently depending on the support. On soil, higher humidity tends to favor pesticide volatilization. On crops, low relative humidity causes faster drying of leaves, which encourages adsorption of pesticide molecules on the leaf surface. Conversely, higher humidity supports both adsorption by plants and volatilization (Bedos et al., 2002a).

Solar radiation directly affects volatilization rates from soils and plants. Volatilization exhibits diurnal fluctuations driven by changes in soil surface moisture and temperature. When the soil surfaces are wet, volatilization peaks in the early afternoon (the time of maximum solar radiation). Conversely, when the soil surfaces are dry, volatilization tends to be higher in the early morning or evening due to dew formation or capillary water fluxes (Bedos et al., 2002a; Reichman et al., 2013).

In Europe, the Directive 2009/128/EC on the sustainable use of pesticides requires member states to develop “National Action Plans” to reduce pesticide-related risks. These plans include restrictions and application guidelines, particularly in adverse weather conditions, such as high winds or high humidity, that may facilitate the pesticide drift into the environment or towards populated areas. France has reinforced these measures by prohibiting pesticide application near residential areas in specific weather conditions, such as strong winds. Since May 2017, the law in France has restricted the conditions under which pesticides can be applied to crops. According to this decree, products can only be used when the wind speed is ≤ 3 on the Beaufort scale (8–12 km/h). They may not be used when the precipitation intensity is > 8 mm per hour. In general, the best time to apply pesticides is when wind speed is low, temperature is cooler, and relative humidity is high because these conditions are associated with reduced drift and volatilization (Desmarteau et al., 2020).

3.2.2. Soil characteristics

3.2.2.1. Pesticide mobility/adsorption. Pesticides applied to soils undergo various physicochemical and biological processes that influence

their environmental behavior. One of the initial and crucial events is their physical adsorption and desorption that significantly influence their mobility, transformation and degradation (Wang et al., 2020). Adsorption and desorption depend on the pesticide chemical nature and the soil properties, particularly the presence of ions, ligand exchange, charge transfer, dipolar interactions, hydrogen bonding, and covalent bonding. The mobility of pesticides in soil is a key factor when assessing their environmental risk because it determines their potential to reach surface water or groundwater systems (Gao et al., 2016).

Moreover, organic amendments can significantly influence the pesticide adsorption and mobility in soil, mitigating the related environmental risks (Jiang et al., 2011; Kodešová et al., 2011). For most pesticides, their adsorption in surface soil is positively correlated with the soil organic carbon content (Alletto et al., 2010). Additionally, the sorption of many pesticides is strongly affected by the soil pH: sorption increases as the soil pH decreases (Alletto et al., 2010).

Soil water content and temperature also influence the pesticide adsorption. In some cases, increased soil water content reduces pesticide retention. In others, it enhances adsorption, likely due to a decrease in the hydrophobicity of organic compounds and improved access to sorption sites enabled by the presence of water (Alletto et al., 2010). Soil moisture plays a pivotal role in determining the volatilization rates. In moist soils, higher rates are observed around midday and early afternoon. Conversely, in dry soils, the maximum volatilization rates occur during periods of increased surface moisture, such as early morning and evening. Atmospheric stability and solar radiation also influence these dynamics, highlighting the complex interplay of environmental conditions (Bedos et al., 2002a). The soil temperature affects the pesticide degradation rate, water-air partition coefficient, and water-soil partition coefficient. These three parameters contribute to determine the pesticide behavior in the environment (Fouad et al., 2024).

3.2.3. Landscape effect

Hedges and forests play a critical role in mitigating wind erosion and its impact on agricultural soils. Unlike forest soils, which are naturally shielded by continuous vegetation, agricultural soils are more vulnerable due to frequent tillage and limited ground cover (Avecilla et al., 2023). Vegetation, such as hedgerows and trees, offers multiple protective benefits. It shelters soil by covering portions of its surface and creating lee-side wakes that reduce the wind impact. It also traps windborne particles, limiting their flux and promoting sediment deposition. Additionally, by introducing surface roughness, vegetation modifies the wind velocity profiles, fostering a boundary layer that weakens wind intensity downwind (Mayaud et al., 2016).

The hedgerow effectiveness in curbing wind erosion depends on their permeability and design. Optimal results are obtained when they filter rather than abruptly deflect airflow. It has been shown that 50 % of wind permeability provides the best reduction (Langenbach et al., 2022). Trees, through their extensive canopies and ability to generate turbulence, further enhance particle interception, outperforming shorter vegetation in capturing airborne sediment (Weninger et al., 2021).

Particulate matter (PM) is closely associated with dust that carries pesticides (insecticides, fungicides and herbicides). A study in Israel found that all planted trees significantly reduce both PM and pesticide dispersion. Thus, integrating hedges and trees into agricultural landscapes mitigates soil erosion and also improves sediment retention and ecosystem stability (Weninger et al., 2021).

3.3. Operating parameters

This section focuses on key factors that influence the three main mechanisms explaining the presence of pesticides in the air. Spraying is the main technic used to apply pesticides. In this context spray drift is the most influent mechanism. Some alternatives applications could be occasionally employed (soil injections, seed coating ...), but the literature provides limited discussion regarding their contribution to airborne

Table 2
Effects of droplet size on spray characteristics and typical applications.

