UJEAS

UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES

UNIZIK Journal of Engineering and Applied Sciences 6(4), December (2026), 3911-3928
Journal homepage: https://journals.unizik.edu.ng/index.php/ujeas
PRINT ISSN: 2992-4383 || ONLINE ISSN: 2992-4391

Volatile Organic Compound Emissions from Degrading Micro- and Nanoplastics: A Survey of the Unseen Footprint and Its Global Climate Feedbacks

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Abstract

The spread of microplastics (MPs; <5 mm) and nanoplastics (NPs; <1 μm) through land, sea, and air now ranks among the most stubborn environmental problems of the Anthropocene. Although the visible, physical side of plastic pollution is well documented, far less attention has been paid to the volatile organic compounds (VOCs) that plastics give off as they break down. This review pulls together what is currently known about how, how much, and with what climatic consequences VOCs escape from degrading micro- and nanoplastics. A structured search of the Scopus, Web of Science, ScienceDirect, and Google Scholar databases for literature published between 2015 and 2025 provided the evidence base. When plastics are exposed to sunlight, heat, mechanical wear, and microbes, polymer chains crack and oxidize, releasing a mixture of volatile compounds. Aromatic hydrocarbons benzene, toluene, ethylbenzene, xylenes (BTEX), styrene, and naphthalene dominate this mixture, and emission rates depend strongly on the polymer, the temperature, and the intensity of irradiation. Polystyrene gives off the most styrene monomer per unit area (up to 0.152 ng cm^{-2} hr^{-1} under UV), whereas polyvinyl chloride releases large amounts of chlorinated organics and plasticizer-derived compounds. Once airborne, these plastic-derived VOCs feed the formation of secondary organic aerosol (SOA), with mass yields of 30–45% for key aromatic precursors under low-NO_x conditions. The ecological stakes are high: marine organisms must cope simultaneously with ingested microplastics, leached additives, and VOC-driven toxicity, while contaminated soils show shifted microbial communities, higher greenhouse gas (N_2O, CH_4, CO_2) emissions, and weaker plant growth. Most importantly, the relationship runs both ways. A warmer climate speeds up plastic degradation, pushing VOC emission rates up exponentially (Q_{10} values of 2.1–3.4 for key compounds); those emissions then feed SOA formation and radiative forcing, which warms the climate further. The review closes by mapping the main knowledge gaps global VOC fluxes from plastic degradation remain unmeasured, nanoplastics are unstudied as SOA precursors, and Earth system models ignore plastic–climate interactions altogether and proposes a research agenda built around standardized emission protocols, long-term field observation, and coupled plastic–climate modelling.

Keywords: volatile organic compounds; microplastics; nanoplastics; emissions; secondary organic aerosol; climate change.

1. Introduction

Few materials capture the contradictions of the Anthropocene as sharply as plastic. The same durability that makes polymers indispensable in packaging, construction, and medicine also means that virtually every piece of plastic ever manufactured still exists somewhere on Earth (Zalasiewicz et al., 2016). Production has climbed relentlessly since the mid-twentieth century, reaching roughly 415 million metric tonnes in 2023, and cumulative output has passed 10 billion tonnes (Plastics Europe, 2024). Around three-quarters of all plastic ever made has already become waste, and a large share of that waste is slowly fragmenting in soils, rivers, oceans, and something researchers have only recently come to appreciate the atmosphere (Evangeliou et al., 2020; Geyer

et al., 2017). The smallest fragments, microplastics below 5 mm and nanoplastics below 1 μm, are no longer just a litter problem: they are a planetary-scale biogeochemical disturbance whose consequences for ecosystems and climate are still being worked out.

These particles come from two directions: primary sources such as deliberately manufactured microbeads, pellets, and fibres, and the secondary breakdown of larger debris through sunlight, abrasion, and biological attack (Andrady et al., 2024). Model studies suggest that anywhere between 0.013 and 25 million tonnes of micro- and nanoplastics move through the coupled ocean–atmosphere system each year, and atmospheric fallout carries them to places as remote as the Arctic, Antarctica, and high mountain ranges (Evangeliou et al., 2020). Fibres travel especially well: their mean atmospheric transport distances exceed those of equal-volume spheres by 157–394%, because they settle more slowly (Koehler et al., 2024). This airborne pathway matters for the present discussion because it spreads not only the particles themselves but also the volatile chemicals they release as they weather.

For Nigeria and the wider West African region, these are not distant abstractions. Nigeria generates an estimated 1.5–2.5 million tonnes of plastic waste every year, and collection systems capture only a small fraction of it; per-capita consumption is rising faster than waste infrastructure can follow, a pattern repeated across the region (Babayemi et al., 2019). West African states sit among the countries whose coastlines receive substantial land-based plastic leakage, much of it concentrated in the Gulf of Guinea (Jambeck et al., 2015). Tropical conditions make the problem worse: year-round temperatures of 25–35 °C and some of the most intense solar UV radiation on the planet accelerate exactly the photodegradation and thermal-oxidation processes that drive VOC release (Andrady et al., 2024). Open burning and informal dumping, still common waste practices in the region, add further emissions, while the Niger Delta and the lagoon systems of Lagos and Abidjan already carry heavy microplastic loads. Any honest assessment of plastic-derived VOCs and their climate effects must therefore reckon with West African environmental realities, and this review gives that regional context explicit attention.

Against this backdrop, the physical harms of microplastics ingestion by marine and terrestrial animals, movement across tissues, and build-up in food webs have attracted sustained scientific attention (Bucci et al., 2022). What has been comparatively overlooked is the chemical dimension: plastics are not inert solids. Ultraviolet radiation, heat, oxidants, and microbial enzymes cleave polymer chains and generate free radicals, and the end products of these reactions include VOCs that escape into air, water, and soil (Romera-Castillo et al., 2018). The emitted mixture contains greenhouse gases such as carbon dioxide and methane, but also hazardous aromatics benzene, toluene, ethylbenzene, xylenes, styrene, phenol, and naphthalene that are both toxic to living organisms and chemically active in the atmosphere (Wu et al., 2022).

Once these VOCs reach the air, they link plastic pollution directly to atmospheric chemistry and, through it, to climate. VOCs are precursors of secondary organic aerosol (SOA), ozone, and other photochemical oxidants, all of which perturb Earth's radiative balance either directly, by scattering and absorbing sunlight, or indirectly, by altering the number and properties of cloud droplets (Shrivastava et al., 2017). Aromatic hydrocarbons of the kind released from degrading plastics are efficient SOA precursors: chamber work reports mass yields of 30–45% under the low-NO_x conditions typical of marine and remote air (Schmitt, 2020). There is an additional twist. SOA can condense onto nanoplastic particles already suspended in the atmosphere, changing how readily those particles take up water and act as cloud condensation nuclei (CCN), so plastic-derived gases and plastic particles interact in ways that neither pollution stream would produce alone (Xu et al., 2024).

The interaction may be self-amplifying. Warming raises temperatures and, in many regions, increases the UV dose reaching plastic surfaces, and both effects speed up the photochemistry and thermal oxidation that break polymers down (He et al., 2024). Measured temperature sensitivities are steep: for key aromatic compounds, emission rates rise by factors of 2.1–3.4 for every 10 °C of warming (Beel et al., 2023). Faster degradation means more VOCs and more SOA, which means additional radiative forcing and further warming. At the same time, a warming, more energetic ocean resuspends microplastics from surface waters and sediments, enlarging the area over which degradation and emission occur (Koehler et al., 2024). This two-way coupling between plastic pollution and climate has only recently been recognized, and it remains almost entirely unquantified.

The ecological reach of plastic-derived VOCs spans every environmental compartment. In the ocean, organisms face microplastic ingestion, leached additives such as phthalates and bisphenol A, and degradation-derived VOCs all at once a multiple-stressor environment that affects phytoplankton photosynthesis, fish reproduction, and coral health (Li et al., 2024). On land, microplastic-contaminated soils show restructured microbial communities, altered nutrient cycling, rising greenhouse gas emissions, and reduced plant productivity (Chen et al., 2024). In the air, additional VOCs mean more ozone and more SOA, with consequences for respiratory health and crop yields (Monks et al., 2015).

The novelty of this review lies in treating VOC emissions from degrading micro- and nanoplastics not as a niche topic within polymer science but as a missing link between two of the defining environmental crises of our time—plastic pollution and climate change. Existing reviews have examined microplastics as physical pollutants, as carriers of adsorbed contaminants, or as sources of dissolved organic carbon; none, to our knowledge, has synthesized the volatile-chemistry dimension across polymer chemistry, atmospheric science,

marine biology, and soil ecology, nor framed it explicitly as a climate feedback. The review is also the first, as far as we are aware, to examine what this nexus implies for tropical regions in general and for West Africa in particular, where high temperature, intense UV, and weak waste infrastructure combine to maximize both emissions and vulnerability.

The gap in the literature that this study addresses can be stated plainly. Laboratory studies have measured VOC emissions from individual polymers under controlled conditions, but these scattered results have never been integrated into a coherent picture of mechanisms, magnitudes, and climatic consequences; field fluxes remain unmeasured; nanoplastics have not been considered as SOA carriers in this context; and no Earth system model includes plastic degradation as an emission source. The innovative contribution of the present work is therefore threefold: (i) it assembles, for the first time, a cross-disciplinary framework that connects polymer degradation chemistry to SOA formation, ecological damage, and radiative forcing; (ii) it articulates the plastic–VOC–climate positive feedback loop as an explicit, testable mechanism, with quantitative anchor points drawn from the most recent measurements; and (iii) it translates the synthesis into a prioritized research and policy agenda, including standardized emission protocols, field flux campaigns, coupled modelling, and integration of plastic–climate interactions into the emerging UN Plastics Treaty. Specifically, the review examines (i) the mechanistic pathways of VOC release under UV radiation, mechanical weathering, and microbial attack; (ii) the chemical identity of the emitted compounds, with emphasis on toxicologically significant aromatics and their SOA-forming potential; (iii) ecological impacts across marine and terrestrial biomes; (iv) the feedback mechanisms through which warming accelerates degradation and emission; and (v) research priorities for the coming decade. Figure 1 provides a conceptual overview of this framework.

