



Passive Sampling Techniques for Monitoring Environmental Pollutants: A Review

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ABSTRACT

Environmental pollution associated with industrialization, urbanization and other anthropogenic activities has increased the need for reliable and cost-effective monitoring. This review critically examines passive sampling principles, performance and applications across air, water, soil and sediment, with attention to volatile organic compounds (VOCs), persistent organic pollutants (POPs), metals and emerging contaminants. A systematic narrative literature review was undertaken using Scopus, Web of Science, ScienceDirect and Google Scholar. Searches focused mainly on peer-reviewed studies published from 2015 to 2026, supplemented by seminal earlier studies; approximately 120–150 records were screened and 85 studies were retained after title, abstract and full-text assessment against relevance and methodological-reporting criteria. The review compares devices including SPMDs, POCIS and DGT and evaluates how temperature, flow, deployment duration, sampler design and biofouling affect uptake and calibration. Passive sampling can provide time-weighted average (TWA) estimates during an appropriate uptake phase, but it does not universally outperform active sampling: suitability depends on the contaminant, environmental medium and monitoring objective. Reported sampling-rate differences of up to approximately twofold are context-specific rather than a universal property and may arise when field conditions differ from calibration conditions or when sampler design and hydrodynamics vary (Liu et al., 2013; Jiang et al., 2025; McLagan et al., 2025). The review distinguishes TWA concentrations from freely dissolved concentrations and operationally defined bioavailable fractions, and identifies calibration, standardization and evidence gaps in resource-limited settings. Future priorities include field validation, transparent reporting and locally appropriate monitoring protocols.

Keywords: Passive sampling; Environmental monitoring; Persistent organic pollutants; Heavy metals; Emerging contaminants; Time-weighted average; Sampling rate; Calibration.

1.0 INTRODUCTION

Environmental pollution remains a significant global issue. It is worsened by rapid industrial growth, urban expansion, and increased human activities (Singh et al., 2024). The introduction of pollutants like volatile organic compounds (VOCs), persistent organic pollutants (POPs), heavy metals, and newly found contaminants into our environment has raised serious concerns about the health of ecosystems and human well-being (Shetti et al., 2023; Liu et al., 2024; Mangotra & Singh, 2024; Jadhav et al., 2026). Polycyclic aromatic hydrocarbons (PAHs) are organic compounds composed of fused aromatic rings and are primarily generated from incomplete combustion processes such as fossil fuel burning and biomass degradation (Umudi et al., 2025). These pollutants are widely distributed in environmental media including air, water, soil, and food systems (Umudi et al., 2025). Therefore, accurate monitoring of these pollutants is essential for effective environmental management and informed regulatory actions. Traditional monitoring methods, while commonly used, often require complicated equipment, a continuous power supply, and a lot of labor. This



makes them less suitable for long-term and wide-ranging monitoring, particularly in remote areas (Li et al., 2025; Olise, 2025).

As a result of these difficulties there is an interest in the utilization of passive sampling techniques as a cheap and robust method for environmental monitoring. Passive diffusion can be defined as the movement of an analyte from an ambient atmosphere into the sampling medium based on natural concentration gradients, in the absence of any mechanically driven sampling. This is the concept that forms the basis of the various types of passive sampling devices, which are often simple, inexpensive, and appropriate for the environmental monitoring in remote areas where a power source is not available (Kinross & Hageman, 2019; Yu et al., 2024). Rather than obtaining a snapshot of the ambient concentration of pollutant at a specific time, passive samplers average contaminant uptake over their whole deployed time. This results in inherent averaging of fluctuating concentrations into a time weighted average value (TWA) that, in general, is a more representative measure of the environmental exposure over a period than instantaneous values such as a grab or spot sample would give (Ahrens et al., 2016; Shakallis et al., 2022). Consequently, the field of passive sampling is an essential part of environmental monitoring of air, water, and soil pollutants. Recent studies have demonstrated the growing applicability of passive sampling in environmental monitoring. For instance, Kim et al. (2023) reported that passive samplers are effective for measuring VOC concentrations in ambient air. However, this effectiveness is limited to controlled environments. In contrast, Mula et al. (2024) highlighted that sampling efficiency can vary significantly under fluctuating field conditions, emphasizing the need for proper calibration and validation. These findings underscore the importance of understanding both the strengths and limitations of passive sampling techniques, particularly in real-world applications where environmental variability plays a critical role.

Physicochemical mechanisms (diffusion, sorption and partition processes) determine the sampling rate and the performance of passive samplers. These processes are affected by environmental conditions like temperature, wind velocity, hydrodynamics and biofouling. For example, temperature was shown to be responsible of a change of diffusion rate and so, the sampling efficiency (Smith et al., 2022), while hydrodynamics were found to control the uptake of analytes by samplers in aquatic environments (Lee et al., 2023). These environmental conditions are thus to be taken into account to ensure the reliability of contaminant quantification.

Other parameters have an influence on the efficiency of passive samplers: sampler design and composition. The nature of membranes, sorbent and housing materials is dependent on the target analyte's affinity for sampler's materials and on the control of uptake process (Ghorbani Gorji et al., 2023). Improvements were made in the field of material sciences with the development of new sorbent phases or membranes, leading to higher sensitivity or selectivity. However, it seems that no universal standards exist for sampler's design and calibration. Another important aspect of passive sampling is the use of performance reference compounds (PRCs), which are employed to account for environmental variability and improve the accuracy of sampling rate estimations. PRCs are pre-loaded into samplers prior to deployment, and their rate of dissipation is used to adjust for factors such as temperature and flow conditions. While this approach has been widely adopted, its effectiveness is dependent on the assumption that PRC behavior closely mimics that of target analytes. However, Brown et al. (2022) noted that differences in physicochemical properties between PRCs and analytes may introduce uncertainties, particularly in complex environmental matrices.

Although passive sampling has many benefits; the relatively lower cost, simplicity, long term monitoring possibility, several constraints associated to this technique, for example the uncertainty with variability of sampling rate, absence of standard calibration procedures, sensitive to environmental parameters still exists. And although passive sampling has been largely investigated in developed countries, the research conducted in developing countries, where environmental monitoring systems are less accessible, has been very limited. More studies are required for this application under various socio-economic situations.

This review provides an overview on passive sampling techniques for environmental monitoring. It explores the underlying theory, various types of passive samplers, sampling materials and applications, and finally considers the strengths and weaknesses of passive samplers. The review focuses also on the present concerns

like calibration uncertainty, variability and lack of uniformity and research needs with emphasis on developing countries.

This review is structured to provide a systematic and critical evaluation of passive sampling techniques. Section 2 outlines the scope of the study, while Section 3 presents the justification. Section 4 describes the methodology used for literature selection to ensure transparency and rigor. Sections 5 and 6 discuss target pollutants and underlying sampling principles, respectively. Section 7 provides a detailed classification and comparison of passive sampling devices, followed by Sections 8 and 9 which examine materials and applications. Sections 10 and 11 critically evaluate the advantages, limitations, and calibration challenges. Finally, Section 12 identifies key research gaps and future directions, particularly in the context of developing countries.

2.0 SCOPE OF THE REVIEW

This review presents a critical overview of passive sampling approaches applied for air, water, sediment, and soil pollutant monitoring. In addition, the basis for the passive sampling approaches, focusing on diffusion and sorption processes and on instrumentation characteristics (SPMD, POCIS, DGT), are presented in some detail. The different sampling techniques presented were shown to be applicable to the detection of various contaminants such as Volatile Organic Compounds, Persistent Organic Pollutants, heavy metals, and novel contaminants (e.g. Drugs, personal care products) and the analytical performance for detection of such contaminants under varying environmental condition was discussed (sensitivity, selectivity, reproducibility and accuracy). Calibration, quality assurance and limitations of passive sampling in real and complex environments were discussed in critical manner, recent developments are reviewed and further research efforts (including Developing Countries) are proposed.

3.0 JUSTIFICATION OF THE STUDY

The world is becoming dangerously exposed to the growing amount of organic and inorganic pollutants. Such pollutants are very dangerous to both the environment and the health of humans. Specifically, the prevalence of polycyclic aromatic hydrocarbons (PAHs) in the natural and food environments promotes the critical importance of constant monitoring with the aid of efficient analytical methods (Umudi et al., 2025).

Traditional (active) sampling techniques, though in common use and usually dependable, tend to be limited by high operation costs, the requirement to have continuous power supply, competent man-power and complicated instrumentation. Passive sampling methods, on the other hand, are a potentially lower-cost complementary option as they can measure time-weighted average (TWA) concentrations of pollutants over time. The techniques are particularly useful in distant and resource constrained settings where traditional monitoring schemes might not be feasible or even sensible. Although passive sampling methods are becoming increasingly important, problems related to calibration, environmental variance and data interpretation still exist. Moreover, the method has been applied with varied techniques and has shown poor results in developing countries; a critical review is needed at this juncture.

This review is therefore, intended to:

- (i) critically examine the passive sampling methods,
- (ii) evaluate the performance of these methods in varied environmental circumstances,
- (iii) identify the method-based limitations and causes of uncertainty and
- (iv) determine the research gap and future trends with reference to developing countries.

4.0 METHODOLOGY OF LITERATURE REVIEW

This current review assumes a systematic narrative review methodology to analyze the history, performance,



and uses of passive sampling methods in environmental monitoring. The important scientific databases, such as Scopus, Web of Science, ScienceDirect, and Google Scholar, were used in finding relevant literature. The search used a mixture of the following keywords: passive sampling, SPMD, POCIS, DGT, environmental monitoring, emerging contaminants and sampling rate calibration. To ensure that the literature search captures the current developments in the field, the literature search was mainly limited to articles published in 2015 to 2026. Nevertheless, some seminal studies of the past were also incorporated where they were needed to give some background information. Preliminary searches were conducted to determine the number of peer-reviewed articles, which resulted in the discovery of about 120-150 articles, with 85 being included in the study following screening of the title, abstracts, and full texts. This filtering helped to filter out irrelevant and low-quality studies to be analyzed. The search criteria were limited to peer-reviewed journal articles that covered:

- i. Mechanisms and principles of passive sampling
- ii. Analytical performance (e.g. sensitivity, selectivity and reproducibility)
- iii. Environmental uses (air, water, soil, and sediment)
- iv. Calibration and uncertainty analysis.

Studies were screened in stages: titles and abstracts were assessed for relevance to passive-sampling principles, device performance, environmental applications, calibration or uncertainty; potentially relevant full texts were then examined. Studies were excluded where they were outside the review scope or provided insufficient methodological information to interpret sampler deployment, analyte measurement or performance. The review used qualitative critical appraisal rather than a formal numerical risk-of-bias score; attention was paid to clarity of objectives, sampler and sorbent description, deployment conditions, analytical procedures, calibration/validation, and treatment of uncertainty. Findings were synthesized narratively and compared across sampler classes, target compounds and environmental media. Because the source literature uses heterogeneous devices, analytes and calibration approaches, the reported number of records should be interpreted as the authors' documented screening estimate, not as a reproducible database export or a formal PRISMA count. No meta-analysis was conducted.

