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REVIEW

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Measuring pesticides in the atmosphere: current status, emerging trends and future perspectives

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Abstract

There is a long history in environmental sciences to investigate and understand the fate of chemicals in the environment. For pesticides, this has led to systematic assessments of compounds by both academic and regulatory bodies, particularly for soil and water. As we show here, in recent years, there is an increasing interest in the potential presence of pesticide residues in air and related exposure risks. Based on a literature review for the years 2002–2022, we find a growing number of air monitoring studies with an average of 6.7 studies/year since 2020, with passive sampling methods contributing significantly to this rise. Most studies are concentrated in Europe and North America, with France leading in the number of monitoring studies. However, due to a lack of harmonization, and thus, the use of diverse methods and approaches, it remains challenging to derive potential exposure risks, to assess data quality of studies, and to compare datasets. In this perspective, we focus on current and emerging trends of different air monitoring approaches and highlight how they influence the interpretation of data. To improve the comparability and utility of data, and to ensure that air monitorings meet certain quality requirements, we propose a path forward, including: (1) Standardization and harmonization of methods: Adopting well-characterized and widely applied methods from air quality research as a basis for standardizing pesticide monitoring, with a clear distinction between relevant exposure and total air concentrations. (2) Tiered approach for monitoring programs: A dynamic concept where initial passive sampling identifies potential exposure risks, followed by active sampling for quantitative data, and, if necessary, extensive monitoring programs. This approach balances the need for detailed data with resource constraints. (3) Data interpretation and transparency: Public availability of data and clear reporting of methods, analysis, and uncertainties are crucial for the credibility and utility of monitoring studies. Overall, we see that harmonization of standards is critical for assessing exposure risks from pesticides in air and for informing regulatory decisions and mitigation strategies. Collaboration with the air quality and atmospheric research community is strongly recommended to leverage existing expertise in sampling, analysis, and data interpretation.

Introduction

There is an ever-increasing trend to investigate and understand the effects of human-made chemicals on the environment and human health [1]. This has led to a systematic assessment of such compounds by academic and regulatory bodies—especially for substances intentionally released into the environment, such as pesticides [2, 3]. Historically, the focus of such assessments has been mostly on soil and water. However, there is increasing

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interest in the potential presence of pesticides in the atmosphere—as demonstrated below.

In modern farming, pesticides are essential in maintaining productivity as part of an integrated approach to pest, weed and disease management [4]. Despite significant improvements in mitigation measures during and after application [5–7], pesticides can be emitted into the atmosphere by volatilization and by wind erosion of particles on which the pesticide is sorbed [8–11]. As the atmosphere represents the largest and most dynamic of the environmental compartments, pesticide residues can be transported relatively far from their application areas to non-target areas [12–14]. Potential impacts on human health, the environment, and ecosystems are typically assessed in a risk assessment during registration of a substance, e.g., by measuring spray drift at the edge of a field as a worst-case scenario. Nonetheless, recent reports claim that current assessment procedures might be insufficient for a comprehensive evaluation [12, 13].

In contrast to this emerging trend for pesticides, there is a long history in atmospheric and air quality research for chemicals that are unintentionally introduced into the environment from traffic and industry, e.g., black carbon, PAHs, NO_x, and persistent organic pollutants (POPs) [15]. Thus, sampling techniques and measurement methodologies for such compounds are well-known, offering the possibility to adapt these for the measurement of pesticides in ambient air.

So far, pesticides in air have been sampled using numerous methods and approaches, and data were often generated with a range of objectives in mind, ranging from exposure assessments for operators, bystanders and residents [5, 12, 16, 17], to studies on airborne transport [7, 18, 19] and quantification of volatilization fluxes [9, 11, 20]. This lack of standardization has created a diverse array of information that needs to be understood to improve future air monitoring programs and to interpret previously collected data appropriately. Therefore, it is important to assess the applied sampling methods and generated data in terms of their capabilities and limitations.