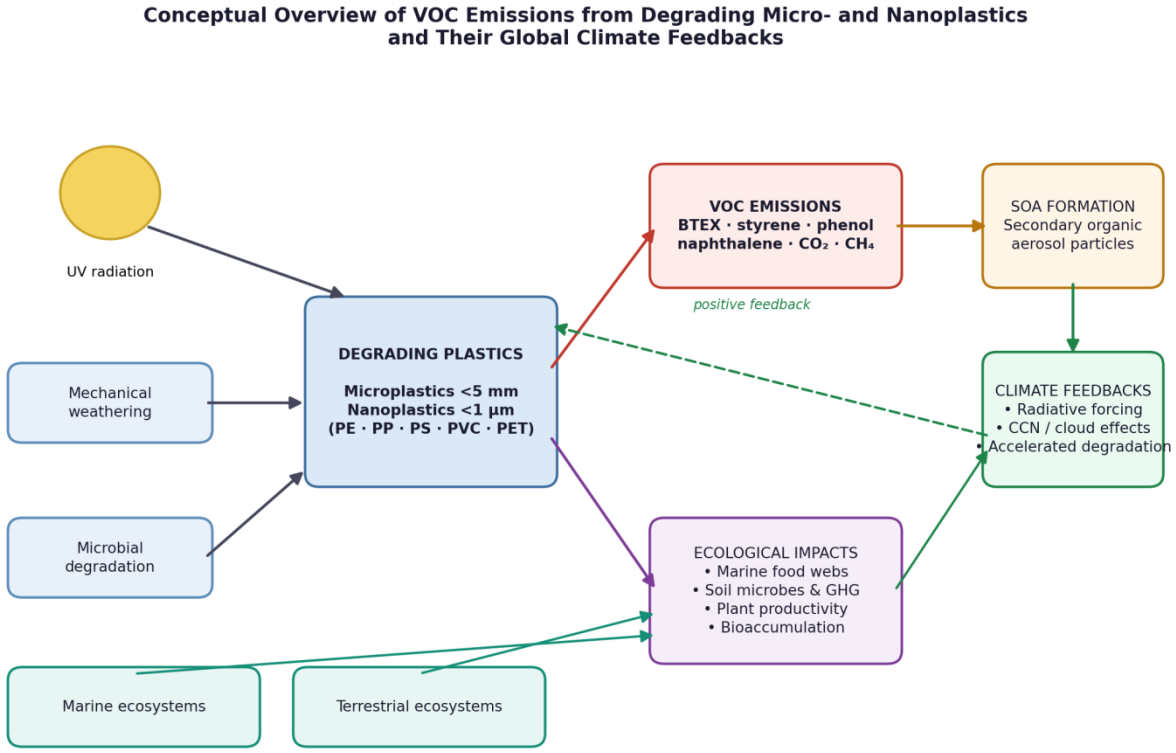


Figure 1.Conceptual overview of VOC emissions from degrading micro- and nanoplastics and their global climate feedbacks (Li et al., 2024; He et al., 2024). S

2.0 Literature Search Methodology

To make the evidence base of this review transparent and reproducible, a structured literature search was carried out between January and June 2025. Four electronic databases such as Scopus, Web of Science Core Collection, ScienceDirect, and Google Scholar were searched using combinations of the following keyword strings like microplastic or nanoplastic, volatile organic compound (VOC), plastic degradation and emission, plastic and secondary organic aerosol, microplastic and climate feedback and plastic waste and West Africa or Nigeria. Reference lists of all retrieved articles were also hand-searched for additional relevant studies (snowball sampling).

Studies were eligible for inclusion if they (i) were published in peer-reviewed journals or as academic theses or institutional reports between 2015 and 2025; (ii) reported primary measurements, modelling results, or substantive syntheses concerning plastic degradation, VOC or greenhouse gas emissions from plastics, SOA formation from plastic-derived precursors, or ecological impacts of microplastics and associated chemicals; and

(iii) were written in English. Conference abstracts, preprints without peer review, and publications earlier than 2015 were excluded, the latter in line with the journal's requirement that all cited literature be current. After removal of duplicates, the search returned 312 records; title and abstract screening excluded 214 records that did not meet the eligibility criteria, and full-text assessment of the remaining 98 records yielded the final body of literature synthesized here, supplemented by authoritative institutional reports (OECD, 2022; UNEP, 2023; UNCTAD, 2025; WHO, 2021). Screening and data extraction were performed independently by two authors, with disagreements resolved by discussion. Emission rates, toxicity classifications, and SOA yields reported below were extracted directly from the primary sources and are attributed in the text, in Table 1, and in the figure captions.

3.0 Mechanisms of VOC Release from Degrading Plastics

Three environmental stressors (sunlight, mechanical wear and microbial attack) do most of the work of dismantling plastics in the environment and each opens a distinct route to VOC release, as summarized in Figure 2. Additives and plasticizers, discussed in Section 3.4, contribute a fourth, overlapping source.

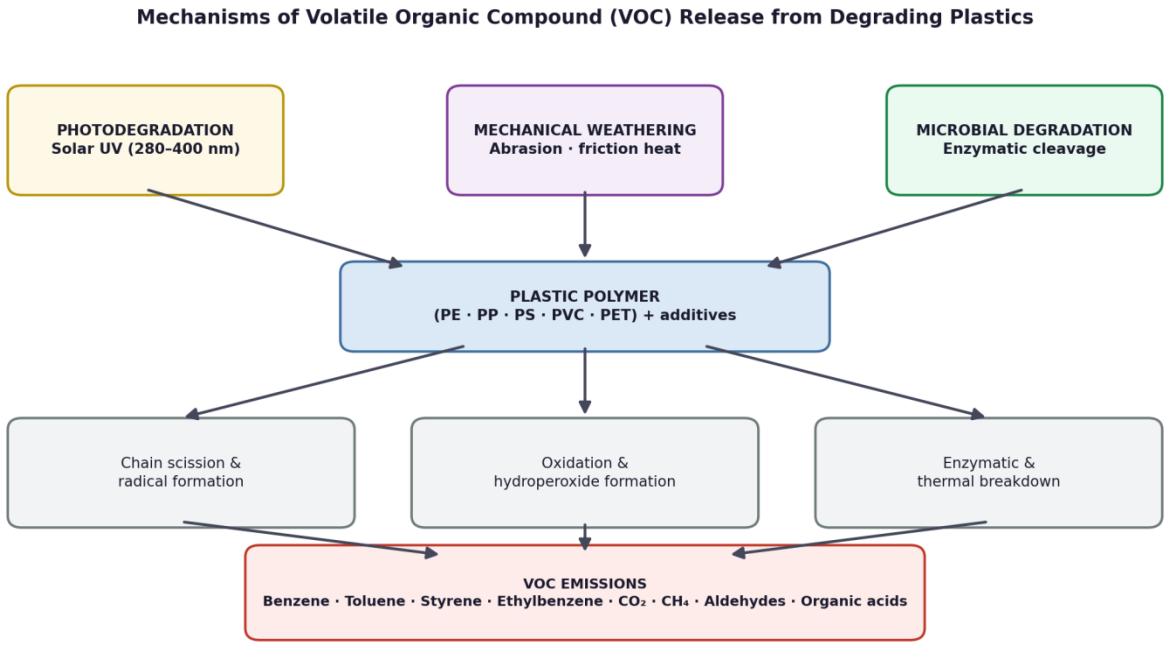


Figure 2. Mechanisms of volatile organic compound (VOC) release from degrading plastics. *Note.* Original diagram drawn by the authors, based on pathways described by Gewert et al. (2015) and Yoshida et al. (2016).

3.1 Photodegradation: The Primary Driver

Sunlight is the single most important driver of VOC release from plastics outdoors. Photons in the 280–400 nm UV band are absorbed by light-sensitive (chromophoric) groups in the polymer, the phenyl rings of polystyrene are a good example or by impurities and additives (Gewert et al., 2015). The absorbed energy breaks chemical bonds and generates free radicals, and from an engineering standpoint the process that follows is best understood as a self-sustaining oxidation chain, similar in logic to the oxidation cycles familiar from fuel and lubricant degradation in process equipment.

The chain has three stages, each with a practical consequence. In the initiation stage, UV photons produce polymer radicals (P•) and hydroperoxides; this is why even brief outdoor exposure can “seed” a plastic item for later damage. In the propagation stage, these radicals combine with oxygen to form peroxy radicals (POO•), which strip hydrogen from neighbouring chains and create fresh radicals, so the damage, once started, feeds on itself and spreads through the material rather than remaining at the point of impact. Hydroperoxides then decompose under continued UV into alkoxy (PO•) and hydroxyl (•OH) radicals, both of which cut polymer chains (Bianco & Passananti, 2020). In the termination stage, radicals recombine, cross-link, or disproportionate, which is why degraded plastics become brittle and crack. For engineers and waste managers, the key insight is that photodegradation is autocatalytic: exposure history matters as much as instantaneous conditions, and partially degraded stock can emit VOCs faster than new material even under identical sunlight.

The volatile end products depend on the polymer. Photo-oxidized polyethylene (PE) yields alkanes, alkenes, aldehydes, ketones, and carboxylic acids, with emission rates that climb with UV intensity and exposure time (Gewert et al., 2015). Polystyrene (PS), with its phenyl-bearing backbone, releases a characteristic aromatic

suite: styrene monomer, benzene, toluene, phenol, benzaldehyde, benzoic acid, and naphthalene (Wu et al., 2022). The radical chemistry behind this, tertiary polystyryl radicals reacting with oxygen to build hydroxyl, carbonyl, and carboxyl groups on the chain also provides a direct route from plastic photodegradation to greenhouse gas release, because terminal carboxyl groups react with •OH to give off CO_2 (Bianco & Passananti, 2020; Gewert et al., 2015).

