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Polystyrene as Hazardous Household Waste

Trisia A. Farrelly and Ian C. Shaw

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Abstract

Polystyrene (PS) is a petroleum-based plastic made from styrene (vinyl benzene) monomer. Since it was first commercially produced in 1930, it has been used for a wide range of commercial, packaging and building purposes. In 2012, approximately 32.7 million tonnes of styrene were produced globally, and polystyrene is now a ubiquitous household item worldwide. In 1986, the US Environmental Protection Agency (EPA) announced that the polystyrene manufacturing process was the fifth largest source of hazardous waste. Styrene has been linked to adverse health effects in humans, and in 2014, it was listed as a possible carcinogen. Yet, despite mounting evidence and public concern regarding the toxicity of *styrene*, the product of the polymerisation of styrene, *PS*, is not considered hazardous. This chapter draws on a series of movements called the 'new materialisms' to attend to the relational, unstable and contingent nature of PS, monomers and other additives in diverse environments, and thus, we highlight the complexities involved in the categorisation of PS as 'hazardous' and the futility of demarcating PS as 'household waste'. While local examples are drawn from the New Zealand context, the key messages are transferrable to most policy contexts and diverse geographical locations.

Keywords: polystyrene, styrene, hazardous waste, New Zealand, materiality, carcinogen, new materialism

1. Introduction

This chapter is the product of an interdisciplinary collaboration between a social anthropologist and a toxicologist. This collaboration has allowed us to present polystyrene with a critical social anthropological approach that is underpinned with the scientific facts about this ubiquitous plastic pollutant. The anthropological contribution to this chapter is its new materialist lens through which the life and afterlife of polystyrene (PS) can be more clearly viewed. To the new materialists, objects are 'alive' because of their capacities to make difference in the world, to have effects and to shape the webs of interrelationships of which they are a part.

Therefore, bacteria, bees, a dead dog or charcoal all have the capacity to ‘animate, to act, to produce effects dramatic and subtle’ [1, 2]. One notable new materialist and physicist, Karen Barad [3] brings our attention to the propensity for science to examine one or a few things (e.g. monomers or species) in isolation from their natural context. She argues that these singular foci result in limited understandings about the full and complex life of matter involved in often unpredictable relationships with other materials, biological systems and ecosystems.

PS is a petroleum-based plastic made from styrene (vinyl benzene) monomer [4] (**Figure 1**). Since PS was first commercially produced in 1931, it has been used for a wide range of commercial, packaging and building purposes, and it has grown to be one of the world's most ubiquitous household items. Most PS is used to make rigid durable products, such as television and computer cabinets and appliances, and nearly all of the rigid PS packaging manufactured in New Zealand (NZ) is used for food contact purposes. PS used for food packaging includes general purpose PS (GPPS) such as disposable cutlery and plates; high-impact PS (HIPS) such as yoghurt containers and single-use cold drink cups; and expanded PS (EPS) foam used as meat trays, coolers and cups [4].

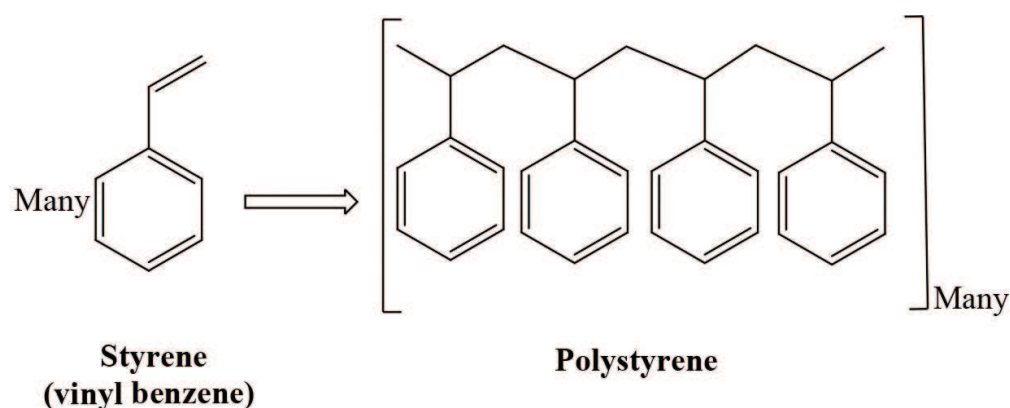


Figure 1. The manufacture of PS by chemically bonding many styrene (vinyl benzene) monomer units to form a long styrene polymer chain.