5.0 COMPOUNDS OF INTEREST IN PASSIVE SAMPLING

5.1 Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) are defined as any chemical compound containing at least one atom of carbon (except for carbon oxides, carbonates, and carbides) that is able to volatilize into the atmosphere from any source. Due to their low boiling points and low vapor pressures they are easily dissipated into the atmosphere at ambient conditions (David & Niculescu, 2021; Tan, 2024). This is a general term for organic substances, like hydrocarbons, alcohols, ketones, aldehydes etc., with a high vapor pressure, to easily vaporize to the air. In terms of pollution, they form a diverse group of low molecular weight carbon based molecules that vaporize easily at room temperature and standard atmospheric pressure. VOCs that can lead to pollution and possibly affect health are found in car emissions, from industrial sites, use of solvent, burning of biomass and biogenic sources. They are characterized by, for example, benzene, toluene, ethylbenzene, xylene (BTEX), formaldehyde and various types of industrial solvents. Many VOCs can be carcinogenic or mutagenic (e.g. Benzene) and many contribute to the formation of ground-level ozone and photochemical smog by reacting with nitrogen oxides in presence of sunlight (Nguyen et al., 2021). It is established that long-term exposure of volatile organic compounds leads to chronic and compromised lung function and it aggravates the progression of chronic lung disease such as chronic bronchitis and asthma (Chatterjee et al., 2026). The advantages of using passive sampling for monitoring VOCs include cost efficiency and simplicity of deployment and integration over the long term. For example, they can accumulate time-weighted average concentration of airborne pollutants. The main type of sorbent-based passive samplers includes activated carbon and Tenax; they trap VOC molecules from air. Indoor environments-Passive samplers are especially useful in assessing



occupant exposures to indoor volatilized organic compounds (VOCs), like formaldehyde and other dangerous vapors, because they reliably deliver time-averaged concentration data and require no pumped flow and power, thus facilitating extended monitoring of average occupant exposures (Zimmerman et al., 2024). Passive sampling in outdoor settings allows the examination of air quality at urban scales by mapping source location and distribution of VOCs (Terry & Shakya, 2024). Relative to other forms of passive sampling, sorbent-based samplers such as activated carbon tubes and Tenax-based media generally have more sensitive responses and quicker capture rates of VOCs due to their superior adsorption capacity and fast sorption kinetics. Diffusion-based devices, conversely, show more stable time-weighted-average concentrations with changing conditions but generally have less sensitivity at trace levels. Results from recent research have established that the choice of sampler for VOC monitoring depends on balancing sensitivity and environmental steadiness especially under unstable urban air conditions (Cartmell & Marshall, 2023; Liu et al., 2024).

5.2 Persistent Organic Pollutants (POPs)/ Polycyclic aromatic hydrocarbons (PAHs)

Persistent organic pollutants (POPs) are defined as organic compounds which are resistant to environmental degradation, highly lipophilic, have the potential for bioaccumulation, and can be transported long distances through the atmosphere (Muhammad Aqeel Ashraf, 2017; Fitzgerald & Wikoff, 2014). Polychlorinated biphenyls (PCBs), organochlorine pesticides (OCPs) and dioxins are examples of such POPs. POPs enter the environment through industrial activities, agriculture and inefficient burning procedures.

Persistent organic pollutants have significant and serious effects on the environment and on health. POPs remain in environmental matrices for a long time since they are resistance to degradation, and they bioaccumulate in living organisms. They biomagnify through food chain, the toxicity increases in higher trophic level (Environmental Toxicology; Wu & Zheng, 2022; Kiki et al., 2025). The exposure to POPs has also resulted in endocrine disruptors, immunotoxicity, reproductive abnormalities, carcinogenicity and developmental abnormalities. Long-range environmental transportation of POPs results in their existence even in regions distant to the sites they are derived from (Damstra, 2002; Szczsna et al., 2023; Vested et al., 2014). Passive sampling plays a critical role in the monitoring of POPs, particularly in atmospheric and aquatic environments. Passive air samplers using polyurethane foam (PUF) disks and polymer-based materials are widely applied for the monitoring of semi-volatile persistent organic pollutants (POPs) in the atmosphere due to their efficiency and simplicity (Melymuk et al., 2021; Herkert et al., 2018). These samplers mimic the partitioning behavior of persistent organic pollutants (POPs) in environmental media, allowing for the determination of freely dissolved concentrations (C_{free}), which are directly related to contaminant bioavailability and potential toxicity (Lydy et al., 2014; Avis, et al., 2020).

Interpretation of passive-sampling results requires distinguishing three related but non-equivalent measures. A time-weighted average (TWA) concentration is an estimate of the average ambient concentration over a deployment interval, commonly calculated from accumulated mass and a validated sampling rate while uptake remains sufficiently integrative. A freely dissolved concentration (C_{free}) refers to the dissolved contaminant fraction not bound to dissolved organic matter or particles; it is most directly estimated by suitable equilibrium or calibrated polymer-based samplers in water. A bioavailable fraction is the portion accessible for uptake by an organism under specified conditions. It may be approximated by labile or freely dissolved measurements for some contaminants, but these terms are not interchangeable: bioavailability also depends on chemical speciation, organism and exposure route. DGT, for example, measures a labile fraction of metals under its deployment conditions rather than total metal concentration, while SPMD-based estimates of hydrophobic organics depend on partitioning and calibration.

SPMDs are often employed in aqueous systems to monitor hydrophobic persistent organic pollutants (POPs) as it is known to collect lipophilic, non-polar contaminants from water over a period of time (Petty et al., 2000; Vrana et al., 2007). These samplers collect pollutants over a period of time and the calculated concentrations represent time-weighted averages that reflect varying pollutant levels in the environment (Shaw & Mueller, 2009). The use of passive sampling has been incorporated into worldwide monitoring networks; for example the Global Atmospheric Passive Sampling (GAPS) network has monitored global distributions and temporal trends of persistent organic pollutants (POPs) which can be implemented for agreements such as the



Stockholm Convention (Schuster et al., 2021). The SPMD performed best in the monitoring of hydrophobic POPs as it contains a lipid matrix which efficiently collects non-polar pollutants and distinguishes them from more polar substances which tend to bind with POCIS more readily. Furthermore SPMDs are proven to estimate bioavailable POP concentrations more reliably in contrast to alternative samplers which tended to underestimate hydrophobic contaminant concentration (Melymuk et al., 2021; Fialov et al., 2024).

Polycyclic aromatic hydrocarbons (PAHs) are a class of persistent organic pollutants (POPs) that are widely distributed in the environment and are of significant concern due to their toxic, mutagenic, and carcinogenic properties (Uzoekwe & Ikpesu, 2019).

Major sources of PAHs include industrial combustion processes, vehicular emissions, and biomass burning, which are particularly dominant in developing regions such as the Niger Delta (Uzoekwe & Ikpesu, 2019; Umudi et al., 2025). Exposure to PAHs has been associated with severe health outcomes, including DNA mutations, reproductive disorders, leukemia, and cancers of the lung, bladder, and other organs (Uzoekwe & Ikpesu, 2019).

Directly relevant Nigerian evidence is provided by Iwegbue et al. (2026), who evaluated naturally occurring cobwebs as indicators of indoor PAH deposition in electronic workshops, public buildings and residential buildings in Nigeria. Using GC–MS, the authors reported total PAH concentrations of 100–3,610 $\mu\text{g kg}^{-1}$ in electronic-workshop webs, 10–8,830 $\mu\text{g kg}^{-1}$ in public-building webs and 400–6,750 $\mu\text{g kg}^{-1}$ in residential webs. The profiles were generally dominated by three- and four-ring PAHs, while preliminary source interpretation pointed mainly to combustion-related inputs. Their study supports the practical potential of cobwebs as low-cost indicators of indoor PAH deposition and provides a locally relevant complement to conventional passive air sampling. However, cobwebs should be interpreted as accumulating bioindicators rather than automatically calibrated samplers: differences in web age, location, spider species, particle deposition and degradation can affect measured burdens. Deployment duration, blanks, recovery and comparison with validated samplers should therefore be considered in future studies.

5.3 Heavy Metals

Inorganic pollutants are of great concern since they are toxic, non-biodegradable, persistent in environmental media and have potential for bioaccumulation and biomagnification which lead to higher ecological and human health risks in Nigeria environments (Olowojuni et al., 2025; Okafor et al., 2024; Owonikoko & Alimba, 2024; Ewubare et al., 2024). The commonly studied heavy metals include Pb, Cd, Hg, As, Cr, Ni. Natural occurrence of heavy metals in the environment includes geogenic factors (rock weathering and volcanic activities) while elevated levels in soil and water result from anthropogenic activities (mining, industrial wastes, agriculture wastes and refuse dump) (Laoye & Olagbemide, 2025). Unlike many organic pollutants that can be degraded, heavy metals are very stable and cannot be biodegraded in the environment, they can remain in soils, sediments, aquatic systems for long period and contribute to ecological and human health risks since they may not undergo any degradation in the system; behavior of these metals in environment can be influenced by speciation and bioavailability (Okafor et al., 2024; Adesakin et al., 2026; Rashid et al., 2023). The toxic health risks associated with heavy metals include neurological effects, impairing the development and functioning of the nervous system, poor cognitive development of children and damage to body organs. For instance, exposure of children to Pb and Hg have shown persistent association to neuro-developmental deficits (Silva et al., 2025) and increased risk of impaired cognitive function in adults (Althomali et al., 2024). Contamination of Nigerian environments with heavy metals has been linked to various systemic health risks (Laoye et al., 2025).

Evidence from Delta Central, Delta State, illustrates why locally grounded monitoring is important. In an assessment of 21 groundwater samples from seven hand-dug wells and 14 boreholes, Apuyor et al. (2024) reported acidic groundwater (pH 3.75–4.80 in boreholes and 5.03–6.23 in wells), along with spatially variable trace metals and elevated lead at selected locations. The authors also identified chloride-dominated hydrochemical characteristics and recommended further investigation and appropriate pre-use treatment. These findings provide regional context for monitoring metals and water quality, but the study used conventional



water sampling and does not itself validate a passive-sampling device.

