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The RINSE Project: Recycling with Pyrolysis Discarded used Plastic made Insecticide Treated Mosquito Nets for a Safer Environment, Ecological and Human Health Considerations

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Abstract

Malaria is still the main parasitic disease in the World and vector control is an absolute need due to the drug-resistant *P. falciparum*. Vector control is mainly based on the large-scale distribution of long-lasting insecticide treated nets which avoided several hundred thousand deaths.

More than three billion of such nets were distributed these last two decades and it is scheduled three hundred million each year.

But, in one or two years, used nets are torn and removed, discarded here and there in the environment. The management of these “end-of-life” nets is of great concern because they are, all, made of plastic (polyester, polyethylene, polypropylene) which are not biodegradable.

They are often left, with other domestic waste, in landfill, and burned, this must be strictly avoided due to well-known toxic vapour. Or they are buried, but plastic, and insecticide, are still present while the goal is their elimination. The physical degradation of plastic, in Macro-Micro and Nanoparticle, is of great concern.

A first trial of pyrolysis of a lot of long-lasting insecticide-treated nets showed that both plastic, and insecticide, were completely eliminated, the “recycling” method procured a fuel which could be used for engine.

From our experience of field surveys for malaria control, and published document noticed in PubMed, we did a synthesis of main risks, to fauna and human, due to plastic and pyrethroid insecticide pollution. Comprehensive programme must be undertaken to get rid of both plastic and insecticide and to get Safer Environment for populations of malarious countries. This could be obtained with pyrolysis of old discarded nets, and their packaging. This is a goal of the RINSE Project.

Keywords Pyrolysis; Plastic made mosquito nets; “end-of-life” nets; “waste-management”; “waste to energy system”; Circular economy; Malaria protection without pollution

1 Background: The Size of the Problem

According to a WHO Report of malaria in the World (World Health Organization, 2024) “Globally, in 2023, the number of malaria cases was estimated at 263 million, with an incidence of 60.4 cases per 1,000 population at risk. This is an increase of 11 million cases from the previous year and a rise in incidence from 58.6 cases per 1,000 populations at risk in 2022. The WHO African Region continues to carry the heaviest burden of the disease, accounting for an estimated 94% of malaria cases worldwide in 2023”. “Globally, in 2023, the number of deaths was estimated at 597, 000, with a mortality rate of 13.7 per 100, 000. The number of malaria deaths and the mortality rate steadily decreased from 622,000 and 14.9 deaths per 100,000, respectively, in 2020. The WHO

African Region continues to carry the heaviest burden of mortality, with 95% of estimated malaria deaths worldwide". "Between 2000 and 2023, an estimated 2.2 billion malaria cases and 12.7 million malaria deaths were averted worldwide, with 1.7 billion cases and 12 million deaths prevented in the WHO African Region alone. In 2023 alone, more than 177 million cases and more than 1 million deaths were averted globally."

Bhatt *et al.* (2015) "found that *Plasmodium falciparum* infection prevalence in endemic Africa halved and the incidence of clinical disease fell by 40% between 2000 and 2015. We estimate that interventions have averted 663 (542-753 credible interval) million clinical cases since 2000. Insecticide-treated nets, the most widespread intervention, were by far the largest contributor (68% of cases averted)."

According to the Alliance for Malaria Prevention (The Alliance for Malaria Prevention, 2025) nearly 3.5 billion long-lasting insecticide treated nets (LLINs) were shipped to malaria endemic countries (Table 1); they represent some 2.24 million tons of plastic (nets, without packaging).

Table 1. Cumulative shipments to malaria endemic countries

Standard	2,636,709,945
Pyr + PBO	491,185,021
Dual a.i.	321,509,322
Total	3,449,404,288

It is scheduled a distribution of 300 hundred million of LLINs each year to get a full and permanent coverage, they represent some 195.000 tons of plastic (without packaging).

But three points must be considered. First, all these nets are made of plastic, polyester or polyethylene or polypropylene (Table 2) which are not biodegradable and this raises the issue of plastic pollution.

Table 2. LLINs recommended by WHOPES

Product name	Product type	Status of WHO recommendation	Status of publication of WHO specification
DawaPlus® 2.0	Deltamethrin coated on polyester	Interim	Published
Duranet®	Alpha-cypermethrin incorporated into polyethylene	Interim	Published
Interceptor®	Alpha-cypermethrin coated on polyester	Full	Published
LifeNet®	Deltamethrin incorporated into polypropylene	Interim	Published
MAGnet™	Alpha-cypermethrin incorporated into polyethylene	Interim	Published
Netprotect®	Deltamethrin incorporated into polyethylene	Interim	Published
Olyset®	Permethrin incorporated into polyethylene	Full	Published
Olyset® Plus	Permethrin and PBO incorporated into polyethylene	Interim	Pending
PermaNet® 2.0	Deltamethrin coated on polyester	Full	Published
PermaNet® 2.5	Deltamethrin coated on polyester with strengthened border	Interim	Published
PermaNet® 3.0	Combination of deltamethrin coated on polyester with strengthened border (side panels) and deltamethrin and PBO incorporated into polyethylene (roof)	Interim	Published
Royal Sentry®	Alpha-cypermethrin incorporated into polyethylene	Interim	Published
Yorkool® LN	Deltamethrin coated on polyester	Full	Published

Notes: 1. Reports of the WHOPES Working Group Meetings should be consulted for detailed guidance on use and recommendations. These reports are available at: http://www.who.int/whopes/recommendations/wgm/en/.
2. WHO recommendations on the use of pesticides in public health are valid ONLY if linked to WHO specifications for their quality control. WHO specifications for public health pesticides are available at: http://www.who.int/whopes/quality/newspecif/en/.

As each net weighs around 0.650 kg it is clear that, added with their packaging, several hundred million of ton of plastic already arrived, and will arrive, each year in malaria endemic countries.

From the recent KAP survey done in Bénin (Ouarou *et al.,* 2021), it was reported that "Djougou has a population of about 35,000 households. There is an average of 2.4 people per ITN. Half of the ITNs are less than 2 months old, indicating a recent distribution campaign. The reported ITNs used the night before the survey was 73 %. Over half of the households (52 %) reported losing at least one ITN in the past year, with an average of 2.53 nets lost per household". It was estimated that "if each household loses an average of 2.53 nets per year, then in the last 12 months 2.53*35,000* 1500 = 133 kg of insecticides were released into the wild, along with 57.6 tons of plastics (support material constituting the net)."