EPS is made of pre-expanded closed-cell foam beads. The manufacturing process involves carrying out the styrene polymerisation in droplets suspended in water. This leads to the formation of PS beads. EPS is useful because it is an excellent insulator (e.g. used to line cool boxes or chilly bins), and it absorbs shock and so it is a good moulded or bead-based packing material for transporting fragile cargo. It is used for a wide range of food contact packaging, such as meat trays, egg cartons and ‘clamshell’ fast food containers. EPS is often referred to by its trademark ‘Styrofoam’ invented by Dow Chemical in 1941. The trademark is informally used (not only in USA and Canada but also in NZ) for all foamed PS products, although strictly it should only refer to the ‘extruded closed-cell’ PS foam (XPS) made by Dow Chemicals and commonly used for building insulation.

While PS is popular because of its light weight and insulating properties, there is a downside to its high rate of production, consumption and disposal. In 2012, approximately 32.7 million

tonnes of PS were produced globally [5]. This figure is concerning, considering the lack of waste management of this man-made material. For example, Plastic NZ estimates that over 6784 tonnes of NZ-produced PS were consumed for packaging in NZ in 2003, with as little as 450 tonnes collected for recycling [4]. There are currently no PS residential collection services in NZ. This figure is also concerning because of the hazardous nature of the product and its components as will be explained.

In 2013, Chelsea Rochman, a scientist who studies the migration of chemicals from plastics when ingested by animals, was the lead author in an article in *Nature* which argued for the reclassification of some key plastics as hazardous so that they could be regulated by environmental protection agencies [6]. These key plastics are PVC, polyurethane, polycarbonate and PS.

Today, tens of towns and cities around the world prohibit the sale, possession and distribution of EPS, including Portland (Oregon, USA), Toronto (Canada), Muntinlupa (Philippines), Paris (France), and Tainan (Taiwan). While it still has been unable to enact a statewide ban, in 2016, the state of California has 65 ordinances (i.e. laws or regulations made by a local government body) on EPS, see Refs. [7, 8] (for full list). The reasons cited for ordinances banning or regulating EPS are primarily based on its potential as an environmental hazard: more specifically, a concern for the environmentally polluting potential of the physical properties of one type of PS rather than the chemical instability and potential for PS (as a family of plastics) to leak toxins into bodies and ecosystems.

Plastics harm in two key ways: chemically, when monomers, plasticisers and other hazardous PS additives leach from PS objects when poorly manufactured; physically, when PS breaks down into microplastics in the environment. The manufacture, composition and interrelationships of PS *in situ* are profoundly important in determining whether it is a 'hazard' [9].

Where the manufacture of PS is complete, the resulting styrene polymer has covalent (i.e. strong) bonds between the styrene monomer units; these bonds are difficult to break to release styrene. For this reason, styrene is not released from PS during environmental degradation. However, if the PS manufacturing process does not result in complete polymerisation, free styrene might remain in the PS product. This free styrene is not strongly bonded to the PS structure and so can, and likely will, leach out into the environment or into food stored in PS containers. In addition to the ability of styrene to leach from PS poorly manufactured products, this chapter will also outline the hazards resulting from the breakdown of PS into microparticles over prolonged periods.

2. Styrene monomer

While the level and nature of the hazard posed by styrene have historically been hotly disputed, a growing body of evidence indicates cause for policy action to protect populations from its misuse. For example, in 2014, the International Agency for Research on Cancer (IARC) determined that styrene is a possible human carcinogen. This is based on studies in animals and emerges from research into styrene's metabolite (i.e. styrene oxide) as a chemically highly

reactive epoxide, which might chemically bond to DNA and thus initiate carcinogenesis (**Figure 2**). It is now largely accepted that styrene oxide is likely to be responsible for styrene's carcinogenicity, and since there are likely to be species and inter-individual differences in metabolism, there are also likely to be differences in susceptibility to carcinogenicity between species and individuals [10].

The EPA National Human Adipose Tissue Survey for 1986 identified styrene residues in 100% of samples of human fat tissue taken in 1982 in the USA [11], which indicates widespread exposure. In laboratory studies (e.g. in rats), styrene monomer and some other ingredients of PS have been shown to be carcinogenic and, in some cases, affect organisms in a similar way to the hormone oestrogen [9, 12, 13] because of their molecular mimicry of the female hormone 17β -oestradiol and occupancy and activation of oestrogen receptors.