Controlled laboratory studies have put numbers on these emissions. Beel et al. (2023) found that VOC emission rates from common household plastics rise exponentially with temperature, with Q_{10} values of 2.1–3.4 for key aromatic compounds. Under simulated sunlight (UVA: 3.5 mW/cm²), polystyrene showed the highest specific emission rate for styrene monomer (0.152 ng cm^{-2} hr^{-1}), followed by PVC for phenol (0.095 ng cm^{-2} hr^{-1}) and naphthalene (0.042 ng cm^{-2} hr^{-1}); polyethylene and polypropylene emitted lower but still measurable amounts of benzene, toluene, and naphthalene. These results confirm that photodegradation is not merely surface weathering it is an active source of atmospheric pollutants with quantifiable fluxes, and one that engineers must factor into the environmental assessment of plastic products over their full life cycle.

3.2 Mechanical Weathering and Thermal Degradation

Mechanical wear releases VOCs in two ways: friction generates local hot spots that thermally crack the polymer, and abrasion continually exposes fresh, reactive surface. Wind-blown sand, traffic on road surfaces, and tillage all supply this kind of stress (Kole et al., 2017). Tyre wear particles illustrate the scale of the issue: the friction between tread and road produces an estimated 0.1–5.9 million tonnes of particles globally each year (Kole et al., 2017), and these particles carry synthetic rubbers together with plasticizers, vulcanization agents, and fillers that can volatilize as the particles form (Li et al., 2020).

Heat alone becomes decisive wherever ambient or surface temperatures climb past a polymer's glass transition point think of asphalt in urban heat islands, composting plants, and, crucially for this review, tropical shorelines and open dumps where dark plastic surfaces in West Africa routinely exceed 50–60 °C in the dry season (Łomża et al., 2024). Above the glass transition, polymer segments move more freely, chains scission more easily, and volatile oligomers and monomers escape (Gewert et al., 2015). Measurements on tyre debris abraded at realistic road temperatures (30–60 °C) have detected benzene, toluene, xylenes, styrene, and 1,3-butadiene compounds of both toxicological and atmospheric concern (Li et al., 2020). In real environments, mechanical stress and heat act together, so their combined effect generally exceeds what either process would predict on its own.

Fragmentation amplifies all of this. As macroplastics break down into micro- and nanoplastics, the surface-area-to-volume ratio rises sharply, and with it the area available for photochemical and thermal attack. Royer et al. (2018) showed that virgin low-density polyethylene emitted greenhouse gases at rates that grew over 212-day incubation, reaching 5.8 nmol g^{-1} day^{-1} of methane and 14.5 nmol g^{-1} day^{-1} of ethylene. Notably, virgin plastics out-emitted aged ones, which suggests that the earliest degradation phase when surfaces are fresh and additives most concentrated constitutes a pulse emission event of particular significance for newly manufactured products entering the environment.

3.3 Microbial Degradation: Biochemical Pathways

Microbes dismantle plastics more slowly than sunlight does, but they contribute VOCs through enzymatic chain cleavage and the metabolism of the resulting fragments. Bacteria and fungi able to attack synthetic polymers have been recovered from marine sediments, landfill soils, and compost (Yuan et al., 2020). Their enzymes such as PET hydrolases (PETases), laccases, manganese peroxidases, and lipases will hydrolyse ester and amide bonds and release oligomers and monomers that enter ordinary metabolic pathways.

For hydrocarbon polymers (PE, PP, PS), microbial attack proceeds through oxidation of the backbone to alcohols, ketones, and carboxylic acids, ending in CO_2 and water where oxygen is available (Yuan et al., 2020). In the oxygen-free conditions of marine sediments and landfills, fermentation and methanogenesis instead add methane to the greenhouse gas footprint of plastic decay (Harrison et al., 2018). The discovery of the PETase of *Ideonella sakaiensis* showed that specific enzymatic breakdown of PET is possible at moderate temperatures (30 °C), yielding terephthalic acid and ethylene glycol (Yoshida et al., 2016). These monomers are less volatile than aromatic hydrocarbons, but they still move carbon out of the plastic and can be transformed biologically or photochemically into volatile products. Biofilms, which form readily on plastics in warm tropical waters such as those of the Gulf of Guinea, appear to concentrate and accelerate these processes.

3.4 Role of Additives and Plasticizers

Commercial plastics are rarely pure polymer. Additives and plasticizers tune material properties and can make up as much as 70% of the mass of flexible PVC (Bui et al., 2016). The most important families are phthalate esters (DEHP, DBP), bisphenol A (BPA), polybrominated diphenyl ethers (PBDEs), organotin stabilizers, and UV absorbers (Hahladakis et al., 2018). Many are semi-volatile at ordinary temperatures, so their escape from weathering plastic adds substantially to the overall VOC emission profile.

Phthalate plasticizers migrate out of PVC and other flexible plastics by diffusion, a process accelerated by heat and surface weathering. Measured DEHP emission rates from PVC rise from 0.01–0.1 μg m^{-2} h^{-1} at 20 °C

to 0.1–1.0 μg m^{-2} h^{-1} at 60 °C (Bui et al., 2016). The upper end of that range is directly relevant to tropical regions: plastic surfaces in West African cities regularly reach 50–60 °C under direct sun, so phthalate release there is likely to run near the top of measured rates for much of the year (Łomża et al., 2024). In landfills and marine settings, phthalate leaching from discarded plastics can push environmental concentrations past toxicity thresholds for sensitive organisms, and migration rates from microplastics climb steeply with temperature in a polymer- and phthalate-specific way (Łomża et al., 2024).

Additives also break down into further volatile products. Phthalate esters hydrolyse to phthalic acid and alcohols, and BPA oxidizes to phenol and substituted phenolics (Hahladakis et al., 2018). These daughter compounds are frequently more volatile and more toxic than their parents, so additive-derived emissions persist even after the initial additive reservoir is depleted. The result is a chemically complex emission mixture—polymer-derived and additive-derived VOCs together whose combined toxicity may exceed what single-compound assessments would predict.

4.0 Characterization of VOC Emissions from Degrading Plastics

4.1 Major VOC Classes and Emission Profiles

The VOCs given off by degrading plastics span a wide range of chemical classes, molecular weights, and volatilities, mirroring the diversity of polymer chemistries and breakdown routes. Proton-transfer-reaction mass spectrometry (PTR-MS), gas chromatography–mass spectrometry (GC-MS), and thermal desorption analysis have identified aromatic hydrocarbons, aliphatic hydrocarbons, oxygenated organics (aldehydes, ketones, alcohols, carboxylic acids), halogenated compounds, and organosulfur species among the products (Beel et al., 2023). Each polymer leaves a distinct VOC fingerprint polystyrene, PVC, and polyethylene are easy to tell apart—which opens the door to using emission profiles as diagnostic tracers for source attribution.

Aromatic hydrocarbons are the class of greatest atmospheric and toxicological significance. Polystyrene's phenyl-bearing backbone produces BTEX, styrene, phenol, cresols, naphthalene, and substituted naphthalenes through radical chain scission and rearrangement (Wu et al., 2022). In •OH-mediated degradation of polystyrene nanoplastics, benzene signals rose to more than 350% of their initial values within 24 hours of irradiation, while phenol rose by 40% before declining through further oxidation (Bianco & Passananti, 2020). Styrene monomer—the signature of polystyrene breakdown reaches emission rates up to 0.152 ng cm^{-2} hr^{-1} under UV, making it a plausible atmospheric tracer of polystyrene degradation sources (Beel et al., 2023).

Polyethylene and polypropylene, the world's most-produced plastics, mainly yield aliphatic products alkanes, alkenes, and α,ω-dicarboxylic acids from photo-oxidative chain scission (Gewert et al., 2015). Even so, benzene, toluene, and naphthalene also appear, most likely from aromatic impurities in the feedstock or from antioxidant additives (Palmisani et al., 2020). PVC degradation has its own signature, dominated by hydrogen chloride, chlorinated organics, and plasticizer-derived compounds, alongside phenol from the antioxidants used in PVC formulations (Łomża et al., 2024).

Emission profiles depend on environmental conditions as much as on polymer identity. Temperature exerts an especially strong, Arrhenius-type influence: warming HDPE from 18 °C to 28 °C multiplied benzene emissions by 3.2, toluene by 2.8, and styrene by 3.5, corresponding to apparent activation energies of 55–75 kJ mol^{-1} (Beel et al., 2023). UV intensity matters too; sunlit plastics emit at rates 1.2–8.2 times higher than temperature-matched dark controls, depending on the compound and polymer. These dependencies are precisely why tropical and subtropical regions—with high temperatures and intense insolation—can be expected to show per-unit-mass emission rates well above temperate-zone values, a point developed further in Sections 6.4 and 7.

4.2 Toxicologically Significant Compounds

Several plastic-derived VOCs warrant particular concern because they are carcinogenic, mutagenic, or endocrine-disrupting. Benzene, a confirmed human carcinogen (IARC Group 1), is emitted by all major polymer types during degradation at measured rates of 0.003–0.045 ng cm^{-2} hr^{-1} (Beel et al., 2023). The World Health Organization maintains that no exposure level for benzene is without risk, and concentrations as low as 0.17 μg m^{-3} are associated with an excess lifetime cancer risk of one in a million (WHO, 2021). Benzene released from environmental plastic degradation therefore constitutes a chronic, low-level exposure source whose cumulative health effects cannot be dismissed.

Styrene, the signature monomer of polystyrene degradation, has been classified by the International Agency for Research on Cancer as probably carcinogenic to humans (Group 2A), an upgrade from its earlier Group 2B classification, and shows neurotoxicity at occupational exposure levels (IARC, 2019). Its release from polystyrene microplastics creates exposure pathways for wildlife and people alike, through inhalation and diet. Studies of polystyrene nanoplastics in UV/NaClO and UV/PMS advanced oxidation systems identified styrene as a major degradation intermediate, formed by hydrogen abstraction from the backbone followed by β-scission (Li et al., 2023). Subsequent oxidation converts styrene to benzoic acid and ring-opened products small carboxylic acids and ultimately CO_2 a degradation cascade with several toxic intermediates along the way.