It was thus possible to extrapolate to the whole country, and to the malarious countries South of Sahara. "In Bénin data indicate that 46,939,986 ITNs were distributed from 2004 to 2023. Based on the results obtained from our sample, if we extrapolate in Bénin which houses 1.8 million households (according to the RGPH4), the amount of insecticides released would be 6.8 tons per year, and the amount of plastic abandoned would be 2,960 tons per year."

For malarious countries sub-Saharan Africa "the number of ITNs distributed in sub-Saharan Africa over the same period from 2004 to 2023 is 2,670,896,648. If we now extrapolate from Benin to sub-Saharan Africa, based on 174.5 million households, the amount of insecticides released would be 662 tons per year and the amount of plastic abandoned would be 287,000 tons per year."

Actually, it was often observed that, in one or two years, these nets are torn and dirty; they are removed and discarded, here and there, in the environment (Carnevale *et al.,* 2021a; Carnevale *et al.,* 2021b; Ouarou *et al.,* 2025), and regular large-scale distributions of treated nets are needed to get the full coverage needed for the expected malaria elimination.

Second point: the management of such "end-of-life" nets, and their packaging, are of great concern due the double pollution they create: physical with decomposition of plastic in macro-micro-nano particles (MNP), and chemical as pyrethroid kill cold blooded animal, insects, earthworm etc, and even fishes.

Discarded old nets are often "forgotten" in the environment, or added to domestic waste in some locally made landfill where they are left in open space with the well-known dispersion by wind of MNP resulting from degradation of plastic; or burned which is dangerous with the well-known toxic vapour, and must be strictly forbidden.

It was also recommended to bury them, but this is just a "transfer", from the surface into the soil, plastic and insecticide are still present with an impact on the edaphic fauna, and this, also, must be forbidden.

It was reported some "transformation" of domestic plastic waste in other "thing" for other purposes, but plastic is still there. Crushing the collected nets to do bricks for houses, or pavement for street, or packaging them, does not solve the problem, and even could worsen the situation as abrasion release micro (MP) and nanoparticles (NP) which have impact on human health.

None of these methods are ecologically, and human health, correct, and another approach must be implemented.

Third point: these nets are treated with a pyrethroid insecticide, but the spreading of pyrethroid resistance is a key issue (Hemingway and Ranson, 2000; Hemingway *et al.,* 2002; Ranson *et al.,* 2011; Hemingway *et al.,* 2016; Ranson and Lissenden, 2016). The insecticide resistance can reduce the efficacy of currently available LLINs (N'Guessan *et al.,* 2007) and underlines the needs for new tools for "averting a malaria disaster." (Hemingway *et al.,* 2016).

The recently developed mosquito nets are treated with two products, such as pyrethroid and chlorfenapyr, (N'Guessan *et al*., 2016) or pyriproxyfen (Ngufor *et al.,* 2014; Ngufor *et al.,* 2016), or PBO (Tungu *et al.,* 2010; Gleave *et al.,* 2017; Martin *et al.,* 2021; Tungu *et al.,* 2021) and are now largely distributed.

WHO developed the Global Plan for Insecticide Resistance Management in malaria vectors (GPIRM) to provide a framework for countries to develop their own strategies.

The average surface of a net is 15m^2, and the concentration in insecticide is 55 mg a.i./m^2 (but usually much more, even 500 mg a.i./m^2), meaning that there is some 825 mg a.i. insecticide per net.

When considering the billion of nets already distributed (≈3.5 billion), and the 300 million scheduled for each year, it is clear that the pressure for pyrethroid insecticide is great, and it will increase, added with insecticide largely used for agriculture purpose. This means a worrying increasing insecticide resistance pressure for mosquitoes, and other insects.

Therefore, a new solution must be found, and implemented, to get rid of plastic and insecticide treated discarded nets for a safer environment and human health. This is the aim of the RINSE Project.

2 Environmental and Human Health Toxicity with Decomposition of Polyethylene

Geyer *et al* (2017) "estimate that 8,300 million metric tons (Mt) as of virgin plastics have been produced to date. As of 2015, approximately 6,300 Mt of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. If current production and waste management trends continue, roughly 12,000 Mt of plastic waste will be in landfills or in the natural environment by 2050."

A great lot of recent publications reported the relation micro-nano particles and environmental impact and human health (Allouzi *et al*., 2021; da Silva Brito *et al*., 2022; Kumar *et al.,* 2022; Sangkham *et al.,* 2022; Yang *et al.,* 2022; Yuan *et al.,* 2022; Zhang *et al.,* 2022; Ramesh *et al.,* 2023; Ullah *et al.,* 2023; Ali *et al.,* 2024; Balali *et al.,* 2024; Carvalho *et al.,* 2024; Donisi *et al.,* 2024; Liang *et al.,* 2024; Qian *et al.,* 2024; Zhu *et al.,* 2024; Anilbose *et al.,* 2025; Deng *et al.,* 2025; Dubey and Thalla, 2025; Fowzi *et al.,* 2025; Krishnendu and Varghese, 2025; Nihart *et al.,* 2025).

2.1 Microplastic (MP) pollution

Microplastic (MP) pollution has emerged as a critical environmental and human health concern.

"Microplastics (MPs) (< 5mm) and nanoplastics (NPs) (< 1µm) are catching attention due to their widespread abundance and distribution, and their impacts on the natural ecosystems, as well as detrimental health risks to humans." (Allouzi *et al.,* 2021; Sangkham *et al.,* 2022; Anilbose *et al.,* 2025).

Landfills are important source of microplastics. (Dubey and Thalla, 2025; Fowzi *et al.,* 2025; Krishnendu and Varghese, 2025).

"Microplastic (MP) pollution has emerged as a critical environmental concern. Landfills, as significant repositories of plastic waste, represent a potential source of MPs. Furthermore, landfill leachate (LL) has been identified as an important pathway for the release of these stored MPs into the environment. MPs found in LL originate from various sources, including discarded plastics, synthetic fabrics and industrial waste.... Polyethylene (PE) was the most dominant type of polymer in LL, followed by polypropylene... The size of MPs sampled from leachate ranged from 0.03 to 5 mm. " (Krishnendu and Varghese, 2025).

Microplastics as emerging contaminants in municipal solid waste compost were recently analyzed (Fowzi *et al.,* 2025) and it was concluded that "Polyethylene-terephthalate, polyethylene, and polyolefin were the dominant polymers in all facilities. The ecological risk indices indicated high levels of risk in all three composting sites, with potential implications for agricultural soils, soil fertility. MPs in compost may enter the food chain, raising concerns for ecosystem health. These findings underscore the significant MP contamination in compost and highlight the need for improved solid waste management strategies to reduce plastic pollution."

It was reported that a simple washing of a cloth made of non natural material can release some 1,900 MP of plastic!