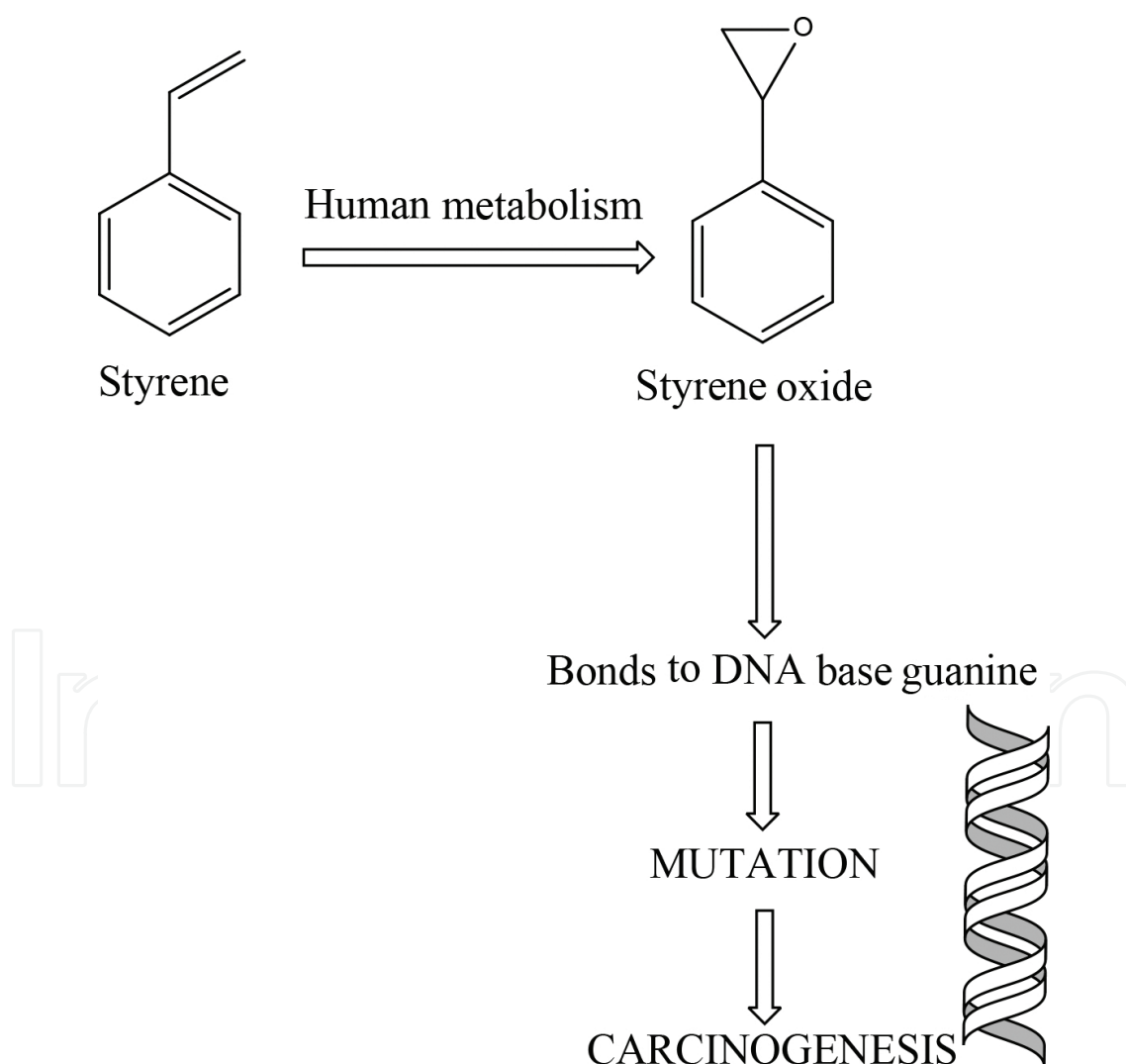


Figure 2. Styrene is metabolised to a highly reactive and toxic epoxide, styrene oxide, which can interact with DNA causing a mutation which might initiate carcinogenesis.