Droplet size (μm)	Coverage	Deposition on target	Drift risk	Evaporation	Typical use
<20	Low	Difficult	High	Rapid	Not recommended
20–100	Low	Difficult	High	Rapid	Limited, drift risk
100–200	Good	Moderate	Moderate	Moderate	Preferred for insecticides and fungicides
200–500	Medium	Good	Low	Slow	Good compromise
>500	Low	Good	Low	Slow	Systemic herbicides

pesticide emissions.

It first examines technical parameters related to the spray (droplet size, liquid viscosity, and application techniques). Then, it briefly discusses a practice that have a important impact on the third mechanism, i.e. erosion. Finally, the operator's role, emphasizing how the user's skills and decision-making influence the application quality and contribute to the adoption of good agricultural practices.

3.3.1. Spray characteristics

3.3.1.1. Droplet size. Droplet size, particularly the proportion of fine droplets (<100 μm), is the technical factor that most influences spray drift (Bourodimos et al., 2019; Schleier et al., 2010). With wind speed and direction, it plays a crucial role in determining the drift potential. The droplet spectrum, shaped by the application system, depends on the spray technique, including pressure, nozzle selection, and the spray liquid physicochemical properties (De Schamphelre et al., 2009). Smaller droplets are more prone to being carried away by air currents, increasing the risk of off-target deposition, while larger droplets tend to settle more quickly. Therefore, optimizing spray parameters is essential to minimize drift and ensure effective pesticide application. Droplet size is crucial when selecting a setup to minimize drift and ensure optimal coverage and penetration (Hong et al., 2021; Xue et al., 2021). Striking this balance can be challenging, but it is essential to reduce drift without compromising the application efficiency. Droplet size is influenced by the nozzle type and size, the spray liquid features, and the pressure at which the liquid leaves the nozzle orifice (Creech et al., 2015). The pesticide and surfactant concentrations also modify droplet size because they relate to the carrier volume.

Effective coverage, defined as the uniform and sufficient deposition of spray droplets on the target surface, is crucial when applying insecticides and fungicides because these products act on very small organisms, such as insects and fungal spores. Fine droplets are particularly effective in this context because they enhance the product surface distribution and facilitate its penetration into target structures, improving the active substance bioavailability. Conversely, insufficient or uneven application can significantly reduce efficacy, enabling pests or pathogens to persist and potentially develop resistance. For this reason, medium-size droplets (100–200 μm) are generally preferred because they offer a good balance between adequate coverage and limited drift potential. Small-size droplets (2–100 μm) are difficult to deposit on the target because their low mass and limited momentum facilitate their suspension in the air, increasing the risk of drift (Hofman and Solseng, 2001). Particularly, <100 μm droplets may evaporate before reaching the target or be carried off-site. Indeed, 100 μm droplets can travel up to 7.5 times farther than 500 μm droplets at a wind speed of 5 km/h (Creech et al., 2015). Their reduced mass causes them to quickly lose vertical momentum, transforming them into fine aerosols that rise into the atmosphere and remain suspended until removed by precipitation (Hofman and Solseng, 2001). A 20 μm droplet evaporates almost instantly, disappearing within a centimeter of travel. On the other hand, systemic herbicides can be effectively distributed using large droplets because coverage and penetration are not so critical (Fishel and Ferrell, 2010). Larger droplets, particularly those >200 μm in diameter, are far less likely to drift than smaller ones. Their greater volume also makes them more resistant to evaporation, a characteristic observed even in

>150 μm droplets (Hofman and Solseng, 2001).

As discussed above, droplet size is a determining factor in balancing application efficiency and environmental safety. Table 2 provides an overview, based on the literature data, of how different droplet size ranges influence key parameters of spray application, including coverage, deposition on the target, drift risk, and evaporation rate. It also highlights the typical uses associated with each range. Drift risk refers to the likelihood that droplets will be carried away from the target area by wind or air currents. This risk is particularly elevated with fine droplets due to their low mass and high susceptibility to atmospheric turbulence. Evaporation rate indicates how quickly droplets lose volume due to environmental conditions, such as temperature and humidity. Smaller droplets evaporate more rapidly, often before reaching the target, reducing the application efficiency. This classification facilitates the selection of the appropriate droplet size according to the target organism, product formulation, and desired application outcome. Typical uses are also indicated, reflecting common agricultural practices associated with each droplet size class.

3.3.1.2. Droplet viscosity and velocity. The spray liquid viscosity and thickness play a crucial role in determining the droplet size and drift potential. Higher viscosity leads to larger, coarser droplets that are less likely to disperse unintentionally, minimizing drift (De Schamphelre et al., 2009). To enhance viscosity and slow down evaporation, drift retardants are often added to the spray mixture. This helps to limit the formation of small droplets (<150 μm) that are more susceptible to drifting. These adjustments directly affect droplet size (Al Heidary et al., 2014) and ultimately reduce the drift potential (Katzman et al., 2021).

Droplet velocity is closely tied to the droplet size. Larger droplets generally maintain higher and more consistent velocities, with speeds ranging from 16 to 18 m/s for droplets up to 70 μm , depending on the nozzle type. Droplets smaller than 70 μm exhibit a significant drop in velocity, to 10–12 m/s for the smallest droplets (D. Nuyttens et al., 2009). In general, droplets display their maximum velocity close to the nozzle orifice and then slow down during transport to the target (Al Heidary et al., 2014). Smaller droplets, due to their low inertia, are particularly susceptible to drift because they are easily carried away by air currents (Arvidsson et al., 2011). This highlights the importance of controlling droplet size to mitigate drift risks.