Naphthalene and substituted polycyclic aromatic hydrocarbons are emitted from degrading PE, PP, and PS, with the highest rates from PVC and HDPE formulations containing naphthalene-derived additives (Beel et al.,

2023). Naphthalene is a possible human carcinogen (IARC Group 2B) and is toxic to aquatic organisms at μg L^{-1} concentrations (IARC, 2019). Its formation during degradation of even aliphatic polymers through cyclization and aromatization of unsaturated breakdown products shows that secondary reaction pathways can generate aromatic VOCs where none existed in the parent material.

Additive-derived compounds add a further dimension of toxicity. The phthalate plasticizers DEHP and DBP are established endocrine disruptors with documented effects on reproductive development in wildlife and humans (Gore et al., 2015). Bisphenol A, used in polycarbonate plastics and epoxy resins, mimics estrogen and has been detected in marine microplastics at concentrations up to 0.1 μg g^{-1} (Hahladakis et al., 2018). Organisms and ecosystems thus face a combined exposure to polymer-derived VOCs, additive leachates, and the particles themselves a mixture whose additive or synergistic effects are not captured by single-compound toxicity testing.

4.3 Quantitative Summary of Key Plastic-Derived VOCs

Table 1 consolidates the key VOCs identified across the reviewed studies, their primary polymer sources, measured emission rates, toxicity classifications, atmospheric lifetimes, and SOA yields.

Table 1: Key Volatile Organic Compounds Emitted from Degrading Plastics: Properties, Emission Rates, and Toxicological Significance

Compound	Primary source polymer	Typical emission rate (ng cm^{-2} hr^{-1})	Toxicity classification	Atmospheric lifetime (days)	SOA yield (%)
Benzene	PS, PE, PP, PVC	0.003–0.045	IARC Group 1 (carcinogen)	9–12	30–37
Toluene	PS, PE, PP	0.002–0.038	CNS depressant	2–4	10–30
Styrene	PS	0.015–0.152	IARC Group 2A (probable carcinogen)	0.5–2	15–42
Phenol	PVC, PS	0.004–0.095	Acute toxicity	0.5–1	8–28
Naphthalene	PE, PVC, PS	0.006–0.042	IARC Group 2B	0.5–1	18–45
Ethylbenzene	PS, PE	0.001–0.015	IARC Group 2B	1–2	20–35
CO_2	All polymers	1.5–22.1[a]	Greenhouse gas	>100 yrs	N/A
CH_4	All polymers	0.5–9.4[a]	Greenhouse gas	9–12 yrs	N/A

Note: SOA = secondary organic aerosol; CNS = central nervous system; PS = polystyrene; PE = polyethylene; PP = polypropylene; PVC = polyvinyl chloride; HDPE = high-density polyethylene. [a] Emission rates for CO_2 and CH_4 are expressed in nmol g^{-1} day^{-1}. Emission rate data are from Beel et al. (2023); greenhouse gas data are from Royer et al. (2018); SOA yields are from Schmitt (2020) and Shrivastava et al. (2017); toxicity classifications are from IARC (2019) and WHO (2021).

5.0 Secondary Organic Aerosol Formation from Plastic-Derived VOCs

5.1 Atmospheric Oxidation Chemistry

Once plastic-derived VOCs enter the atmospheric boundary layer, they are attacked by hydroxyl radicals (•OH), ozone (O_3), and nitrate radicals (NO_3•), setting off reaction cascades that can end in secondary organic aerosol (SOA). For the aromatic hydrocarbons that dominate plastic emissions benzene, toluene, xylenes, and styrene the chemistry begins with •OH adding to the aromatic ring, followed by O_2 addition to form bicyclic peroxy radicals (Shrivastava et al., 2017). What happens next hinges on the concentration of nitrogen oxides (NO_x), which controls the volatility, and hence the aerosol-forming potential, of the oxidation products.

In the low-NO_x air typical of remote marine and rural regions, peroxy radicals (RO_2•) react mainly with hydroperoxy radicals (HO_2•) to form hydroperoxides and carbonyl compounds of low volatility that condense readily onto particles. In the high-NO_x air of cities and industrial zones, RO_2• + NO reactions instead yield more volatile organic nitrates and carbonyls, and SOA yields fall. Chamber measurements quantify the contrast: toluene gives SOA yields of about 30% at low NO_x but only ~10% at high NO_x; m-xylene gives 36% and 10%; benzene, 37% and 12% (Schmitt, 2020). Styrene, the characteristic polystyrene degradation product, yields up to 42% under low-NO_x conditions an unusually efficient SOA precursor (see Table 1 and Figure 3).

SOA formation does not stop with the first generation of products. Continued oxidation—"aging"—raises the oxygen-to-carbon ratio of the aerosol and drives it from semi-volatile towards effectively non-volatile states over hours to days, substantially increasing the total aerosol mass (Shrivastava et al., 2017). Because plastic-derived aromatics are emitted mainly in source-rich coastal and urban areas and then transported into lower-NO_x air, this aging may lift the ultimate SOA yield well above what single-generation chamber studies suggest.

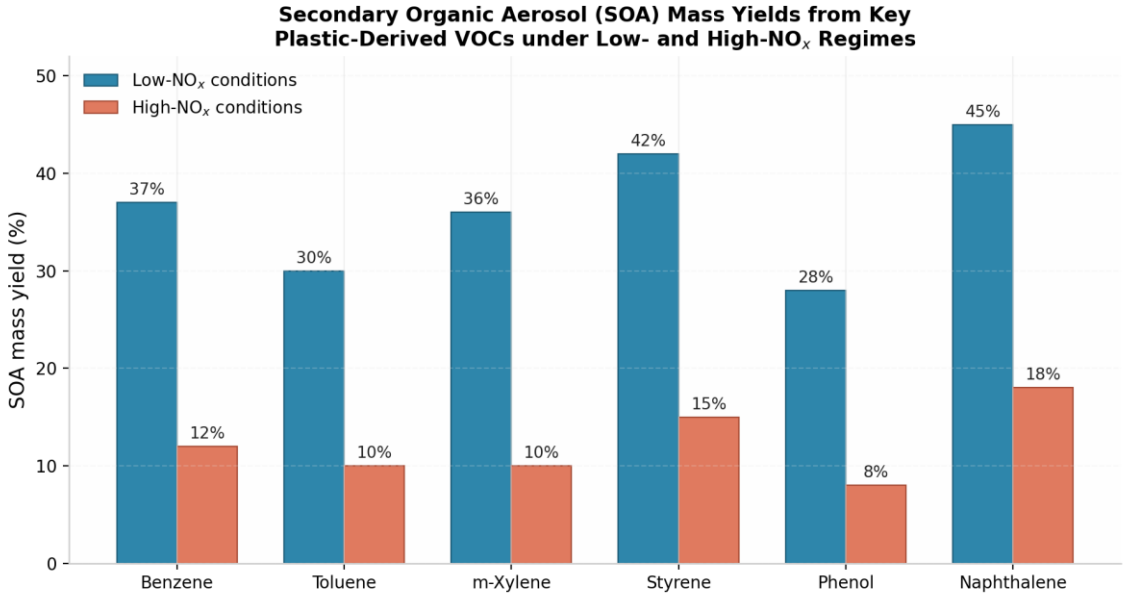


Figure 3. Secondary organic aerosol (SOA) mass yields from key plastic-derived volatile organic compounds under low-NO_x and high-NO_x conditions. *Note.* Original figure plotted by the authors from yield data reported by Schmitt (2020) and Shrivastava et al. (2017).

5.2 Nanoplastics as SOA Carriers and Cloud Condensation Nuclei

A newer strand of research concerns what happens when SOA meets nanoplastics in the air. Nanoplastic particles (<1 μm) have been detected in atmospheric samples over land and ocean and can travel long distances to remote regions (Xu et al., 2024). Bare nanoplastics are hydrophobic and cannot act as cloud condensation nuclei (CCN), but atmospheric aging can coat them with hygroscopic material—and that changes their climate relevance entirely.

Laboratory work shows that SOA from α-pinene ozonolysis condenses onto polystyrene nanoplastics to form internally mixed particles (Xu et al., 2024). At low coating volumes the SOA covers only part of the plastic surface (a partially engulfed morphology). On humidification, the coating takes up water, softens, and flows around the nanoplastic core, producing a more spherical, more hygroscopic particle. The measured hygroscopicity parameter (κ = 0.02) means that SOA-coated nanoplastics can serve as CCN at realistic supersaturations, whereas the uncoated particles cannot.

The climate implication is direct: SOA formed from plastic-derived aromatic VOCs can coat nanoplastic particles, switch on their CCN activity, and thereby influence cloud droplet numbers and cloud brightness. How large this effect is depends on the relative fluxes of plastic-derived VOCs (which set SOA production) and atmospheric nanoplastics (which provide condensation surface). Both are expected to grow with rising plastic production and a warming climate, so this plastic–SOA–CCN pathway—absent from every current climate model—may represent a growing contribution to aerosol–cloud interactions.

5.3 Comparison with Biogenic and Fossil VOC Sources

How much do plastic-derived VOCs matter in the global budget? Total global VOC emissions are estimated at roughly 1,000–2,000 Tg C yr^{-1}, of which vegetation (isoprene and monoterpenes above all) supplies about 90%, with the remainder from fossil fuel combustion, industry, and solvent use (Sindelarova et al., 2022). Anthropogenic aromatic hydrocarbon emissions are put at 20–40 Tg C yr^{-1}, dominated by toluene, benzene, and xylenes.

No global estimate yet exists for plastic degradation. A first-order calculation—combining an ocean plastic stock of 150–300 million tonnes, typical aromatic VOC emission rates of 0.01–0.1 ng g^{-1} hr^{-1}, and the fraction of plastic exposed to degrading conditions suggests plastic-derived aromatic fluxes of roughly 0.01–0.1 Tg C yr^{-1}. That is below 1% of anthropogenic aromatic emissions, but four considerations argue against dismissing it: environmental plastic stocks are growing exponentially; pollution concentrates in coastal zones of high photochemical activity; plastics co-emit highly reactive, high-yield species such as styrene; and some plastic-derived compounds (chlorinated organics, additive derivatives) have no other significant source.