2.2 The impact of MP and NP on human health

The impact of MP and NP on human health is an important issue.

A review of the endocrine disrupting effects of micro and nano plastics, and their associated chemicals in mammals, was recently published (Ullah *et al.,* 2023). It was concluded that "Over the years, the vast expansion of plastic manufacturing has dramatically increased the environmental impact of microplastics [MPs] and nanoplastics [NPs], making them a threat to marine and terrestrial biota because they contain endocrine disrupting chemicals [EDCs] and other harmful compounds. MPs and NPs have deleterious impacts on mammalian endocrine components such as hypothalamus, pituitary, thyroid, adrenal, testes, and ovaries.... MPs and NPs disrupt hypothalamic-pituitary axes, including the hypothalamic-pituitary-thyroid/adrenal/testicular/ovarian axis leading to oxidative stress, reproductive toxicity, neurotoxicity, cytotoxicity, developmental abnormalities, decreased sperm quality, and immunotoxicity. The direct consequences of MPs and NPs on the thyroid, testis, and ovaries are documented. Still, studies need to be carried out to identify the direct effects of MPs and NPs on the hypothalamus, pituitary, and adrenal glands."

Recent toxicological researches (Zhang *et al.,* 2022) reported that "MPs/NPs can act as carriers of bacteria, viruses, or pollutants (such as heavy metals and toxic organic compounds), and may potentially change the toxicity and bioavailability of pollutants. Ingested, or attached MPs/NPs, can also be transferred from low-trophic level organisms to high-nutrient organisms, or even the human body through the food chain transfer process. The inherent toxic effects of MPs/NPs mainly include the following: physical injury, growth performance decrease and behavioral alteration, lipid metabolic disorder, induced gut microbiota dysbiosis and disruption of the gut's epithelial permeability, neurotoxicity, damage of reproductive system and offspring, oxidative stress, immunotoxicity, etc."

A review of "the potential impacts of micro-and-nano plastics on various organ systems in humans" was recently published (Ali *et al.,* 2024). It was concluded that "Humans are exposed to micro-and-nano plastics (MNPs) through various routes, but the adverse health effects of MNPs on different organ systems are not yet fully understood." "The summarized results suggest that exposure to MNPs can lead to health effects through oxidative stress, inflammation, immune dysfunction, altered biochemical and energy metabolism, impaired cell proliferation, disrupted microbial metabolic pathways, abnormal organ development, and carcinogenicity." And "Most of the published research has focused on specific types of MNPs to assess their toxicity, while other types of plastic particles commonly found in the environment remain unstudied. Future studies should investigate MNPs exposure by considering realistic concentrations, dose-dependent effects, individual susceptibility, and confounding factors."

The Minderro-Monaco Commission on Plastics and Human health stated that "This Commission finds that plastics are both a boon to humanity and a stealth threat to human and planetary health. Plastics convey enormous benefits, but current linear patterns of plastic production, use, and disposal that pay little attention to sustainable design or safe materials and a near absence of recovery, reuse, and recycling are responsible for grave harms to health, widespread environmental damage, great economic costs, and deep societal injustices. These harms are rapidly worsening. The evidence available today demonstrates unequivocally that these impacts are great and that they will increase in severity in the absence of urgent and effective intervention at global scale. Global intervention against the plastic crisis is needed now because the costs of failure to act will be immense." (Landrigan *et al.,* 2023) (Annex 1).

This could be considered as an important perspective of works in comprehensive studies, where plastic made discarded nets must be taken into consideration, with other domestic waste, for their impact on human health if not quickly eradicated from human environment by radical and definitive method.

The presence of MP and NP in brain is of great concern (Nihart *et al.,* 2025) (Annex 2).

Microplastics were also recently involved as neurovegetative disease, such as Parkinson Disease (PD) or Alzeimer Disease (AD) with "six MP-related mechanistic pathways associated with AD were identified...and six MP-related mechanistic pathways associated with AD were identified." (Siu *et al.,* 2025) (Annex 3).

Recently Bayattork *et al*. (2026) "examined the growing evidence that textile-derived MNPs can translocate across biological barriers following inhalation or ingestion, reaching the brain via both direct olfactory pathways and systemic circulation through the blood-brain barrier. Experimental studies increasingly implicate MNPs in oxidative stress, neuroinflammation, and protein aggregation, processes central to the pathogenesis of neurodegenerative disorders such as Alzheimer's and Parkinson's disease."

Several studies were recently devoted to these issues of the potential neurotoxicity of micro and nanoplastics (Siu *et al*., 2025; Bayattork *et al.,* 2026; Gao *et al.,* 2025; Vojinits *et al.,* 2025; Ma *et al.,* 2025; Yang *et al.,* 2023) and further researches are needed.

2.3 Micro and nanoplastics (MNP) and global warming

It was recently reported that "Microplastics (MPs) are characterized by small particle sizes (<5 mm) and are widely distributed in the soil environment. To date, little research has been conducted on investigating the effects of MPs on the soil microbial community, which plays a vital role in biogeochemical cycling. In the present study, we investigate the influence of two particle sizes of MPs on dissolved organic carbon (DOC) and its relative functional groups, fluxes of greenhouse gases (GHGs), and the bacterial and fungal communities in fertilized soil." And it was concluded that "Our findings suggest that MPs have selective effects on microbes and can potentially have a serious impact on terrestrial biogeochemical cycles. Thus, the study of the effect of MPs on emission of GHGs is of great importance." (Ren *et al.,* 2020).

A question was raised "Could soil microplastic pollution exacerbate climate change?" (Iqba *et al.,* 2024). After "A meta-analysis of greenhouse gas emissions and global warming potential" it was considered that "Microplastics pollution and climate change are primarily investigated in isolation, despite their joint threat to the environment. Greenhouse gases (GHGs) are emitted during: the production of plastic and rubber, the use and degradation of plastic, and after contamination of environment. Overall, microplastics contamination was associated with increased GHGs emissions, with the strongest effect (60%) on CH_4 emissions. Polyethylene caused the maximum (60%) CH_4 emissions. Larger-sized microplastics had higher GWP (125%) due to their 9% CO_2 and 63% N_2O emissions. GWP rose sharply if soil microplastics content exceeded 0.5%." And "We conclude that microplastics contamination can cause raised GHGs emissions, posing a risk of exacerbating climate-change. We show clear links between GHGs emissions, microplastics properties, soil characteristics and soil microbe functional gene expression. Further research is needed regarding underlying mechanisms and processes."

3 Toxicity of Pyrethroids

The main pyrethroids used for treated mosquito nets are permethrin, deltamethrin, lambdacyhalothrin and alphacypermethrin (Table 2). Physical and chemical properties of pyrethroids are well known (Laskowski, 2002).