3.3.2. Equipment and application techniques

Pesticides are typically applied using sprayers equipped with nozzles that produce a range of droplet sizes, some of which are susceptible to drifting. Larger droplets may be carried away by the wind and deposited outside the target area or further downwind (Van den Berg et al., 1999). Specialized nozzles are designed to limit drift during application (Jensen and Olesen, 2014).

3.3.2.1. Nozzle and spray pressure. Before application, operators mix the pesticide with water to create a spray liquid of the desired concentration (Jensen and Olesen, 2014). The pump draws this mixture from the tank and forces it under pressure toward the spray nozzles. Operators should choose nozzle types that provide thorough coverage while minimizing drift (Zhang et al., 2024). Spray from nozzles consists of drops of different sizes (Al Heidary et al., 2014). Depending on the orifice size, nozzle shape and used pressure, the drop size distribution of different nozzles may

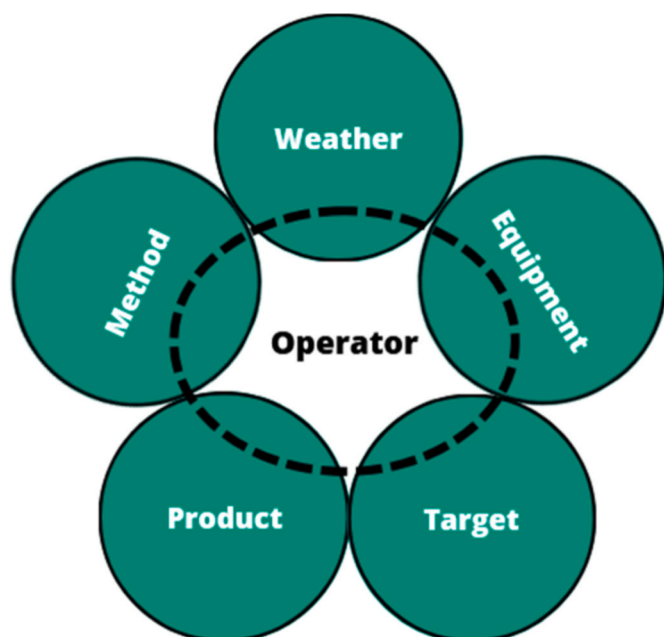


Fig. 2. Key factors that influence pesticide application and the central role of the operator, adapted from (Damalas and Eleftherohorinos, 2011).

differ. Most major agricultural nozzle manufacturers now offer “low-drift” nozzles that reduce the number of small droplets and thus decrease spray drift compared with conventional nozzles.

Classification systems have been developed to categorize drop size distribution for agricultural use. These systems use recognizable terms to describe the spray quality, such as Fine, Medium and Coarse, to facilitate understanding by operators (Van De Zande and Holterman, 2002).

Higher pressures and lower liquid flow rates result in smaller droplets, whereas higher flow rates increase droplet size. However, excessively high liquid flow rates can lead to poor atomization (Hong et al., 2021). Moreover, changes in nozzle position can result in up to a fivefold variation in pesticide deposition (Zhang et al., 2024).

3.3.2.2. Application speed and height. The application speed significantly influences drift. The sprayer forward speed is a key operational parameter that influences its overall performance. Variations in forward speed can alter the spray deposition pattern and affect the drift behavior (Lešnik et al., 2015). Higher speed puts more stress on the equipment, is harder to control, and creates air currents that promote drift. At faster speeds, spray can be deflected into upward wind currents and vortices behind the sprayer, where smaller droplets are trapped, further increasing the drift risk (Fishel and Ferrell, 2010). The application height is another critical factor in pesticide drift. The higher the spray is released, the longer droplets remain suspended in the air, giving ambient wind more time to carry them laterally, away from the target area (Damalas, 2015). However, when using ground sprayers with low boom height, where the nozzles are pointed downwards, most spray material does not remain in the atmosphere for long and therefore, is not much influenced by the weather conditions (Damalas, 2015).

3.3.3. Tillage effect

Agriculture is a major source of atmospheric PM pollution. The most polluting activities are soil tillage and crop harvesting that generate significant PM emissions (Chen et al., 2017). Tillage and crop harvesting are the main anthropogenic sources of agricultural PM emissions in Europe and North America. Tillage, a common practice that involves soil disturbance for crop planting, weed control and fertilizer incorporation, significantly contributes to airborne particle release (Pokharel et al.,

2023). Mechanical soil disruption generates fine PM₁₀ particles composed of soil minerals and organic dust. Emission levels vary depending on the soil composition: silt- and clay-rich soils produce more PM due to aggregate formation (Pokharel et al., 2023). Tillage can also resuspend pesticides previously adsorbed onto the soil surface, further contributing to atmospheric contamination.

Although these activities are short-lived, their particle emissions can significantly exceed those generated by wind erosion of agricultural land (Chen et al., 2017). Wind erosion of soil contaminated with pesticides can be minimized using conservation tillage, by maintaining adequate residue cover on the soil surface and crops.

3.3.4. Operator's skills

In Fig. 2, the five interconnected circles (Weather, Equipment, Target, Product, and Method) represent the various elements that the operator must manage to minimize pesticide drift and volatilization.

- **Weather:** Wind speed, temperature, and humidity directly affect pesticide dispersal and volatilization rates. In poor weather conditions, the operator can choose not to apply pesticides to limit drift and wait for a more advantageous period that will reduce losses during application.
- **Equipment:** The type and calibration of the spraying equipment can influence the droplet size and the pesticide amount released into the air.
- **Target:** The target nature (e.g., crop type or surface) affects how much pesticide remains on the surface versus how much evaporates or drifts.
- **Product:** Different pesticides have different volatilities and formulations (mix of pesticides) that can influence their potential to become airborne.
- **Method:** The application technique (e.g., timing, spraying height) plays a significant role in determining the extent of pesticide emissions.