This work presents a perspective on current and emerging trends of the different approaches used to measure pesticides in air. It highlights the major differences in these approaches and how they influence both the setup of studies and the interpretation of data. Moreover, it also introduces a tiered approach for potential future monitoring programs, forming the basis for a cost-efficient risk assessment of pesticide residues in air.

Although already suggested prominently in 2008 [10], there is still little guidance available on how to assess the quality of monitoring studies on pesticides in air and how to set up such monitoring programs to meet certain quality requirements. Thus, it is hoped that this work will inform both data generators and data users during their work and initiate improvements towards standardization of monitoring pesticides in air. Harmonization of sampling procedures and methods would have a positive impact on the quality and comparability of data. The integration of best practices, techniques, and standards from atmospheric chemistry can contribute to the advancement of reliable environmental risk assessments.

Current status and emerging trends in the measurement of pesticides in the atmosphere

A review of the scientific peer-reviewed literature on corresponding monitoring studies over two decades (i.e., 2002–2022) provides a picture of the current status and trends in the monitoring of pesticides in the air (see Additional file 1). The identified studies clearly show a strong geographical bias towards Europe and North America which likely reflects the larger public and political interest in monitoring data as well as the available resources. As shown in Fig. 1A, most monitoring studies on pesticides in air have been conducted in France ($n = 14$), followed by Spain and the USA (both $n = 6$), and Canada ($n = 5$). To the best of our knowledge, data from

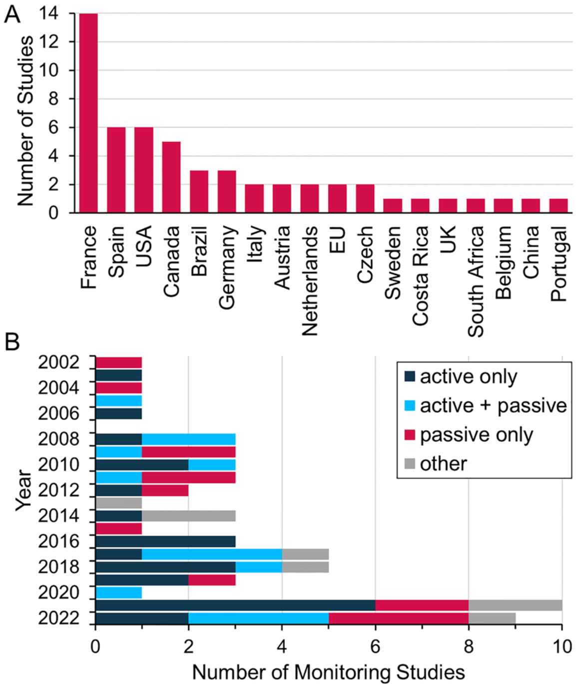


Fig. 1 **A** Sampling locations of studies on pesticides in ambient air. **B** Yearly number of published studies on pesticides in ambient air, grouped according to the applied sampling methods (passive sampling may include additional deposition sampling)

other parts of the world are solely available for Brazil ($n=3$), Costa Rica, South Africa, and China (all $n=1$).

Besides the large number of scientific publications on pesticides in air, French monitoring programs by regulatory agencies and governmental bodies certainly belong to the most detailed and extensive studies in Europe and world-wide. Since 2002, the French Air Quality Monitoring Associations (AASQA) conduct regular and continuous monitoring studies to collect data not only on common air pollutants (e.g., NOx, SO_2), but also on pesticide residues in ambient air. By August 2023, the Phytatmo database contained data on 321 active substances from > 10,000 samples taken at 176 sites throughout metropolitan France and overseas [21]. As these programs commonly have been organized by regional or local authorities, only few data were available at the national scale until 2018 when the most recent initiative was started. For a 12-month period (June 2018–June 2019), the CNEP (*Campagne Nationale Exploratoire des Pesticides dans l'air ambiant*) monitoring campaign sampled residues of 75 pesticides in ambient air at 50 different field sites across France, resulting in 1800 samples and > 100,000 data points for the investigated compounds. In contrast to previous monitoring studies, the CNEP program was the first nation-wide campaign with the goal to establish a harmonized inventory of pesticide levels in air based on synchronized measurements following a common protocol [22].

