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A Review on the Effects of Flame Retardant Additives Towards the Environment and Human Health

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Abstract: Flame retardant additives (FRAs) are normally the addition of chemicals that function to prevent or slow the spread of fires. These chemicals are used in consumer products and industries and could retain in the environment even after several decades. The toxicity mechanism and risk assessment methods of FRAs are also discussed in this paper. Papers from Scopus, Elsevier, Environmental health perspectives (EHP), Research gate, Semantic scholar, Hindawi, and Pubmed from 2003 to recent years were reviewed to provide some views on the possible risks of FRAs and their pathways into our environment as well as into human body. While FRAs could enter the environment during the manufacturing process and the usage period, consumer items are treated with FRAs, through waste streams, during illegal open burning of solid wastes, from incineration plants from landfill leachate and wastewater treatment plant (WWTP) sludge. FRAs are hazardous to humans and the environment; therefore, toxicology assessment should also be consistently conducted on the latest FRAs to ensure that they would not have adverse effects on humans and the environment.

Keywords: environmental pollution; human exposure; health risk assessment; SDG-3; silver nanoparticles; halogens.

1. Introduction

Flame retardant (FRs) is a type of chemical that can be added or layered onto combustible material to prevent or slow the spread of fires. This chemical is widely used in consumers and industrial products [1,2]. However, most of the commercial FRs used back in the day are now removed from the market. The nature of FRs that are highly resilient and can remain in the environment for decades is the primary concern. It has also been identified that those FRs can bio-accumulate or retain in both humans and the environment [2]. During the manufacturing of FRs, the chemicals present in them would leak into water and soil, while the smaller dust particles from the chemicals used to produce FRs would become air-borne particles. The widespread use of FRs in producing a wide range of consumer goods has resulted in unavoidable environmental discharges and human exposures [3]. There are three identified exposure routes for humans (inhalation, ingestion, and dermal contact), while there are several ways for the chemicals to enter the environment (wastewater, burning, landfill leachate, chemical production, etc.).

Nowadays, bio-composites are rapidly gaining popularity among various industries due to their cost-friendly and sustainable properties. As more bio-composites are being manufactured, their flame retarding properties should also be considered according to the Malaysian Standards for Fire Safety and Protection [4]. FRs can be added to bio-composites to enhance further the flame retarding properties of the materials; in this case, the FRs are known as FRAs. These FRAs are also chemicals with their unique flame retarding mediums, whereby the halogen mentioned previously is one of the types of FRAs. This study focuses on two types of FRAs, namely halogens and metallic nanometric particles.

Halogens are non-metals and are in group 17 in the periodic table. Halogens are extremely reactive. In large enough quantities, it can be damaging or deadly to biological organisms. The strong electronegativity and effective nuclear charge of halogens contribute to their high reactivity [5]. Research [6] indicated that when exposed to halogens, the lung and other organs will be vulnerable to environmental and occupational hazards. Chlorine causes hypoxemia, dyspnoea, airway blockage, pulmonary edema, pneumonitis, and acute respiratory distress syndrome when inhaled (ARDS). At the same time, inhalation of bromine causes airway hyperresponsiveness, bronchospasm, ARDS, and even mortality, even though it is less reactive and oxidative than chlorine [6]. An example of the dangers of halogen exposure is an incident that occurred in 2005. A local mill in Graniteville of South Carolina, USA, accidentally released 54 900 kg of chlorine, which resulted in the instant death of 8 victims from asphyxiation or acute respiratory failure after exposure on-site [7], while 529 victims survived the ordeal [8]. The surviving victims reported coughs and shortness of breath even after eight to ten months after the incident [9].