The “Operator” central role highlights the users’ critical responsibility in integrating and managing various factors to minimize the environmental impact and exposure risks associated with pesticide use.

The farmers’ education and training play a crucial role in reducing pesticide use and exposure, promoting safer agricultural practices, and protecting human health and the environment. As pesticide application involves complex decision-making influenced by personal biases and habits, proper training ensures that professional users adopt the best practices to minimize the risks (Grimbuhler et al., 2024).

To address these challenges, the EU has established regulations that require member states to provide certified training for professional pesticide users (Sacchetti and Calliera, 2017). In France, this obligation is fulfilled through the Certiphyto certification that farmers must obtain and renew every five years to legally purchase and apply pesticides. The training, delivered by occupational health and agronomy experts, covers essential topics, such as pesticide legislation, risk assessment, exposure reduction measures, and integrated pest management.

Despite these training efforts, studies have revealed persistent gaps in knowledge and implementation. Many farmers understand the importance of pesticide storage. Conversely, their awareness of safe application and disposal practices remains insufficient. Reports indicate frequent spills and improper waste management, suggesting a lack of adherence to environmental precautions (Calliera et al., 2013). Additionally, risk perception and hygiene practices vary, further influencing pesticide safe use (Damalas and Eleftherohorinos, 2011).

On the other hand, studies have highlighted the positive impact of training on pesticide safety and management. For example, farmer field schools are effective in enhancing knowledge and promoting responsible pesticide use in various contexts (Goeb and Lupi, 2021). In France, Certiphyto training significantly improved the safety climate perception

Table 3

Overview of the parameters driving pesticide presence in air through spray drift, volatilization and wind erosion.

Parameter	Sub-parameters	Spray drift	Volatilization	Wind erosion
Physicochemical properties	Vapor pressure	✓	✓	
	Henry's law constant	✓	✓	
	Soil mobility		✓	
	Environmental persistence (e.g., degradation rate)		✓	✓
Environmental parameters	Wind speed and direction	✓	✓	✓
	Temperature		✓	
	Relative humidity	✓	✓	
	Rainfall		✓	
	Soil moisture		✓	
	Air stability (vertical mixing potential)	✓	✓	
	Soil texture (clay, loam, organic matter content)		✓	✓
Operational parameters	Particle size	✓		✓
	Application method and equipment	✓	✓	
	Viscosity (affecting droplet formation and spray characteristics)	✓		
	Tillage practices (e.g., reduced tillage, no-till systems)			✓
	Operator care and skill	✓		

by farmers, increasing their awareness of best practices and risk management strategies (Grimbuhler et al., 2024). Furthermore, training enhances the knowledge on pesticide toxicity, efficacy and pest control mechanisms, helping farmers to make more informed choices (Afshari et al., 2021; Ayaz et al., 2022).

However, not all aspects of pesticide safety have improved equally. Goeb and Lupi found that training increased the knowledge about the pesticide attributes (e.g., toxicity and efficacy), but not the awareness of the exposure risks (Goeb and Lupi, 2021). This may be due to an already high baseline understanding, leaving limited room for further gains.

Overall, training programs, such as Certiphyto, contribute to improve pesticide management, but they must be continuously adapted to address the remaining gaps in knowledge and practice.

3.4. Summary

Table 3 summarizes the previously discussed parameters and sub-parameters, highlighting their respective roles in influencing the three main mechanisms by which pesticides may be present in the atmosphere (spray drift, volatilization, and wind erosion). Physicochemical properties, such as vapor pressure and Henry's law constant, are key indicators of the compound tendency to volatilize, but they also contribute to the spray drift potential through their effect on droplet evaporation. Environmental conditions (wind speed, temperature, and humidity) modulate the behavior of pesticide particles and vapors once released in the environment. For example, wind (speed and direction) is a common driver in all three mechanisms. Operational parameters, including equipment settings and product viscosity, directly modulate the droplet size and spray quality, impacting drift. Soil-related practices, such as tillage, influence the potential for particle-bound pesticide erosion. Beyond these local processes, long-range atmospheric transport can carry both gaseous and particle-bound pesticides over hundreds or even thousands of kilometers, leading to their detection in remote regions far from agricultural sources, including mountainous and polar areas