Although less represented in terms of publication numbers, Belgium has intensively investigated pesticide residues in air in the Wallonia region. The EXPOPESTEN and PROPULPP programs running from May 2015–May 2016 and from March–September 2018, respectively, focused specifically on the exposure of the population to plant protection products and protective measures to limit this exposure [23–25].

A much smaller monitoring program with about 10 air samples per year is maintained by the Swedish University of Agricultural Science in the South of Sweden (i.e., Vavihill and Hallahus). Nonetheless, data on air samples reach back to 2009 for up to 120 different substances [26, 27].

Similar to France and Belgium, in Germany the federal Office of Consumer Protection and Food Safety is planning to conduct a multi-year monitoring program to investigate pesticide residues in air with the intention to facilitate more precise statements on exposure, transport and deposition. These data shall enable a more reliable and detailed risk assessment and, in the long term, to be incorporated into authorization procedures for plant protection products [28, 29].

In the US, the air monitoring program by the California Department of Pesticide Regulation (CDPR) is the most extensive initiative aimed at assessing the presence of pesticides in air. With a specific focus on agricultural regions where pesticide application is prevalent, since 2011 this program has operated a network of up to 8 monitoring stations strategically positioned across the state. These stations collect air samples at regular intervals, enabling the determination of air concentrations of up to 35 pesticides and 5 breakdown products. Due to taking continuous measurements, by the end of June 2023 the CDPR database already contained a total of 98,823 ambient air sample records [30].

Besides the geographical bias towards Europe and North America, there is a clear time trend observable for the number of monitoring studies on pesticides in air (Fig. 1B). While the average number of publications remained rather low until 2010 ($n_{avg}=1.4$ studies/year) with a slight increase during the following decade ($n_{avg}=2.9$ studies/year), this number has more than doubled since 2020 ($n_{avg}=6.7$ studies/year). This remarkable increase, likely driven by a combination of societal, political, and technical reasons, clearly shows that in recent years there has been an increased interest in measurements of pesticides in ambient air. Although these studies eventually have similar objectives, a very diverse method set has been applied for the measurements, which we group here according to the sampling methods used because of its significant impact on the results obtained. Noteworthy, the use of passive samplers and other methods (e.g., biomonitoring) has significantly contributed to the strong increase in study numbers since 2020. We speculate that this is at least partly due to the fact that the studies were often initiated from outside of the traditional air quality and atmospheric research community where active samplers are commonly applied. Thus, if this trend on measuring pesticides in air continues, guidance and standardization are needed to assess the quality of obtained monitoring data and to set up measurements which meet basic quality requirements and reliably yield the desired information.

Air sampling methods, standards and data: limitations, advancements and challenges

In general, air sampling methods can be separated into active and passive techniques depending on whether ambient air is actively drawn into the sampling device or not. Figure 2 gives an overview of the most common setups and a qualitative estimate on time resolution, technical complexity and costs, data accuracy and commercial availability.

In active samplers (Fig. 2A), the sample air is drawn by a pump through a combination of a filter substrate for particle collection and a sorbent material for sampling of gaseous compounds. A critical parameter is the use of a