Plastic-derived VOCs also carry a chemical signature notably a high styrene-to-toluene ratio that could serve as a tracer to separate plastic sources from fossil fuel combustion in atmospheric observations. Deploying advanced mass spectrometry (PTR-ToF-MS, iodide-CIMS) at plastic-polluted coastal sites, including in the Gulf of Guinea, would allow direct measurement of these fluxes and their contribution to regional SOA formation.

6.0 Ecological Impacts of Plastic-Derived VOCs and Microplastics

6.1 Marine Ecosystems: Multiple Stressor Effects

Marine life now faces plastic pollution on several fronts at once: physical ingestion of microplastics, exposure to leached additives, and toxicity from degradation-derived VOCs. These stressors interact, and the combined effect can exceed the sum of the parts particles cause physical injury and ferry contaminants, while VOCs and additives act as chemical stressors (Li et al., 2024). Figure 4 summarizes the impacts across the marine, terrestrial, and atmospheric compartments discussed in this section.

Phytoplankton—the base of marine food webs and a pillar of the global carbon cycle are sensitive to both microplastic particles and the chemicals they carry. Polystyrene microplastics at environmentally relevant concentrations (1–100 μg L^{-1}) inhibit photosynthesis in diatoms and dinoflagellates, through a combination of shading and release of styrene monomer and other VOCs (Shen et al., 2024). Even a 10% reduction in phytoplankton productivity across the global ocean could weaken the biological carbon pump by 0.1–0.5 Gt C yr^{-1}—a climate feedback in its own right (Koehler & Sandow, 2020).

Fish and higher predators take up microplastics by ingestion and, in some cases, across biological membranes. Beyond gut blockage and false satiation, chemical exposure from microplastics includes leached additives and degradation-derived VOCs. Fish exposed to polystyrene microplastics show liver and intestinal lesions, altered immune function, oxidative stress, and reduced acetylcholinesterase activity, a marker of neurotoxicity (Bucci et al., 2022). The specific share attributable to VOCs, as distinct from additives or physical effects, still needs to be isolated, but the demonstrated toxicity of benzene, styrene, and other plastic-derived aromatics to fish at μg L^{-1} concentrations makes VOC-mediated effects biologically plausible.

Coral reefs, already pressed by warming and acidification, face additional stress from microplastic accumulation and its chemical cargo. Microplastic exposure increases bleaching susceptibility and depresses calcification, and the effects worsen at elevated temperature (Shen et al., 2024). VOCs released from plastics lodged on reef surfaces—including naphthalene and substituted aromatics may add to coral stress through direct toxicity and by encouraging microbial biofilms that compete with coral symbionts.

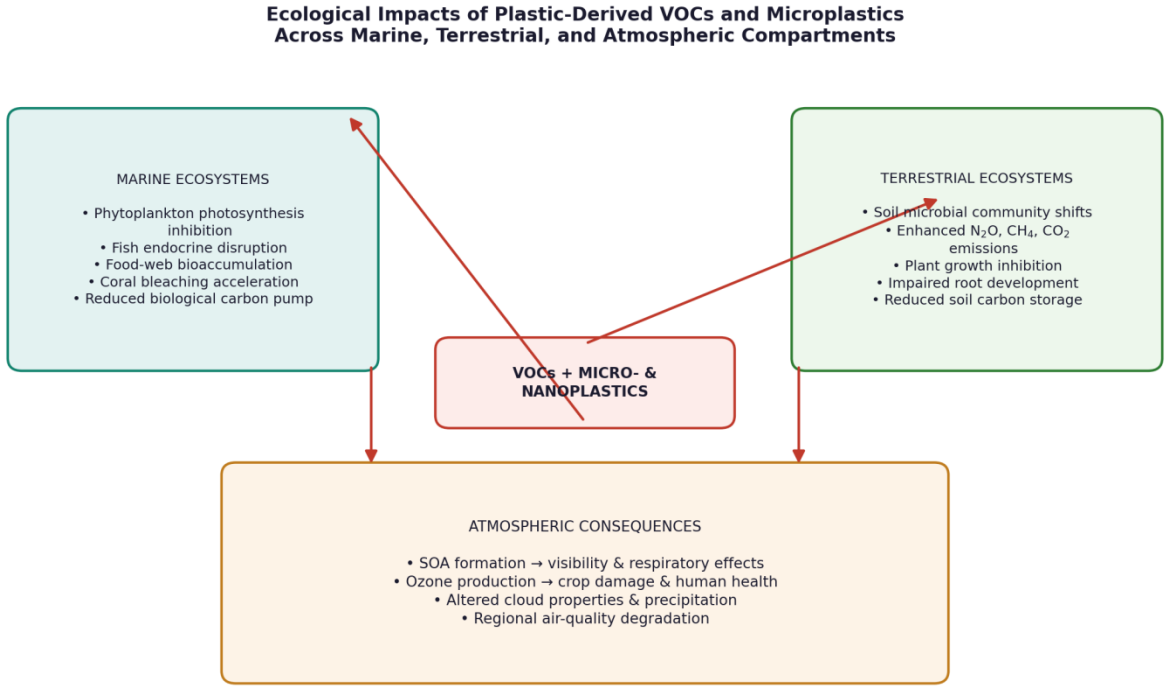


Figure 4. Ecological impacts of plastic-derived volatile organic compounds (VOCs) and microplastics across marine, terrestrial, and atmospheric compartments (Li et al.,2024; Shen et al., 2024; Chen et al.,2024).

6.2 Terrestrial Ecosystems: Soil Biogeochemistry

Soils are both a major sink for microplastics and a critical interface for VOC interactions. Agricultural land receives microplastics through sewage sludge application (up to 300,000 particles kg^{-1} dry weight), fragmentation of mulch films, contaminated compost, and atmospheric fallout (Rillig, 2018). Once in the soil, these particles interact with microbial communities, nutrient cycling, and plant roots, with knock-on effects for soil biogeochemistry and greenhouse gas emissions.

Adding microplastics to soil measurably restructures microbial communities and raises greenhouse gas output. Chen et al. (2024) found that five common polymer types (PVC, PP, PE, PS, PET) at concentrations of

0.25–7% (w/w) all promoted emissions of N_2O, CO_2, and CH_4 from farmland soil; polyethylene contributed most to warming potential, with emissions tracking microbial biomass (total phospholipid fatty acid content). The mechanism runs through soil physics: microplastics alter porosity and water retention, creating oxygen-poor microsites that favour denitrification (N_2O) and methanogenesis (CH_4).

The VOCs released within soil—benzene, toluene, and styrene among them—can themselves reshape microbial communities, acting both as toxins and as substrates. Aromatic hydrocarbons above about 1 mg kg^{-1} soil reduce microbial diversity and shift communities towards hydrocarbon-degrading taxa (Pseudomonas, Burkholderia, Rhodococcus), with potential consequences for nitrogen fixation and phosphorus mineralization (Rillig, 2018). Such selective enrichment may also change soil carbon storage dynamics, weakening the soil carbon sink.

Plant outcomes in contaminated soils vary with polymer, particle size, and accompanying stressors. Particles below 10 μm can enter root tissues and move to shoots (Li et al., 2020), and exposure triggers oxidative stress, impairs photosynthesis, and alters growth- and defence-related gene expression (Li et al., 2024). Co-released VOCs likely aggravate these effects: benzene and toluene are phytotoxic, damaging cell membranes and inhibiting root elongation at mg L^{-1} concentrations. Because reduced plant productivity means reduced CO_2 uptake, contamination of agricultural soils erodes an important terrestrial carbon sink.

6.3 Case Study: The Great Pacific Garbage Patch as a VOC Source

The Great Pacific Garbage Patch (GPGP), between Hawaii and California, is the largest ocean plastic accumulation on Earth: roughly 80,000 tonnes of floating debris spread over more than 1.6 million km^2 (Lebreton et al., 2018). Its physical toll on wildlife—entanglement and ingestion by seabirds, turtles, and marine mammals is well known; the chemical emissions from its degrading plastics are not.

Conditions in the GPGP are close to ideal for photodegradation: high UV (annual average UV index 8–12), warm surface waters (22–28 °C), and constant wave action. Debris recovered there shows advanced photo-oxidation—elevated carbonyl indices and reduced molecular weight relative to pristine polymer (Lebreton et al., 2018)—and this weathering feeds a continuous supply of BTEX, styrene, and greenhouse gases to the marine boundary layer.

Combining available emission rates with the estimated plastic inventory yields a first-order flux of 0.1–1.0 tonnes of aromatic hydrocarbons per year from the GPGP alone. Modest beside regional anthropogenic sources, this flux is nonetheless continuous (emission proceeds around the clock under daylight), occurs in an otherwise clean region, and is co-emitted with microplastic particles that can act as condensation nuclei for the resulting SOA. The aerosol so formed may influence cloud properties and radiative forcing across the North Pacific subtropical gyre.

6.4 Tropical and West African Perspectives

Much of the experimental evidence reviewed above comes from temperate-zone laboratories and field sites, but the mechanisms it documents are strongly temperature- and UV-dependent—and that has direct consequences for tropical regions. Along the West African coast, air temperatures of 25–35 °C, sea surface temperatures of 26–29 °C, and UV indices that routinely reach 11 or more create degradation conditions far more aggressive than those of the mid-latitude sites where most measurements have been made (Andrady et al., 2024). Applying the Q_{10} values reported by Beel et al. (2023), a plastic item weathering at 32 °C rather than 22 °C would be expected to emit aromatic VOCs roughly two to three times faster; where dark surfaces heat to 50 °C or more as open dumps and roadside accumulations in Lagos, Port Harcourt, or Accra routinely do rates could be an order of magnitude higher.