On the other hand, metallic nanometric particles or engineered nanomaterials are engineered chemical substances or materials with particle sizes between 1 to 100 nm and are separated into two categories; organic and inorganic [10]. The smaller size of nanometric particles allows it to cover a larger surface area and enables penetration into hard-to-reach areas. The previous study concluded three main reasons why nanometric particles are hazardous [11]: (1) it can penetrate deep into the lungs, causing significant harm, (2) it could enter the human body through the skin, lungs, or digestive system, generating "free radicals" to harm cells and DNA, and (3) the human body lacks natural immunity to novel compounds; hence nanometric particles would most likely be classified as harmful. Inhalation of carbon nanotubes suppresses the immune system by altering T cell activity, whereas exposure to nanoparticles causes brain injury in fish and dogs because nanometric particles can pass through the blood-brain barrier and move into the brain [11].

This paper focuses on bromine as the halogenated FRAs (BFRAs) and silver nanoparticles (AgNPs) as the metallic nanometric particle FRAs. The exposure routes to humans and entrance pathways to the environment of bromine and AgNPs additives will be further discussed in this paper. Other than that, the toxicity and health risk assessments conducted by previous studies will also be elaborated in this review, together with the relevant research results. It is important to conduct toxicology and health risk assessments, especially for novel chemicals that are introduced as potential FRAs. This is crucial as flame retardants are widely used in consumer products, buildings, and constructions. This paper will further highlight the side effects of chemicals on both humans and the environment, showing the importance of toxicology and health risk assessments.

2. Pathways and Exposure Routes for FRAs into the Environment and Human Body

The pathways into the environment and exposure routes into the human body for both BFRAs and AgNPs are similar. The major routes of entry of FRAs into the human body: ingestion, inhalation, dermal contact, and directly into the systemic circulation either by intraperitoneal or intravenous injection [1]. The main function of these FRAs is added to increase the .existing flame retardancy efficiency or provide flame retardant properties to consumer products such as furniture and electronic devices [12]. Thus, leading to the leaching of FRAs as it has been found in household dust, personal cars, interior air, and aquatic ecosystems [13].

2.1. Landfills.

Wastes such as kitchen wastes, municipal solid wastes, and yard wastes are dumped and buried in landfills. These landfills are exposed to the environment, and rainwater is free to flow and seep through the soil and buried wastes. The rainwater will mix with the degrading waste and form leachate, while the waste that degrades over time will form sediments. The leachate and sediments formed in the landfill are a complex mixture containing organic and inorganic compounds, influenced by the composition and solubility of the waste constituents [14]. A landfill is a significant source of existing environmental FRAs [15] as unwanted consumer products that contain FRAs are dumped into a landfill. The landfill is a significant food source for various vertebrates and a source of environmental pollution [16,17]. There are two main pathways for FRAs to enter the environment: leaching leachate to groundwater and emission into the air [18]. These two pathways were promoted by the photolytic and biodegradation of high molecular weight.

2.2. Wastewater treatment plants.

Wastewater sources may be from industrial, commercial, and domestic use and are released into the environment, such as oceans, lakes, and rivers. Wastewater is made up of 99.9% water and 0.1% organic matter. The organic content in wastewater originates from protein, fat, human feces, sugar material, and vegetables from food preparation and soap [19]. Polybrominated diphenyl ethers (PBDE) and novel brominated flame retardants (NBFRs) found in manufacturing, industrial and domestic waste may enter wastewater streams and would often preserve in sludge during the municipal treatment process [20]. These BFRAs and other substances may enter the environment through effluent discharge and biosolid land application [21]. PBDE is still the main concern as it is present in various consumer products and is discharged into the environment through WWTPs [22].

While for silver nanoparticles it is widely applied in consumer clothing articles due to their antibacterial property. When washed, AgNPs would enter the wastewater stream [23–25]. Even though most of the silver nanoparticles would be removed in the WWTPs process, there are still traces of AgNPs that retain in the WWTPs effluent [26,27]. Other than that, the AgNPs removed would retain in the WWTPs sludge, leading to soil contamination when the sludge is applied to soil for nutrient rectification [28,29].