Over the past decade, there has been a significant increase in the use of passive sampling techniques for monitoring of heavy metals such as diffusive gradients in thin films (DGT). One reason for the increasing interest in passive samplers for monitoring heavy metals is that they quantify the bioavailable (labile) fraction of metal ions, not the total concentration of metals, which has direct implications for human and ecosystem health (Zhu et al., 2023; Rougerie et al., 2021; Menegrio et al., 2017). During operation of a DGT sampler, metal ions from the surrounding medium diffuse across a hydrogel diffusive layer to a chelating resin where they bind and become incorporated in the resin. The analytical measurement of this accumulated fraction gives a time weighted average (TWA) concentration which gives a representative measure of metals within the surrounding environment that grab samples are less able to predict.

The measurement of bioavailable fractions of contaminants, such as metals, in aqueous and sedimentary environments, are of major importance and traditional grab sampling techniques can often provide a poor reflection of both the temporally varying concentrations of metals and the bioavailable metal content in environments. Traditional grab sampling also only gives an instantaneous snapshot of metal concentrations, whereas diffusive gradients in thin films (DGT) measures the time integrated labile fraction, thereby improving the validity of environmental monitoring assessments and giving better understanding of exposure in ecosystems (Cindri et al., 2020; Okafor et al., 2024).

A DGT is better able to capture bioavailable fractions of metals as they measure labile species over time compared to conventional grab sampling techniques. Also, relative to other passive samplers, DGT has shown greater ability in quantifying and sampling ionic contaminants compared to other passive samplers due to its controlled sampling, although a lower sampling rate compared to other passive samplers has been noted which may be preferred where higher accuracy of labile fraction is of importance and lower sensitivity acceptable (Zhu et al., 2023; Cao et al., 2024).

5.4 Emerging Contaminants

Emerging contaminants are defined as substances that are not subject to regulation, but which have been frequently detected in the environment, and are considered potentially harmful to ecosystems and human health (Bu & Ma, 2025; Boahen, Owusu & Adjei Anim, 2025). Emerging contaminants are composed of pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), microplastic-associated chemicals, per- and polyfluoroalkyl substances (PFAS), and various industrial additives.

The prevalence of emerging contaminants in the environment has increased dramatically due to recent developments in industrialization, urbanization and consumer trends, which have introduced a variety of pollutants (such as pharmaceuticals, personal care products and industrial additives) into wastewater, agricultural run-off, and waste streams (Boahen et al., 2025; Varatharajan et al., 2025). In Nigeria, it has been documented in systematic reviews that these contaminants are prevalent in water and soil environments, and are associated with endocrine disruption and adverse chronic effects in humans (Egbuna et al., 2021; Zakari Jiya et al., 2022). Antibiotic residues found in aquatic ecosystems have been shown to contribute to antibiotic resistance in microbial communities and represent a public health risk (Okoye et al., 2022).

Passive sampling techniques have been successfully used to measure emerging contaminants at trace level concentrations, over long deployment periods. Polar Organic Chemical Integrative Samplers (POCIS) for instance accumulate hydrophilic organic contaminants, such as pharmaceuticals and endocrine disruptors, providing time weighted average concentrations, which are a more accurate representation of environmental exposure compared to grab samples (Godlewska et al., 2020; Mathon et al., 2022; Taylor et al., 2020).

Passive sampling also enables capture of episodic pollution events and variable contaminant concentrations which are typically not monitored by grab samples. The combined use of passive samplers and high resolution mass spectrometry (HRMS) is demonstrated to be successful in identifying and semi quantifying a broad range of emerging contaminants, including pesticides, pharmaceuticals and transformation products in waters giving



time integrated values more representative of the actual environmental exposures (Serasinghe et al., 2024; Tadi et al., 2022; Pinasseau et al., 2019).

In addition, its coupling with ecotoxicological investigations is shown to enable the assessment of the biological effects associated with emerging contaminants, giving a broader insight of the environmental hazard, and helping the management of emerging contaminants (Macas et al., 2023; Smith & Jeong, 2021; Egbuna et al., 2021).

The usage of passive sampling for the monitoring of these compounds has already been described in many investigations. As an example, Mula et al. (2024) used Radiello passive and diffusive samplers to monitor VOCs at multiple urban locations during a long term field study. This work demonstrated the efficient use of passive samplers for ambient VOC assessment.

Despite POCIS being recognized as being more sensitive, and likely the most suitable passive sampling devices for hydrophilic emerging contaminants like pharmaceuticals and endocrine-disrupting compounds, comparative studies have demonstrated that DGT can offer more steady accumulation rates under various environmental conditions and especially when the target compound is ionizable. In general, however, POCIS accumulates compounds more rapidly and sensitive, hence being more suitable to measure low concentrations of emerging contaminants in more stable environment (Bonnaud et al., 2023; Domnguez-Garca et al., 2025).

5.5 Sulphur (IV) Oxide (SO₂)

Sulphur (IV) oxide (SO₂) is one of the key atmospheric pollutants that are produced mostly by the burning of sulphur fuels, industrial processes and burning of biomass, especially in developing economies like Nigeria. It has been well-established to have negative impact on human health as well as the environment, as a respiratory irritant, impacting the upper respiratory system, particularly in the vulnerable groups of children and the aged. In addition, the atmospheric oxidation of SO₂ is known to cause acid rain that can destroy ecosystem, lower soil fertility and agricultural productivity (Uzoekwe and Ahonkhai, 2008). These effects underscore the need to ensure a sustained check of the SO₂ levels, especially in the developing world where the biomass burning is common as a source of emissions.

6.0 PRINCIPLES OF PASSIVE SAMPLING

A long-established environmental monitoring approach, passive sampling relies on neither a pump nor any energy input, but takes advantage of the natural physicochemical processes such as diffusion, sorption and partitioning, which transport analytes from the environment into a receiving phase on the sampler, resulting in time averaged contaminant concentrations that reflect exposure under ambient conditions (Yu et al., 2024; Garca Garcinuo et al., 2024). In fact, recent reviews emphasize the ability of passive samplers to integrate pollutants collected during their deployment periods and offer simultaneous time integrated monitoring of organic and biological pollutants in air and water, without the need for powered sampling devices (Hayes & Gagnon, 2024). One important fact about passive samplers is its potential to provide integrated concentration data over days to weeks of exposure rather than discrete 'grab' samples. This is highly advantageous for monitoring volatile contaminants present in air and water environments (for example, Lagos urban atmosphere and aquatic systems) as time weighted averages of contaminants are integrated rather than peak concentrations being captured (Alani et al., 2021; Sultana et al., 2024; Vrana et al., 2005).

Essentially, passive sampling operates using mass transfer theory and diffusion-driven transport: chemicals in the medium being sampled diffuse into the passive sampler due to a chemical potential gradient and accumulate with time to form an average, time weighted concentration (Garca Garcinuo et al., 2024; Salim & Grecki, 2019). Therefore, passive samplers designed in practice, such as in Nigeria, will have been optimized to sample using a diffusion mechanism rather than an active pumping one (Onafeso et al., 2008). Passive sampling techniques operate based on molecular diffusion of gaseous pollutants onto an absorbent medium, followed by chemical analysis. For instance, sulphur (iv) oxide (SO₂) can be collected on filters coated with sodium carbonate and later quantified using ion chromatography, which offers high sensitivity and reliability (Uzoekwe & Ahonkhai, 2008).



6.1 Diffusion Mechanism

Passive sampling operates on the principle of molecular diffusion, whereby contaminant molecules are transported from a high concentration in the surrounding environmental matrices (e.g., air, water, soil) to a lower concentration within the passive sampler. This mass transfer can be quantified using Fick's First Law of Diffusion which demonstrates that the diffusion flux is directly proportional to the concentration gradient across a space (Abdoulkader & Komai, 2025; Kiwfo et al., 2024). The concentration gradient provides the driving force that continuously accumulates pollutants over time without active pumping or energy, providing time weighted average readings during environmental sampling studies. The contaminant then continues to move across a diffusion space, (e.g., stagnant boundary layer, diffusion membrane), until it reaches the sorption phase. Continual removal or binding of the target contaminant within the passive sampler is necessary to maintain a continuous concentration gradient to drive the diffusion process for the entire duration of deployment.

Mathematically, the uptake rate can be expressed as:

where J represents the flux, D is the diffusion coefficient, and dC/dx is the concentration gradient across the diffusion path. This relationship highlights that the efficiency of passive sampling depends on environmental conditions such as temperature, wind speed, and turbulence, which can influence diffusion rates (Kot, Zabiegała, & Namieśnik, 2000).

In the field, the actual rate of diffusion is dependent upon physical processes such as ambient temperature, wind velocity (in air systems) or water current (in aquatic systems). The rate of diffusion is directly related to the thickness of the boundary layer around the sampler; a thinner boundary layer results in increased mass transfer and increased diffusion, whereas a thicker layer impedes diffusion and reduces sampling rates. This dependence of diffusion varies between different passive sampling devices; for example, the POCIS sampling devices offer fairly direct diffusion pathways with relatively high uptake rates, whereas DGT employs a gel layer which retards diffusion, leading to lower, more robust (but less sensitive) uptake values, which is much less susceptible to changing ambient conditions (Cao et al., 2024; Garca-Garcinuo et al., 2024).

The nature of this diffusion process ensures that passive samplers obtain cumulative pollutant measurements over a range of times, thereby being able to determine concentrations of pollutants at low trace levels and allowing temporal fluctuations to be characterized (Vrana et al., 2019). The general mechanism of passive sampling is illustrated in Figure 1.

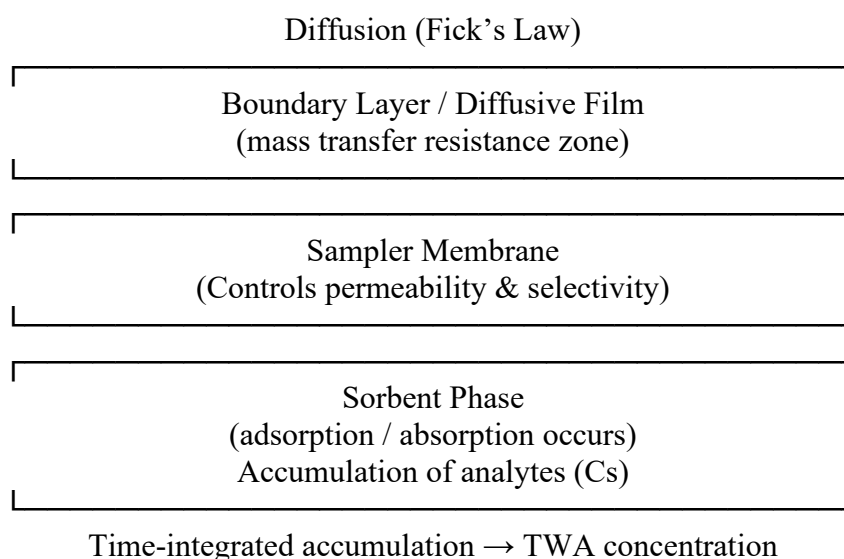


Figure 1: Schematic presentation of passive sampling mechanism illustrating diffusion, boundary layer transport, membrane permeability, and sorption processes leading to time-weighted average (TWA) concentration of pollutants.