Nigeria illustrates the stakes. The country generates well over a million tonnes of plastic waste annually, recycles only a small share, and relies heavily on open dumping and burning, so large standing stocks of plastic weather for years under tropical sun (Babayemi et al., 2019). Nigeria is also among the countries contributing substantial land-based plastic leakage to the ocean, much of it reaching the Gulf of Guinea (Jambeck et al., 2015). Mangrove creeks of the Niger Delta, lagoon systems around Lagos, and heavily used fishing grounds therefore combine high microplastic loads with the warm, high-UV conditions that maximize VOC and additive release—while the coastal communities depending on these ecosystems are among the most exposed and least resourced to adapt (UNEP, 2023). Tropical agricultural soils add another pathway: plastic mulch residues and sludge-borne microplastics weather rapidly under tropical temperatures, and the resulting shifts in soil microbial communities and greenhouse gas emissions documented by Chen et al. (2024) are likely to be amplified where soil temperatures are higher year-round. Regional monitoring of plastic-derived VOCs and targeted waste-management investment in West Africa are therefore priorities in their own right, not footnotes to a temperate-zone literature.

7.0 The Plastic–VOC–Climate Positive Feedback Loop

7.1 Temperature-Dependent Degradation Kinetics

Chemical reaction rates follow the Arrhenius equation, so plastic degradation accelerates exponentially with temperature. For polymer photo-oxidation, apparent activation energies of 50–80 kJ mol^{-1} mean that rates roughly double for every 10–15 °C of warming (Beel et al., 2023). Under projected warming of 1.5–4.5 °C by 2100, temperature sensitivity alone implies VOC emission increases of 15–50% from the existing environmental plastic stock.

Beel et al. (2023) measured VOC emissions from common household plastics between 18 °C and 28 °C and found Q_{10} values of 2.1 for benzene from HDPE, 2.8 for toluene from HDPE, and 3.4 for styrene from polystyrene (Figure 5). These exceed the Q_{10} of about 2 often assumed for generic chemical reactions, so warming may act on plastic VOC emissions with disproportionate force. The higher values for aromatics reflect the greater activation energies of the bond-cleavage and rearrangement steps needed to free aromatic rings from polymer backbones.

Urban heat islands intensify the effect. City surfaces asphalt, concrete, dark plastics run 2–8 °C hotter than surrounding countryside (Santamouris, 2020), so the plastics embedded in buildings, street furniture, vehicles, and infrastructure degrade faster and emit more than identical items in rural settings. In rapidly growing tropical cities such as Lagos, Kano, and Accra, heat island effects stack on top of an already warm baseline, creating localized hotspots of plastic-derived VOC emissions that degrade urban air quality while feeding an unaccounted source of SOA precursors into some of the world's most densely populated airsheds.

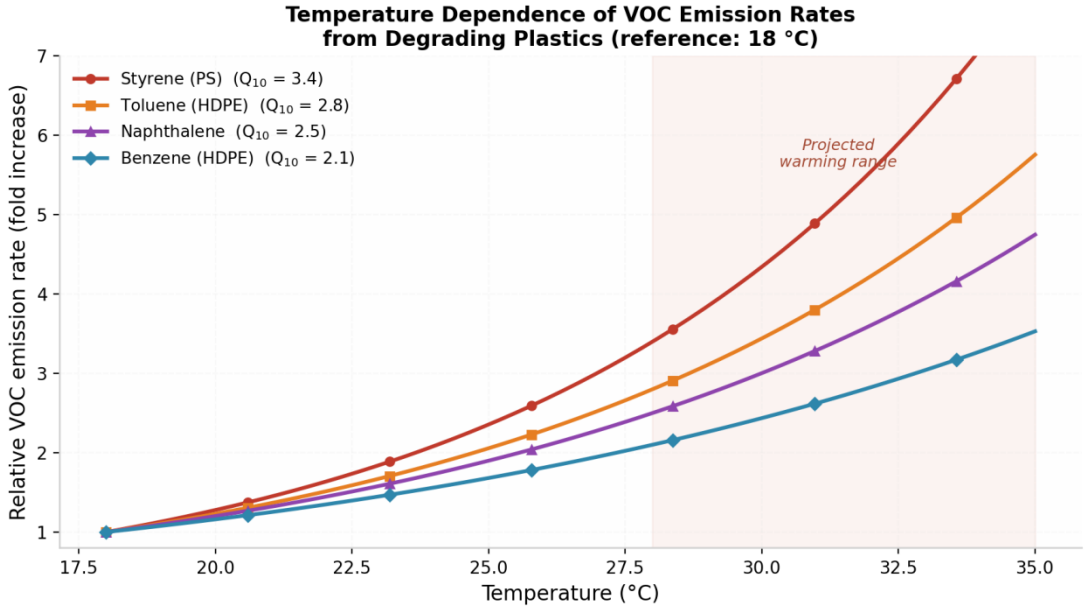


Figure 5. Temperature dependence of volatile organic compound (VOC) emission rates from degrading plastics, referenced to 18 °C, for Q_{10} values. The shaded band indicates the projected warming range (Beel et al., 2023).

7.2 UV Radiation Intensification

Climate change alters the UV radiation reaching Earth's surface through changes in stratospheric ozone, cloud cover, and aerosol loading. The Montreal Protocol has curbed stratospheric ozone loss, but continued warming may shift UV penetration through changes in cloud optical properties and tropospheric ozone (Andrady et al., 2024). In polar regions—where microplastic contamination is rising quickly through long-range atmospheric transport—even modest UV changes could markedly affect photodegradation of deposited plastics.

Temperature and UV act synergistically. Warmer polymer matrices allow faster diffusion of oxygen and reactive species, which raises the efficiency of photo-oxidation. Experiments on polystyrene microplastics show that combined UV exposure and elevated temperature produce larger changes in physicochemical properties and higher VOC emission rates than either stressor alone (He et al., 2024). The combined influence of warming and UV change will therefore exceed the sum of its parts, tightening the plastic–climate feedback loop.

The UNEP Environmental Effects Assessment Panel has flagged the interconnections among UV radiation, climate change, and plastic pollution as an emerging research priority (Andrady et al., 2024). Climate-driven shifts in rainfall affect wet deposition and the surface moisture that controls hydrolytic degradation, while changing wind patterns alter the transport and atmospheric residence time of both microplastic particles and their volatile products. Unravelling these multi-factor interactions calls for modelling that couples atmospheric chemistry, climate dynamics, and polymer degradation.

7.3 Greenhouse Gas Emissions from Plastic Degradation

Beyond VOCs, degrading plastics release the greenhouse gases CO_2 and CH_4 directly. Royer et al. (2018) made the first such measurements under natural conditions, exposing virgin and aged PE, PP, and PS to ambient sunlight in marine and terrestrial settings; all polymers produced measurable methane and ethylene, with virgin material emitting at rising rates over the 212-day incubation (Figure 6).

The measured rates were appreciable: LDPE emitted 5.8 nmol g^{-1} day^{-1} of methane and 14.5 nmol g^{-1} day^{-1} of ethylene; HDPE, 3.2 and 8.3; PP, 4.1 and 11.2; PS, 2.8 and 7.6 nmol g^{-1} day^{-1}, respectively (Royer et al., 2018). PVC showed the highest methane and CO_2 emissions (9.4 and 22.1 nmol g^{-1} day^{-1}), consistent with its heavy additive loading and lower polymer stability. Scaled to the estimated 150 million tonnes of plastic afloat in the global ocean, these rates imply an annual methane flux of 0.01–0.1 Tg CH_4 comparable to other minor marine methane sources.

Particle morphology matters here as well. As plastics fragment, rising surface-area-to-volume ratios expose ever more polymer to degrading conditions, so a given mass of plastic releases progressively more greenhouse gas as weathering advances (Royer et al., 2018). This creates a compounding cycle nested inside the larger feedback: warming accelerates fragmentation, fragmentation increases surface area, and increased surface area raises emission rates.

Plastic-derived greenhouse gases remain a small share of the global budget about 0.01% of anthropogenic CH_4 but the contribution grows with the environmental plastic stock and is unusually persistent: plastics already in the environment will keep emitting for decades to centuries, a legacy source that outlives the products themselves. Including these emissions in lifecycle assessments and carbon accounting would give a more honest picture of the climate cost of plastic consumption.

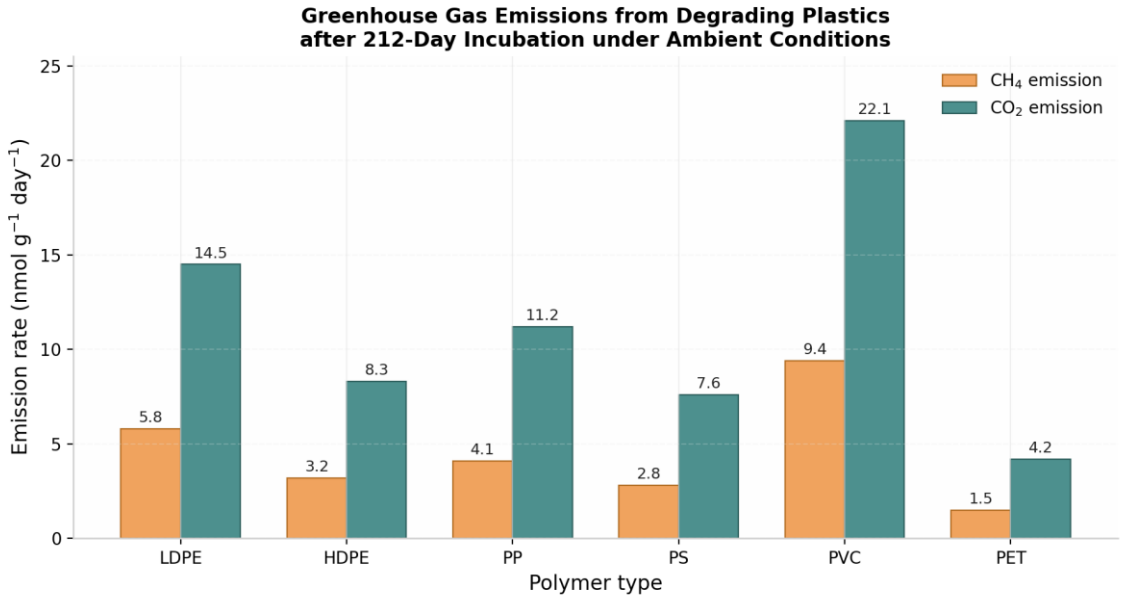


Figure 6. Greenhouse gas emissions from degrading plastics after 212-day incubation under ambient conditions (Royer et al., 2018).