Model/Tool	Main objective	Model type	Spatial scale	Input parameters	Key features/strengths	Limitations	Reference
AGDRIFT	To assess offsite drift from agricultural applications	Empirical/mechanistic	Fine scale (meters to hundreds of meters)	Application parameters, meteorological data	Fine-scale estimation of pesticide drift	Limited to drift processes, mainly in US context; less adapted to European crops/practices	Bird et al. (2002)
IDEFICS	To calculate drift from boom sprayers	Mechanistic	Fine scale	Sprayer characteristics, meteorology, application conditions	Dedicated to conventional sprayers, process-based	Not adapted to all spraying techniques; limited generalizability	Holterman et al. (1998)
PEARL	To simulate pesticide volatilization	Mechanistic (resistance-based)	Fine to intermediate (field to regional)	Soil properties, meteorological data, pesticide properties	Resistance-based volatilization modeling; flexible for various products	Requires detailed site-specific inputs; computationally demanding	Leistra et al. (2001)
Volt'Air Pesticides	To estimate volatilization fluxes after application	Mechanistic	Fine (extendable to regional/national)	Soil and crop data, meteorology, pesticide properties	Can be integrated into atmospheric transport models; local to national scale	Complex parameterization; uncertainties in large-scale upscaling	Bedos et al. (2009)
SURFATM-Pesticides	To evaluate volatilization from soil/crop surfaces	Mechanistic	Fine to broad scale	Soil/crop properties, weather data, product parameters	Modular approach; coupling with transport models	Data-intensive; model complexity can limit operational use	Lichihieb et al. (2014)
CHIMERE	To simulate the spatiotemporal distribution of pesticide concentrations in air	Integrated (air quality + volatilization)	National (France)	Spatialized pesticide application data (BNVD-S), agricultural survey data, meteorology, soil/crop data	Coupled emission-transport-chemistry; validated with atmospheric data	High computational cost; uncertainties in timing of emissions	Menut et al. (2021); Couvidat et al. (2022)
Pesticide Sale Spatialization Model	To spatialize sale data for estimating actual pesticide use	Spatial allocation model	Parcel to regional scale	Sales data, land use, legal authorization (doses, products)	Produces fine-scale pesticide use maps; validated in test sites	Relies on availability and quality of sales data; indirect estimation of applications	Martin et al. (2023); Lungsarska et al. (2023)
TyPol	To estimate the volatilization potential of pesticide compounds	Statistical/multivariate	Non-spatial (global emission potential)	Molecular descriptors (vapor pressure, sorption, lipophilicity, etc.)	Distinguishes airborne vs. non-airborne compounds; efficient early screening	Not process-based; does not simulate dispersion or dynamics	Mamy et al. (2021)

Table 4
Models to simulate pesticide presence in the atmosphere.

(Mayer et al., 2024). This phenomenon reflects the complex interplay between air, particles, and water, which governs the partitioning, transformation, and eventual deposition of pesticides in the environment.

4. Contribution of modeling

Modeling the presence of pesticides in the air is essential for understanding and predicting their dispersion, exposure risks, and environmental impact. These predictions support the development of more effective mitigation strategies (Costanzini et al., 2018). Various modeling approaches have been developed to estimate the emissions, simulate the dispersion, and assess the atmospheric concentrations of pesticides. These approaches differ in structure, spatial scale, data requirements and objectives. In this section, they are organized in four main categories: empirical models, mechanistic models, integrated models, and supporting or hybrid tools (Table 4).

4.1. Empirical models

Empirical models rely on statistical relationships or simplified assumptions derived from the observed data. They are particularly useful when limited input information is available or when many compounds must be assessed rapidly.

An illustrative example is TyPol (Mamy et al., 2021). This tool was used to investigate the relationships between the volatilization potential of 178 pesticides, at the global, soil, and plant levels, and their molecular descriptors. Using clustering techniques that emphasize parameters such as vapor pressure, soil sorption, and lipophilicity, TyPol successfully discriminated between compounds that were detected in the atmosphere and those that were not. The model identified compounds characterized by low molecular weight, high total energy, and specific connectivity and polarizability features as pesticides with high atmospheric emission potential. Therefore, TyPol is a valuable screening tool for the early-stage assessment of air contamination risks.

The spatialization model is another example of empirical approach (Martin et al., 2023). This model was used to redistribute the annual pesticide sale data in France, originally reported at the postal code level, to the scale of individual agricultural parcels. It combined land use data, types of pesticide products, and authorized application doses to generate spatially explicit pesticide use maps. Its application in two French rural areas (Bourville and Pleine-Fougères) with different characteristics demonstrated its accuracy and adaptability. In Bourville, where direct pesticide use data were available, the model outputs closely matched the actual application patterns. In Pleine-Fougères, the absence of ground-truth data did not prevent the model from generating consistent and spatially differentiated usage patterns, confirming its relevance for policy monitoring at the territorial scale.

4.2. Mechanistic models

Mechanistic models are used to simulate the physical and chemical processes that govern pesticide emissions in the atmosphere. These process-based models often require detailed input data, such as meteorological parameters, soil characteristics, and product properties; however, they provide a more accurate representation of the environmental dynamics.

Some mechanistic models specifically address spray drift. For instance, AGDRIFT (Bird et al., 2002) and IDEFICS (Holterman et al., 1998) operate at a fine spatial resolution, ranging from few meters to several hundred meters, and focus on estimating the off-target drift in different application and weather conditions.

Other models focus on volatilization, simulating the emission of pesticides from soil and plant surfaces following their application. PEARL (Leistra et al., 2001) uses a resistance-based modeling approach to estimate the volatilization rates at the field level. Similarly, Volt'Air

Pesticides (Bedos et al., 2009) and SURFATM-Pesticides (Lichiheb et al., 2014) quantify the volatilization fluxes at the local scale. These models were initially developed for fine-resolution applications, but they can be scaled up to regional or even national levels when coupled with atmospheric transport models, extending their utility to policy-relevant assessments.

4.3. Integrated models

Integrated models couple pesticide emission estimates with atmospheric transport and chemistry components to simulate the pesticide dispersion and transformation in the air across larger spatial and temporal scales.