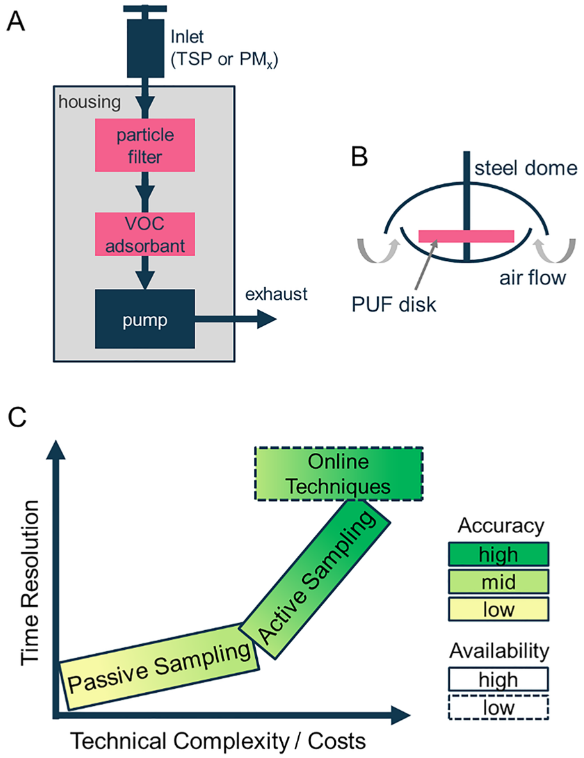


Fig. 2 **A** Established setup for active sampling (e.g., AFNOR XP X 43–058). [31] (**B**) Established setup for passive sampling (i.e., PUF-PAS). [36, 37] (**C**) Classification of sampling techniques regarding time resolution, technical complexity and costs, measurement accuracy, and commercial availability (passive sampling may also include biomonitoring)

pre-separator at the inlet of the sampling device which will determine if total suspended matter (TSP) or a certain size fraction of airborne particles is sampled (e.g., PM_{10}–meaning that particles with an aerodynamic diameter of 10 µm have a 50% chance to be sampled).

To the best of our knowledge, there are so far only four dedicated technical standards available on measuring pesticides in air—the French AFNOR XP X 43–058, the US EPA TO 4 and TO 10, and the derived ASTM D4861-23 [31–34]. These standards summarize a selection of best practices regarding sampling methods, sample storage, transport, handling and analysis as well as the calculation of the final results. The US standards focus solely on pesticides in the gas phase and give guidance for active sampling on sorbent materials, such as polyurethane foams (PUFs), with high and low flow rates. Airborne particles may also be collected with these approaches, but the sampling efficiency is unknown [32–34]. In contrast, the French AFNOR standard describes sampling procedures for both gas and particle phases. It suggests the use of a pre-separator (PM_{10} or $PM_{2.5}$), a quartz microfiber filter for particulate matter, and a PUF sorption filter to retain pesticide residues in the gas phase. Depending on the chosen flow rates and corresponding sampling frequencies, the method gives daily to weekly samples. Extraction and analysis of the particle filter and the PUF is later combined. Therefore, this method yields only total concentrations for a certain compound in PMx and the gas phase. [31]

Despite its implementation since 2007, hitherto only a few studies follow the AFNOR standard completely—even when conducted within France. Thus, it must be speculated that the standard is either not sufficiently known within the scientific community or that it is regularly ignored for other reasons, like a conflict with the intended study design. An important feature of the standard is that it is focused on human exposure via inhalation and respiration, which should not be confused with the determination of total air concentrations, which would also include larger particles (i.e., total suspended matter, TSP). In addition, the commonly applied omnidirectional inlets exhibit non-ideal sampling performance with increasing wind speeds and have been suggested to be biased by as much as 66% [35]. Moreover, as no differentiation between gas and particle phases is implemented, the procedure only gives limited information on transport and deposition mechanisms for a certain substance. Nonetheless, the standard remains the only official guidance on monitoring pesticides in air specifically including the measurement of particle-bound residues.