The National Toxicology Programme's Report of Carcinogens states that styrene is

reasonably anticipated to be a human carcinogen. First listed in the Twelfth Report on Carcinogens (2011) HC CH 2 Carcinogenicity Styrene is reasonably anticipated to be a human carcinogen based on limited evidence of carcinogenicity from studies in humans, sufficient evidence of carcinogenicity from studies in experimental animals, and supporting data on mechanisms of carcinogenesis [14].

The National Regional Council concurred in 2014:

Review of the Styrene Assessment in the National Toxicology Program 12th Report on Carcinogens concurs with the NTP determination that there is limited but credible evidence that exposure to styrene in some occupational settings is associated with an increase in the frequency of lymphohematopoietic cancers. Additionally, the NRC report authoring committee independently reviewed the scientific evidence from studies in humans, experimental animals, and other studies relevant to the mechanisms of carcinogenesis and made level-of-evidence conclusions. Based on credible but limited evidence of carcinogenicity in traditional epidemiologic studies, on sufficient evidence of carcinogenicity in animals, and on convincing evidence that styrene is genotoxic in exposed humans, this report finds that compelling evidence exists to support a listing of styrene as, at a minimum, reasonably anticipated to be a human carcinogen [14].

More recently, on 22 April 2016, the Office of Environmental Health Hazard Assessment OEHHA added styrene to the list of chemicals known to the state to cause cancer [15]. The NZ EPA (and similarly, the US EPA) determines that styrene is 'possibly carcinogenic to humans' and classifies the chemical as otherwise hazardous due to its following characteristics: flammable, acutely toxic, suspected human mutagen, carcinogen, and human reproductive or developmental toxicants, toxic to organs/systems, very ecotoxic in the aquatic environment to algal and crustaceans, slightly harmful to fish and ecotoxic to terrestrial vertebrates [16].

The categorisation of styrene as 'toxic' is unequivocal because, due to its high chemical reactivity, it interacts with cell systems causing widespread metabolic damage. In particular, styrene can chemically react with specific components of DNA resulting in changes, which affect the rate of division of cells (**Figure 2**). This mutation is the basis of chemical carcinogenesis and explains why styrene is a carcinogen in animal studies and reasonably anticipated to be a carcinogen in humans [14].

The IARC's statement that styrene is a possible human carcinogen is reinforced in statements made by the USA and NZ Environmental Protection Agencies (EPAs). The USA and the NZ EPA, among other EPAs globally, classify styrene as 'hazardous' under a wide variety of ecotoxic and toxic categories (see later in this chapter). The NZ EPA rates the environmental hazards associated with styrene as follows: 9.1A (algal): very ecotoxic in the aquatic environment; 9.1B (crustacean): very ecotoxic in the aquatic environment; 9.1D (fish): slightly harmful in the aquatic environment or otherwise designed for biocidal action; 9.3B: ecotoxic to terrestrial vertebrates [14]. In addition, the European Union currently places styrene in Category 1 in their list of potential endocrine disruptors,ⁱ see Ref. [17], also Refs. [12, 18]. These new categorisations align with a growing global interest in the hazardous nature of the ingredients used in the production of plastics. Interestingly, according to a hazard-ranking model based on the United Nations' Globally Harmonized System of Classification and Labelling of Chemicals, the chemical ingredients of more than 50% of plastics have now been determined to be hazardous [19].

3. The polymerisation of styrene

Despite building evidence and public concern regarding the toxicity of styrene, the product of the polymerisation of styrene, PS, is not listed as 'hazardous' in any policy documents. Regardless, some community groups [20] and a growing number of independent scientists [6] now treat PS as a hazardous waste item. When styrene is fully polymerised in the manufacturing process to form PS, the reactivity of the styrene component of the polymer is removed completely because the chemical bond that forms between the monomer units changes the nature of the reactive moieties of the styrene molecule. This explains why PS has very low mammalian toxicity. In addition, as discussed earlier, the monomer units are very strongly bonded together which means that styrene monomer cannot be released, in an environmental context, from its polymerised form. The bacterial degradation (e.g. in landfill) of PS does not liberate styrene, but rather produces substances such as 4-phenylvaleric acid which is of low toxicity [21].

