Problems with Polystyrene Foam

Environmental fate and effects in the Great Lakes

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Contents

Abbreviations

EPS	expanded polystyrene
HBCDD	hexabromocyclododecane
HDPE	high-density polyethylene
PAH	polycyclic aromatic hydrocarbon
PBDE	polybrominated diphenyl ether
PET	polyethylene terephthalate
PFAS	per- and polyfluoroalkyl substance
PP	polypropylene
PS	polystyrene
PVC	polyvinylchloride
XPS	extruded polystyrene

Executive Summary

Polystyrene (PS) foam can be found littering habitats in the Great Lakes and St. Lawrence River basin. More commonly known as Styrofoam®, polystyrene foam is widely available, cheap, and often used in food and beverage containers, building insulation, and floating docks. One way polystyrene foam pollutes the Great Lakes is through the fragmentation of expanded polystyrene (EPS) and extruded polystyrene (XPS) used in docks and floats.

Large PS foam litter collected, 2019

Fragmented PS foam shoreline litter, 2019

Litter source: Unencapsulated PS dock foam

Litter source: Unencapsulated PS foam, fragmenting

Polystyrene contamination - When unencapsulated PS foam docks and floats come into contact with their surroundings – sun, wind, waves, ice, and burrowing animals – the foam can break apart and be released into the environment. Small foam pieces are microplastics (plastic <5mm), which are persistent in the environment and pose a risk to fish and wildlife.

Widespread and global contamination has resulted in PS foam being found in the gut contents of wildlife, including Great Lakes – St. Lawrence River species. PS foam has been recorded in the gastrointestinal tracts of several species of fish and birds from the Great Lakes (Brookson et al., 2019; McNeish et al., 2018; Thaysen et al., in review; Wagner et al., 2019). Fish and wildlife in habitats around the world are contaminated with PS.

PS foam is one of the top items of debris found on shorelines, beaches, and surface water around the world, including the Great Lakes – St. Lawrence River basin. Over 500,000 foam pieces were collected in shoreline cleanups on the Great Lakes recorded by Great Canadian Shoreline Cleanups (GCSC) and the International Coastal Cleanups (ICC) in 2016-2018. In 2019, shoreline clean-ups on Georgian Bay recorded polystyrene foam as the most common litter item and collected over 5,000 pieces in nine shoreline cleanups. Polystyrene foam is one of the top items collected in Seabins on Lake Ontario. Important volunteer efforts continue to remove some of this litter, but polystyrene foam pollution is still widespread.

The problem - PS foam can hurt wildlife by ingestion through physical damage, including blockage and abrasion, and through exposure to chemicals. PS foam can contain two types of chemicals: (1) additives and polymeric raw materials (e.g. monomers) originating from the plastics, and (2) chemicals adsorbed from the surrounding environment. Overtime, these chemicals can leach out of plastics and often these leachates can act as toxic or endocrine disrupting chemicals (Hermabessiere et al., 2017).

When ingested, PS microplastics pose adverse effects to wildlife. Laboratory experiments show negative impacts of PS on growth, survival, feeding and swimming behaviour, hepatosomatic index (HSI), and reproduction (Cole et al., 2015; Sussarellu et al., 2016; Qiang and Cheng 2019; Yu et al., 2018). Under certain conditions, PS foam leaches styrene, benzene, and ethylbenzene which have known toxic properties (Thaysen et al., 2018). The leaching of PS monomers is one of the reasons why there is greater concern with polystyrene relative to other types of plastic.

PS foam impacts aesthetic enjoyment of the Great Lakes and navigation. In some instances PS docks and floats have been banned due the hazards of PS "icebergs" to boat traffic.

1. Introduction

1.1 Background

Polystyrene (PS) foam is widely used, which is why it is found in the environment. A common material used in floating docks, unencapsulated PS foam floats are directly exposed and can fragment into pieces of foam. Large pieces of foam litter from boat docks are sometimes referred to as "icebergs," and the small fragmented pieces of foam that litter shorelines and waterways have the potential to break down even further into small foam microplastics (plastic pieces <5mm). Many mechanisms that physically and chemically degrade PS foam into microplastics are outlined in this report.

This report describes the production and use of PS foam, describing some of the sources of PS foam to the environment. Common types of PS foam include expanded polystyrene (EPS) and extruded polystyrene (XPS). These materials are used in water for dock floatation and contain a range of different chemicals. This report then provides evidence on how PS foam is often reported as one of the most common types of plastic pollution around the world and in the Laurentian Great Lakes.

The impacts of PS foam in the environment are wide ranging. PS foam impacts fish and wildlife, navigation, beach aesthetics, and there are potential health concerns from exposure to chemical additives. These PS foam docks, especially when unencapsulated, are a known source of plastic pollution and chemical contaminants to waterways around the world. When PS foam enters habitats, it can be ingested by animals in the wild. Examples of PS effects demonstrated in the laboratory include reduced growth, mortality, oxidative stress, changes to behaviour, and reduced reproductive output. Reducing environmental impacts from dock floats is a known challenge to managers worldwide (ERDC, 2009).

"Iceberg" PS foam litter picked up by volunteers in 2019

Examples of the thousands and thousands of fragmented pieces of PS foam on shorelines

The results presented in the main body of the document are brief so as to facilitate quick reference for what is known about the production, fate, and effects of PS foam, and associated chemicals. More detail on the underlying evidence base is provided as a series of annexes.

1.2 Objectives

The objectives of the report are:

1. to provide evidence on the relationship between dock floats and plastic pollution;
2. to present on the known fate and effects of PS foam in the environment;
3. to share data on where PS foam pollutes the environment in Georgian Bay and the Great Lakes basin from (1) shoreline cleanups and other citizen science efforts, (2) the Seabin Pilot Project, (3) peer review journal articles and (4) reports;
4. to facilitate evidence-based information on the ecotoxicity of PS by bringing together a number of existing studies;

1.3 Scope

The report provides evidence to identify sources, understand environmental fate and determine effects to aquatic species of PS foam. This report shares data from shoreline cleanups and other citizen science efforts, the Seabin Pilot Project, peer review journal articles and other reports. This report also outlines what is known currently about PS foam associated chemicals. The evidence presented here relies on aquatic studies from Georgian Bay, the Great Lakes, St. Lawrence River, and other freshwater and marine studies.