For passive samplers the setup is commonly reduced to a disc of sorbent material (e.g., PUF), placed between two steel bowls, to sample volatile and semi-volatile compounds from the gas phase (Fig. 2B). The setup was first described by Shoeib and Harner [37] and allows ambient air to flow through the sampling device while protecting the sample from precipitation and solar irradiation. Variations of this setup employ additional polyethylene foam disc or glass fiber filters to sample also low volatile compounds in the particle phase [12, 38]. The technical simplicity and low cost of such samplers makes them easy to deploy even in very remote areas and is one of the main reasons for their use in global monitoring programs, such as the Global Atmosphere Passive Sampling (GAPS) network and the MONET program on POPs [39–41]. Common sampling times are in the range of several months after which the sorbent disc is extracted, and the extracts analyzed for the compounds of interest. However, in contrast to the simple sampling procedure and low maintenance efforts, it remains a major challenge to derive reliable air concentrations from the collected samples. We will focus here on a brief overview on the limitations and challenges as a detailed review was recently published by Wania and Shunthirasingham [36]. The largest challenge when deriving air concentrations from passive samplers is the estimation of sampling rates. It has been shown that sampling rates are highly variable and are associated with an uncertainty factor of up to ~ 30, as they are strongly influenced by wind speed, wind direction, and the physicochemical properties of the analytes [42, 43]. Additionally, parameters such as uptake capacity, ambient temperature, and time of linear uptake vs. time to equilibrium need to be considered for each target compound separately. Moreover, for low and semi-volatile compounds in the particle phase, the sampling process is further influenced by parameters such as particle size distribution. Thus, air concentrations for particle-bound substances are considered to exhibit uncertainties of at least an order of magnitude. Several studies attempted to reduce uncertainties and to derive air concentrations from passive samplings by determining sampling rates with an active sampler. However, in all studies a large variety in passive sampling rates is observed depending on location, season, and meteorological conditions, leading to very diverse sampling rates for the same compounds, and thus, requiring at least regular re-calibrations by active samplers [14, 44]. Besides these known difficulties, we emphasize that in contrast to POPs, which are widely monitored by passive samplers [39–41], pesticides are designed to degrade in the environment with half-lives in the range of several days to months, thus, adding an additional layer of complexity to the aforementioned difficulties in deriving air concentrations.

Due to the large variety of passive sampler setups and the difficulties in deriving air concentrations, there remains a great uncertainty in the evaluation of the corresponding reports and data sets. This uncertainty could be reduced, at least in part, by standardization efforts, as has already been done in the past, e.g., for compounds such as ammonia or polyaromatic hydrocarbons and the corresponding European standards EN 17346 and EN 15980 [45, 46]. This is particularly necessary if passive samplers continue to be increasingly used to determine pesticide residues in air, in order to reach a fundamental agreement in the scientific and regulatory community on how to interpret these monitoring data. Importantly, any standardization of passive sampling should not only focus on the technical aspects but needs to include guidance on how to report the uncertainties related to the sampling method as well as to the data analysis and interpretation. Only through such transparent reporting on uncertainty will the benefits of passive samplers be maintained, e.g., for trend analysis of pesticide residues in air. Although beyond the scope here, similar efforts would be helpful for deposition estimates via biomonitoring approaches using plant material, e.g., moss, curly kale, etc., as passive deposition samplers.

In the future, besides the common active and passive sampling setups, online techniques could play an increasingly important role for monitoring of pesticides in ambient air (Fig. 2C). Such techniques mostly rely on mass spectrometric apparatus and have been used extensively in air quality and atmospheric research during the last decade. Examples include techniques such as proton transfer reaction mass spectrometry (PTR-MS) [47], aerosol mass spectrometry (AMS) [48], and different combinations of thermal desorption/soft ionization mass spectrometry (e.g., EESI-MS, AeroFAPA-MS, online-APCI-MS, CIMS) [49–53]. These techniques typically offer near real-time measurements of single organic compounds in the gas and/or particle phase, and thus, are capable of accurately observing peak concentrations, which are otherwise diluted by sampling times of several hours or even days when using active samplers. Unfortunately, the high time resolution and data accuracy comes with higher technical complexity, costs, and limited availability of standards and personnel with the required technical knowledge. But there are also currently developments in the utilization of the ever-increasing amounts of data from atmospheric mass spectrometric online measurements that aim to achieve a better and more comprehensive recording of atmospherically relevant compounds through standardization and collective archiving (also referred to as *data-driven mass spectrometry* and *aerosolomics*) [54, 55]. Nevertheless, such online techniques will likely remain an exception for targeted measurement campaigns until these hurdles are lowered, despite their advantageous combination of high time resolution and high data accuracy. For established methods, ongoing developments regarding the choice of sampling equipment might extend analytical capabilities and the range of analytes, e.g., the use of PUF-XAD2-PUF sandwich sorbents.