However, if the styrene polymerisation process used in the manufacture of PS is *not* complete, styrene monomer might contaminate the PS (termed 'residual monomer'). This styrene can migrate into food packed in styrene-contaminated PS. Since styrene is reasonably fat soluble ($\text{LogP}_{\text{OW}}[\text{styrene}] = 3.6$; i.e. styrene is $10^{3.6}$ times more soluble in fat than water), migration is greater in fatty foods (e.g. milk) in PS containers [22]. On these solubility grounds, migration of styrene into a water-based ecosystem is less likely than into fat-containing foods, but taking account of the vast quantities of water in the environment, even at low water solubility, significant transfer of styrene to aqueous ecosystems will occur. Once in the aquatic environment, styrene will be rapidly absorbed via the lipid-based cell membranes of aquatic organisms and will concentrate up the food chain. Thus, styrene is more likely to affect animals at high trophic levels (i.e. predators).

Other chemicals (e.g. plasticisers) are sometimes added to PS to modify its physical properties for particular applications. For example, tris(4-nonyl-phenyl) phosphite is sometimes added as an antioxidant to prevent PS degradation. Such molecules can leach from PS and contaminate both the environment and products (e.g. food) stored in PS containers.

Regardless of whether styrene is completely polymerised or not during the manufacture of PS, all PS waste have significant implications for the environment. This is because the complete environmental degradation of PS is very slow and produces small PS particles *en route*. These PS particles have significant implications in ecosystems as they build up in, for example, marine environments. In addition to the physical hazards they pose, hydrophobic plastics such as PS are the most hazardous of plastics in fresh water and marine ecosystems because of their ability to adsorb persistent organic pollutants (POPs)—such adsorbed POPs can be released following ingestion of PS microparticles by animals (e.g. fish).

4. Polystyrene as an environmental hazard

While PS is highly valued for its light weight, strength, thermal insulation and shock absorbing properties, its production and disposal reveal significant threats to the environment. Today, most plastic waste goes to landfills where chemicals can leach from the plastic and

contaminate soil and groundwater [23]. The US EPA reports that '[e]ach year Americans throw away 25,000,000,000 [25 billion or 47,565 per minute] Styrofoam cups. Even 500 years from now, the foam coffee cup you used this morning is likely to survive intact in a landfill' [24].

There is no domestic kerbside collection of any form of PS provided by councils in NZ. The lack of PS recycling services available to householders in NZ and the volume of EPS make disposal via council rubbish bags expensive. Consequently, littering or 'fly tipping' and household Burning of PS can become residential alternatives, thus raising the likelihood of releasing PS and its potentially toxic combustion products into the environment.

4.1. Ecotoxicity in the manufacture of polystyrene

In 1986, a US EPA report on solid waste declared PS manufacturing the fifth largest source of hazardous waste in the USA [16]. In addition, the manufacture of PS is energy intensive, creating large amounts of greenhouse gases (e.g. CO₂) and liquid and solid waste. To add to this life-cycle-based harm to the environment, PS is manufactured from petroleum: a non-sustainable and heavily polluting resource. Consequently, the environmental production costs of PS have been ranked the second worst in the USA by the California Integrated Waste Management Board [25].

It is possible that differences in manufacturing practices might lead to different levels of monomer residues remaining in the final product. For example, very preliminary studies on polycarbonate plastics showed that very different amounts of bisphenol A (BPA) monomer leached from different plastic products manufactured in Korea, China and NZ [26]. While very preliminary, this might reflect differences in manufacturing processes and controls between these countries. As Asia becomes the region of choice (on economic grounds) for manufacture of many plastic products, it is possible that PS products made with residual plastic monomers will increase. Consequently, the risk of monomer leaching into the environment and into products stored in plastic containers will rise as a result. The increase in free trade of these PS objects across geopolitical boundaries means that regulating the manufacture and responsible disposal of PS is very complex indeed [26].

4.2. Physical and ecotoxic threats in marine environments

Plastic pollution in marine environments has become so dire that the term 'plastic pollution' is now synonymous with 'marine pollution' [7]. A 2016 World Economic Forum report predicts that the ratio of plastic to fish in the ocean is expected to be 1:3 by 2025 [27]. Currently, 60–80% of waste found in marine environments is plastic [28], and in 2014, it was estimated that more than 226,796 tonne of plastic is currently afloat at sea [29]. Because of its light weight, PS is highly mobile and can transport invasive species across marine boundaries. PS is prevalent in NZ coastal areas: for example, in a 2016 study of microplastics on Canterbury's (NZ) coastlines, the majority of plastics (55%) found were PS [30].