A prominent example is the modeling framework developed by Couvidat et al. (2022) that incorporates a pesticide volatilization module into the CHIMERE air quality model (Couvidat et al., 2022; Menut et al., 2021). This model uses spatialized application data derived from the French BNVD-S database and time-specific application windows informed by agricultural surveys. The framework was applied to simulate the atmospheric concentrations of S-metolachlor and folpet at the French national level. Results were validated against the observed air concentration data and showed good agreement in terms of concentration magnitude and geographic distribution. Although some uncertainties remain, particularly regarding the temporal dynamics of emissions, this integrated modeling approach demonstrates strong potential for characterizing airborne pesticide exposure at broad spatial scales.

4.4. Hybrid and supporting tools

In addition to dedicated emission and dispersion models, several tools support pesticide air contamination modeling by increasing data availability, refining input variables, or guiding compound prioritization.

The TyPol tool, although empirical in nature, contributes essential information for assessing the emission potential and guiding monitoring efforts. Similarly, the spatialization approach developed by Martin et al. (2023) provides critical input for more complex emission and dispersion simulations. These tools bridge the gap between raw datasets, such as national sale records, and detailed environmental modeling, improving the spatial and conceptual resolution of risk assessments.

Nevertheless, the current models do not fully take into account the wide range of parameters that influence pesticide emissions in the air, particularly qualitative factors such as agricultural practices, user behavior, or local environmental and socio-economic conditions. These aspects are more difficult to quantify but can play a critical role in determining the actual pesticide dispersion dynamics. To address these limitations, the development of a conceptual model based on systems thinking approaches, as already done in other contexts (e.g., urban areas), could provide a valuable framework. Systems thinking focuses on the behavior of whole systems, examining the interactions and feedback between their constituent elements (Newberry et al., 2024; Sterman, 2000). This model would allow integrating quantitative and qualitative variables to facilitate the identification of key interactions and consequently a more comprehensive understanding of the involved processes. Ultimately, this approach could guide the refinement of existing models or the development of new tools that better reflect the complexity of real-world scenarios.

5. Monitoring pesticides in the air: the French case

According to the review by Brüggemann et al., studies conducted between 2002 and 2022 reveal a predominance of pesticide air monitoring efforts in Europe and North America (Brüggemann et al., 2024). France accounts for the largest number of studies ($n = 14$), followed by Spain and the USA ($n = 6$ each), and Canada ($n = 5$). Methodological

Table 5

Summary of pesticide concentrations and detection characteristics in mainland France during the national campaign (2018–2019) (LCSQA, 2020).

Frequently detected substances	9 pesticides with detection rates >30 %: AMPA, propyzamide, chlorpyrifos methyl, prosulfocarb, S-metolachlor, triallate, pendimethalin, glyphosate, lindane
Most quantified pesticides	Glyphosate, prosulfocarb, S-metolachlor (herbicides)
Annual average concentrations	Generally <0.1 ng/m ³
Substances exceeding 1 ng/m ³	Folpet (fungicide), prosulfocarb (herbicide) (occasionally >1 ng/m ³ ; peak concentrations >100 ng/m ³ for some substances)
Detection periods	Closely aligned with pesticide application periods (spring and autumn)
Regional specificity	- Folpet (fungicide): mainly detected in viticultural areas - Pendimethalin (herbicide): more common in large-scale crop-growing regions
Arboriculture sites	High variability → potential influence of meteorological conditions and pest pressure
Glyphosate	Frequently detected, but low annual average concentration (0.04 ng/m ³) → likely influenced by sampling techniques
Banned substance	Lindane, lindane has the lowest average concentrations, at 0.06 ng/m ³ , with a detection frequency of over 20 %, despite its ban in agriculture since 1998 and as a biocide since 2005

approaches show both convergence and national specificities: France relies on the AFNOR XP X 43–058 standard, while the US mainly uses EPA TO-4, TO-10, and ASTM D4861-23; in Spain and Canada, monitoring generally adapts US or French protocols (Brüggemann et al., 2024). To date, four technical standards are formally established worldwide, underscoring the need for greater international harmonization. Thus, a focus on France is justified, as it is the only country with a long-term national monitoring program and the one where the largest number of studies has been conducted.

5.1. Airborne pesticide monitoring in France

In France, several regional studies highlighted the presence of airborne pesticides and their connection to agricultural practices. For instance, Schummer et al. (2010) demonstrated that in the Alsace region, pesticide concentrations in the air closely follow the seasonal application patterns (Schummer et al., 2010). Similarly, Coscollà et al. (2010) showed how in the Centre region, local agricultural activities and meteorological conditions influence the spatial and temporal distribution of airborne pesticides (Coscollà et al., 2010). These studies contributed to a growing body of knowledge about the pesticide impact on air quality and public health.

In 2018, as part of a program to harmonize air monitoring procedures, 75 pesticides were measured at 50 sites nationwide. Table 5 presents a summary of the key findings. Detection rates varied depending on the compound: 56 pesticides were identified at least once in mainland France and 16 in the French overseas territories. Moreover, in mainland France, only nine pesticides were detected in more than 30 % of samples, highlighting a relatively limited subset of substances with high atmospheric occurrence. Glyphosate, prosulfocarb, and S-metolachlor were among the most frequently quantified compounds, reflecting their widespread use in agricultural practices. Although the annual average concentrations were generally below 0.1 ng/m³, some substances, such as folpet and prosulfocarb, occasionally exceeded 1 ng/m³, with some peak values surpassing 100 ng/m³. These fluctuations closely followed the pesticide application periods, underscoring the direct influence of agricultural activities on airborne pesticide levels. Region-specific detection patterns also emerged. Folpet was primarily detected in viticultural areas and pendimethalin in large-scale crop production zones. Furthermore, the

variability observed at arboriculture sites suggests that meteorological conditions and pest pressure may significantly influence pesticide concentrations in ambient air. Glyphosate was frequently detected; however, its relatively low annual mean concentration (0.04 ng/m³) indicates that the detection frequency may also be influenced by sampling and analytical sensitivity (LCSQA, 2020).