2. Polystyrene (PS) production and use

Polystyrene (PS) is a widely used plastic with a range of applications. PS can be produced into several material types, although the majority of PS production is expanded polystyrene (EPS) and extruded polystyrene (XPS) foam. The global demand for PS reached 14.9 million tons in 2010, and the market for this material is expected to grow (EUMEPS, 2020). As a result of its high production and use, PS foam has become a major commodity, but also a major contaminant. PS foam is commonly reported as one of the top items reported in habitats and wildlife (Convey et al., 2002; Garrity and Levings, 1993; Hinojosa and Thiel, 2009; Morét-Ferguson et al., 2010).

2.1 PS production

PS is as a simple compound manufactured from styrene monomer ($C_8 H_8$), which is formed when ethylene ($C_2 H_4$) and benzene ($C_6 H_6$) react in a polymerisation process (Gausepohl and Niesnser 2001). In its "raw" form, PS is a hard, transparent resin. From this basic form, PS can be transformed into different material types (i.e. foam, hard plastic, film) through processing, and can be made into a range of different materials from disposable goods to construction materials. For example, EPS and XPS are formed by different techniques that include "blowing agents," causing PS to expand and making the material suitable for insulation and floats. PS materials can be comprised of different chemicals, some of which are used in processing or added as ingredients (Gortz 2001).

The following section provides an overview of the different PS types, production, and use.

2.1.1 PS types

The group of PS types comprises four main material types, including (1) expanded polystyrene (EPS) and extruded polystyrene (XPS), (2) clear, general purpose polystyrene (GPPS), (3) impact modified polystyrene (more commonly called high impact polystyrene (HIPS), and (4) syndiotactic polystyrene (sPS) (Gausepohl and Niesnser, 2001). The PS types and examples of use are summarized in Table 1.

FOUR POLYSTYRENE TYPES

Expanded and extruded polystyrene (EPS, XPS) foam

Expanded PS (EPS; also known as Styrofoam®) and extruded PS (XPS) are different types of foam produced from PS. EPS includes the most well-known and widely used products (i.e. packaging, single use food items), and XPS is a higher density, extruded material (Gausepohl and Niesnser, 2001). EPS and XPS are both common materials used for disposable goods, construction material, and dock floats.

Photos: Wikipedia Commons

General purpose polystyrene (GPPS)

General purpose PS (GPPS) is a hard-plastic copolymer, formed when PS is combined with other materials. Applications include toys, rigid packaging, CD cases, cosmetic packs, and laboratory materials (i.e. Petri dishes). Manufacturing GPPS is based on a bulk polymerization process (Gausepohl and Niesnser, 2001).

Photos: Wikipedia Commons

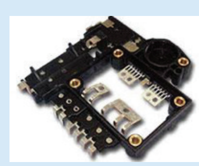
High impact polystyrene (HIPS)

High impact PS (HIPS) is a hard-plastic copolymer, formed when PS is combined with other materials. Uses of HIPS include rigid and high-impact uses. Manufacturing HIPS is based on a bulk polymerization process similar to GPPS (Gausepohl and Niesnser, 2001).

Photos: Wikipedia Commons

Syndiotactic polystyrene (sPS)

Syndiotactic PS (sPS) is a relatively newer type of PS and is a semi-crystalline polymer (Gortz 2001), and is used in electronics, including phones and electric vehicles.



Photos: Wikipedia Commons

Table 1: Four Polystyrene (PS) types.

2.2 PS foam types

PS foam has been called a "wonder product" because of its unique physical characteristics, including its low specific density, toughness, moisture resistance (Martinelli, 2018). When PS is transformed into foam, it is comprised of over 95% air and is incredibly lightweight. The two types of PS foam, expanded polystyrene (EPS) and extruded polystyrene (XPS), are widely used in food and beverage containers, packaging, toys, floating docks, aquaculture floats, and many other applications. As a buoyant and low-cost material, EPS and XPS have become commonplace in our lives.

PS foam has dominated PS production since World War II. Originating from an accidental discovery in a Dow Chemical Company laboratory[1] , PS foam was put to market, and the demand for PS foam quickly grew. During the war effort, PS foam provided an inexpensive building material for aircrafts during a global balsa wood shortage (Breskin, 1947). This new product was a strong material that was 30 times lighter and more flexible than solid PS, and could be easily produced (National Inventors Hall of Fame, 2020). In 1946, the Dow Chemical Company patented Styrofoam®.

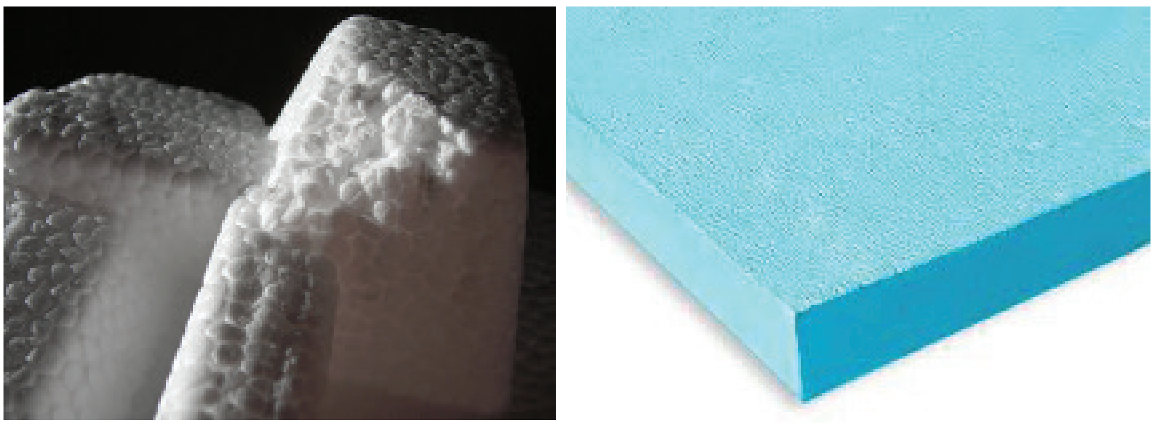


Figure 1: Image of expanded polystyrene (EPS) showing individual cells (left) and extruded polystyrene (XPS), a material without defined PS beads; a material with more consistency (right).