Douglas McCauley, a marine biology professor at the University of California, Santa Barbara, USA studied the mechanical and chemical causes of harm to marine animals from EPS. The environmental degradation of PS (e.g. by bacteria) leads to the production of small fragments (microplastics) which survive for a very long time in the environment (e.g. in marine systems)

and cause physical effects. For example, fish mistake the PS particles for food and eat them. This leads to malnutrition as PS provides fish with no nutritional benefit while making them feel full, thus suppressing a desire to eat [6, 31]. Plasticisers and other additives are less common in PS products than in other plastics (e.g. polyvinyl chloride [PVC]). However, the antioxidant tris(4-nonylphenyl) phosphite sometimes used in PS products is a potent oestrogen mimic and is part of a cocktail of estrogenic environmental contaminants that is thought to be responsible for male feminisation in animals and humans [32]. To be clear, styrene is *not* produced by the environmental degradation of PS but by the leaching of residual styrene from incomplete polymerisation.

As outlined above, there is a further, very important, property of PS that has a significant bearing on its environmental and human toxicity: its extreme hydrophobicity. Since, in a chemical context, like chemical properties attract like, PS attracts and adsorbs (i.e. sequesters on its surface) other hydrophobic molecules (e.g. POPs). This is important because it means that micro PS particles (produced as part of the environmental degradation of PS) will sequester and transport POPs and other hydrophobic toxins in the aquatic environment. If PS microparticles are ingested by animals (or humans), the sequestered POPs might be stripped from the PS and absorbed into the animal's system. This makes PS an excellent vector for highly toxic hydrophobic chemicals.

Seabirds that have consumed plastic waste have been found to have polychlorinated biphenyls (PCBs) and POPs in their tissues at 300% greater concentrations than in similar birds that have not eaten plastic [31]. PS is particularly good at attracting oily (i.e. hydrophobic) chemicals such as PCBs, flame retardants such as polybrominated diphenylethers (PBDEs), pesticides (e.g. DDT) and surfactants (e.g. 4-nonylphenol an endocrine disruptor). These chemicals have been estimated to be adsorbed by PS at concentrations up to a million times greater than in the surrounding water [33].

The chemicals PS attracts are regarded as 'priority pollutants':

...[C]hemicals that are regulated by government agencies, including the US EPA, because of their toxicity or persistence in organisms and food webs. These chemicals can disrupt key physiological processes, such as cell division and immunity, causing disease or reducing organisms' ability to escape from predators or reproduce [6].

Rochman and her team found that at least 78% of priority pollutants listed by the EPA and 61% listed by the European Union (EU) were associated with plastic debris (either ingredients of plastic or adsorbed from the environment) [6]. PS microplastics contaminated by these POPs enter the food chain when eaten by marine species and might end up on our dinner tables at home [34].

Taking all of these chemical and toxicological properties of PS into account, PS *per se* is one of the less problematic plastics in a purely toxicological sense. However, its high rates of production, poor waste management, slow environmental degradation to form microparticles and adsorption of hydrophobic toxic chemicals have led, at the macro level, to huge quantities of PS waste presenting physical problems at all environmental levels, and, at a micro level, PS transporting adsorbed toxins to unsuspecting marine ecosystem consumers. It is

clear that a policy connection has not yet been made between these hydrophobic polymer 'carriers' and priority pollutants in the marine environment. If there were, it would be more likely that there would be cause to categorise hydrophobic plastics as 'hazardous.' Growing evidence, however, continues to highlight the previously unforeseen and complex relational behaviours of PS and its additives with other materials and bodies in marine environments. This growing evidence supports Liboiron's [9] argument that the governance of plastic pollution via 'safe levels' may not adequately capture the 'afterlives' of plastic polymers. The next section will further advance the argument that a more nuanced and context-specific approach is needed. This approach attends to the complex relational nature of polymers, monomers and other additives when they come into contact with other matter and materials in diverse environments.

4.3. Polystyrene combustion

The incomplete combustion (at temperatures that equate to household burning) of PS produces myriad products including styrene, PAHs, including fluoranthene which has been shown to be carcinogenic in mouse studies [35, 36] and the IARC, have classified it as a Group 3 carcinogen (i.e. not classifiable as to its carcinogenicity to humans). Concerns have also been raised about PS as a hazard during house or commercial building fires or the disposal of PS by burning due to the toxins it releases when PS is combusted, particularly when incinerated as household waste in residential areas. The National Bureau of Standards Center for Fire Research identified 57 chemicals released during the combustion of EPS. Of these, perhaps the most toxic include, PAHs, carbon black (i.e. the copious soot produced when PS burns) and carbon monoxide [11].