Permethrin is a pyrethroid type I; deltamethrin, cyhalothrin, cypermethrin are pyrethroids type II (with a group α-cyano). Their chemical formulations are given in Annex 4.

Deltamethrin, permethrin, and alpha-cypermethrin were long considered to have very low toxicity for humans of all ages because they degrade rapidly. However, recent evidence shows that they could have an impact on the neurological development.

3.1 Modes of action

Like natural pyrethrum, pyrethroids act by contact, irreversibly blocking sodium channels in neuronal membranes. Type II pyrethroids also block other ion channels, such as chloride and calcium channels, and therefore have a more severe effect on the nervous system. Pyrethroids generally act very quickly on almost all insects. They are highly toxic to cold blood animals (Hermant, 2014; Brander *et al.,* 2016; Ramesh *et al.,* 2024) such as fish, crustaceans, amphibians, earthworms, and reptiles; the blockage of ion channels leads to paralysis in these animals.

3.2 Ecotoxicity

Pyrethrinoids exhibit significant selective ecotoxicity, primarily targeting insects (for example, the median lethal dose (LD50) for insects is 0.45 mg/kg). They also have the advantage of being easily degraded, and not very persistent in the environment, disappearing through hydrolysis, photolysis, and biodegradation by microorganisms.

Acute exposure shows toxicity targeting the nervous system (Na+ channels). On rodents T-type symptoms (tremors, ataxia, excitability, and hypersensitivity) are observed with type I pyrethroids; while CS-type symptoms (choreo-athetosis, salivation, tremors, convulsions) are observed with type II pyrethroids.

Environmental emissions: the main pathways for pyrethroid emissions into the aquatic environment are water runoff (rain, irrigation) and wind. Therefore, it can be expected runoff of pyrethroid from old nets in land fill, or discarded here and there, when raining.

The impact of pyrethroids on fishes is well known (Brandner *et al.,* 2016; Ramesh *et al.,* 2023) as well as on other non target organisms (Rosa *et al.,* 2016), notably earthworm (Inglesfield, 1984) which "immensely contribute in increasing the fertility of soils" (Tiwari *et al.,* 2019) and are recognized as a biomarker in ecological risk assessment (Sanchez-Hernandez, 2006).

Being highly hydrophobic, pyrethroids readily bind to organic carbon and particulate matter, and accumulate in soil and sediments where they degrade within a few months. In the aquatic environment, they are bioavailable in dissolved form, or bound to particles. A large amount of studies was devoted to the ecotoxicity of pyrethroids.

"Pyrethroids are degradable in soils with half-lives ranging from 3 to 96 days aerobically, and 5 to 430 days anaerobically. For those pyrethroids studied in water (cypermethrin, deltamethrin, esfenvalerate, fenpropathrin, and lambda-cyhalothrin), aerobic and anaerobic degradation often continued at rates similar to that displayed in soil." (Laskowski, 2002).

3.3 Human toxicity

Chemical markers indicate that the two main sources of contamination in the human body are permethrin and cypermethrin. Pyrethroids, or their degradation products, can also be found in breast milk, infant formula, and some baby foods.

A great lot of work was devoted to toxicity risks of pyrethroid for human being (Barr *et al.,* 2010; Institut National de la Santé et de la Recherche Médicale, 2015; 2021; 2025; Qi *et al.,* 2022; Reyene and Nadia, 2022).

Short-term skin exposure to pyrethroids can lead to abnormal facial sensations (paresthesia). Ingestion can cause sore throat, nausea, vomiting, abdominal cramps, and mouth ulcers. Excessive salivation and difficulty swallowing are often observed. Most affected individuals recover within 12 to 48 hours.

Lethal doses vary considerably depending on the molecule (from approximately 55 mg/kg of body weight for bifenthrin or λ-cyhalothrin to over 10,000 mg/kg of body weight for d-phenothrin). Poisoning is rarely fatal, but high doses cause tremors, coma, and seizures, which are medical emergencies (Annex 5).

In adult humans, the main routes of contamination are percutaneous absorption (through the skin), inhalation (especially after using aerosol sprays or other sprays) (Hermant, 2014) and ingestion of contaminated food or water.

Pyrethroids, and their metabolites, have hormonal activity, generally estrogenic or anti-androgenic. They, thus, reduce the production of progesterone and estradiol in mammals.

In the early 2000s, it was estimated that at environmental doses, no chronic organ damage was observed in chronically exposed individuals, but poisoning is possible at high doses.

Epidemiological studies subsequently showed that repeated exposure to pyrethroids, even at low doses and without causing acute effects such as cardiovascular events, can be associated with chronic disorders. These manifest in young children exposed *in utero* as behavioral problems (anxiety and withdrawal), while fertility impairments (particularly sperm abnormalities) have been observed in the general population.

Spermatogenesis can also be negatively affected. Deltamethrin, one of the compounds in this family, has also been linked to an increased risk of chronic lymphocytic leukemia, or lymphocytic lymphoma in people exposed in their work.

A recent study by Public Health France, revealed significant levels of exposure, especially in children (INSERM, 2025).

In China, a large epidemiological study showed, in 2022, that prenatal exposure, even at low levels, particularly in malaria-endemic areas, is associated with delayed neurological development in infants (affecting cognition, motor development, and adaptive behavior); it also showed that high exposures during the first six months of pregnancy lead to the most pronounced effects (Zhiye *et al.,* 2022).

Children are also more vulnerable and more exposed to these products (Barr *et al.,* 2010).

Recent studies in a cohort of three hundred mother-child pairs, reported that pyrethroids are, indeed, neurotoxic to the youngest children. According to the 2021 updated version of this study: “New studies on pyrethroids highlight a link between exposure during pregnancy and an increase in internalizing behavioral disorders such as anxiety in children. Experimental data on rodents suggest increased permeability of the blood-brain barrier to pyrethroids at the earliest stages of development, supporting the biological plausibility of this link.” This meta-study confirms “the role of prenatal exposure to pyrethroid insecticides in the development of neuropsychological and motor disorders in children.” (Institut National de la Santé et de la Recherche Médicale, 2015; 2021).

Pyrethroids are endocrine disruptors for human being (Reyene and Nadia, 2022).

4 A Solution: Pyrolysis: the RINSE Project

4.1 Principle of pyrolysis

The word "pyrolysis" comes from Greek: "pyro" meaning heat, and "lysis" meaning breaking down. It refers to the thermal decomposition of materials at high temperatures in the absence of oxygen. (IUPAC, 2025; Mamta *et al.,* 2020; Hafting *et al.,* 2023; Eastern Regional Research Center, USDA, 2025).