PS foam can be grouped into two major types; expanded polystyrene (EPS) and extruded polystyrene (XPS). Both materials have low density and low water absorption which make them good thermal insulators. Because of these properties, these materials are often used in construction as insulation (Ibo Osterreichisches Institut Fur Baubiologie Und-Okologie, 2016). PS foam also exhibits good buoyancy properties, and thus is widely used in boat docks and aquaculture floats (Davidson, 2012; ERDC, 2009).

The trademark Styrofoam® by the Dow Chemical Company is informally used for all PS foam, although strictly it refers only to "extruded closed-cell" PS foams made by Dow (The Dow Chemical Company, 1946). The physical differences EPS and XPS are shown in Figure 1 and described in the following sections.

[1] In the process of trying to make a flexible insulator, scientist Ray McIntire mixed styrene and isobutene in a reactor and heated them, in which he produced a lightweight material known today as PS foam (National Inventors Hall of Fame, 2020).

2.2.1 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is a closed-cell PS foam, which consists of expanded PS beads, which are the individual cells that make up the material. The most common uses for EPS are food containers, molded sheets for construction, and packing materials such as packing "peanuts." EPS is also a common material for docks and floats (Davidson, 2012; Rani et al., 2013; ReVelle and ReVelle, 1992). Developed by the Kopper Company in 1954, EPS entered the market after Styrofoam®. The rise in popularity of EPS ice chests and coolers grew in the late 1950s and early 1960s (Figure 2).

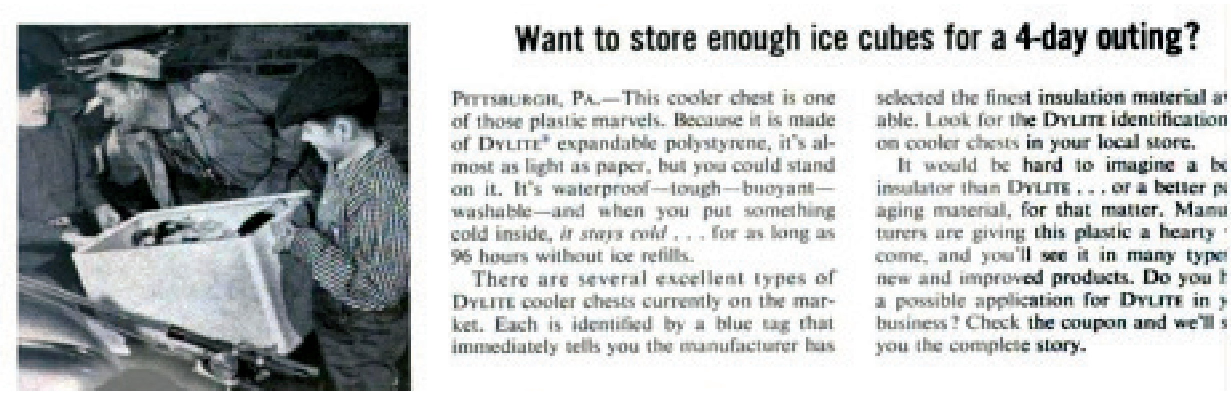


Figure 2: Newsweek advertisement for Kopper's EPS foam, which was invented in 1954 (Koppers, 1960)

To form EPS, PS beads are treated with "blowing agents," which cause the small, hard beads to expand (Richardson, 1983). When moulded, EPS consists of low-density, loosely attached cells, and the material is nearly 98% air (Richardson, 1983). Additives and external coatings are often added to give EPS added properties. For example, EPS can be produced with a surface finish as a protective coating to prevent EPS from breaking apart. A US Army Corps of Engineers Special Report reported on a 1971 California Legislation requiring surface treatments on PS dock floats as to minimize PS from entering the environment (Dunham and Finn, 1974). While the full picture of the environmental impacts were unknown in the 1970s, attention was given to durability for long term use of materials in water (Dunham and Finn, 1974).

2.2.1 Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is slightly different to EPS. Similar to EPS, XPS also consists of attached cells, but instead, XPS is a hard foam. As a hard foam, XPS provides a greater stiffness and strength compared to EPS (Ibo Osterreichisches Institut Fur Baubiologie Und-Okologie, 2016). Due to its higher density and extrusion process, XPS also has a higher moisture resistance compared to EPS. Because of its enhanced water resistant properties, XPS has been recommended for many decades as a preferred material for building docks and floats (Dunham and Finn, 1974). Waterlogging can occur in XPS when the material is exposed to water over a long period of time, although XPS does not contain the same open network of interstitial gaps between the expanded beads in EPS, and thus is less likely to become waterlogged.

To form XPS, raw materials – PS beads, processing agents and chemical additives (i.e. fire protection agents) – are added to an extruder and processed into a molten mass. A liquid foaming agent is then mixed in and the extrusion process creates foam from the molten mixture. While some of these additives are eliminated in production, the rest remain in the cells of the XPS and can be slowly released over the years (Ibo Osterreichisches Institut Fur Baubiologie Und-Okologie, 2016).

2.3 Chemical ingredients and additives

PS foams are complex compounds and are often produced with a variety of chemicals. These chemicals include base ingredients (benzene, styrene), additives (UV stabilizers, dyes, flame retardants), and chemical intermediates. While PS foam usually includes a suite of these chemicals, each individual product is unique. Some common ingredients and additives in PS foam are outlined below, however, precise lists of additives are not easily obtained (regarded as proprietary information).