The use of extruded XPS and EPS in building construction is also a focus of concern due to the persistence, toxicity and ecotoxicity of the brominated flame retardant HBCD used in the manufacture of these PS foams. In response to these growing concerns, the EU (under the Stockholm Convention) banned the use, import or export of HBCD on 26 November 2015 [37].

5. Polystyrene and food safety

PS can be hazardous to human health in the following circumstances: eating marine animals contaminated with the residual monomers and additives in PS and the POPs adsorbed onto PS; inhalation of gases created when PS is heated or combusted; chemical exposure in the manufacture of PS; and exposure to tropospheric ozone caused by HFCs in the manufacture of PS. In this section, we will discuss the possibility that PS food containers that have been exposed to certain conditions [fats (e.g. Vitamin A) and heat] can increase the potential for styrene contaminants to migrate into food and bodies.

New scientific research is raising some doubt about the safety of food when in contact with PS under certain conditions. One of those conditions has been recognised in the US FDA guidelines in contact with fat above ambient temperature [22, 38, 39]. In 2014, the European Food Safety Authority (EFSA)'s Panel on Food Contact Materials, Enzymes, Flavourings and

Processing Aids (CEF) conducted a study requested by the Food Standards Agency (FDA), UK. They concluded the following:

...substances (butadiene, ethyl acrylate, methyl methacrylate, styrene) copolymer, (butadiene, ethyl acrylate, methyl methacrylate, styrene) copolymer crosslinked with divinylbenzene and (butadiene, ethyl acrylate, methyl methacrylate, styrene) copolymer crosslinked with 1,3-butanediol dimethacrylate, in nanoform do not raise a safety concern for the consumer if used as additives individually or in combination at up to a total of 10% w/w in non-plasticised PVC used in contact with all food types at ambient temperature or below including long-term storage [40].

However, household PS is not always used in contact with food at ambient temperatures; food is often heated in PS containers in microwave ovens; polystyrene cups and food containers are most commonly used for hot beverage consumption. This again raises the question of safe levels of styrene monomer and safe conditions of use when PS items are exposed to a wide range of untested conditions introducing a toxic risk.

One notable study emphasising the need for further attention to the potential leaching of styrene from PS containers into food is that of Matiella and Hsieh [41]. The researchers reported that volatile styrene monomer was found in shells of eggs after they were stored for 2 weeks in PS containers at supermarkets. Dishes cooked with these contaminated eggs contained seven times more ethylbenzene and styrene compared to those prepared from fresh farm eggs not packaged in PS. Not surprisingly, the American Chemistry Council (representing the plastics industry) vehemently denies any health risks posed by PS food packaging to the US public [42].

6. Discussion

The central dogma of modern toxicology is the Paracelsus principle: 'the dose makes the poison' [43] (the higher the dose, the greater the effect). However, some plastic monomers have a high biological impact at low doses (e.g. oestrogen mimics work at 10^{-5} M) meaning that testing regimes and the policies they inform need to change to address these trace environmental and food contamination exposure levels [44]. Testing regimes and their subsequent 'safe limits' significantly influence what is defined as 'hazardous' or 'safe'.

Under current testing regimes, we can no longer be certain about the production of risk-free objects (arguably nothing is risk free) [45]. Laboratory testing for safety may not provide us with a clear indication of how monomers may act within a variety of ecological and biological contexts, and what the consequences may be. Specifically, toxicity testing regimes simply do not mimic environmental systems and the interrelationships between pollutants well enough for them to give us a reliable indication of the environmental fate and behaviour of complex plastics.

The work of the new materialists is valuable in illuminating the complex nature of materials, the politics of testing regimes and the interpretation and categorisations of what is 'hazardous'. Objects, discourses, identities and politics emerge through particular relationships. In this case, whether PS is 'hazardous' or not largely depends on how scientists establish testing regimes and categorise, analyse, and interpret data. The ethics of categorising PS as

'hazardous' (or not) is not fixed and predetermined; it changes and unfolds as scientific findings, and their interpretations are negotiated [3].