The campaign also revealed the persistence of several banned substances, including lindane, a prohibited insecticide still detectable in both mainland France and overseas territories. Other banned compounds, such as pentachlorophenol and oxadiazon, were detected at low concentrations and sporadically. Similarly, previous studies reported lindane detection in the air in various regions of the world despite its ban. For example, in the United States, lindane concentrations up to 9.3 ng/m³ were measured using passive air samplers in Mississippi. In Europe, active sampling methods recorded lindane concentrations between 35 pg/m³ and 2 pg/m³ at 71 sites (IARC Working Group, 2015). In Canada, passive air sampling showed annual concentrations of γ -HCH, a lindane isomer, between 1.8 pg/m³ and 60 pg/m³ (IARC Working Group, 2015).

This campaign provided a crucial benchmark for assessing pesticide contamination in the air and laid the foundation for long-term national monitoring efforts launched in 2021 to ensure continuous and consistent tracking of airborne pesticides (Brüggemann et al., 2024). As part of this program, eighteen fixed monitoring sites have been established nationwide to provide long-term, harmonized surveillance. These sites allow precisely tracking pesticide levels across regions (LCSQA, 2024). The first results are generally consistent with the previous data (LCSQA, 2024). They also showed a decrease in both concentrations and quantification frequencies of various compounds across mainland France. The most frequently quantified pesticides (>20 %) with mean annual concentrations exceeding 0.1 ng/m³ included prosulfocarb and triallate in mainland France, pendimethalin in mainland France and overseas territories, and s-metolachlor in overseas territories. In mainland France, prosulfocarb levels increased between 2018 and 2021 (annual mean concentration of 1.5 ng/m³), likely due to its increased use to replace glyphosate-based products. Although glyphosate was reapproved at the European level for a ten-year period in 2023, many commercial formulations containing glyphosate have been withdrawn from the French market. Today, only 13 of the 726 previously available, authorized glyphosate-based products remain authorized in France, prompting a shift toward alternative herbicides, such as prosulfocarb. The mean annual folpet concentration was ~1 ng/m³, but it is less frequently detected and at lower levels than in 2018, like chlorothalonil and chlorpyrifos-methyl (>20 % compared with >5 % and >10 % respectively). The quantification frequencies for pendimethalin have remained relatively stable, but the annual mean concentration has declined (LCSQA, 2024).

5.2. Studies in Brittany

Brittany is a particularly relevant region for studying the presence of pesticides in the air due to its intensive agricultural activity. According to data from the Brittany Chamber of Agriculture, the region accounts for 5 % of the national Utilized Agricultural Area (UAA) and 64 % of its territory is dedicated to agriculture. This corresponds to approximately 1.6 million hectares dedicated to agriculture, compared with the 26.8 million hectares nationwide. According to data from 2020, Brittany is home to more than 25,000 farms (7 % of all French farms), many of which rely heavily on chemical inputs, such as herbicides, fungicides and insecticides.

The regional Air Quality Monitoring Society in Brittany (“Air Breizh”) has been conducting regular measurement campaigns since 2003, with durations ranging from few weeks to several months, depending on factors such as the sensor proximity to agricultural plots and the farming activity type (e.g., market gardening, arable farming). In total, eleven different sites were monitored between 2003 and 2022 (Fig. 3).

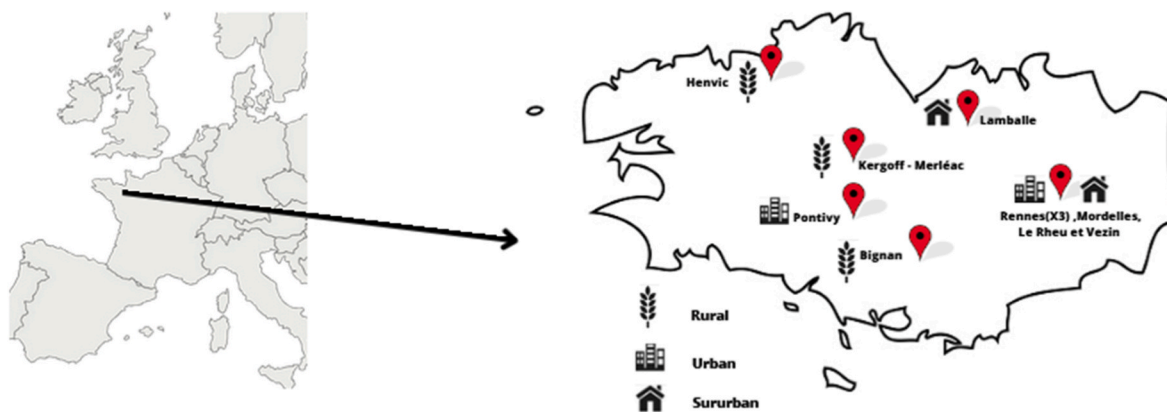


Fig. 3. Geographic location of the study sites in Brittany, northwestern France. The map shows the distribution of the selected study areas in three environment types: rural, urban and peri-urban. The study sites include Henvic, Lamballe, Kergueff-Merléac, Rennes (3 sites), Mordelles, Le Rheu et Vezin, Bignan, and Pontivy.