Over time, these ingredients and additives can leach out and often these **leachates** can act as toxic or endocrine disrupting chemicals in the environment (Hermabessiere et al., 2017). For more on chemical fate and effects, see Section 3. The list below does not represent a comprehensive list, although this section aims to outline the main substances used as monomers, additives, intermediates and catalysts in PS foam production.

Leachate

A **leachate** is a liquid that extracts soluble compounds or suspended solids when it passes through a material. For example, under certain conditions, when polystyrene is exposed to water, it can leach chemicals (i.e. styrene), and the result is a **leachate** containing water, styrene, and other chemicals.

Benzene – Styrene

The main component of PS foam is PS, which is made from a polymerisation process with benzene, styrene, and ethylene (see Section 2.1). Leachates from benzene, styrene and ethylbenzene are one of the reasons why there is often greater concern over PS compared to other plastic types, since these leachates have known toxicity (Thaysen et al., 2018). Benzene is used mainly as an intermediate to make other chemicals. Over half of all benzene production is processed into ethylbenzene (a precursor to styrene). Benzene is also an additive in gasoline (U.S. Environmental Protection Agency, 2006). Styrene evaporates easily and has a sweet smell when aerosolized and styrene fumes are a known irritant (ATSDR, 2010). Under certain conditions, EPS has shown to leach styrene, benzene, and ethylbenzene, chemicals with toxic effects (ATSDR, 2010; Gibbs and Mulligan, 1997; Thaysen et al., 2018)

Additives

Hahladakis et al. (2018) reported on a comprehensive list of chemical substances known as "additives" contained in plastics for enhancing polymer properties and prolonging their life. PS is slightly brittle, and additives are often incorporated into PS to achieve strength and durability. Since PS foam is used in a range of different products, chemical additives included depend on the end use (Smith and Taylor 2002). Common PS additives include antioxidants, UV stabilizers, lubricants, colour pigments, nucleating agents, and flame retardants (Smith and Taylor 2002). This complex mixture can vary depending on the manufacturer and end use. For example, some EPS panels used in construction for thermal and sound insulation are made up of 91-94% PS, 2-7% pentane, < 1% fire protection agent, and small amounts of PE waxes, paraffin, and other additives (Ibo Osterreichisches Institut Fur Baubiologie Und-Okologie, 2016). Some EPS and XPS blocks used in dock construction have a thin surface layer finish to give increased protection from UV degradation and physical abrasion (Dunham and Finn, 1974).

Antioxidants and **UV stabilizers** are commonly added to plastics to prevent oxidation and degradation (Tikuisis and Dang, 1998). When plastics are exposed to ultraviolet (UV) light, it can lead to oxidative degradation in polymers (Hahladakis et al., 2018). UV stabilizers prevent this type of degradation, which is often a "yellowing" reaction observed in PS (Andrady and Pegram, 1991). While the chemical reactions causing this reaction are poorly understood, the mechanism of yellowing is likely due to a variety of chromophores, which lead to discoloration (Andrady and Pegram, 1991). Antioxidants and UV stabilizers often markedly slow light-induced degradation of plastic, including PS.

Lubricants enhance polymers with antistatic and anti-stick properties. Some of the most common compounds are fatty acid amides, which can also be used as emulsifiers in the polymerization processes (Ašmonaitė et al., 2018). Some lubricants are external, while others are internal to the plastic (Lau and Wong, 2000).

Other common additives include **dyes** and **nucleating agents**. Colourants and pigments are considered "non-functional" additives, but are widespread in the production of plastics (Rochman et al., 2019). In PS foam, some of the most common colours reported are white, pink and blue. Nucleating agents typically are used to increase resin clarity and reduce processing times (Hahladakis et al., 2018).

Flame retardants are commonly added to PS foam to give fire resistance and are of concern for their environmental and human health effects (Marvin et al., 2011). Prior to 2015, Hexabromocyclododecane (HBCDD) was the principal brominated flame retardant added to PS to make it flame resistant (Rani et al., 2013). It has been estimated that primary application of HBCDD (over 90 % worldwide) is in extruded (XPS) and expanded (EPS) PS foam, into which it is reportedly added at concentrations of 0.7 % and 2.0 % by weight, respectively (European_Commission, 2011, Marvin et al., 2011). Concentrations of flame retardants have been found in different PS foam materials (Jang et al., 2016; Rani et al., 2013). HBCDD has been found in docks and floats as well as packaging foams, ice boxes and food trays (Jang et al., 2016; Rani et al., 2013). It has been hypothesized that production facilities that are not fully cleaned from one production run to the other can contaminate other products that do not require flame retardants (i.e. floats) (Jang et al., 2016).

HBCDD has been banned since August 2015 (Ibo Osterreichisches Institut Fur Baubiologie Und-Okologie, 2016; Su et al., 2017). The EPS industry was granted a two-year grace period until 2017 (Ibo Osterreichisches Institut Fur Baubiologie Und-Okologie, 2016). There is also no limiting period for the stocks and stored goods that remain, and it is unclear whether these replacement chemicals are also found in docks and floats. Due to the long-shelf life of EPS, it is likely that EPS containing HBCDD is still in use. Other brominated flame retardants used in foam include Tetrabromobisphenol A (TBBP-A) and Polybrominated diphenyl ethers (PBDEs) (Eljarrat and Barceló, 2011).

Intermediates and catalysts

In addition to monomers and additives, other substances such as **intermediates** and **catalysts** are used in plastic manufacturing. Certain chemicals are used in the reactions to produce PS foam. For example, dicumyl peroxide is a chemical that is commonly used in XPS for the copolymerization of styrene. This compound also gives slight flame resistant properties (Ibo Osterreichisches Institut Fur Baubiologie Und-Okologie, 2016).