Plastic pyrolysis is a chemical recycling process that converts plastic waste into valuable products like fuel oil, carbon black and syngas (Annex 6). Unlike other plastic recycling solutions, plastic pyrolysis has relatively low requirements on the type and quality of plastics. Generally, apart from PVC and PET plastics, other plastic waste all can be recycled with the plastic pyrolysis machine.

By heating plastic materials to high temperatures, it breaks them down into simpler components: biochar (a solid charcoal-like material), syngas (a mixture of combustible gases), and a liquid called pyrolytic oil. This process differs from combustion because the lack of oxygen prevents burning, allowing for the creation of valuable products instead of just ash.

4.2 Safety challenges

Because pyrolysis takes place at high temperatures which exceed the autoignition temperature of the produced gases, an explosion risk exists if oxygen is present. Careful temperature control is needed for pyrolysis systems, which can be accomplished with a pyrolysis controller (Rollinson, 2018; Hedlund, 2023).

Pyrolysis also produces various toxic gases, such as carbon monoxide. The greatest risk of fire, explosion, and release of toxic gases comes when the system is starting up and shutting down, operating intermittently, or during operational upsets (Springer Theses, 2017). Inert gas purging is essential to manage inherent explosion risks. The procedure is not trivial and failure to keep oxygen out has led to accidents. This underlines the absolute need of well trained and skilled technicians to run the operations.

Pyrolysis can also be used to treat municipal plastic waste (Zhou *et al.,* 2015; Pandey *et al.,* 2020; Geyer *et al.,* 2017). Pyrolysis of plastics is one of the efficient ways to recover plastic waste. A strong plastic waste management solution is crucial (Plastics Europe, 2019). The European Commission is planning to implement a circular economy with a key focus on plastics. The objective is to ensure that all plastic packaging is reused or recycled by the year 2030 (Plastics Europe, 2019).

The products from pyrolysis are oil and monomers, which can substitute diesel fuel, and monomers for plastic production. In addition to higher recovery value, the primary driving factor at present is the global warming issues and stricter emission rules which are forcing forward mechanisms to recover valuable plastic wastes that are usually incinerated, or sent to landfills (Wojnowska-Baryla *et al.,* 2022; Akan *et al.,* 2021) which are "a common method for utilizing plastic waste at its end-of-life, but environmental and technical complications encountered during plastic disposal, and the formation and spread of microplastics (MPs) which can act as both vectors and carriers of pollutants in the environment." (Wojnowska-Baryla *et al.,* 2022).

Plastics wastes are propitious sources for production of diesel fuels or monomers, due to the high heating value and high availability. The catalytic fast pyrolysis process yields liquid rich in hydrocarbons (C11-C20), which has similar thermal and chemical properties as diesel. The optimal pyrolysis temperature for thermal degradation of plastic waste into liquid fuel is found to be in the range of 450 °C-700 °C.

4.3 The RINSE project: the first pyrolysis of insecticide treated nets

Pyrolysis was tested on Royal Sentry® Long-Lasting Insecticide-treated Net LLINs, made from polyethylene and impregnated with alpha-cypermethrin (Carnevale *et al.,* 2025). A special equipment was prepared to make this pyrolysis, (picture) following the same protocol as the one currently used for treating plastic waste at large-scale in the factory Geo Trash Management (Lombok).

The special equipment prepared for the first pyrolysis of insecticide-treated mosquito nets (Carnevale *et al.,* 2025).

The pyrolysis machine can test 4 - 5 kg batches, at a temperature of 400°C in a sealed, zero-oxygen environment. It runs on pyrolysis oil or diesel, 240V AC and CO_2 gas.

The machine features include a multistage, forced air fuel-oil burner, and syngas-scavenging, gas recycling system as a heating source. This includes a gravity-fed fuel oil flow regulation system and air throttle to regulate temperature. The heating chamber is insulated with a flume silica sealed ceramic fiber layer over 2mm sheet steel housing held in place by 15mm galvanized steel mesh. The cooling system includes two recycled water condensers / heat exchangers to quickly convert syngas to liquid hydrocarbons (pyrolysis oil).

For safety and product quality a CO_2 injection system is included for purging oxygen before startup and evacuating syngas during shutdown. All digital thermal sensing instruments monitor internal and external temperatures during the process. Digital and analogue pressure sensing instruments monitor internal pressure during the reaction. Other safety features include an over pressure relief valve; emergency stop systems and Residual Current Device (RCD) safety switch across all electrical circuits.

The GTM pyrolysis reactor produced, per LLIN: 374 g of pyrolysis oil (81.5%); 62 g of oil residue (13.5%); and 23 g of carbon residue (5%).

4.6 kg of LLIN was packed into the pyrolysis reactor which produced a total of 4.8 liters of oil which was analyzed with GC-MS method in Mataram University (Indonesia).

A total of 36 different hydrocarbons (65.2%), 7 Alcohols (24.9%) and 1 form of Acid (phthalic acid) (2.01%) were identified. But not a single molecule of plastic and not of insecticide alphacypermethrin.

The system get completely eliminates plastic and insecticide and appeared as the adapted technical solution for plastic depollution of discarded “end of life nets.”

Sample of oil obtained by pyrolyis of nets (left) and domestic plastic waste (right).

5 Perspectives

Impacts of pyrethroids on human health and environment: what we know, what we don’t know, and related recommendation” was recently published (Hénault-Ethier *et al.,* 2016).

5.1 Some technical studies

Several further technical studies could be identified.

After the first successful pyrolysis of polyethylene made nets, pyrolysis must be done with polyester and with polypropylene made nets; with nets treated with other pyrethroid (permethrin, deltamethrin, lambdacyhalothrin) and with the newly developed nets, treated with CFP, or PPF, or PBO, moreover insecticide itself.

It seems that on some nets PFAS were added (Annex 7) and it has to be known if pyrolysis can destroy them.

Washing and release of MP: it has been reported that the washing a cloth made with non-natural material releases a great lot of microparticles. It is important to evaluate the release of micro and nanoparticles when washing LLINs taking into consideration: the plastic (polyester, polyethylene, polypropylene); the insecticide (permethrin, deltamethrin, lambdacyhalothrin, alphacypermethrin), the impregnation (insecticide sticked on the thread or inside the thread), the method of washing (wash machine: speed of spin, time, temperature, soap etc. or traditional hand washing with local soap etc).