7.4 The Complete Feedback Loop: Conceptual Framework

Figure 7 assembles the pieces of this section into a single positive feedback loop linking plastic pollution, VOC emissions, and climate change. The loop starts with warming driven mainly by fossil fuel combustion, but with a growing contribution from plastic production, use, and degradation. Warming raises temperatures and UV intensity, which accelerate photodegradation, thermal oxidation, and microbial decomposition. Those processes release VOCs (aromatic hydrocarbons, aldehydes, organic acids) together with CO_2 and CH_4.

The VOCs oxidize in the atmosphere to form SOA, which forces climate directly, by scattering and absorbing sunlight, and indirectly, by modifying clouds. Where SOA condenses onto nanoplastics it activates their CCN behaviour, with possible effects on cloud droplet numbers and brightness; the greenhouse gases warm the planet directly, closing the loop. The net radiative outcome depends on the balance of direct and indirect effects and on where the SOA forms.

Several additional pathways reinforce the loop. Ocean warming resuspends microplastics from sediments and promotes their aerosolization through bubble bursting and wave breaking, raising the atmospheric burden of particles and VOCs alike (Koehler et al., 2024). Carbon sequestration by phytoplankton and terrestrial vegetation weakens under microplastic and VOC stress, leaving more CO_2 in the air. Shifting precipitation patterns alter both the wet deposition of microplastics and the moisture regimes that govern terrestrial degradation.

The loop's magnitude is not yet quantified, but first-order estimates suggest regional significance. In heavily polluted coastal zones East Asia, the Mediterranean, the Caribbean, and increasingly the Gulf of Guinea the combined forcing from plastic-derived SOA and greenhouse gases may reach 0.01–0.1 W m^{-2}, comparable to other minor forcing agents. That is small beside total anthropogenic forcing (~2.7 W m^{-2}), but with production projected to reach 650 million tonnes by 2040, the contribution will grow substantially without intervention.

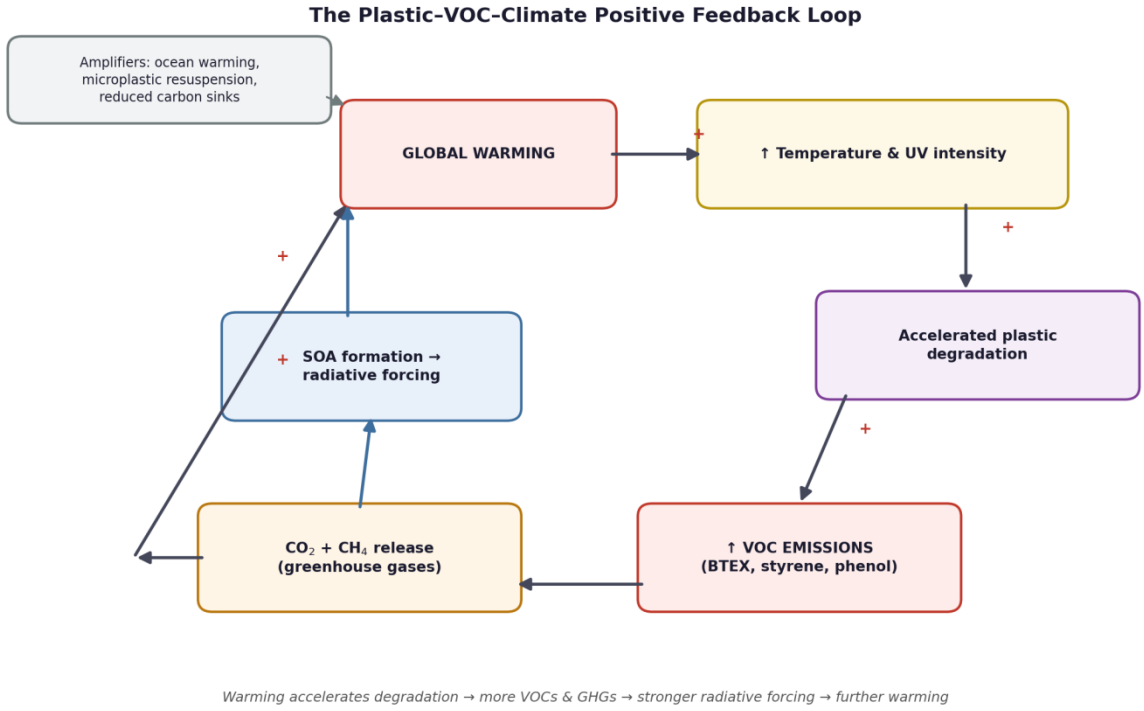


Figure 7. The plastic–VOC–climate positive feedback loop: climate warming accelerates plastic degradation, which increases VOC and greenhouse gas emissions, which in turn strengthen radiative force (He et al., 2024; Koehler et al., 2024).

8.0 Global Plastic Production and Projections

The scale of what is at stake follows directly from production trends, summarized in Figure 8. Global output reached about 415 million tonnes in 2023, double the level of the early 2000s (Plastics Europe, 2024). On current trajectories, production will hit 650 million tonnes by 2040 and could pass 1 billion tonnes a year by 2050 under business-as-usual growth (OECD, 2022). Because about 98% of plastics are made from fossil fuels, production alone already accounts for an estimated 1.8 billion tonnes of CO_2 equivalent emissions annually around 3.4% of the global total (Zheng & Suh, 2019).

Roughly 36% of annual production goes into packaging with lifetimes under a year. Globally, only 9% of plastic waste is recycled; 19% is incinerated, 49% landfilled, and 22% mismanaged dumped, openly burned, or leaked from waste systems (Geyer et al., 2017). The cumulative environmental stock was estimated at 4.9 billion tonnes by 2015, and that legacy mass will keep degrading and emitting VOCs and greenhouse gases for centuries.

The implications for future emissions are sobering. Business-as-usual growth could add 150–250 million tonnes to the environmental plastic inventory by 2040 an expanding emission source. Geography matters: the fastest growth in consumption and leakage is projected for sub-Saharan Africa, South Asia, and Southeast Asia, exactly the regions where high insolation and temperature maximize photodegradation rates (Babayemi et al., 2019; OECD, 2022). Growing stocks and rising temperatures therefore compound one another in ways that current air-quality and climate projections do not capture.

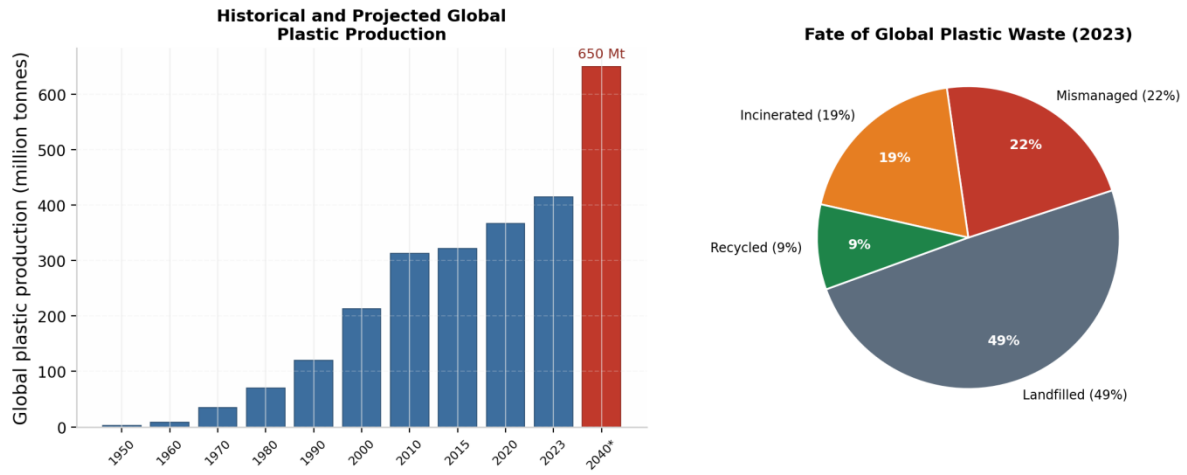


Figure 8. Global plastic production, historical trends and projections (left), and the fate of plastic waste in 2023 (Plastics Europe, 2024; OECD, 2022; Geyer et al., 2017).

9.0 Future Directions and Research Priorities

9.1 Standardized Emission Measurement Protocols

The field urgently needs agreed protocols for measuring VOC emissions from degrading plastics under realistic environmental conditions. Existing studies differ in experimental design, temperature and UV regimes, sample preparation, and analytical method, which blocks cross-study comparison and prevent the construction of emission factors for inventories and models. An international consensus protocol analogous to those long established for biogenic VOC measurement (Sindelarova et al., 2022) should specify standard polymer samples (virgin versus aged, additive-free versus commercial formulation), irradiation spectra and intensities representative of equatorial, mid-latitude, and polar environments, temperature and humidity ranges, and sampling and analysis methods (PTR-MS, GC-MS, or thermal desorption).

Aged plastics recovered from real environments marine surface waters, beach sediments, agricultural soils deserve particular attention, since they are the substrates actually degrading outdoors. Virgin-polymer studies are valuable for mechanistic insight but may over- or under-estimate real emission rates depending on how weathering history has depleted or exposed different chemical moieties. Measurements should cover the most common polymers (PE, PP, PS, PVC, PET) and common product categories (packaging films, bottles, foam, textiles, tyres) so that atmospheric observations can be source-apportioned.

9.2 Field Observations and Flux Measurements

Translating laboratory emission rates into environmental flux estimates requires direct field measurement in plastic-impacted environments. Priorities include: (1) eddy covariance or relaxed eddy accumulation flux measurements over known accumulation areas beaches, landfills, ocean gyres; (2) ship-based measurement of atmospheric VOC concentrations and microplastic loadings along ocean transects, especially in the North Pacific and Mediterranean; (3) coastal monitoring stations with PTR-ToF-MS or comparable instruments able to track styrene and other plastic-specific tracers at sub-ppbv detection limits; and (4) aircraft profiling of the vertical transport and boundary-layer mixing of plastic-derived VOCs and SOA.