2.4 Adsorbed chemicals from the surrounding environment

It is well understood that PS and other microplastics can adsorb metals ions, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and antibiotics (Graca et al., 2014; Guo et al., 2019; Llorca et al., 2018; Rochman, 2013; Velzeboer et al., 2014). Rochman et al (2013) found that PS floating on the sea surface had a large potential for adsorbing polycyclic aromatic hydrocarbons (PAHs), and this was greater than polypropylene (PP), polyethylene terephthalate (PET), and polyvinylchloride (PVC). These chemicals can be passed onto animals when ingested, where they can bioaccumulate in animals and have negative effects, including hepatic stress (Rochman et al., 2013). Graca et al. (2014) observed the high accumulation of mercury in EPS debris stranded on beaches, which can then be transferred to soil. Research has also shown that in some cases, microplastics can have higher adsorption capacity in freshwater compared to seawater because of fewer sodium ions in freshwater. Higher adsorption in freshwater has been shown for antibiotics (Li et al 2018) and per- and polyfluoroalkyl substances (PFASs) (Llorca et al 2018), which could make microplastics in freshwater more of a risk to adsorb and pass on contaminants to wildlife.

Absorption vs. Adsorption:

Absorption is the process where one substance enters the volume of another substance. For example, a sponge absorbs water.
Adsorption occurs on the surface of a substrate due to intermolecular forces that cause molecules to be held to a surface. For example, metal ions or chemical contaminants can adsorb onto the surface of plastic.

PS foam can also absorb fuel and oil. In a few instances, PS docks have been reported to catch fire. This can occur when foam in docks forms a thick sludge when mixed with oil and fuel, causing PS to become flammable (ERDC, 2009). The US Army Corps of Engineers have documented marina gas docks with PS foam floatation catching fire after a fuel spill (ERDC, 2009).

3. PS foam from docks and floats – environmental concerns

The initial large volumes of PS foam production were attributed to its use in airplanes (Breskin, 1947), although as PS foam production grew, new applications were identified, including for use in boats and construction:

> *"Applications are broadening…Even bigger than the aviation field is that of building, where the plastics core material has made a beginning as the filling of a sandwich with aluminum sheets outside. And there are boats to be considered…*
> *The boating field should find use for it because of its moisture resistance and buoyancy."*
>
> *— Scientific American article "Expanding Fields for Expanded Plastics" (Breskin, 1947).*

Examples of unencapsulated PS foam uses (Rock makers, docks)

Since the 1940s, PS foam use has grown in many applications, such as boating, aquaculture, and boat docks. PS foam grew in popularity in the 1960s and 1970s as a material in docks and floats because of its low density, low water absorption, and low material costs (Dunham and Finn, 1974). PS floats are still commonly used in recreational docks and in fisheries (Davidson, 2012; ERDC, 2009; Jang et al., 2016). Floats used in docks and aquaculture typically include both EPS or XPS foam, although XPS grew in popularity due to higher durability compared to EPS (Davidson, 2012; ReVelle and ReVelle, 1992).

As early as the 1970s, reports found PS debris in seawater and fish (Carpenter and Smith, 1972), and littering shorelines (Shiber 1979). Early toxicity research at the beginning of the 1980s also discovered that styrene monomers – as well as other compounds related to PS, including ethylbenzene and benzene — were toxic to **Daphnia magna**, a species of freshwater zooplankton (LeBlanc, 1980). While effects of polystyrene microplastics were largely ignored by the wider scientific and non-scientific community for many years, considerable attention is given to the environmental impacts of many different types of microplastics today, including polystyrene.

Today, our understanding of the environmental impact of PS and other types of plastic is improving. Environmental concerns associated with PS foam include fragmentation degradation of foam, ingestion of particles by fish and wildlife, exposure to chemicals (i.e. styrene, HBCDD), aesthetics of plastic pollution, and recycle challenges. These environmental concerns are outlined in the following sections.

Daphnia magna

Common name: water flea.
D. magna is a planktonic crustacean (adult length <1cm) and is an important part of freshwater food webs.

3.1. Fragmentation and degradation

Degraded and fragmented pieces of PS foam litter

Several studies show PS foam can break up into microplastics more easily than other plastic types (Lee et al 2013, Biber et al 2019). While all plastics exposed to sun, wind, waves, ice and biota can eventually fragment, the breakdown of plastic depends on the environment and the type of plastic (Eubeler et al., 2010). Large plastic pieces often break apart (fragment) into smaller pieces due to physical abrasion. Due to its physical structure, polystyrene foam can easily fragment. In a recent study, Biber et al. (2019) found PS deteriorated more rapidly compared to PE, PET, and a biodegradable plastic. This showed that PS is expected to break up into microplastics more quickly in the environment than other polymers (Biber et al., 2019). A study by Leonas and Gorden (1993) investigated PS degradation and showed that the aquatic environment can slow polymer degradation. Other studies, however, show that aquatic environments can speed up degradation (Andrady and Pegram, 1991). Fragmentation varies by the polymer type and environmental conditions, and due to the wide range of plastic types and habitats where plastic pollution is found, this can be highly variable (Sivan 2011; Gewert et al. 2015; Andrady, 2015). PS foam in docks has been reported to fragment into macro- and micro-plastics due to **abiotic** and **biotic** factors such as water, ice, sunlight, and biota.

Abiotic

The breakup of PS foam floats and docks can be due to a number of abiotic factors, including water, ice, and sunlight. Fluctuating water levels can cause the breakup of PS foam docks (Figure 3). In the Lake of the Ozarks, for example, PS foam debris was created from seasonal water level changes (Missouri Department of Natural Resources, 2006). The amount of debris eventually prompted a lake-wide ban of PS docks and floats (Missouri Department of Natural Resources, 2006). Since PS foam is not perfectly waterproof, it can become waterlogged. In areas with cold winters, this waterlogging can cause fragmentation. EPS can be especially vulnerable to this fragmentation because of its open network of interstitial gaps between the expanded beads. When water is trapped in the interstitial gaps, ice can form inside the foam, causing material to break apart (Dunham and Finn, 1974). Sun exposure also deteriorates PS foam. UV can make PS brittle, and prone to fragmentation (Andrady and Pegram, 1991). When PS foam fragments enter the environment, these fragments can be further broken down by other abiotic and biotic factors.