2.3. Soil.

FRAs may enter the environment through atmospheric emissions from sources such as waste incineration, manufacturing, recycling facilities, and other industrial processes [20]. The chemicals that enter the environment can travel long distances in the air and settle on the soil. Another way for FRAs to contaminate soil is the application of wastewater treatment sludge to the soil for nutrient rectification as high concentrations of contamination are retained in sludge. In addition, leachate from landfills that do not have a bottom liner or a punctured bottom liner could seep through soil and travel with the underground water to contaminate larger soil areas.

2.4. Indoor dust.

Dust is made up of complex heterogeneous mixtures of organic compound and particle-bound matters. Indoor dust consists of materials that can be found within our homes, such as animal hair, textile fibers, human skin cells, and paper fibers. While outdoor dust is a combination of outdoor sources materials such as soil particles, vehicle combustion particles, pollen, or insect follicle parts [30]. FRAs combined with dust from outside our home could enter the house when the door or windows are opened or dust that adhered to our clothing when we were outside. The FRAs that are mixed with environmental dust are released during the manufacturing, washing, or disposal process of a product containing FRAs [31]. FRAs have often been discovered in indoor dust at concentrations surpassing 1µg/g [32]. Indoor dust is one of the major sources of human exposure to environmental contaminants and leads to a higher chance of toddlers' exposure to FRAs.

2.5. Breastmilk and blood or serum.

As FRAs are lipophilic in nature, food high in lipid content tends to have a higher contamination level. Therefore, the highest concentration levels can be found in aquatic foods, then meat, animal and vegetable fats, oils, dairy products, and finally eggs [33]. Mothers that ingest food contaminated with FRAs would be contaminated, which leads to bioaccumulation of FRAs in their bodies. Human breast milk and blood or serum is one of the exposure pathways of FRAs to infants. Infants obtain nutrients from their mothers' placenta (blood and serum transfer), which causes a contaminant transfer. After delivery, infants will feed on their mothers' breast milk, another pathway for contamination transfer. Therefore, breast milk and blood or serum are used as markers to assess human exposure and provide details on contaminant transfer from mother to infant [14].

3. Toxicity of FRAs to the Environment and Humans

FRAs are known to have the ability to accumulate in humans, animals, and the environment. Other than that, some researchers found that the FRAs in a mother's body could be transferred to a child either through placenta or breastmilk. This signifies that each child has been contaminated since they are still a fetus or a baby. It is difficult to study the toxicity of FRAs as a group because their physicochemical features are so diverse [3].

3.1. Ecotoxicity.

BFRAs such as PBDE were detected in birds' eggs and were linked as a culprit to the decline in breeding success and further decreasing their population [34]. Failed eggs were collected as it is a less intrusive analysis method. Previous study conducted stable isotope analysis, which indicated that the glaucous-winged gulls from the Salish Sea had become more dependent on terrestrial invertebrates and human refuses instead of their natural marine food [35]. This caused the decrease in clutch size and egg volume of that species starting as early as the 20th Century [36]. The authors from ref [37] identified that exposure to PBDE disrupts the thyroid system of common starlings. The oxidative metabolism of PBDE in the liver microsomes of juvenile common starlings is lowered, according to [38], implying that certain PBDE is likely to accumulate in individuals over time. The ring-billed gulls that breed in Quebec, Canada, were found to have demineralized bones due to PBDE exposure [39] and liver type-1 deiodinase mRNA conversely associated with hepatic ∑octa-BDE [40].