Comprehensive studies identifying in the field, some places in the river where clothes, and nets, are washed with traditional method and soap, then they could analyze micro and nanoparticles in the place of washing, and at some distances (considering the river, turbidity etc, studies made in collaboration with hydrologist, microbiologist). Studies could analyze micro-nanoparticles in fishes caught at distance of the washing place (collaboration with ichthyologist, veterinary, microbiologists). Studies could analyze micro-nanoparticles in human population eating these fishes, at close and distance of this (these) river (collaboration with medical doctor, microbiologists etc).

It would also be interesting to analyze MNP levels in populations living with, or using, plastic objects, made from used mosquito nets—simply shredded and recycled into items like house bricks or street pavers—especially given the known generation of MNPs from car tire abrasion.

Ethological studies could be done on the behavior of population in term of use, misuse (nets for fishing!) of nets, washing habits etc and the level of MNP which can be found in different organs.

5.2 Some operational studies

The currently in process EOLIN project in Nigeria shows that large-scale collection of discarded nets can be done; but the questions are: what about the follow-up of these old nets? Gathered in warehouse? And after? It is clear that a pyrolysis equipment, close to these warehouses, could be of great help, transforming these nets in fuel for engine, which allows a circular economy system giving financial input in communities, while cleaning their environment.

In some villages in Angola we developed a "*barter system*" with an exchange an old mosquito net for a new one; we arrived in the village with a lot of new nets and proposed their exchange for old one; it worked very well, and very easily. The question remained; what about these old nets collected in the field.

We propose the development of mobile teams with pyrolysis equipment, to treat old nets as close as possible to communities, and procuring them the fuel for their engines.

The RINSE project has a dual purpose: on one hand, to advance pyrolysis technology to enable the processing of all types of discarded "end-of-life" mosquito nets; and on the other hand, to transfer these techniques to countries where malaria remains prevalent. These nations will receive millions of LLINs, but they are still made of plastic, and added of already distributed nets, they could protect people from malaria vectors but they could contribute to environment, physical and chemical pollution, if not properly processed in due time.

Pyrolysis of these discarded nets will procure a Safer Environment to communities along with a circular economy and "waste for energy" system.

The RINSE project can, and want, transfers the technology, equipment and training, to do pyrolysis safely, with strengthening national capacities.

This pyrolysis technology could be a part, and a booster, of a national large-scale comprehensive adapted plastic depollution programme involving a central part, with large-scale pyrolysis equipment (treating domestic waste at tons level), and decentralized pyrolysis structures with mobile teams.

These results in a clean environment, a guarantee of improved health, combined with additional financial income. Still maintaining a *protection against malaria without pollution*.

Authors participation

Guillaume Carnevale was involved in pyrolysis technique, implementation and led the RINSE Project.
Andrew Sinclair did the first pyrolysis of LLINs.
Nicolas Carnevale was involved in toxicity issues.
Florence Fouque was involved in all issues of LLINS use and pyrolysis implementation.
Pierre Carnevale was involved in LLINs, composition, field use and management of end-of-life nets and writing.

Declaration of competing interest

The authors declare no competing financial or personal interests that could influence the work reported in this publication.

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This article did not need any ethical agreement as it did not involve any human implication.

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Annex 1.

The Minderoo-Monaco Commission on Plastics and Human Health.

Landrigan PJ, Raps H, Cropper M *et al*. Ann Glob Health 2023; 89 (1): 71.

Human health findings: Coal miners, oil workers and gas field workers who extract fossil carbon feedstocks for plastic production suffer increased mortality from traumatic injury, coal workers' pneumoconiosis, silicosis, cardiovascular disease, chronic obstructive pulmonary disease, and lung cancer. Plastic production workers are at increased risk of leukemia, lymphoma, hepatic angiosarcoma, brain cancer, breast cancer, mesothelioma, neurotoxic injury, and decreased fertility. Workers producing plastic textiles die of bladder cancer, lung cancer, mesothelioma, and interstitial lung disease at increased rates. Plastic recycling workers have increased rates of cardiovascular disease, toxic metal poisoning, neuropathy, and lung cancer. Residents of "fenceline" communities adjacent to plastic production and waste disposal sites experience increased risks of premature birth, low birth weight, asthma, childhood leukemia, cardiovascular disease, chronic obstructive pulmonary disease, and lung cancer. During use and also in disposal, plastics release toxic chemicals including additives and residual monomers into the environment and into people. National biomonitoring surveys in the USA document population-wide exposures to these chemicals. Plastic additives disrupt endocrine function and increase risk for premature births, neurodevelopmental disorders, male reproductive birth defects, infertility, obesity, cardiovascular disease, renal disease, and cancers. Chemical-laden MNPs formed through the environmental degradation of plastic waste can enter living organisms, including humans. *Emerging, albeit still incomplete evidence indicates that MNPs may cause toxicity due to their physical and toxicological effects as well as by acting as vectors that transport toxic chemicals and bacterial pathogens into tissues and cells*. Infants in the womb and young children are two populations at particularly high risk of plastic-related health effects. Because of the exquisite sensitivity of early development to hazardous chemicals and children's unique patterns of exposure, *plastic-associated exposures are linked to increased risks of prematurity, stillbirth, low birth weight, birth defects of the reproductive organs, neurodevelopmental impairment, impaired lung growth, and childhood cancer*. Early-life exposures to plastic-associated chemicals also increase the risk of multiple non-communicable diseases later in life.

Conclusions: It is now clear that current patterns of plastic production, use, and disposal are not sustainable and are responsible for significant harms to human health, the environment, and the economy as well as for deep societal injustices. The main driver of these worsening harms is an almost exponential and still accelerating increase in global plastic production. Plastics' harms are further magnified by low rates of recovery and recycling and by the long persistence of plastic waste in the environment. The thousands of chemicals in plastics-monomers, additives, processing agents, and non-intentionally added substances-include amongst their number known human carcinogens, endocrine disruptors, neurotoxicants, and persistent organic pollutants. These chemicals are responsible for many of plastics' known harms to human and planetary health. The chemicals leach out of plastics, enter the environment, cause pollution, and result in human exposure and disease. All efforts to reduce plastics' hazards must address the hazards of plastic-associated chemicals.

Annex 2.

"Microplastics Found in Human Brains: An Alarming link to Dementia".