A coupled diffusion-sorption mechanism describes the uptake of analytes in passive samplers in which analytes diffuse through a concentration gradient into the sampler and bind to a sorbent material so that time-weighted average concentrations can be determined (Barah et al., 2025; Lach & Okoniewska, 2024; O'Keeffe et al., 2025).

6.2 Sorption and Uptake Kinetics

After the analytes diffuse into the sampler, they are accumulated by sorption. Sorption is the process of adsorption onto solid surface and absorption into polymer matrix. It is the key step that dictates the amount of analyte uptake and therefore the method sensitivity (Li et al., 2023). Uptake rate and sorption in passive sampler system are closely related to the physiochemical properties of analytes and sampler. Hydrophobic interaction is the main factor that controls the sorption in passive sampler system as lipophilic compounds tend to preferentially transfer into organic or polymer based sorbent. This is normally measured using partition coefficients like octanol-water partition coefficient, K_{ow} . The uptake rate is controlled mainly by lipophilic interactions and the physiochemical properties of analytes as well as the polymeric sampler (for example). According to Ogbeh et al. (2025) in Nigeria, sorption (adsorption) of organic micropollutants is influenced by the nature of organic micropollutants based on their molecular properties like hydrophobic (partition coefficient, K_{ow}), polar and functional group and their specific interaction to the adsorbent material which determines their total removal efficiency. Also, the study from Umeh et al. (2023) shows that physical and chemical characteristics of the contaminants (like hydrophobicity, ionic strength and pH) are dominant in determining sorption behavior of contaminants like PFAS. They all indicate that partitioning mechanism, often represented by K_{ow} and other coefficient, controls contaminant transport and removal.

Sorption is a rate limiting step controlling uptake kinetics. Uptake kinetics describes time dependent uptake of contaminants which has three stages. The first phase is the linear, kinetic phase. The second stage is the intermediate, curvilinear and equilibrium phase. The initial kinetically (linear) phase is characterized by a linear increase in the analyte uptake as a function of time because a constant sampling rate occurs and is influenced by the processes of diffusion and sorption. This phase is crucial for achieving time-weighted the sorption sites on the sampler are not saturated and the analyte uptake rate is solely governed by mass transfer mechanisms including diffusion through the boundary layer and the membrane of the sampler (Salim & Grecki, 2019). As the sampling period continues, the intermediate (curvilinear) phase is reached in which the uptake rate begins to slow down because of the partial saturation of sorbent sites on the sampler and decreasing concentration gradients; sorption-desorption interactions began to affect the analyte concentration accumulation in the sampler and deviate the sampling rate from the linear. The resistance to mass transfer increased and includes diffusion limits across the sampler matrix and boundary layer resistance (Zhang et al., 2012). Eventually, the system reaches equilibrium stage where concentration of analyte in the sampler and ambient environment is balanced such that there is no net uptake. During this phase, Sorption/desorption mechanisms are equal and the sampler achieve equilibrium. Equilibrium stage plays a major role for equilibrium-based passive samplers since the concentration of analytes in the sampler is proportional to the concentration of analytes in the surrounding environment (Mayer et al., 2014; mentioned as passive sampling framework).

In recent works, Sorption controlled uptake kinetics have been shown to be affected by numerous factors, including physicochemical properties of analyte, physical and chemical characteristics of the sorbent, and ambient parameters such as temperature, water flow rate, and biofouling (Liu et al., 2024; Li et al., 2025). Comparative studies indicated that different passive samplers possess distinct analyte uptake kinetics, for example POCIS, due to high-affinity sorption sites, typically possesses quicker sorption kinetics while the lipid-based membrane in SPMD possesses strong partitioning affinity towards hydrophobic compounds.

The Linear (Integrative) Phase: The beginning of passive sampling is characterized by the linear, time-proportional, uptake of analyte by the passive sampler. This reflects the phase when the passive sampler has not reached equilibrium, with a significant concentration gradient between the ambient environment and the passive sampler. In this phase the sampling rate remains constant, making it very suitable for estimating the time-weighted average concentration (TWA) of pollutants. Ghosh et al. (2014) describe that during the first



period of deployment the concentration of the analyte accumulating within a passive sampler increase linearly over time which allows to estimate concentration of free dissolved contaminant. Also Salim and Grecki (2019) report that during this phase the sampling is controlled by the diffusion and follows first order kinetics that are dependent upon concentration gradients. The use of this phase in environmental monitoring is very attractive as the data are highly reliable and quantifiable.

ii. The Curvilinear Phase. As time goes on the sampling rate begins to slow down and the accumulation profile within the passive sampler is curvilinear. This is due to the fact that after a while a smaller concentration gradient between the environment and the passive sampler will be developed as the concentration of analyte will build up within the sorbent. Kot-Wasik et al. (2020) reports this intermediate phase is characterized as a transition between kinetics controlled and equilibrium controlled conditions. The accumulation of the analyte is still occurring but not at constant rates. Moreover Vrana et al. (2005) reported that the reduced rate is also due to the diffusion limitations and a partially saturated sorbent. During this phase, the interpretation of the data and estimation of environmental concentrations becomes challenging and models or correction factors are needed.

iii. Equilibrium Phase: Under extended exposure periods, the system ultimately reaches equilibrium when analyte uptake rate equals desorption rate, resulting in no net build up of contaminants in the sampler. The definition of equilibrium by Ghosh et al. (2014) was based upon the stabilization of analytes concentration over time in sampler material as this represents completed partitioning between sampler and environment, while Kot-Wasik et al. (2020) further elaborated this by explaining that at equilibrium the concentration values of contaminants can be determined by partition coefficients which are of interest in assessing bioavailability and potential of long term exposure. While equilibrium sampling is advantageous as it allows for determining the concentration distribution, it may require prolonged deployed period especially for hydrophobic organic compounds. It has been noted from several studies that the type of material used in samplers significantly influence its sorption characteristics. For example, sorbent material such as activated carbon, polyurethane foam or polymer membranes will produce selective and capable of sampling the analytes in a given volume and efficiently absorb the compounds while temperature and flow rate and the nature of the matrix will have great impact on the kinetics of sampling since it may change diffusion coefficients and partition equilibrium (Wu et al., 2009).

6.3. Sampling rate

The sampling rate (R) is an important parameter for passive samplers. It is the volume of water or air that the sampler processes per unit time, and it is used to determine the environmental concentration based on the mass of analyte taken up by the sorbent. This means it is essential for R to be well understood for reliable data analysis and interpretation. According to Benjamin Becker et al., the sampling rate is the fundamental basis for modeling analyte uptake, and thus for observing temporal variation in environmental concentrations. Sampling rates are not consistent and can vary widely due to environmental and operational factors. As passive sampling operates based on diffusion processes and environmental gradients, it is expected that anything affecting mass transfer would also affect R according to Faten Salim and Tadeusz Grecki (2019). Some important parameters that have been identified in recent studies to affect sampling rate:

i. Hydrodynamic conditions (flow rate of water or air):

The flow rate of the surrounding medium (water or air) greatly affects the thickness of the boundary layer around the sampler. Increased flow rate reduces the boundary layer and so increases diffusion to the sampler and thus sampling rate. Static conditions tend to have less efficiency (Becker et al., 2024).

ii. Temperature: Increased temperature leads to higher diffusion coefficients, higher R values; while lower temperatures result in slower analyte transport, i.e. Lower R values.

iii. Physicochemical properties of analytes: Sampling rates are influenced by molecular weight, hydrophobicity and solubility. Compounds with greater diffusivity and partition coefficient for the sampler are accumulated more readily (Godlewska et al., 2021)



iv. Water chemistry: Effects of pH on the partitioning process is mainly through changes of ionized form of the pollutants. High salinity of water may cause salting-out effects and affect water solubility and partitioning, and organic matter in the water can sometimes accelerate and sometimes retard analyte transport (Godlewska et al., 2018).

v. Biofouling: Accumulation of biofilm on the membrane will slow down and reduce the permeability of the membrane and the mass transfer of the analytes, which cause a decrease of sampling rates during sampling period.

vi. Sampler material and design: Different materials have different resistances to biofouling and affinity for different analytes. For example, it is better to choose a membrane with low affinity and less resistance to biofouling.

vii. Time of deployment: Sampler could be in kinetics uptake phase or equilibrium phase. Over-sampling the sampler is not appropriate because sampling rates might have already reduced after the steady-state was reached.

7.0 TYPES OF PASSIVE SAMPLING TECHNIQUES

Passive sampling methods can be broadly classified according to the media that they are deployed to (air, water and soil/sediment) and they utilize the diffusion and sorption processes to collect analytes over a period of time, providing time weighted average concentrations (instead of instantaneous concentrations) and these techniques optimize contaminant uptake by factoring in environmental conditions, the analyte and the device configuration (Vrana et al., 2005; Onafeso, Akeredolu, & Sonibare, 2010; Godlewska, Stepnowski, & Paszkiewicz, 202; Godlewska et al., 2021; Shakallis, Fallowfield, Ross, & Whiley, 2022). There is not one method of passive sampling which is suitable for all contaminants and environments and as has been concluded from comparing passive sampling techniques, POCIS's are best suited for hydrophilic organics due to its fast uptake rates and high sensitivity whereas the SPMD is more appropriate for the analysis of hydrophobic organics as it mimics lipids, whereas DGT provides good stability for metals and ions, though it has lower sampling rates, particularly during varying environmental conditions (Bonnaud et al., 2023; Cao et al., 2024; Fialov et al., 2024). As shown in Figure 2, POCIS exhibits higher sensitivity for polar organic contaminants, whereas DGT demonstrates greater stability under fluctuating environmental conditions, and SPMDs show strong affinity for hydrophobic compounds but less useful for polar analytes. Passive sampling methods such as SPMD, POCIS, and DGT exhibit distinct performance characteristics depending on the target analytes and environmental conditions. A comparative summary of these techniques is presented in Table 1.