The widespread use of AgNPs could lead to severe consequences to microorganisms living in natural systems [25]. AgNPs are also listed under the priority engineered nanomaterials needed to undergo environmental risk assessment (ERA) [41]. It was found that silver ions (Ag^+) are potentially toxic to bacteria that are crucial towards nitrogen fixation in soil. Whereby the bactericidal activity of Ag^+ prevents microbial growth in soil [42,43]. Ag^+ interrupts environmental denitrification, leading to eutrophication in water bodies, a major drinking water pollutant [44]. Acute silver toxicity appeared to be induced mainly by silver ions interaction with the fish gills, disrupting basolateral sodium and potassium ion-ATPase activity, resulting in suppression of active sodium (Na^+) and chloride (Cl^-) ion intake and thus osmoregulation by the fish [45]. In order to analyze the hazards associated with the widespread usage of AgNPs, it is necessary to assess the effects of AgNPs on diverse cells as well as individual organisms, as well as the probability of their translocation in trophic chains via deposition in the plant, human, and animal tissues [46]. Compared to nanoparticles coated with peptides, AgNPs were shown to have a greater lethality [47]. The toxic effects of Ag^+ were higher than that of AgNPs, and therefore more research is needed to determine how nanoparticles (NPs) behave under environmental conditions such as the presence of cations and anions, pH, and the percentage of dissolved organic carbon. [48]. Another study by [49] found that the decrease in root length and germination rate are common side effects of the phytotoxic activity of AgNPs. It is noted that reactive oxygen species (ROS) production and bacterial cell porosity changes are the common silver toxicity mechanisms [50]. However, the photo-transformation, dissolution, or aggregation of AgNPs to soil particles may decrease AgNPs toxicity towards microorganisms [51]. In general, BFRAs and AgNPs' ecotoxicities are summarized in Table 1.

Table 1. Summary of BFRAs and AgNPs ecotoxicity.

Type of FRAs	Effects	Reference
BFRAs (PBDE, ∑octa-BDE)	Decreases clutch size and egg volume of glaucous-winged gulls’	[36]
	Disrupts common starlings’ thyroid system	[37]
	Diminishes juvenile common starlings’ liver oxidative metabolism	[38]
	Demineralization of ring-billed gulls’ bones	[39]
	Causes liver type- deiodinase mRNA in ring-billed gulls	[40]
AgNPs	Prevents microbial growth in soil	[42], [43]
	Disrupts environmental denitrification leading to uncontrolled eutrophication	[44]
	Restrain active Na^+ and Cl^- ion intake, interrupting osmoregulation in fish	[45]
	Decreases root length and germination rate of plants	[50]

3.2. Toxicity to the human body.

BFRAs are lipophilic, able to retain and accumulate in the lipids of animals and fish. The harmful effects of BFRAs are due to their persistency and ability to bio-magnify and bio-accumulate in humans [52]. The pediatric serum has higher concentrations of BFRAs than adults' serum [53–55]. They identified that breastfeeding and dust ingestion from children's mouthing behavior is the main contributor to the higher levels of BFRAs. The concentration of BFRAs in a fetus is remarkably similar to the concentration of BFRAs in their mothers [56]. As PBDE, a type of BFRAs, has a similar chemical structure with thyroid hormones (triiodothyronine, T3, and thyroxin, T4), PBDE can imitate and interrupt homeostatic conditions within the human body [57]. A study by [58] suggested that PBDE can cause autism or affect brain development. Children with higher PBDE concentrations scored lower in neurodevelopment tests than other children with lower concentrations of PBDE [59]. In human populations, PBDE and organophosphorus FRAs (OPFRAs) have also been linked to neurological and reproductive problems [60]. FRAs exposure appears to affect neurodevelopment, morphogenesis, muscle development, immune development, metabolism, and the development of numerous organs like the liver and heart. According to the data presented by [61-63], that chlorinated FRAs, BDE-47, and aryl FRAs interrupt the neurodevelopmental genes. Tetrabromobisphenol A (TBBPA), a type of BFRAs, were found to possibly induce increased expression of several genes involved in ROS production and osteoclast differentiation and promote the lysosomal exocytosis in cancer cells [64,65]. According to [59], TBBPA has been linked to thyroid abnormalities, neurobehavioral and developmental issues, reproductive health, immunological, oncological, and cardiovascular diseases. Human umbilical vein endothelial cells (HUVESs) were also found to be sensitive to PBDEs, while BDE-209 triggers HUVECs apoptosis and autophagy [66]. HUVECs' physiology and vascular function could be upset by NBFRs and their metabolites [67].