Groundbreaking researches found that microplastics are accumulating in human brains at alarming levels, with concentrations increasing over time and potentially linked to dementia.
The presence of microplastics in human tissues has been a growing concern, and a recent study has confirmed their accumulation in the brain, liver, and kidneys of decedents. Scientists from the University of New Mexico and collaborating Institutions analysed post-mortem samples from 52 individuals. Their research highlights a concerning trend: microplastics concentration in the brain surpasses those in other organs, raising questions about potential health implications.
To conduct the study, researchers obtained liver, kidney, and brain samples from autopsies performed in 2016 and 2024. Using advanced detection methods, including pyrolysis gas chromatography-mass spectrometry and electron microscopy, they identified microplastics in all three organs, with polyethylene being the dominant polymer. Notably the concentration of microplastics in brain tissue increased from 3,345 µg/g in 2016 to 4,917 µg/g in 2024 (p=0.01). This significant rise aligns with broader environmental plastic pollution trends. Interestingly, microplastic accumulation did not correlate with age, sex, race, or cause of death, but individuals with dementia exhibited even greater plastic concentrations, particularly with cerebrovascular walls and immune cells. While no direct causa link has been established between microplastics and dementia, the findings suggest a need for further investigation.
These results underscore the urgency of understanding how microplastics enter, and persist, in the human body, particularly in the brain. While the liver and kidneys appear to clear some plastic particles, the brain's ability to expel them remains unclear.
The long-term health effects of microplastics exposure, including potential neurotoxicity, warrant further clinical and epidemiological studies. For healthcare professionals, these findings highlight the need for increased awareness of environmental pollutants as a factor of neurological health.
As plastic pollution continues to rise, mitigation strategies including reducing plastic exposure in food and water sources could become an essential aspect of public health policy. Future research should focus on elucidating the mechanisms of plastic uptake and clearance in human tissues and evaluating potential interventions to limit exposure."
Kattrina Thomber, EMJ
Reference
Nihart AJ *et al.* Bioaccumulation of microplastics in decedent human brains. Nat Med. 2025: DOI 10.1038/s41591-024-03453-1

Annex 3.

Siu A, Paudel K, Singh G *et al*. Do microplastics play a role in the pathogenesis of neurodegenerative diseases? Shared pathophysiological pathways for Alzheimer's and Parkinson's disease**.** Mol Cell Biochem 2025: doi: 10.1007/s11010-025-05428-3.

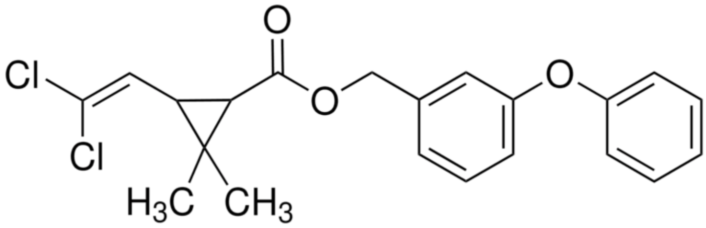
Abstract

The widespread presence of *microplastics (MPs*) in the environment has raised significant concerns about their potential impact on human health. As of 2023, the Ocean Conservancy estimates that adults may ingest up to 121,000 MPs annually. While the majority of these particles are cleared from the body, a small fraction can persist, as MPs are non-biodegradable and resist breakdown, posing long-term health risks that remain poorly understood. This review explores the emerging link between MP exposure and the development of neurodegenerative diseases, particularly **Alzheimer's disease (AD)** and **Parkinson's disease**. MPs appear capable of triggering neurotoxic pathways, including activation of resident immune cells in the brain, oxidative stress, *blood-brain barrier (BBB)* disruption, mitochondrial dysfunction, and neuronal damage, which may contribute to neuroinflammation and disease progression. Specifically, six MP-related mechanistic pathways associated with AD were identified: BBB disruption, chronic inflammation, oxidative stress and ROS generation, mitochondrial dysfunction, impaired autophagy and proteostasis, and epigenetic alterations. Similarly, six pathways were implicated in PD: BBB disruption, oxidative stress in dopaminergic neurons, mitochondrial dysfunction, microglial-driven neuroinflammation, α-synuclein aggregation, and gut-brain axis disruption. *Ultimately, our findings underscore the urgent need for further research into the neurological consequences of chronic MP exposure in humans and highlight the importance of strengthening global policies to curb plastic pollution and mitigate its long-term health risks*.

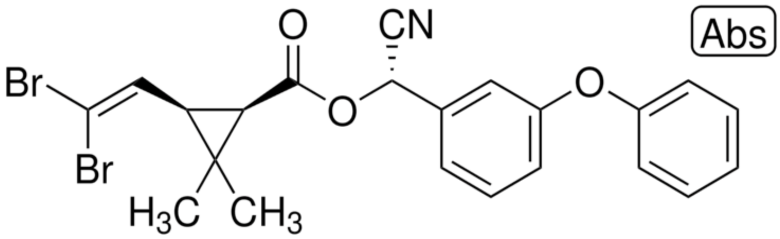
Keywords: Alzheimer’s disease; Microplastics; Neuro-pathophysiology; Neurodegenerative diseases; Parkinson’s disease; Plastic environmental pollution

Annex 4.

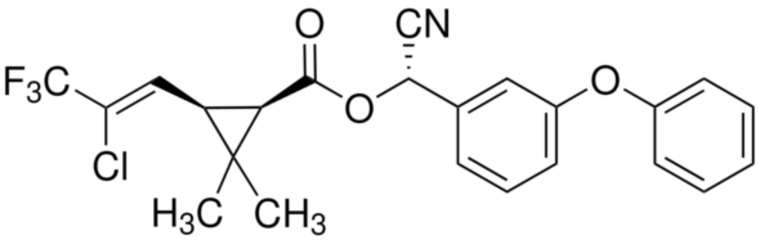
Formula of pyrethroids used for treating mosquito nets