Using best practices from atmospheric research to measure pesticides in air: proposed path forward

As the number of studies on pesticide residues in ambient air is increasing globally (cf. Figure 1), it is essential to ensure intercomparability of the obtained data. Therefore, guidance and standards are required to evaluate previous studies and to perform measurements that meet basic quality requirements and provide the intended information. In the following, based on best practices, routines and methods from air quality and atmospheric research, we propose the basis for future focus in research and corresponding policies. Moreover, we provide a generic template to initiate and plan future monitoring programs for pesticides in air.

(1) *Standardization and harmonization of methods*

In air quality and atmospheric research, active samplers with PM_{10} and $PM_{2.5}$ inlets are widely used as these particle size fractions are inhalable and respirable, and thus pose the largest risk to human health. Therefore, several national and international technical standards are nowadays in place for such sampling setups in air quality studies (e.g., EN 12341, EN 15980) [46, 56], ensuring standardization, comparability, and a certain data quality. Although none of these standards explicitly focuses on pesticides in air, they offer a solid basis for further standardization of monitoring studies on pesticides in air, relying on well-characterized and widely applied methods. The above-mentioned French AFNOR XP X 43–058 standard is largely based on these air quality procedures [31], thus, offering a well-suited starting point for other national and international standardization approaches. However, it is essential for such efforts to distinguish clearly between the determination of exposure levels towards pesticides in $PM_{2.5}$ / PM_{10} and the measurement of total concentrations of pesticides in air (i.e., TSP, spray drift, wind erosion, etc.). Especially for agricultural areas, wind eroded soil particles are typically larger than $PM_{2.5}$, [57, 58] thus, indicating to collect PM_{10} samples if exposure towards pesticides adsorbed on airborne soil particles is to be measured. Moreover, a detailed risk assessment of pesticides in air can only be conducted when data on gas-particle-distributions are obtained, and effects on sampling efficiencies from windspeed and direction [35] are accounted for.

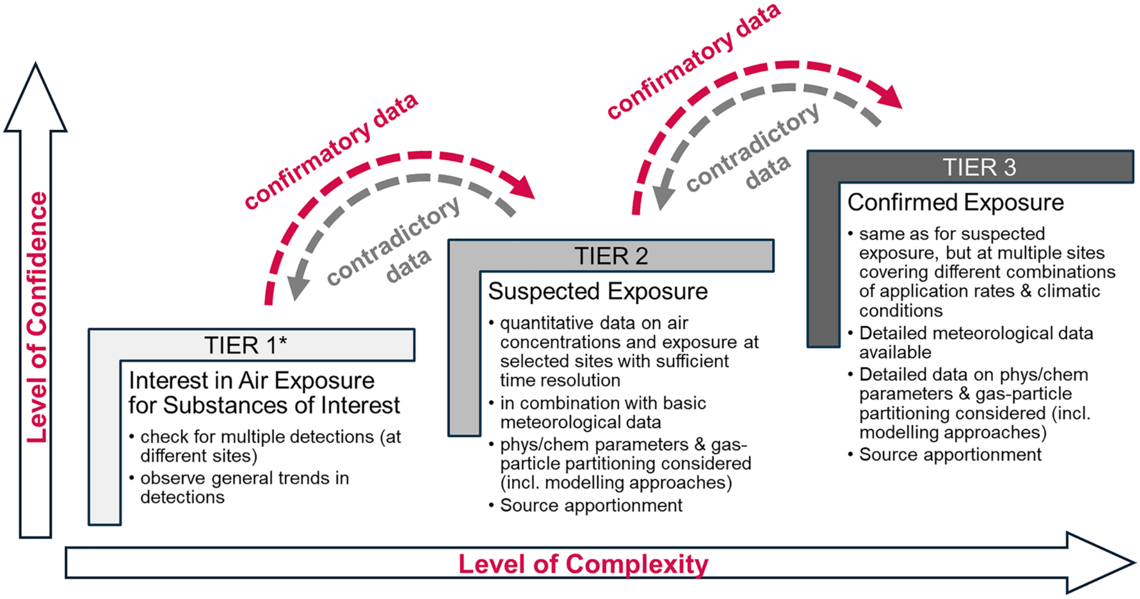
Besides active sampling approaches, standardization is also essential for passive sampling approaches. So far, the assessment and interpretation of passive sampling datasets is drastically hampered by the large variety in sampling setups. This is especially frustrating as passive sampling is significantly more cost- and resource-efficient and can easily be carried out simultaneously at many locations, thus, bearing the potential for wide-spread use in air monitoring programs on pesticides. Standardization could, therefore, play a crucial role for the setup and allocation of resources for future monitoring studies. Examples for standardization of passive sampling methods are compounds such as ammonia or polyaromatic hydrocarbons and the corresponding European standards EN 17346 and EN 15980 [45, 46]. These already existing standards could be used as a basis to determine recommended sampling setups, chemical analysis, calculation of uncertainties, and data interpretation.