Table 1: Comparative Performance of Major Passive Sampling Techniques

Parameter	SPMD	POCIS	DGT
Target Analytes	Hydrophobic organics (PAHs, PCBs, POPs)	Polar organic compounds (pharmaceuticals, pesticides, PPCPs)	Metals and inorganic ions (Cd, Pb, Zn, nutrients)
Sensitivity	Moderate (effective for lipophilic compounds)	High (especially for trace-level polar contaminants)	Moderate–Low (focus on labile fraction rather than total concentration)
Selectivity	High for non-polar compounds	High for polar compounds	High for ionic species
Sampling Rate (R)	Moderate, influenced by hydrophobic partitioning	High uptake rate, faster kinetics	Low but stable and controlled
Environmental Stability	Moderate (affected by temperature & flow)	Lower stability under fluctuating conditions	High stability across varying conditions
Calibration Complexity	High (requires PRCs and partition models)	Moderate–High	Moderate (well-defined diffusion layer)
Detection	Low for hydrophobic	Very low (excellent for	Moderate (not designed for ultra-

Limits	compounds	trace analysis)	trace detection)
Major Strength	Mimics bioaccumulation of POPs	High sensitivity for emerging contaminants	Measures bioavailable fraction directly
Key Limitation	Poor for polar compounds	Sensitive to environmental variability	Lower sensitivity and slower uptake
Environmental applications	Water/sediment; hydrophobic organics	Water; polar organics, pharmaceuticals and pesticides	Water/sediment; labile metals and selected ions
Typical calibration needs	Sampling-rate/partition model; PRCs often used for in-situ correction	Analyte-specific sampling rates or validated uptake models; field/lab calibration	Diffusive-layer characteristics, deployment time and binding capacity; method-specific validation
Key limitations	Weak for polar compounds; uptake affected by temperature and flow	Uptake can be sensitive to hydrodynamics, temperature and sorbent condition	Measures labile fraction, not total concentration; performance depends on speciation and gel/resin properties
Measurement interpretation	Accumulated hydrophobic compounds; concentration estimates require partition/calibration data	TWA estimates when uptake remains integrative and rate is known	Time-integrated labile fraction under deployment conditions; not equivalent to total metal or universally bioavailable metal

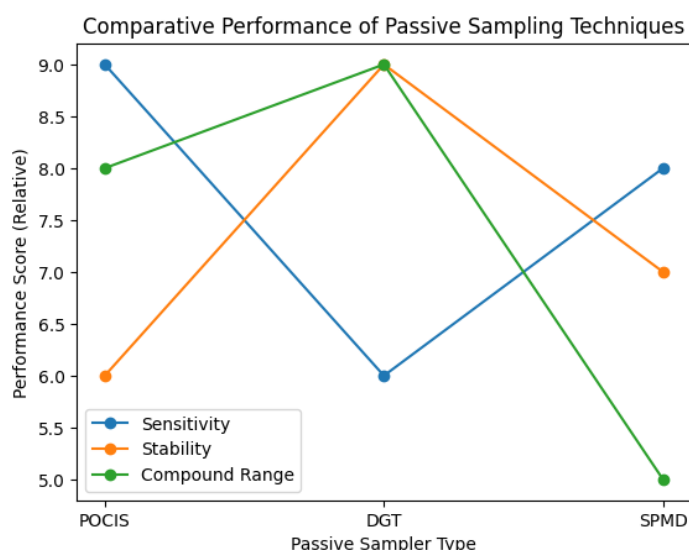


Figure 2: Comparative performance of passive sampling techniques (POCIS, DGT, and SPMD) based on sensitivity, environmental stability, and target analyte applicability.

There are significant variations in analytical performance of passive sampling methods, especially in terms of sensitivity, selectivity and resistance to changes in the environment. Polar Organic Chemical Integrative Samplers (POCIS) have a high polar organic contaminant detection capability owing to the high degree of polar organic sorption and high rate of uptake and is therefore suited to identifying emerging pollutants at trace levels. By comparison, Semi-Permeable Membrane Devices (SPMDs) are able to be more selective of hydrophobic compounds, because their lipid-like membranes mimic biological accumulation mechanisms, but polar analytes are less effectively extracted. Diffusive Gradients in Thin Films (DGT) have a clear benefit in quantifying the labile and bioavailable fractions of metals, which offer relevant data to the environment, even though with relatively lower sensitivity. Also, DGT systems are more stable in a changing environment as diffusion is controlled by a well-defined gel layer, whereas POCIS performance is more affected by hydrodynamics.

All these variations imply that there is no universal approach to passive sampling. Rather, sampling decisions



ought to be informed by the physicochemical characteristics of the contaminants of interest and environmental site-specific features, emphasizing the need to combine various methods to effectively monitor the environment.

7.1 Air passive sampler

Air passive samplers can provide effective sampling of gaseous and semi volatile air pollutants as they have no external pump but rely on molecular diffusion to carry airborne contaminants from the atmosphere to a sorbent material (Wania & Shunthirasingham, 2020). Common designs for passive air sampling include diffusion tubes (e.g. Palmes tube for NO), badge samplers for the purpose of personnel/occupational exposure assessment, and PUF disk samplers used to collect semi volatile organic compounds (Wania & Shunthirasingham, 2020; Huang et al., 2018). Locally fabricated passive samplers have also been used in Nigerian field sites for ambient NO measurements indicating suitability for low infrastructure environments (Onafeso et al., 2010).

Air passive samplers are useful for measurement of pollutants like VOCs, SVOCs and POPs (Wania & Shunthirasingham, 2020). PUF disks and polymer based passive samplers (e.g. Polyethylene sheets) have been used for capturing SVOCs and POPs due to their high sorptive capacity and similarity in representing the environmental partition coefficients (Lamel et al., 2025). The biggest advantage is that passive air samplers give time-weighted average concentrations over long time scales. They are most useful for: urban air monitoring, global monitoring network, indoor air studies, and occupational health assessment (Seethapathy et al., 2008; Okeme et al., 2026).

7.2 Water Passive Samplers

A useful Nigerian comparison is the hydrochemical assessment by Apuyor et al. (2024), which used conventional samples from wells and boreholes in Delta Central to characterize physicochemical parameters, major ions, coliforms, and selected metals. The study illustrates the value of direct water-quality measurements for identifying local concerns, including acidic pH and site-specific lead contamination. In a monitoring programme, such measurements could provide a baseline against which a suitably selected and field-validated passive sampler is evaluated. However, passive samplers measure only the analyte fraction and exposure interval for which their uptake and calibration have been established; they should not be assumed to replace routine hydrochemical or microbiological testing.

Water passive samplers The devices developed for the analysis of dissolved contaminants in surface waters, rivers, lakes, groundwater and wastewater have already been mentioned. These devices provide the opportunity to obtain time integrated concentration of contaminants that can overcome the disadvantages related to a grab sample that provide instantaneous concentration. Two common types of water passive samplers include:

- **Semi-permeable Membrane Devices (SPMDs)** Commonly used for the analysis of hydrophobic organic contaminants, such as PCBs, PAHs and organochlorine pesticides (Stuer-Lauridsen, 2005). SPMDs are comprised of a membrane that is permeable to organic compounds, and they resemble biological uptake where by non polar contaminants can diffuse across the membrane into the device (Aravind Kumar et al., 2022).
- **Polar Organic Chemical Integrative Samplers (POCIS)** The main difference between POCIS and SPMDs is the type of organic contaminant they analyze; with POCIS devices used to target polar compounds, such as pharmaceuticals, pesticides and endocrine-disrupting chemicals. They contain sorbent materials that absorb the polar contaminants that are in the dissolved state (Domnguez-Garca et al., 2025). Water passive samplers are suitable for determining trace contaminants and for monitoring short-term and long-term changes in contaminant concentrations, and are used in wastewater sampling and analysis, and surface water monitoring.



7.3 Soil and Sediment Samplers

Soil and sediment passive sampling methods are developed in order to estimate the bioavailable and mobility contaminants. Traditionally soil contamination was measured by extractives methods, in which the concentration is total amount and is considered the only meaningful measure, however in many cases what is needed is the free dissolved fraction of contaminants for ecological risk assessment. Common types of soil and sediment passive samplers include polyethylene (PE) strips, polyoxymethylene (POM), and solid-phase microextraction (SPME) fibers, which are often used to extract hydrophobic organic contaminants such as PAHs and PCBs from porewater and sediment (Mayer et al., 2022).

A further monitoring tool employed for trace metals in soils and sediments is the Diffusive Gradients in Thin Films (DGT) device. The devices monitor the labile portion of metals in order to characterize bioavailability, toxicity, etc., in support of Ecological Risk Assessment (Lohmann et al., 2012). A primary element of environmental quality assessment is metal and inorganic pollutant monitoring because many inorganic contaminants, which do not degrade, may be harmful to ecosystems and public health. Some commonly identified inorganic environmental pollutants (based on elevated contaminant levels) include Cd, Pb, Cr, As, Ni, and Hg and the ions nitrate (NO) and fluoride (F). They may enter the environment as a result of human activities such as industrial and mining discharge, agricultural run-off, vehicles emissions and waste disposal and/or through natural geochemical processes (Kadadou et al., 2024; Balaram et al., 2023). Metals and inorganic pollutants are dangerous because they do not readily decompose in environments, persisting and accumulating over time due to their inert nature bioaccumulating into organisms, resulting in toxic effects at all trophic levels as well as serious public health risks, including neurological and kidney and liver damage and even developmental effects and carcinogenicity, in organisms exposed to levels exceeding thresholds (Kadadou et al., 2024). It is therefore imperative to be able to accurately monitor metals and inorganic pollutants as regulatory (e.g., WHO standards), ecological, health, risk assessment and management factors all depend upon effective contaminant detection. Passive soil and sediment samplers are an indispensable tool for use in long term monitoring studies, studies on pollutant transport, and monitoring the efficiency of remediation strategies.

The type and design of passive sampling devices will depend upon the matrix environment and the properties of pollutants being monitored. The principal types of passive samplers and the pollutants they target are outlined in Table 2, summarizing information from recent literature.