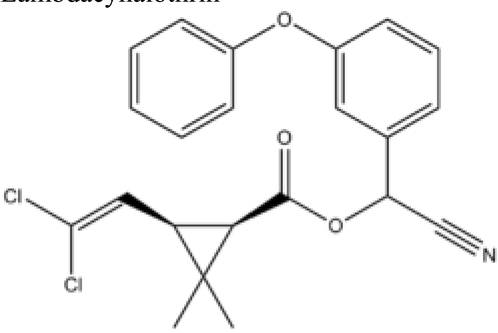
Permethrin



Deltamethrin



Lambdacyhalothrin



Alphacypermethrin

Annex 5. Emergency Pyrethroid

Main Risk
At very high doses, myoclonus, coma, and seizures are possible

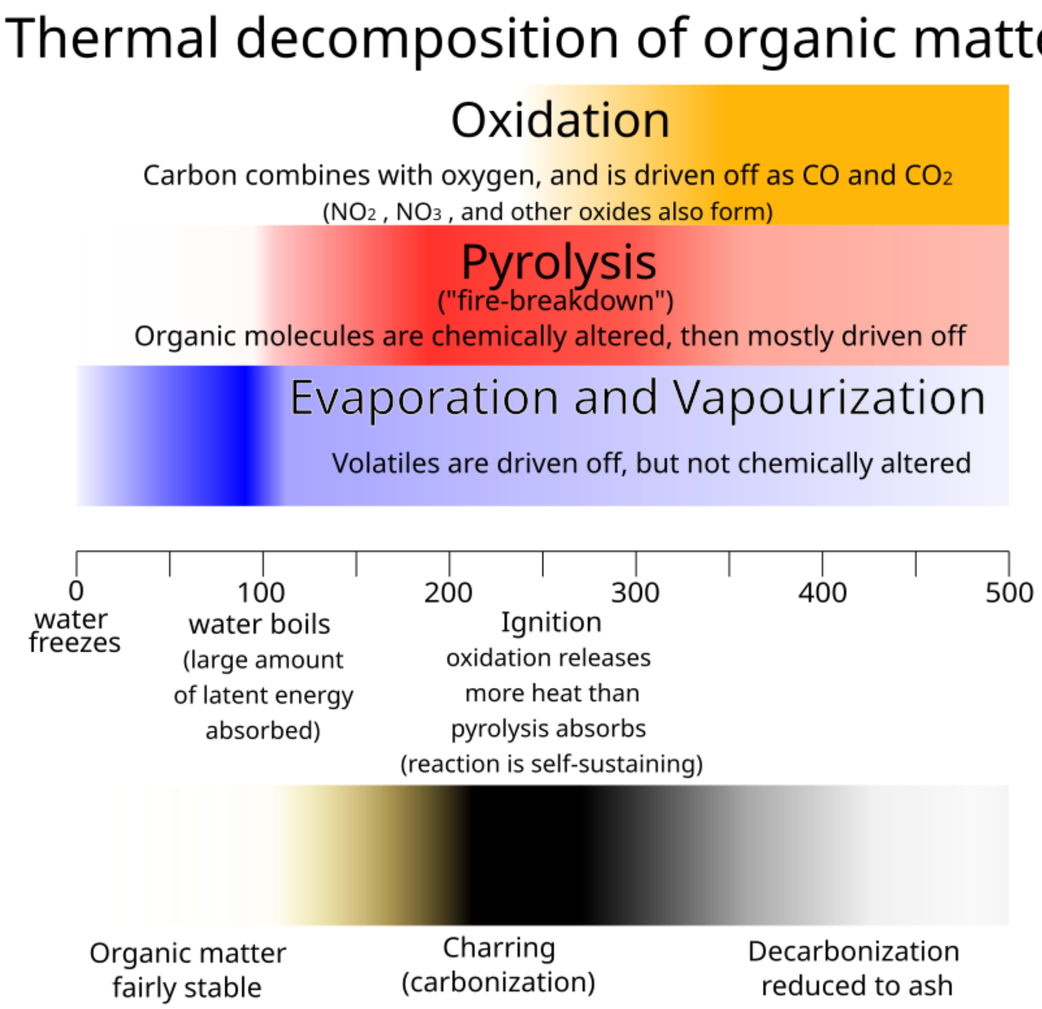
Key points
• Large doses (several grams) must be ingested to produce a significant toxic effect
• Solvents can contribute to the symptoms

General Information
• Widely used and relatively non-toxic insecticides
• Pyrethrum is derived from chrysanthemum
• Pyrethroids are produced through chemical synthesis
• Second- and third-generation derivatives are more insect-specific

Diagnostic elements
• During use
Skin and mucous membrane irritation, conjunctivitis
Skin and respiratory allergy
Facial and lip paresthesia and loss of consciousness (for professional use)
• When high doses are ingested
Initial digestive disturbances
Dizziness, headaches
Neuromuscular disorders: paresthesia, hyperexcitability, tremors, myoclonus, convulsions
Altered consciousness: drowsiness to brief coma

Action to take
• Treatment of eye splashes
• Treatment of skin splashes
• The clinical benefit of activated charcoal has not been formally demonstrated. Its administration as a single dose (50 g for adults, 1 g/kg for children) should be early, ideally within one hour of ingestion
• Symptomatic treatment

Annex 6. Principle of pyrolysis



Annex 7.

Per- and polyfluoroalkyl substances (PFAS)

Per- and polyfluoroalkyl substances (PFAS) are a large class of thousands of synthetic chemicals that are used throughout society. However, they are increasingly detected as environmental pollutants and some are linked to negative effects on human health.

They all contain carbon-fluorine bonds, which are one of the strongest chemical bonds in organic chemistry. This means that they resist degradation when used and also in the environment. Most PFAS are also easily transported in the environment covering long distances away from the source of their release.

PFAS have been frequently observed to contaminate groundwater, surface water and soil. Cleaning up polluted sites is technically difficult and costly. If releases continue, they will continue to accumulate in the environment, drinking water and food.

What are PFAS

PFAS have a wide range of different physical and chemical properties. They can be gases, liquids, or solid high-molecular weight polymers. Some PFAS are described as long-chain or short-chain, but this does not cover all of the different kinds of structures that are present in the PFAS class, which is very diverse. PFASs can be sorted in many ways based on their structure.

PFAS are widely used as they have unique desirable properties. For instance, they are stable under intense heat. Many of them are also surfactants and are used, for example, as water and grease repellents.

Some of the major industry sectors using PFAS include aerospace and defense, automotive, aviation, food contact materials, textiles, leather and apparel, construction and household products, electronics, firefighting, food processing, and medical articles.

Over the past decades, global manufacturers have started to replace certain PFAS with other PFAS or with fluorine-free substances. This trend has been driven by the fact that scientists and governments around the world first recognized the harmful effects of some PFAS (particularly long-chain PFAS) on human health and the environment. As the focus shifted to other PFAS, these have also been found to have properties of concern.

Concerns

The majority of PFAS are persistent in the environment. Some PFAS are known to persist in the environment longer than any other synthetic substance. As a consequence of this persistence, as long as PFAS continue to be released to the environment, humans and other species will be exposed to ever greater concentrations. Even if all releases of PFAS would cease tomorrow, they would continue to be present in the environment, and humans, for generations to come.

The behaviour of PFAS in the environment means that they tend to pollute groundwater and drinking water, which is difficult and costly to remediate. Certain PFAS are known to accumulate in people, animals and plants and cause toxic effects. Certain PFAS are toxic for reproduction and can harm the development of foetuses. Several PFAS may cause cancer in humans. Some PFAS are also suspected of interfering with the human endocrine (hormonal) system.

PFAS are released into the environment from direct and indirect sources, for example, from professional and industrial facilities using PFAS, during use of consumer products (e.g. cosmetics, ski waxes, clothing) and from food contact materials. Humans can be exposed to them every day at home, in their workplace and through the environment, for example, from the food they eat and drinking water.