Figure 3: Shoreline cleanup from Lake of the Ozarks, Missouri in 2019 removing large PS debris. Lake of the Ozarks has banned PS foam docks because of debris caused by fluctuating water levels and boat traffic. Recent shoreline cleanups report less dock foam debris after the local ban (Miller, 2019). Photo used with permission from Mitch Prentice.

Abiotic and biotic

Abiotic factors are non-living physical and chemical elements in an ecosystem. Examples of abiotic factors are water, air, sunlight, and minerals.

Biotic factors are living or once-living organisms in an ecosystem. Examples of biotic factors are animals, birds, plants, fungi, and other organisms.

Other possible sources of PS foam include intentional and unintentional loss of floats, breakup due to passing boat traffic, and destruction from storms. Accumulation of foam debris has been reported near recreational marinas and boat docks (ERDC, 2009; Miller, 2019; Missouri Department of Natural Resources, 2006; ReVelle and ReVelle, 1992). Studies from Korea, Japan, and Chile have found serious PS foam pollution on shorelines in proximity to fisheries and aquaculture (Chesson, 2013; Eo et al., 2018; FAO, 2008; Heo et al., 2013; Hinojosa and Thiel, 2009; Lee et al., 2013). PS floats have also been discovered in places as remote as Antarctica, where Japanese and Russian fishing floats have been found in shoreline surveys (Convey et al., 2002). While it can be difficult to identify sources, and whether debris originates from intentional discard or unintentional loss, there are many reports of illegal dumping. The intentional discard of old docks and aquaculture floats are both known sources of PS debris (ERDC, 2009; Miller, 2019; Missouri Department of Natural Resources, 2006; ReVelle and ReVelle, 1992). Unintentional loss is certainly a source as well; PS foam blocks are commonly collected in shoreline cleanups after storms, which can cause the loss of entire docks (ERDC, 2009).

Biotic

PS floating docks exposed to biota are a known source of microplastics to the environment. In marine environments, marine isopods are well known to damage floats. Colonies of isopods can release millions of microplastic foam on a single float (Davidson, 2012). This phenomenon has been recorded in Asia, Australia, Panama, and the USA (Davidson, 2012). Figures 4-5 show evidence of the isopod damage in EPS floats from docks in Oregon, USA. Reports have also identified PS floats being broken down by mussels (Jang et al., 2016) and muskrats (ReVelle and ReVelle, 1992).

Isopods

Thousands of isopod species (all belonging to the order "Isopoda") live around the world. Belonging to arthropods subphylum of crustaceans, isopods contain diverse species. Isopods inhabit many different environments, from freshwater, to deserts, to the deep sea. Approximately half of isopod species live in marine ecosystems.

Sources: NOAA, https://oceanexplorer. noaa.gov/ facts/isopod.html. Picture: Masumi Palhof, www. projectnoah.org

Figure 4: Extensive burrowing boring isopods (Sphaeroma quoianum) damaged PS floats from docks in Yaquina Bay, Oregon, USA. Photos used with permission from Davidson (2012).

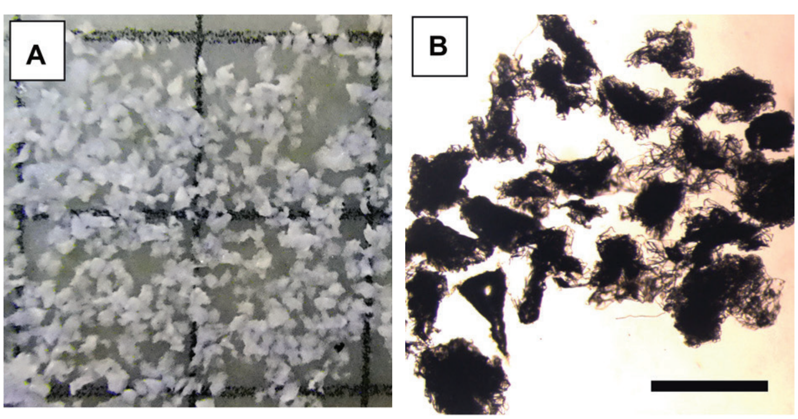


Figure 5: PS fragments from isopod damage of EPS floats. The images are shown at two different magnifications: (A) each square in the image is 0.25cm^2. (B) The scale bar in the image is 500um. Photos used with permission, from Davidson (2012).

The physical properties of plastic have important consequences for the pattern and distribution of plastic pollution in the environment. Since exposed PS foam can easily be chewed by animals, the material breakup is common. Muskrats are an example, as noted by the Washington Department of Fish and Wildlife: "Muskrats will burrow into floating docks, generally those floating on Styrofoam, scattering the broken white foam along the shoreline. This becomes an environmental danger, due to birds and other small animal eating this foam" (Washington Department of Fish & Wildlife, 2020).

As a result of the widespread use of PS foam and its mismanagement, PS foam has become widespread in habitats around the world (Hinojosa and Thiel, 2009; Moore et al., 2001). PS fragments are found on shorelines (Garrity and Levings, 1993), the open ocean (Morét-Ferguson et al., 2010), and the sea floor (Keller et al., 2010). However, often the sources of the debris are often unknown. While some studies identify macro debris as cups and plates, fast food containers, floral Styrofoam, grocery packaging, beverage container, packing foam, buoys, and floats, often the majority of PS foam pieces are small fragments with unknown origins (Garrity and Levings, 1993; Heo et al., 2013; J. Lee et al., 2013; Morét-Ferguson et al., 2010).

3.2 Navigation and aesthetics

Dangers to navigation and aesthetic issues related to floating PS debris are also of concern. In sufficient size or quantity, PS foam debris poses a hazard to boat traffic. Navigation hazards have even prompted local PS dock floats bans (Missouri Department of Natural Resources, 2006). Often EPS litter on lakes is so common they are colloquially referred to as "icebergs" (ERDC, 2009). In addition to being a hazard, PS debris is reported to litter shorelines and impacts the aesthetics of beaches around the world (Gregory, 2009; ReVelle and ReVelle, 1992). A study in Illinois found that that the absence of litter and floating debris were ranked of high concern by lake managers and recreators (Mullens and Lant, 1991). The economic impact of plastic debris can be considerable, especially for municipalities that regularly need to remove beach litter to maintain tourist revenue (Gregory, 2009).