Table 2: Types of Passive Samplers and Target Pollutants

Passive Sampler Type	Environmental Medium	Target Pollutants	Typical Examples of Analytes	Key Features / Notes
Diffusive (Air) Samplers (e.g., Palmes tubes, badges)	Air	Volatile and gaseous pollutants	NO ₂ , SO ₂ , O ₃ , VOCs (benzene, toluene)	Operate via molecular diffusion; widely used in ambient and occupational air monitoring (Analytical Methods Committee, 2025) (RSC Publishing)
Polyurethane Foam (PUF) Disk Samplers	Air	Semi-volatile organic compounds (SVOCs), POPs	PCBs, PAHs, organochlorine pesticides	Mimic atmospheric partitioning; widely used in global monitoring networks (Wania and Shunthirasingham, 2020)
SPMD (Semipermeable Membrane Devices)	Water	Hydrophobic organic pollutants	PCBs, PAHs, dioxins, pesticides	Lipid-based uptake mimics bioaccumulation; suitable for non-polar compounds (Godlewska et al., 2021)

POCIS (Polar Organic Chemical Integrative Sampler)	Water	Hydrophilic organic contaminants	Pharmaceuticals, pesticides, hormones, PPCPs	Effective for polar compounds ($0 \leq \log K_{ow} \leq 5$); widely used for emerging contaminants (Godlewska et al., 2021; recent wastewater studies 2024)
Chemcatcher®	Water	Polar and semi-polar organic pollutants	Herbicides, pharmaceuticals, endocrine disruptors	Modular design; adaptable sorbents enhance selectivity (Godlewska et al., 2021).
DGT (Diffusive Gradients in Thin Films)	Water / Soil / Sediment	Metals, nutrients, some organics	Cd, Pb, Zn, Hg, phosphates	Measures labile (bioavailable) fraction; widely used for metals and nutrients (Shakallis et al., 2022)
Polyethylene (PE) / Silicone Samplers	Water / Sediment	Hydrophobic organic contaminants	PAHs, PCBs, petroleum hydrocarbons	Simple polymer-based samplers; equilibrium-based measurements
SPME (Solid Phase Microextraction Fibers)	Air / Water / Soil	VOCs, semi-volatile organics	BTEX, pesticides, solvents	High sensitivity; often coupled with GC-MS
PIMS (Passive Integrative Mercury Sampler)	Water	Mercury species	Hg ²⁺ , methylmercury	Specialized sampler for mercury monitoring (Godlewska et al., 2021)
o-DGT (Organic-DGT)	Water	Organic contaminants (modified DGT)	Antibiotics, pesticides	Extension of DGT for organic pollutants Shakallis et al., 2022)

8.0 MATERIALS & COMPONENTS OF PASSIVE SAMPLERS

Material and construction of passive samplers are key for the efficiency and reliability. These material types include membrane, sorbents and housing. Each part is important for different process of analyte absorption, selectivity and stability.

8.1 Membranes

Membranes play a very important role in many of passive samplers as the selective medium which can limit the mass transfer of analyte in sampler. It can limit the rate of mass transfer and also prevent the interference in sorbent. Membrane is made of some polymer material such as low-density polyethylene (LDPE), silicone rubber or other semi-permeable polymer. This type of material permits only specific components across and they can be passed through depending on their size, polarity and solubility (Belden et al., 2015; Gautam et al. 2014). SPMD use the membrane to control the diffusion and imitate the uptake process in biology system (Sderstrm, & Bergqvist, 2004; Pogorzelec, M., & Piekarska, K. 2018; Narvaez Valderrama et al., 2023).. Membrane thickness and material determine the sampling rate and selectivity.

8.2 Sorbents

Sorbents are the actual material which trap and retain analyte in the passive samplers. Their type determines sampler's sensitivity, selectivity and capacity. The typical sorbents are:

- Activated carbon (VOCs) (Kwon et al., 2025)
- Tenax (organic vapor) (Haper, 2000)



- iii. PUF (SVOCs & POPs) (Hazrati & Harrad, 2007; Bohlin et al., 2014)
- iv. XAD resins and polymeric sorbent (Haper, 2000)
- v. Ion exchange resin (metals in DGT)

Passive sampling devices have different performance with regard to their design, target analytes, and the environment. Comparative analysis of the most popular samplers SPMD, POCIS, and DGT shows significant differences in their applicability and analytical characteristics.

Hydrophobic organic contaminants like PAHs and PCBs are highly soluble in SPMDs as it has lipid-like membrane properties. Conversely, a polar organic compound such as pharmaceuticals and pesticides are more appropriate in POCIS due to the hydrophobic sorbent phase. DGT, in turn, is particularly developed to trace metals and metalloids in terms of labile species in water systems.

Although they have their strengths, all these samplers are not universal in all classes of contaminants. Environmental factors like temperature, flow dynamics and biofouling have a strong impact on their performance and can significantly change the sampling rates and uptake kinetics.

According to the recent research, the sampling rate variation can also be up to two times in the case of changing environmental conditions, whereas inter-laboratory variation can be as high as 30, pointing to the issues of reproducibility (Boonstra et al., 2025; McLagan et al., 2025).

The choice of a suitable passive sampler should, therefore, be informed by:

- i. Target analyte properties
- ii. Environmental matrix
- iii. Sensitivity and detection limits required.
- iv. Calibration strategy

This supports the importance of standardization of methods and better calibration models to increase comparability between studies.

8.3 Casing materials.

The casing of a passive sampler houses the internal components and ensures that the physical integrity and contents of the sampler are maintained against damaging factors. The casing design also ensures reproducible exposure conditions around the sampler, controlling airflow or water flow. The materials that are used to manufacture passive samplers are non-reactive, for example stainless steel, aluminum, or plastic. This design of passive sampler housing affects airflow, turbulence and the efficiency with which analytes can diffuse towards or away from the sensor and affect the degree of reproducibility between deployments. Passive sampler housing design is essential to avoid contamination and maintain reproducibility between sampling events.

9.0 APPLICATIONS OF PASSIVE SAMPLING

Passive sampling offers a wide variety of applications including the assessment of air and water quality, public health impacts and industrial assessments, primarily because of the ease of deployment and relative inexpensiveness compared to active sampling techniques. The successful application of passive samplers varies according to the sampler type. For example the POCIS technique has been found to be extremely useful for the analysis of trace organic pollutants in water systems, while the DGT technique is more useful for analysis of metals in water and sediment for determination of bioavailable metals. The SPMD technique is



suitable for analysis of hydrophobic organic compounds in air and water systems. Research suggests that a more reliable picture of environmental pollution can be obtained using a combination of passive sampling techniques (Cartmell & Marshall, 2023; Domnguez-Garca et al., 2025).

9.1 Air Quality monitoring

Passive samplers are widely used to monitor air quality and, a variety of analytes, including volatile organic compounds (VOCs), NO₂, SO₂, ozone and persistent organic pollutants (POPs). Field studies that have been done using passive sampling methods have been able to determine spatial differences in the concentration of air pollutants. As an illustration, the case of monitoring SO₂ in several points in a university setting showed a high spatial variability due to the sources of local emissions and the environmental factors (Uzoekwe and Ahonkhai, 2008). The information that passive samplers gather is used to measure the effect on human exposure and environmental factors in air quality studies, global monitoring systems, and indoor air quality studies (Kwon et al., 2025). Field researches have revealed that PAH concentrations vary widely on spatial scales, and their distribution is mainly determined by local human activities, including industry and traffic emissions (Uzoekwe and Ikpesu, 2019). Exposure to PAHs in humans can be inhalation, ingestion, and dermal exposures, and in many cases, exposures occur in various forms at the same time (Umudi et al., 2025).

The long-term exposure has been linked to negative health consequences such as immune suppression, organ damage, respiratory diseases, and carcinogenicity (Umudi et al., 2025).

Risk assessment indicators like hazard quotient (HQ) and excess lifetime cancer risk (ELCR) are becoming increasingly popular in environmental monitoring research to determine the possible health effects of pollutant exposure (Uzoekwe & Ikpesu, 2019).

9.2 Water Quality Assessment

Passive samplers are employed in aquatic settings to monitor organic pollutants, pharmaceuticals, pesticides and heavy metals and have the ability to collect time-weighted data, thus increasing accuracy for monitoring and compliance (Ahrens et al., 2016; Shakallis et al., 2022; Yu et al., 2024).

9.3 Monitoring of Soils and Sediments

Passive samplers are used to investigate the mobility, bioavailability and ecological risk of soil and sediment contaminants. The utility of these devices includes tracing the behavior of trace metals and hydrophobic organic contaminants in contaminated soils and sediments.

9.4 Monitoring of Emerging Contaminants

Passive sampling is useful for determining levels of emerging contaminants such as endocrine disruptors, pharmaceuticals, personal care products and PFASS, since they provide continuous data at low concentrations. POCIS is a form of passive sampler capable of continuous, low level monitoring (Zhang et al., 2008).

9.5 Monitoring Occupational and Indoor Exposure

Passive samplers are widely used for worker and indoor exposure monitoring in the assessment of hazards from chemicals such as formaldehyde, benzene and other Volatile Organic Compounds (VOCs) and are highly useful for personal exposure monitoring due to their ease of use and small size (Kwon et al., 2025).

9.6 Ecotoxicological and Biomonitoring Studies

Passive samplers are utilized as biomimetic tools and have the potential to determine bioavailable fractions of contaminants and predict bioaccumulation of contaminants in organisms. It can be used in combination with bioassays to estimate risk.



10.0 ADVANTAGES OF PASSIVE SAMPLING TECHNIQUES

Passive sampling methods offer a number of advantages compared with active sampling. The key benefit of passive sampling is that it is cost-effective and does not require power, elaborate instrumentation or continuous operational time and is ideally suited for long-term monitoring of resources in areas which are inaccessible. Passive samplers provide time-weighted averages, resulting in a useful representation of average exposure over the deployment period than a single grab measurement, although active methods may be preferable for short-term peaks, total concentrations or regulatory methods requiring instantaneous measurements. Furthermore, passive samplers are generally simple to deploy, lightweight, and minimally invasive, reducing logistical challenges during fieldwork. Their ability to operate continuously over extended periods enhances their usefulness in detecting low-concentration contaminants and assessing temporal variations in pollutant levels. Despite these advantages, their performance may be influenced by environmental conditions, necessitating proper calibration and validation.

11.0 LIMITATIONS AND CHALLENGES OF PASSIVE SAMPLING TECHNIQUES

Although passive sampling has a number of benefits in environmental monitoring, a number of shortcomings impact the accuracy, reproducibility and general applicability of this method. The major advantages and limitations associated with passive sampling techniques are summarized in Table 3, highlighting both their operational strengths and methodological constraints.

The environmental factors that have a significant effect on passive sampling performance include temperature, hydrodynamics, and turbulence, humidity, and water flow. The factors influence the diffusion and sorption processes, which causes changes in the sampling rates with time. It can therefore be seen that the assumption of a constant uptake rate can frequently be invalid in practice in the field with real conditions leading to possible errors in estimated concentrations of pollutants (especially in dynamic or non-steady-state conditions) (Harman et al., 2008; Cartmell and Marshall, 2023).

Passive samplers do not directly measure concentration but rather grow the weight of an analyte with time, and necessitate conversion with sampling rates. This adds the calibration error particularly when the environmental conditions are not similar to the laboratory calibration conditions. Even with the reduction in in situ calibration that is brought by the use of Performance Reference Compounds (PRCs), uncertainty still exists because of differences in physicochemical behavior between target analytes and PRCs. Reported differences are up to two-fold differences in sampling rate, inter-laboratory differences of about 30 percent, time-weighted average (TWA) error of 25 percent, and systematic bias of 10-16 percent versus active sampling (Liu et al., 2013; Jiang et al., 2025; McLagan et al., 2025).

Aquatic environments, Microorganisms, algae and organic matter can be biofouled on the surface of sampler membranes in aquatic environments. This layer decreases diffusion and mass transfer of analysis, resulting in lower uptake capability and inaccurate estimation of contaminant levels. Biofouling also changes sampler permeability and serves to enhance variability in long-term deployments (Dominguez-Garcia et al., 2025).