Regardless of the applied sampling setup, standardization and harmonization efforts should not only focus on technical aspects and sample handling, but also include a dedicated plan for data treatment procedures. This is particularly of importance to ensure comparability between datasets from different studies.

(2) *Tiered approach for monitoring programs*

Large-scale air monitoring programs that attempt to follow high technical standards and apply active sampling strategies to assess the exposure of residents and bystanders (e.g., the CNEP program) are commonly extensive, lengthy, and expensive. Although the acquired data are of high quality and can establish a solid database for the determination of environmental fate and exposure risks, such approaches are very resource-intensive, and thus, can rarely be maintained for longer periods of time. Therefore, we propose to follow a tiered approach when there is a general interest in exposure for pesticides in air. This approach allows the generation of extensive large-scale data with less resources and the identification of increased exposure risks to residents and bystanders.

As shown in Fig. 3, in a first step, a monitoring program on pesticides in air using passive samplers is set up for compounds of interest. To reduce logistic efforts, samplers can be added to existing sampling sites, e.g., for ground and surface water or air quality, and similar analytic approaches can be followed. An initial active sampling period in parallel to the passive samplers can aid in characterizing site- and compound-specific sampling efficiencies, and moreover, to determine whether compounds of interest are generally detectable with the applied setup. At this first tier, the acquired data cannot be used to determine air concentrations or undertake risk assessments. However, it is possible to detect multi-year trends, to observe unexpected transport mechanisms, and to identify sites that need a more detailed exposure risk assessment [18]. In the past similar approaches have also been used to determine representative measurement sites for active samplings [59]. Nonetheless, it is essential to operate the samplers over several years and at several sites because data from single sampling sites or timepoints need to be evaluated in context [18, 60–62]. Furthermore, prior to the start of any measurements, the methods to be applied as well as sampling periods and frequencies should be well conceived and compatible with the monitoring objectives, as a subsequent change of parameters means a break in the time series making direct comparisons of past measurements impossible.



*selection of substances based on prioritization according to properties, such as by Hulin *et al.* (2021)

Fig. 3 Dynamic tiered concept for future monitoring efforts. Level of complexity and level of confidence increase stepwise with confirmed exposure risks (red arrows) towards pesticide residues in air, whereas contradictory data (grey arrows) prompt a return to the previous tier

Therefore, passive sampling should also be continued if Tier 2 and 3 samplings are necessary, in order to continue the time series.

As commonly the number of substances to be monitored needs to be constrained because of limited analytical capacities, we propose to follow the prioritization approach of Hulin et al. [63] which preceded the French CNEP campaign. In a theoretical first step, the authors constructed a hierarchy of substances according to (1) national uses, (2) emission potential to air, (3) persistence in air, and (4) chronic toxicity. Secondly, substances were selected based on existing monitoring data. Afterwards, based on the theoretical and the observational data, substances were identified and prioritized for further monitoring.

If the proposed first-tier monitoring program indicates an elevated exposure risk, we suggest a second-tier approach for more detailed investigations at the respective sites to confirm identified trends and elevated air concentrations. For this second tier, active sampling methods are mandatory to obtain quantitative data on air concentrations. Ideally, basic meteorological data are recorded simultaneously and physicochemical data of the substances of interest are considered when selecting appropriate sampling methods. Eventually, source regions of the substance of interest can be estimated or even specifically identified through a source apportionment approach via an integrative data analysis [55, 64–66].