3.3 PS foam low recycling rates

While there are some efforts to recycle used PS foam floats, these materials have a low recycling rate. Recycling of EPS and XPS is possible, although due to high costs of transport and its low value, PS foam is often not recycled (Ragan, 2007). Dock foam can be especially expensive to transport and dispose of since used dock foam is often waterlogged (Missouri Department of Natural Resources, 2006). In some areas, recycling programs have been developed as an effort to recover the material where dock foam has been banned (Missouri Department of Natural Resources, 2006). However, these programs have seen limited success due to costly landfill tipping fees for waterlogged foam and no commercial market for PS dock foam (Missouri Department of Natural Resources, 2006; "Sheltered workshop recycling dock foam," 2016).

3.4 Distribution of PS foam litter in the Great Lakes and St. Lawrence River

The Great Lakes St. Lawrence River Basin is the largest surface freshwater resource on Earth, accounting for a full one-fifth of the world's freshwater supply and supplying essential drinking water to 40 million people. The Great Lakes are home to some of the world's most unique ecosystems; they provide continentally significant habitat for large numbers and diverse species of North America's fish, migratory birds, waterfowl, amphibians, reptiles and invertebrates, as well as many different underwater and coastal plant species. PS foam is present throughout the Great Lakes in sediment, surface water, and wildlife, littering a critical freshwater resource for people and wildlife.

3.4.1 Transport

Research shows that plastic pollution often follows the same hydrological pathways as water (Windsor et al., 2019). In the Laurentian Great Lakes, transport models show that plastic follows patterns driven by water movement and wind (Hoffman and Hittinger, 2017). Hoffman and Hittinger (2017) recognized good correlations between plastic abundances in beach surveys (Zbyszewski et al., 2014) and modeled accumulation for Lake Huron. Particle movement can depend on many factors, such as shape, size and density, all which can change over time. The proportion of plastics present in surface water, sediment, and accumulating on shorelines depends on several factors, which can vary around the world. On the Great Lakes, factors such as wind, surface water circulation, and temperature have been shown to impact the distribution of plastic pollution on shorelines (Corcoran et al., 2015; Zbyszewski et al., 2014) and surface water (Eriksen et al., 2013a).

PS may be transported to sediment more easily than other particles. On a global scale, volumes of microplastics in sediment appear to be greater than in surface water (Besseling et al. 2019). Biofouling, the fouling of particles by organisms such as algae, is a mechanism for buoyant plastics to move from the water column into sediment (Ballent et al., 2016). Kaiser et al. (2017) evaluated PS and PE particles, and found sinking velocities of PS particles increased by 16% in estuarine water after 6 weeks due to biofilms. PE particles, however, were not impacted by any biofouling over the same period. Thus, biofouling can enhance the deposition of plastics into sediment, and occurs more for PS than other polymers. Andrady et al. (1993) showed biofouling can occur faster in freshwater environments compared to marine environments. While sediment is largely considered to be a sink for plastic pollution (Eriksen et al., 2014; Woodall et al., 2014), microplastics may also mobilize during high flow events, or through biological activity. Bottom-feeding fish may be a way for plastics to move from the benthos into pelagic habitats (Munno et al., 2016).

3.4.2 Fate

The following section presents available data for the fate of PS foam in the Great Lakes St. Lawrence River Basin. Peer reviewed studies and beach cleanup data are both considered, and particular attention is given to what is known for Georgian Bay and Lake Huron. Evidence shows that plastic pollution contamination in the Great Lakes is as widespread and in concentrations as high as marine environments.

A total of 19 studies reported the presence of PS foam in the Great Lakes St. Lawrence River Basin. Every study investigating microplastics in the Great Lakes have reported PS foam, except for one study (Castañeda et al., 2014)[2]. The following studies presented in the following sections often use different sampling and analysis methodologies, which can make it difficult to compare trends (Twiss 2016). However, it is abundantly clear that microplastic pollution is an issue across the Great Lakes St. Lawrence River Basin, and PS foam is ubiquitous.

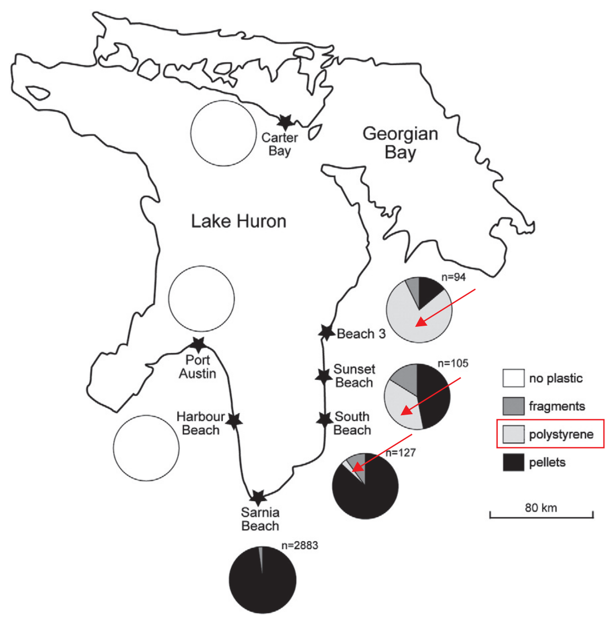


Figure 6: Abundance and distribution of plastic debris along the Lake Huron shoreline. Stars indicate sampling areas. A total of 7 beaches were sampled on Lake Huron. No samples were taken on Georgian Bay. Pie diagrams illustrate the relative abundances of pellets, fragments, and PS foam. There was an absence of plastic debris in the north and west, and the high relative abundance of pellets at Sarnia beach (indicated by n=). (Zbyszewski et al., 2014).