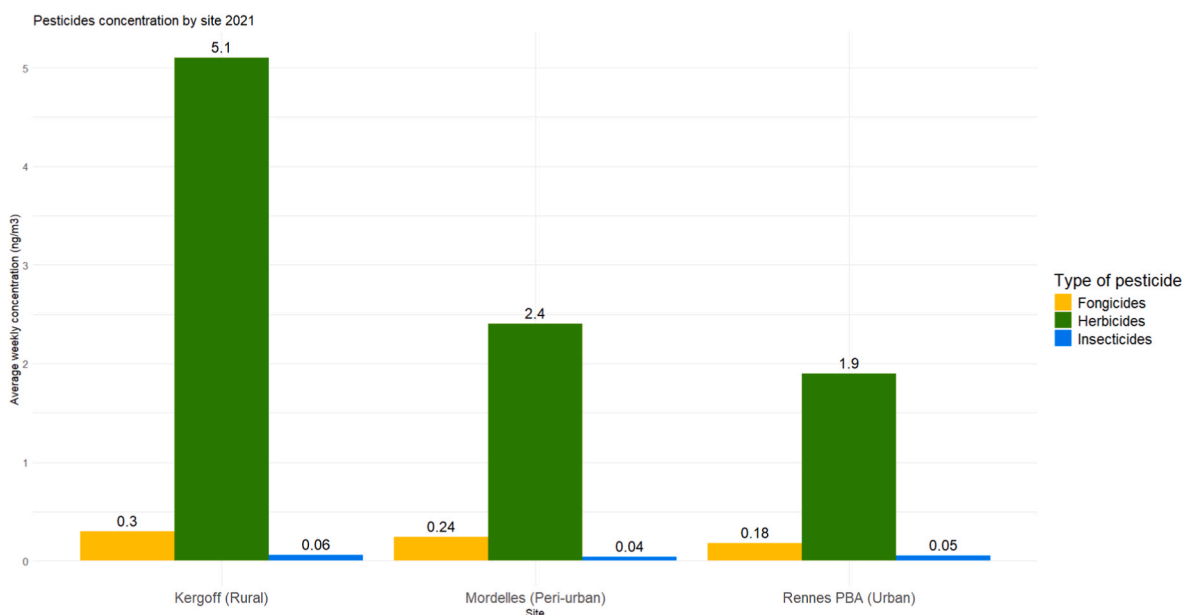


Fig. 4. Spatial variations in pesticide concentrations across rural, peri-urban, and urban sites (2021).

A marked seasonal variation was observed: herbicides were more frequently detected in autumn and fungicides in spring, at all sites. Pesticide concentrations in the air were significantly influenced by the agricultural profile of the studied areas: arable farming was associated with the highest levels, for example, of prosulfocarb and S-metolachlor. The distance from farmland also played a crucial role: pesticide concentrations tended to decrease with the increasing distance, although the diversity of detected substances remained stable (Air Breizh, 2023).

Fig. 4 shows that herbicides were the main pesticide type detected at all sites (rural, peri-urban and rural) with a rural > peri-urban > urban concentration gradient. Fungicides and insecticides were present at significantly lower concentrations at all sites (0.18–0.3 ng/m³ and <0.1 ng/m³, respectively). These results highlight a clear gradient in herbicide concentrations, with higher levels recorded in areas closer to agricultural activity. This predominance of herbicides reflects their widespread use in crop management practices during the sampling period, compared with fungicides and insecticides, for which such spatial differences were less pronounced.

A general downward trend has been observed for some widely used substances in Brittany, such as prosulfocarb and S-metolachlor, potentially due to changes in regulations and agricultural practices. Unsurprisingly, like in the rest of the French territory, lindane continues to be

detected despite having been banned for several years, highlighting its persistence and long-term presence in the environment.

6. Conclusions and perspectives

The presence of pesticides in the atmosphere represents a complex and unresolved issue that is influenced by many interactions between users' practices, pesticide physicochemical properties and meteorological conditions. This narrative review summarized the current knowledge on pesticide emissions in the air, transport mechanisms and key influencing factors, and identified critical gaps in scientific understanding.

Atmospheric pesticide pollution is not confined to intensive agricultural regions but can extend to remote areas through volatilization and medium- to long-range transport. Some pesticides degrade rapidly, although not always into less harmful compounds. Conversely, others, such as persistent organochlorines, remain detectable years after their ban, not only as parent compounds but also as stable metabolites, posing long-term risks to ecosystems and human health.

Despite regulatory progress, including national air monitoring networks, the absence of specific air quality standards for pesticides highlights a major policy gap. Future research should focus on linking

monitoring data with territorial data on climate, soils and landscape, and with farming practices to better identify emission sources and transfers, and to develop models that integrate environmental, agronomic, and health perspectives. Such research would help better inform and calibrate future public policy actions: (i) strengthen surveillance, (ii) establish regulatory thresholds for relevant airborne pesticides, and (iii) promote agroecological strategies and application techniques that minimize dispersion. Addressing these challenges will require interdisciplinary approaches and coordinated action across science, agriculture, and public health.

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CRediT authorship contribution statement

K. Guillaume: Writing – review & editing, Writing – original draft, Validation, Conceptualization. **O. Cesbron:** Writing – review & editing, Validation, Supervision. **N. Bonvallot:** Writing – review & editing, Validation, Supervision, Conceptualization. **O. LE Bihan:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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