In the case of AgNPs, it is known to have the "Trojan-horse effect". This effect can be explained as the mechanism of nanotoxicity where AgNPs can penetrate through biological barriers and accumulate in cells. As time passes, it would release Ag^+ in high local concentrations when oxidizing agents are present. The silver element is harmless but not the Ag^+, as it is the main contributor to AgNPs toxicity [68].

Table 2. Summary of BFRAs and AgNPs toxicity to the human body.

Type of FRAs	Effects	Reference
BFRAs (PBDE, BDE-47, TBBPA)	Lipophilic nature causes it to be able to bio-magnify and bio-accumulate	[52]
	Imitates thyroid hormones, interrupting homeostatic conditions	[57]
	Causes autism or affect brain development	[58]
	Linked to neurobiological and reproductive problems	[60]
	Disrupts neurodevelopmental genes	[61-63]
	Increases the expression of genes involved in ROS production and promote lysosomal exocytosis in cancer cells	[64,65]
	Triggers HUVECs apoptosis and autophagy	[66]
AgNPs	Lead to blueish tinting of skin (argyria) and eyes (argyrosis)	[25]
	Able to pass blood-testes barrier and deposit in testes, harming sperm cells	[69]
	Causes ROS production leading to protein denaturation, membrane malfunction, apoptosis or genetic material damage	[71]
	Excessive ROS production, damaging biological components via oxidation of DNA, proteins and lipids	[72]

An estimation made by [1] was that humans ingest approximately 20 to 28 µg of silver daily. When exposed for extended periods to colloidal silver or silver salt deposits, it would lead to skin diseases such as argyria (skin) or argyrosis (eyes), which appears to be a bluish tint [25]. As AgNPs can pass through the blood-testes barrier, they could deposit in the testes and harm the sperm cells [69]. NPs can be administered in various ways, resulting in them passing biological barriers, being transported through the bloodstream, and then being distributed and deposited in various tissues and organs [70]. As a result, the kinetics of these processes should be carefully considered. Moreover, NPs or the Ag^+ released from AgNPs influence cells via ROS production, resulting in protein denaturation, membrane malfunction, apoptosis, or genetic material damage [71-79]. Excess ROS production could damage biological components via the oxidization of DNA, proteins, and lipids [80-87]. In general, BFRAs and AgNPs toxicities to the human body are summarized in Table 2.

4. Conclusions

FRAs are harmful to both humans and the environment. It can retain and bio-accumulate and bio-magnify in humans, animals, and the environment. FRAs enter the human body via ingestion, inhalation, dermal contact, and directly into the systemic circulation through intraperitoneal or intravenous injection. The environment is more susceptible to FRAs pollution as FRAs could enter the environment during the manufacturing process, during the usage period consumer items treated with FRAs, through waste streams, during illegal open burning of solid wastes, from incineration plants from landfill leachate and WWTP sludge. It can be concluded that all FRAs have similar entry routes into the environment and the human body. To prevent substantial amounts of these chemicals from entering the environment and our bodies, manufacturers should use FRAs in moderation. Waste streams should be properly treated before release, and sludge is tested from traces of FRAs before being used as nutrient source alternatives. Toxicology assessment should also be consistently conducted on the latest FRAs and FRs to ensure that it would not adversely affect humans and the environment. This is to ensure that future generations can live in a safer and cleaner environment. It is recommended in future studies to conduct toxicology assessments using in silico method to create a database to ease future researchers in identifying the side effects of the chemicals before mast production.

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Conflicts of Interest

The authors declare no conflict of interest.

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