Long-term monitoring networks should be established where plastic loads are high: the Hawaiian Islands (downwind of the GPGP), Mediterranean coastal stations, major Asian cities and, we argue, the Gulf of Guinea, where high plastic leakage meets tropical degradation conditions (Jambeck et al., 2015). Such networks would provide the trend data needed to detect changing emission rates as plastic stocks accumulate and the climate warms. Co-locating them with standard air-quality monitoring (NO_x, O_3, $PM_{2.5}$) would allow the contribution of plastic-derived VOCs to regional air quality and SOA formation to be quantified directly.

9.3 Coupled Plastic–Climate Modelling

Bringing plastic degradation into Earth system models (ESMs) and chemical transport models (CTMs) is an essential step towards quantifying the feedbacks described here. Priority developments include: (1) plastic degradation modules in ESM land and ocean surface schemes that track environmental stocks, degradation state, and VOC/greenhouse gas emissions as functions of temperature, UV, and microbial activity; (2) explicit representation of plastic-derived VOCs styrene as a tracer plus the BTEX suite in CTMs, with appropriate emission factors, oxidation schemes, and SOA yields; (3) treatment of nanoplastic–SOA interactions and their effects on CCN activity and cloud microphysics; and (4) two-way coupling between degradation emissions and atmospheric chemistry–climate interactions.

The CESM, UKESM, and MIROC frameworks offer suitable platforms, building on existing biogenic and anthropogenic VOC schemes. A practical first step would treat plastic-derived VOCs as an additional source category within existing aromatic inventories, distributed spatially according to plastic waste generation and environmental stock models; more sophisticated treatments tracking individual sources and degradation pathways could follow as observational constraints improve.

Integrated assessment models used in policy analysis should likewise incorporate plastic lifecycle emissions, including the end-of-life degradation contribution, so that the costs and benefits of plastic-reduction strategies can be compared fairly. Current frameworks focus on production-phase emissions; adding environmental degradation emissions would strengthen the case for waste reduction, circular-economy transitions, and alternative materials as climate mitigation measures.

9.4 Human Health Risk Assessment

The health implications of plastic-derived VOC emissions remain a critical, understudied gap. Priority areas include: (1) inhalation exposure assessment for communities living near plastic waste accumulations, recycling facilities, and informal burning sites; (2) dietary exposure through bioaccumulation of plastic-derived VOCs in seafood and farm produce; (3) mixture toxicity assessment covering VOCs, additives, and particles together; and (4) epidemiological studies linking residential proximity to plastic waste sites with respiratory disease, cancer incidence, and reproductive outcomes.

Styrene's value as a tracer of polystyrene degradation offers a starting point for exposure assessment in high-impact areas. Biomarkers of styrene exposure urinary mandelic acid and phenylglyoxylic acid and markers for other plastic-specific VOCs would enable population-level exposure characterization (IARC, 2019; WHO, 2021). Occupational cohorts in plastic recycling and waste management could supply high-exposure data to anchor risk assessment at lower environmental levels.

9.5 Mitigation Strategies and Policy Implications

Recognizing plastic degradation as a source of VOCs and climate-active compounds strengthens the case for comprehensive plastic-pollution control. Priority interventions include: (1) curbing virgin plastic production through extended producer responsibility, plastic taxes, and bans on unnecessary single-use items; (2) investing in waste collection and management infrastructure, especially in developing economies where mismanagement is highest; (3) developing genuinely biodegradable alternatives that do not emit toxic VOCs as they break down; (4) remediating existing accumulations in marine and terrestrial environments; and (5) bringing plastic–climate interactions into international climate agreements and nationally determined contributions.

The negotiations towards a legally binding UN Plastics Treaty are a critical opportunity to address the climate dimension of plastic pollution. Treaty discussions so far centre on marine litter and physical pollution; bringing VOC emissions and climate feedbacks into scope would recast plastic pollution as a climate concern and could mobilize greater political and financial resources for mitigation (UNCTAD, 2025). UNCTAD's recent Global Trade Update underscored the stakes: 75% of all plastic ever produced has become waste, and trade in plastics has passed US$1.1 trillion about 5% of global merchandise trade while waste-management capacity lags far behind (UNCTAD, 2025).

Near-term technological measures VOC capture at landfills and recycling facilities could trim emissions while deeper circular-economy transitions proceed. Bio-based and biodegradable alternatives need rigorous lifecycle assessment to confirm that their degradation products do not carry similar or greater VOC and climate risks. And UV-stable, non-volatile additives that do not compromise recyclability could lower the emission intensity of the plastics that remain genuinely necessary.

10.0 Conclusion

This review set out to examine a dimension of plastic pollution that has largely escaped scientific and policy attention: the volatile organic compounds released as micro- and nanoplastics degrade, and the consequences of those emissions for the global climate. Drawing together evidence from polymer chemistry, atmospheric science, marine biology, and soil ecology and grounding the discussion in a structured search of the 2015–2025 literature it reveals a web of interactions that ties plastic pollution to atmospheric chemistry, ecosystem health, and climate change.

Four conclusions stand out. First, degrading plastics are an active chemical source. Under sunlight, mechanical wear, heat, and microbial attack, plastics emit hazardous aromatic hydrocarbons (benzene, toluene, styrene, naphthalene), oxygenated organics, and greenhouse gases (CO_2, CH_4); emission rates are polymer-specific polystyrene leads for styrene, PVC for greenhouse gases and rise steeply with temperature, with Q_{10} values of 2.1–3.4. Second, these emissions feed atmospheric aerosol. The aromatic VOCs are efficient SOA precursors (30–45% mass yields under low-NO_x conditions), and the resulting SOA can coat nanoplastic particles and switch on their cloud-nucleating behavior a pathway missing from every current climate model. Third, the ecological costs span every compartment: marine ecosystems face combined particle, additive, and VOC stress; contaminated soils emit more greenhouse gases and support weaker plant growth; and air quality suffers through added ozone and SOA. Fourth, and most consequentially, the system forms a positive feedback

loop: warming accelerates degradation and emission, and the resulting SOA and greenhouse gases feed further warming—a self-reinforcing cycle that will intensify as the environmental plastic stock grows.

These conclusions carry a clear regional message. The tropical belt, and West Africa in particular, combines intense UV, high temperatures, rapidly growing plastic consumption, and limited waste infrastructure; it is where per-unit emissions are likely to be highest and where vulnerabilities to fisheries, agriculture, and public health are acute. Nigerian and regional evidence on plastic waste flows underscores the need for monitoring and management capacity in the Gulf of Guinea and its catchments.

Much remains unknown. Global VOC fluxes from plastic degradation have never been measured in the field; the balance of photochemical, thermal, and microbial pathways across environmental gradients is poorly constrained; the SOA-forming potential of the full plastic-derived VOC mixture, additive compounds included, is uncharacterized; and Earth system models omit plastic degradation entirely. Closing these gaps demands a coordinated programme: standardized emission protocols; field flux campaigns in plastic-impacted environments; chamber studies of complete emission mixtures; coupled plastic–climate modelling; human health risk assessment; and lifecycle evaluation of alternatives and mitigation measures.

The plastic–VOC–climate nexus is where the pollution crisis and the climate crisis meet. With production projected to reach 650 million tonnes by 2040, the environmental plastic stock and its invisible gaseous footprint will grow for decades. Folding plastic pollution into climate policy, from nationally determined contributions to the UN Plastics Treaty, would acknowledge this connection and unlock the resources needed to act on it. Confronting the unseen footprint of VOC emissions from degrading plastics is, ultimately, not only an environmental measure but a climate imperative one that touches the Sustainable Development Goals, biodiversity protection, and human health alike in the Anthropocene.

11.0 Recommendation

This review advances several evidence-based recommendations to address the climate and ecological implications of plastic-derived volatile organic compound emissions. First, the development of standardized emission protocols is imperative, as extant laboratory studies utilize disparate temperature regimes, ultraviolet spectra, and analytical methods that preclude cross-study comparison and the construction of reliable emission inventories. Second, direct field observations employing eddy covariance, ship-based atmospheric transects, and aircraft profiling are urgently required to quantify ambient VOC fluxes from marine and terrestrial plastic accumulation zones, given the current absence of empirical environmental measurements. Third, integration of plastic degradation modules into Earth system models (e.g., CESM, UKESM, MIROC) is necessary to capture temperature-dependent emission dynamics and nanoplastic–aerosol–cloud interactions presently excluded from climate projections. Fourth, human health investigations should utilize biomarker surveillance and longitudinal epidemiological cohorts to assess chronic exposure risks among populations residing near waste accumulation sites. Finally, policy interventions must transcend physical litter management to include reductions in virgin polymer production, enhanced waste infrastructure in developing economies, and formal incorporation of plastic–climate feedbacks within the United Nations Plastics Treaty.

Acknowledgement

The authors wish to thank the management and technical staff of the Department of Chemical Engineering at Federal University Otuoke, Nigeria for granting the authors access to their laboratories and workshops.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used four electronic databases Scopus, Web of Science Core Collection, ScienceDirect, and Google Scholar to ensure exhaustive, multidisciplinary retrieval of peer-reviewed scholarship published from 2015 to 2025. Database searches were augmented by snowball sampling of reference lists to identify foundational studies potentially overlooked by keyword algorithms. Dual-independent screening and data extraction were undertaken by two reviewers, with discrepancies adjudicated through deliberation, thereby mitigating selection bias and strengthening methodological rigor. Eligibility was confined to English-language peer-reviewed articles, academic dissertations, and authoritative institutional reports presenting primary experimental measurements, atmospheric modelling outputs, or substantive syntheses concerning polymer degradation and volatile emissions; conference abstracts and non-peer-reviewed preprints were excluded. Chemical characterization evidence synthesized throughout this review was derived from established analytical methodologies specifically proton-transfer-reaction mass spectrometry (PTR-MS), gas chromatography–mass spectrometry (GC-MS), and thermal desorption analysis as these constitute the standard instrumental approaches employed across the primary literature.

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