Passive sampling is also constrained by analytical and methodological challenges. These are the inability to measure short term peaks of pollution because of time integration in sampling, the interference of non target compounds because of the sorbent selectivity problem and the use of sophisticated analytical equipment like GC-MS or LC-MS. Moreover, the absence of standardization of sampling protocols and calibration methods decreases the comparability of studies. This can be especially problematic in resource-constrained environments where the analytical infrastructure can be lacking (Seethapathy et al., 2008; Cartmell and Marshall, 2023).

Table 3: Advantages and Limitations of Passive Sampling Techniques

Aspect	Advantages of Passive Sampling	Limitations of Passive Sampling
Cost and	Low cost, simple design, and no need for	Requires laboratory analysis after

logistics	electricity or pumps, making it suitable for large-scale and remote monitoring (Macías et al., 2023; Hayes & Gagnon, 2024)	deployment, often involving sophisticated instruments (e.g., GC–MS, LC–MS), which can limit use in low-resource settings (Hayes & Gagnon, 2024)
Temporal monitoring	Provides time-weighted average (TWA) concentrations, enabling better representation of long-term exposure compared to grab sampling (Macías et al., 2023)	Cannot capture short-term fluctuations or peak pollution events, leading to possible underestimation of episodic contamination (Hayes & Gagnon, 2024)
Field applicability	Suitable for deployment in remote or difficult environments where active sampling is impractical (Saltonstall et al., 2024)	Performance varies across environmental conditions and may require site-specific calibration (Liu et al., 2024)
Sensitivity and detection	Capable of detecting trace-level contaminants over extended periods, improving sensitivity for low concentrations (Karamati et al., 2024)	May exhibit lower recovery of total analyte mass or DNA compared to active sampling methods in some cases (Saltonstall et al., 2024)
Environmental relevance	Measures freely dissolved or bioavailable fractions of contaminants, improving ecological risk assessment (Macías et al., 2023)	Equilibrium may not always be reached, causing uncertainty in quantification and interpretation (Liu et al., 2024)
Integration with modern techniques	Compatible with advanced tools such as molecular detection and wastewater epidemiology for emerging contaminants and pathogens (Mejías-Molina et al., 2023; Hayes & Gagnon, 2024)	Method selectivity may differ from active sampling, meaning results from both approaches are not always directly comparable (Saltonstall et al., 2024)
Scalability and coverage	Allows deployment of multiple samplers simultaneously for wide spatial coverage and hotspot identification (Macías et al., 2023)	Lack of standardized protocols and calibration approaches can reduce comparability between studies (Hayes & Gagnon, 2024)

Passive sampling techniques present significant advantages in environmental monitoring; however, several methodological and operational limitations must be considered (Macías et al., 2023; Hayes & Gagnon, 2024).

Table 4: Summary (Quantitative Synthesis)

Limitation	Quantitative Range	Impact
Sampling rate variability	Up to 2× deviation	Major uncertainty
Inter-lab variability	~30%	Reproducibility issue
TWA error	Up to 25%	Accuracy limitation
Bias vs active methods	10–16% overestimation	Systematic bias
Precision (RSD)	~14% ± 13%	Moderate reliability
PRC improvement	Up to 80.6% error reduction	Calibration benefit
Environmental influence	Highly variable	Non-constant uptake

11.0 CALIBRATION AND QUALITY ASSURANCE

Calibration and quality assurance procedures in passive sampling ensure that the data produced is accurate, reliable and reproducible. In passive sampling, concentration is determined from the mass of analyte accumulated on the sampler, hence calibration is required to transform mass measurements into actual concentration values (Seethapathy et al., 2008). Quality assurance (QA) is defined as the entire set of activities



designed to maintain the data quality throughout sampler preparation, deployment, collection and analysis. The use of field and laboratory blanks can help detect possible contamination during handling and analysis, and replica samplers to improve the precision and reproducibility of the results (Harman et al., 2008). It is crucial that environmental variables, such as temperature, flow rate and exposure time, are well documented for the proper interpretation and correction of measured concentrations for environmentally driven uptake variations (Domnguez-Garca et al., 2025).

11.1 Sampling rate calibration

The sampling rate (R) is a fundamental parameter in passive sampling, and is defined as the volume of ambient sample (air or water) sampled per unit time, to be used in the conversion of accumulated mass to environmental concentration (Seethapathy et al., 2008). Sampling rate is highly sensitive to several environmental factors including; temperature, turbulence and flow rate, causing potential inaccuracy where there is an assumption of constant uptake in long term exposures (Cartmell & Marshall, 2023). Two methods may be used to establish sampling rate calibration;

- i. Laboratory calibration; the main benefit of this approach is that it can be performed under constant, controlled conditions, allowing the R value to be determined (Harman et al., 2008). However the limitation is that R values determined under controlled conditions do not necessarily reflect actual environmental rates.
- ii. Field calibration; this approach allows for R to be measured under authentic environmental conditions, though it adds complexity and significant variability to the measurement (Domnguez-Garca et al., 2025).

One of the commonly employed techniques to improve the calibration accuracy is the use of performance reference compounds (PRCs). These compounds are pre-loaded into the sampler and the rate at which they dissipate during field deployment can be used to calculate in situ sampling rates and environmental influences (Liu et al., 2013). Although such advancements have been made, uncertainties in sampling rate estimation remain one of the key challenges and thus continuously improving calibration methods and standardizing procedure is essential to gain better data from passive sampling techniques (Seethapathy et al., 2008; Cartmell & Marshall, 2023).

11.2 Performance Reference Compounds (PRCs)

Performance reference compounds (PRCs) are commonly applied to passive samplers to improve the quantification accuracy of contaminants under various environmental conditions. PRC are compounds pre-loaded into the passive sampler before being deployed in the field and their dissipation rates throughout field exposure can be utilized to predict in situ sampling rate. They also allow to identify the kinetics of mass transfer between sampler and ambient environment and improve the prediction of freely dissolved contaminant concentration (C_{free}) (Abigail & Robert, 2018). Ambient pollutant concentrations are influenced by meteorological factors such as wind direction, turbulence, and dispersion patterns, which may result in higher pollutant levels at locations distant from emission sources (Uzoekwe & Ahonkhai, 2008). Usage of PRCs helps in taking into account environmental factors, which include temperature, hydrodynamics, and biofouling that influence the kinetics of analyte uptake and equilibrium process during deployment of passive samplers (Morrison & Belden, 2016). It is also regarded as a reliable method in order to correct non-equilibrium process through comparing loss rate of PRCs from sampler to rate of target analyte uptake and it also contributes in determining TWA concentration reliably (Apell & Gschwend, 2014). They are particularly effective under a complex environmental settings like aquatic and sediment systems that are impacted by external mass transfer resistance and heterogeneity of environmental parameters.

In less developed countries, like Nigeria, where environmental monitoring instrumentation is often less available, the use of PRC-calibrated passive sampling has shown itself to be an inexpensive and accurate way of evaluating exposure under varying environmental conditions. However, the usefulness of performance reference compounds (PRCs) depends on the assumption that their rate of dissipation is a reasonable proxy for the rate of uptake of analytes of interest. Physicochemical parameters between PRCs and target analytes (polarity, size of molecules, partition coefficients) will differ between compounds, affecting the rate of mass



transfer across the boundary, hence influencing accuracy of PRC calibration and concentration predictions. Nonetheless, PRCs provide a viable means to increase accuracy within passive sampling, specifically when studying variable field conditions where calibration using direct methods is problematic (Liu, Wong, & Zeng, 2013; Joyce & Burgess, 2018).

12.0 CRITICAL EVALUATION AND RESEARCH GAPS

12.1 Conflicting Findings in Passive Sampling Techniques

While passive sampling techniques are commonly used in environmental monitoring, recent work has reported conflicting information regarding its accuracy, calibration and field performance particularly in non-steady state condition. In recent work, there are conflicting data concerning the performance, calibration, and interpretation of passive sampling data especially in field environmental condition. Different sampling kinetics, environmental variation, and methodological assumptions cause the conflicts (Table 5). The main assumption of passive sampling technique is to achieve accurate time weighted average concentration (TWA). Some study found high accuracy and precision in steady state condition especially in the linear phase. However, recently the work in this field showed that variable environmental condition brings large error to TWA estimate. For instance, an article published in Water Research (2025) reported that TWA obtained with passive samplers deviate considerably at time-varying conditions with sampling error influenced by nonlinear uptake kinetics and exposure kinetics, showing the bias can be as high as three-fold if not correct (Jiang et al., 2025). And he also revealed the result can be heavily impacted by pollutant episodic peaks (20 fold) and they would underestimate it until carefully corrected. The sampling rate (R) which is fundamental to determine the sample concentration based on the accumulated mass also have large contradictions in literatures. While traditionally studies assume a stable sampling rate in different environmental condition, the latest meta-analysis revealed the sample rate can be highly variable among studies and different conditions. One meta-analysis (2025) including 298 studies, shown that the sampling rate can differ up to a factor of two, and are strongly influenced by factors such as flow velocity, chemical properties of contaminant, and physical parameters of sampler design (Jiang et al., 2025).

Also, inter-laboratory comparisons demonstrate that there may be as much as 30% variation from the results based on uncertainty in sampling rate (also indicating poor reproducibility across laboratories and studies). PRCs are very commonly used to compensate for the environment; however, there is still controversy in whether this correction is accurate. Numerous studies have supported the use of PRCs as correction for environmental effects, however there are some limitations for dynamic systems that suggest otherwise. Research indicates that PRC dissipation does not reflect asymmetric uptake and release mechanisms and fails to completely compensate for asymmetric uptake and release under concentration dependent and varying flow regimes (Jiang et al., 2025). However this study was also able to show that complex PRC stratification can reduce this error to about 80%, suggesting PRCs are valuable if utilized correctly (Jiang et al., 2025). Also there is inconsistency in the values of precision and accuracy achieved between laboratory experiments and actual field conditions. Laboratory work can be very accurate and reproducible while real world conditions lead to a much more variable set of measurements. It has been widely demonstrated by several reviews that physical environmental conditions such as turbulence, temperature, and biofouling influence uptake differently than was initially assumed thus compromising calibration curves from laboratory conditions for real world applications (Jiang et al., 2025). Finally, hydrophobic and hydrophilic samplers are used, with generally hydrophobics assumed to be more reliable, however, a debate exists between the use of the two. It is largely accepted that hydrophilic samplers have more error and less understood mechanisms compared to their hydrophobic counterparts. PRC applications have also been well-developed and demonstrated for hydrophobic sampling, yet seem to have less success for hydrophilic systems which limits quantitative performance (Jiang et al., 2025).