The current approach to defining something as 'hazardous' or 'safe' involves an almost singular focus (e.g. on styrene monomer). However, if we are to safely manage PS production, consumption and disposal, we must scrutinise the life and 'afterlife' of each component that is used in the production of each PS product in the context of its fate and behaviour in the environment. This involves the engagements of its additives and intended end-products to other matter, materials and ecological and biological systems. This brings to question the term 'PS end product' and 'end of life'. If the 'end product' or the 'end of the life' of the product is defined as when the product no longer serves its original function, we are missing the ongoing impacts of the product on bodies and environments long after it is considered 'defunct'. The toxicity of PS continues long after its useful life.

The new materialisms also require a mobile approach. This would involve following PS objects and their interrelationships with other things. This is a call to reimagine PS in its various forms as unstable and impermanent with indeterminate consequences and trajectories. This is also a political call to scrutinise *how* PS is culturally constructed as 'hazardous' or 'safe' and by *whom*: a concern captured by what has been referred to recently as 'the politics of plastics' [46, 47]. In addition, this scrutiny might encompass the cumulative impact of substances in bodies. For example, chemicals that humans are exposed to from food and the environment might have additive effects both physiologically and toxicologically and thus should be considered together rather than individually [32].

This chapter also serves as a reminder that 'household waste' is a misnomer as it implies a kind of simplistic demarcation of space, whereas PS enters the home and can only be intentionally removed intact as solid 'waste'. Yet, PS household waste items can never be fully and successfully 'managed' by waste management infrastructures to a final resting place in landfills or recycling centres where they magically disappear from our lives and no longer impact on the environment. The PS items that enter households often originate from far flung places, diverse components and industrial processes (with varying levels of regulation). They enter bodies and become entangled with other materials and matter in the household, while other PS solid objects are constructed as 'waste items' and their invisible, ungoverned and now free-floating chemical components move on. They leave households to continue their unpredictable journeys to landfills or to impact other ecosystems and bodies. Outside the regulatory and technological structures of policy and waste management systems, the kinds of risks PS poses become even more difficult to detect and mitigate.

7. Conclusion

As Liboiron reminds us, the 'afterlives' of industrially produced objects are the longest part of their lives' [7]. This means that we can no longer limit our analyses and determinations of the hazardous nature of PS within the bounded spaces of the factory, retail store, home, landfill, marine environment and their return via the food chain to the dinner plate back home. That

said, shall we continue to treat polymers and monomers as discrete points of analysis in the development of legislation, policy and activism around hazardous waste and follow each one through all these spaces and beyond? Or in combination? And with other matter as they move through these spaces? How do we determine safe levels; or whether a PS is, or is not, 'hazardous' (considering the infinite and indeterminate contingencies and contexts of PS's interrelationships with other chemicals and bodies)? And who determines the safety of PS when this determination depends on pre-existing cultural values and agendas [48]?

While humans have the capacity to produce PS, we can never make it go 'away' when it no longer fulfils its, often short-term, function. However, at current rates of consumption, another 33 billion tonnes of plastic will be produced by 2050. Rochman et al. suggest that if the most problematic plastics were to be classified as hazardous immediately and replaced with safe alternatives, this rate could be reduced to 4 billion tonnes [6]. PVC, polystyrene, polyurethane and polycarbonate make up 30% of all plastic production. They are considered 'priority' plastics by Rochman and her team because they are particularly difficult to recycle and are made of potentially toxic materials. However, as we have argued, these plastics may only be considered 'hazardous' when in certain biophysical or ecological contexts. Does this mean that we should continue to produce these plastics and seek ways to ensure these hazard-causing scenarios do not occur? Or are the possibilities for PS to be located in contexts where they are hazardous unavoidable, meaning that a blanket ban on the production of these plastics is the only option?

This chapter has raised more questions than it can answer. However, we hope that it broadens attention to the 'aliveness' [1] of PS. The material quality of PS (its materiality) allows it to slip through the net of human intention, and outside the waste management infrastructure, the economic system and the policies and legislation designed to contain it, profit from it, and keep us safe. We have created these rogue materials and like Pandora's Box, they have escaped human management systems. Now, we need to recapture them, if only in our mind's eye for now, if we are to act to mitigate their real and future risks for human and non-human life—inside and outside the household.

Author details

Trisia A. Farrelly^{1*} and Ian C. Shaw²

*Address all correspondence to: T.Farrelly@massey.ac.nz

1 Massey University, Palmerston North, New Zealand

2 University of Canterbury, Christchurch, New Zealand

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