In case the substance of interest exhibits elevated air concentrations and a certain exposure risk for residents or other reasons for further investigation were identified in the second-tier monitoring, a continuous, extensive monitoring program can be established at multiple sites. In addition, the toxicological profile of the substance should be evaluated in more detail, and if necessary, inhalation studies should be initiated. We suggest inferring the selection of sites from a combination of climatic conditions and application intensities, as recently suggested by Kubiak et al. [28] Moreover, a detailed investigation of sources and possible mitigation measures should be included at this stage. It should also be noted that air concentrations determined from second or third tier monitoring approaches will commonly need to be evaluated during the re-registration of a substance. Thus, such monitoring data from active samplings are linked to the registration status of a substance.

In contrast to several existing monitoring programs and initiatives, an important feature of the proposed tiered approach is that it allows the identification of exposure risks while avoiding a technically complex national monitoring program with the concomitant large resource requirement. Thus, we emphasize that if a second-tier monitoring study did not suggest elevated risks, it is strongly advised to step back to tier one, i.e., monitoring by a well-characterized passive sampling approach that monitors trends for the selected site. By following this approach, costs are reduced, and resources are focused on substances and locations where high-quality monitoring is required. The same applies for tier three studies if no elevated air concentrations can be detected anymore (cf. Figure 3).

Moreover, while regulatory processes and corresponding monitoring programs are mostly focused on national levels, we stress that for atmospheric transport such boundaries do not exist. Thus, it is essential to keep in mind the trans-national nature of transport and exposure via air when setting up such studies but also when analyzing and interpreting the acquired data.

(3) *Data interpretation and transparency*
Whether studies are conducted according to the proposed approach or in some other way, both the gathered data as well as their analysis should be made publicly available, following the open access and FAIR principles [67]. As a minimum for the reporting of acquired data, the following parameters need to be accessible: sampling site, methods, sampling periods and frequencies. Ideally, also details are given on sampling materials, inlet heights, manufacturers, storage conditions, and analytical characteristics such as limits of detection and recoveries. Also, study goals should be clear and available before the start of the measurements. Similarly, for the data analysis and interpretation, it should be made clear and transparent which calculations and conversions have led to the final results—and, importantly, what uncertainty is connected to these results. Ideally, data analysis is following standardized practices regarding, e.g., the treatment of measurement values below or close to the detection limit. Only then comparison of data from different studies and monitoring programs is readily feasible.

In conclusion, we note that the measurement of pesticide residues in air is only one component for a comprehensive understanding and assessment of atmospheric transport potential, as well as for corresponding implications for environmental processes, air quality, and human health. For example, data on emission and deposition behavior of a substance are rarely available, but essential for reliable model predictions. Nonetheless, to assess potential exposure risks and the fate of pesticides in the atmosphere, we see that particularly the harmonization of technical standards and procedures is desperately needed. The development and establishment of such standards is key for any further regulatory advancements, such as discussions on the implementation of mitigation measures and acceptable air concentration levels. Moreover, it is essential that the air quality and atmospheric research community is included in such developments, as a large expertise on appropriate sampling procedures, analytical methods and data interpretation is readily available.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00870-4.

Additional file 1. Overview on air monitoring studies for pesticide residues and corresponding publications for the years 2002–2022.

Author contributions

MB and SM developed the concept and outline of the paper. MB, DB, and AT conducted the literature search. JR and TH contributed references, comments, and suggestions regarding standardized sampling methods and emerging trends in the fields of atmospheric chemistry and air quality research. MB wrote the manuscript. All authors contributed comments to the final draft.

Availability of data and materials

All data related to this work are directly available from the manuscript and supporting material.

Declarations

Competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M.B. and S.M. are employed by the Bayer AG (Crop Science Division). D.B. and A.T. are employed by Cambridge Environmental Assessments, a contractor of the Bayer AG.

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