Table 5: Synthesis of Conflicting Evidence

Aspect	Agreement	Contradiction
TWA accuracy	Good under stable	Poor under fluctuating



	conditions	environments
Sampling rate	Measurable	Highly variable and uncertain
PRCs	Useful correction tools	Not universally reliable
Lab vs field	Lab-controlled accuracy	Field uncertainty
Sampler types	Broad applicability	Unequal reliability
Temporal resolution	Integrative strength	Weak for peak detection

While passive sampling techniques are widely regarded as reliable tools for long-term environmental monitoring, recent studies reveal significant inconsistencies in their performance under dynamic environmental conditions. These contradictions highlight the need for improved calibration models, standardized protocols, and context-specific validation, particularly in complex field environments.

13.0 RESEARCH GAPS IN DEVELOPING COUNTRIES

Despite the growing and steady adoption of passive sampling in environmental monitoring, the trend is still geographically skewed to developed nations. Most of the studies have been carried out in Europe, North America, and some parts of Asia, and Africa is grossly underrepresented. This is especially worrying considering the fact that most African nations such as Nigeria are facing serious levels of environmental pollution and poor monitoring systems. As an example, in Nigeria, air quality surveillance systems can be described as limited in terms of spatial coverage and data availability, which limits the capabilities of environmental evaluations and prevents the creation of evidence-based policies (Olise, 2025). In addition, high levels of polycyclic aromatic hydrocarbons (PAHs) and related health hazards have been observed in the Niger Delta, which highlights the critical importance of environmental surveillance in the developing world (Uzoekwe & Ikpesu, 2019). Equally, the research activities in Nigeria have shown a high level of contamination of environmental and food samples with PAHs which is an indicator of a poor pollution control system and monitoring (Umudi et al., 2025). These results emphasize the importance of implementing cost-effective and reliable monitoring strategies, including the use of passive sampling methodologies, especially in resource-constrained environments (Umudi et al., 2025). On the same note, the world estimate shows that despite the fast development of technologies that detect pollutants, their usage is not uniform because of the lack of infrastructures and economic constraints (Yang Li et al., 2025). The main research gap is a critical lack of validation in the field of passive sampling methods in tropical and resource-limited conditions. The majority of calibration models and performance evaluations have been created in temperate climates but environmental factors in the tropics, including high temperatures, changing hydrological cycles, and higher biofouling rates, can have a large effect on the uptake rates of sampler and overall performance. The environmental variability is important in the definition of pollutant behavior, as well as the monitoring accuracy, which means that it is necessary to conduct region-specific validation studies (Xinghui Liu et al., 2024). Moreover, the pathways and dynamics of contaminant transportation are highly contextually specific, which supports the necessity of localized calibration models that are specific to particular environmental conditions (Sarvesh Jadhav et al., 2026). Intimately connected with this is the absence of locally derived calibration data and context-sensitive datasets that adds uncertainty to quantitative estimation of the pollutant. Salinity, pH and organic matter content are physicochemical parameters that exhibit variation in the systems with regard to analyte partitioning and uptake kinetics. In addition, not only the volatility, persistence, and bioavailability of contaminants differ considerably between environments, but due to these differences, the use of models derived in temperate areas in tropical environments is also fraught with limitations (Mangotra & Singh, 2024). Furthermore, passive sampling has not been integrated into the policy systems and environmental monitoring frameworks in developing countries to an extent. Although they have the benefits of low cost and the ease of operations, poor technical expertise, poorly equipped laboratories, lack of standardized guidelines, financial constraints and lack of awareness among policymakers limit their use. The issue of persistent data gaps and infrastructural issues remains a hindrance to the deployment of modern monitoring technologies in Nigeria (Olise, 2025). In addition, sources of pollution in developing countries are not necessarily the same as in the industrialized countries, as biomass burning related to agricultural and land-use activities in developing countries is a significant source of atmospheric pollutants like sulphur dioxide, and therefore requires context-specific



monitoring methods (Uzoekwe & Ahonkhai, 2008). The potential in improving environmental monitoring with emerging technologies- such as biosensors, systems based on nanotechnology, and data-driven analytical systems- is enormous. They can only be used in developing countries, however, with the limited technical capacity and infrastructure (Yang Li et al., 2025). Additionally, the inability to combine pollutant detection and remediation schemes still impedes successful environmental management, especially in low resource conditions (Xinghui Liu et al., 2024). The lack of strong regulatory frameworks and the lack of skilled personnel further complicates this issue, posing greater risks in the context of emerging contaminants (Sarvesh Jadhav et al., 2026). The other gap that has been noted is the scanty use of passive sampling in developing areas like wastewater-based epidemiology, pathogen surveillance, and antimicrobial resistance surveillance. Even though these methods have shown great potential in early warning of the risks involved with the health of the population, their implementation in developing nations is low as a result of financial, technical, and institutional barriers (Mangotra & Singh, 2024). To fill these gaps, the focus of future research must be on the creation of region-specific calibration models, growth of long-term monitoring networks, as well as the development of cost-effective and locally-adapted passive sampling instruments. Enhancing technical capacity, bettering laboratory infrastructure, and setting standardized procedures that fit the tropical and low-resource settings are also crucial. Moreover, greater global cooperation and transfer of technology will be important in the sealing of the existing gaps and facilitating evidence-based environmental management and policy formulation in the developing nations.

Local groundwater studies can help define the environmental questions that passive-sampling research should address. For example, Apuyor et al. (2024) documented acidic well and borehole water and selected locations with elevated lead in Delta Central. Although this was not a passive-sampling study, it demonstrates the need for site-specific baseline data and supports future paired field studies in which conventional water samples and validated passive samplers are deployed together. Such comparisons should evaluate analyte-specific agreement, temporal integration, sampling-rate uncertainty, and the distinction between total concentrations and labile or freely dissolved fractions.

14.0 PASSIVE SAMPLING IN THE DEVELOPING COUNTRIES.

A recent Nigerian cobweb study provides a concrete example of locally applicable, low-cost monitoring. Iwegbue et al. (2026) measured PAHs in webs collected from electronic workshops, public buildings and homes, demonstrating that these materials can capture differences in indoor PAH deposition. This evidence is relevant where continuous instrumental monitoring is constrained. Nevertheless, cobweb monitoring requires a clear sampling protocol and should be paired, where feasible, with conventional or calibrated passive air samplers before measured burdens are interpreted as time-weighted air concentrations.

Passive sampling techniques have not been used extensively in developing countries despite its inherent benefits of cheapness, ease and practicality of remote deployment. Due to high levels of urbanization, ineffective regulatory measures, and insufficient surveillance facilities, these areas usually experience severe environmental pollution problems.

In these situations passive sampling can be a viable alternative to large scale environmental monitoring, especially in situations where traditional active sampling techniques are limited by their high cost of operation and technical demands.

Recent literature has highlighted the possibilities of passive sampling to aid environmental risk assessment and pollution monitoring in resource-constrained environments (Hayes and Gagnon, 2024; Macias et al., 2023).

Nevertheless, there are a number of obstacles to its widespread use, such as:

- i. Deficiency in technical knowledge.
- ii. Poor access to calibration facilities.
- iii. Lack of standard procedures.



iv. Poor financing of environmental surveillance schemes.

To enhance the application of passive sampling in developing countries, there is a need for:

- i. Technical training and capacity building.
- ii. Low-cost calibration method development.
- iii. Collaboration and sharing of data internationally.
- iv. Integration of policies into the environmental monitoring systems.

Increased study in these areas will present imperative information to make informed decisions and manage the environment sustainably.

15.0 CONCLUSION AND FUTURE PERSPECTIVES

This review has critically analyzed passive sampling methods in analyzing environmental pollutants in different environmental media, such as air, water, soil and sediment systems. It also becomes clear that the principle of passive samplers operation is a coupled diffusion-sorption system, which allows the determination of the time-weighted average (TWA) concentrations of pollutants. Passive sampling is, therefore, an alternative strategy that is more affordable and reliable as compared to the traditional active sampling. The results of this review suggest that the functioning of passive samplers differs widely in various environmental conditions. Quantitative data indicates that the sampling rates may differ twofold with consideration to temperature, hydrodynamics, and biofouling. Also, the inter-laboratory variation can be up to about 30 and the error in the estimation of TWA can be up to 25 in complex field conditions. Such differences indicate the necessity of effective calibration processes and standard methodologies to enhance the reliability of data. Comparative evaluation of typically employed passive samplers, such as semipermeable membrane devices (SPMDs), polar organic chemical integrative samplers (POCIS), and diffusive gradients in thin films (DGT) indicates that no single device is applicable to all types of environmental pollutants in all environments. Physicochemical interactions between the sampler and the analyte control their performance to a great extent. In particular, SPMDs can be used to treat hydrophobic organic contaminants, POCIS can treat polar organic compounds, and DGT can treat metal species. Passive sampling devices have a number of operational benefits such as low cost, easy deployment and applicability to long-term monitoring. They are particularly useful in developing countries where traditional methods of monitoring might be constrained by financial and infrastructural factors. Nevertheless, they have some challenges that have to be resolved to improve their overall performance e.g. calibration uncertainties, environmental variability, limited selectivity and biofouling. These shortcomings emphasize the necessity of additional methodological enhancements and standardization in order to ensure accuracy, reproducibility and comparability among studies. Future studies ought to aim at development of superior and dynamically responsive calibration models, development of multi analyte and highly selective sorbent materials and incorporation of passive sampling with more sensitive analytical methodologies, including high resolution mass spectrometry. Moreover, to create region-specific data that can be used to make informed decisions in environmental management; there is a need to increase the use of passive sampling in unexplored areas and especially in developing nations. Passive sampling is currently being accepted as a useful instrument in monitoring the environment and has great potential to be a major instrument in the assessment of environmental pollution in the nearest future. The bioaccumulation and toxicity of polycyclic aromatic hydrocarbons (PAHs) in the environment and food system further highlight the importance of enhanced monitoring measures, especially in developing countries (Uzoekwe and Ikpesu, 2019; Umudi et al., 2025).

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Ethical Responsibilities of Authors

The authors declare that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. No human participants or animals were involved in this study. This article is based entirely on published literature and therefore did not require ethical approval or informed consent.

Author Contributions

Stanley E. Apuyor (S.E. Apuyor): Conceptualization, literature search, data curation, methodology development, analysis and interpretation of literature, manuscript drafting, visualization, and preparation of the original manuscript.

Samuel A. Uzoekwe (S.A. Uzoekwe): Supervision, conceptual guidance, critical review of the manuscript, validation of scientific content, and manuscript editing.

Kingsley E. Apuyor (K.E. Apuyor): Literature review, data organization, manuscript editing, reference management, and proofreading.

All authors contributed to the interpretation of the reviewed literature, reviewed and approved the final manuscript, and agreed to its submission for publication.

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