Beaches and sediment

PS foam has been reported along beaches along the northeast shoreline of Lake Huron near Georgian Bay. Zbyszewski et al. (2014) surveyed beaches on Lake Huron, Lake St. Clair, and Lake Erie. On Lake Huron near Kincardine, beach surveys showed high proportions of polystyrene foam: 79% of plastic particles collected were PS foam. In contrast, the southern region near Sarnia and "Chemical Valley," where plastics manufacturers are located, contained a high abundance of pellets, and a lower reporting of PS foam. Near Sarnia, approximately 94% of all plastics collected were plastic pellets attributed to industrial sources (Zbyszewski and Corcoran, 2011). Researchers reported no plastics on beaches along the western shoreline of Lake Huron and on Manitoulin island, and found the overall amount of plastic and relative number of industrial plastic pellets decrease northward along the eastern shoreline of Lake Huron (Figure 6).

[2] Polystyrene foam was out of the scope of this study, as the authors were interested in microbeads only

PS foam has been recorded in sediment and beaches on Lake Erie and Lake Ontario. PS foam is abundant on shorelines in Lake Ontario (Ballent et al., 2016; Corcoran et al., 2015) and Lake Erie (Dean et al., 2018). In some cases, due to both the amount of PS foam collected and the fragility of the material, PS foam is quantified as a mass, whereas other particles can be given as a count and weight (Corcoran et al., 2015). PS foam was not found in lake bottom sediment cores from Lake Ontario (Corcoran et al., 2015), and was uncommon in sediment sampled from Lake Michigan (Lenaker et al 2019).

Figure 7: Anika Ballent, at the Department of Earth Sciences of the University of Western Ontario, and Lisa Erdle, biologist at Ontario Streams, sample submerged surface sediments for plastics in sediment.

In an effort to record and remove plastic pollution and other litter, shoreline cleanup programs classify types of plastic and remove it from the environment. The International Coastal Cleanup (ICC) began cleanups over 30 years ago, and the Great Canadian Shoreline Cleanups (GCSC) has organized cleanups across Canada since 1994. Shoreline cleanup data show a large collection of plastic debris, including foam. A majority of foam is PS foam, although it is possible for other material types to be included in these counts (i.e. PE foam). Over a three-year period (2016-2018), more than 3.5 million pieces of plastic were collected along shorelines in the Great Lakes watershed. Approximately 14% of this plastic was foam – 509,759 pieces (Table 2). In 2019, over 5,000 foam pieces were collected in 9 shoreline cleanups on Georgian Bay. More foam was collected than all other litter items combined (Figure 8). Many large foam blocks docks were observed, as well as smaller foam pieces with same colour and physical characteristics as the larger blocks. A subsample of these foam pieces was analyzed in 2019 to determine the chemical id for these particles collected in Georgian Bay cleanups. Laboratory analyses using FTIR (Fourier transform infrared spectroscopy) indicate foam collected was PS, and also contains copolymers (Appendix 6.1 and 6.2).

Province / State	Foam pieces
Ontario	338,610
Indiana	10,007
Illinois	24,462
Ohio	52,880
Minnesota	2,454
Michigan	42,043
Wisconsin	20,506
New York	16,207
Pennsylvania	2,590
Total	**509,759**

Table 2: Shoreline cleanup data Great Canadian Shoreline Cleanups (GCSC) and International Coastal Cleanups (ICC) on the Great Lakes. 509,759 foam pieces were collected from 2016-2018. Contains data from Ontario and 8 Great Lakes – bordering states.

Figure 8: Shoreline cleanups from Georgian Bay Forever (GBF) on Georgian Bay. Of the top 12 litter items, the arrow indicates the 1st column "Big and Tiny pieces of foam". Over 5,000 foam pieces were collected in 9 shoreline cleanups on Georgian Bay (left).

Research shows that regular beach cleaning (also called beach "grooming" or "raking") can decrease plastic pollution (Hoellein et al., 2015, Vincent and Hoellein 2017). Beach grooming on Lake Michigan beaches have been shown to drive temporal trends in plastic pollution. After summer, when beach cleaning ended, beaches experienced an increase in plastic litter (Hoellein et al., 2015, Vincent and Hoellein 2017). Beach grooming can also remove it from shorelines before it becomes part of the sediment record (Ballent et al., 2016, Ballent personal communication).

Water

Microplastics, including PS foam, have been recorded in surface water in all of the five Great Lakes, with the highest microplastic concentrations exceeding 1.9 million microplastics / km^2 (Cable et al., 2017). Eriksen et al. (2013a) completed the first study of microplastics in surface water, and trawled for microplastic (foam, film, and spheres) in Lake Superior, Lake Huron and Lake Erie (Figure 9). Foam particles were abundant in this study, although particle types were not identified through chemical analysis (i.e. FTIR, Raman) (Eriksen et al., 2013a). Chemical identification of particles is now more common, and PS foam has been recorded in other surface water studies and confirmed with chemical id (Cable et al., 2017; Lenaker et al., 2019; Mason et al., 2016). Lenaker et al (2019) reported PS in 26% of analyzed particles. Mason et al. (2016) identified PS foam in Lake Michigan surface water, and Hendrickson et al. (2018) identified PS foam in western Lake Superior. Cable et al., (2017) found foam in their surface water surveys on Lake Superior, Lake Huron and Lake Erie, found microplastic concentrations over 1.9 million microplastics / km2 which is higher than concentrations recorded in marine studies, which typically report between 0 and 350,000 microplastic particles/ km^2 in the ocean gyres (Eriksen et al., 2013b; Lavender Law et al., 2010; Moore et al., 2001; Rochman et al., 2014).

Rivers have also been identified as a pathway for PS to enter the Great Lakes. Baldwin et al. (2016) reported PS foam in 8% of particles collected in 29 tributaries across the Great Lakes. Concentrations of foam (as well as fragments, pellets, and film) were positively correlated with urban land use (Baldwin et al., 2016). In tributaries to Lake Ontario, PS foam was found in stormwater and agricultural runoff (Grbic et al., 2019). Agricultural runoff can contain microplastics from plastic used as crop covers, or via fertilizers (Grbic et al., 2019) (Crossman et al., 2020). Although there are likely several different sources of PS foam to the Great Lakes, it is clear that PS foam is abundant in this freshwater system.

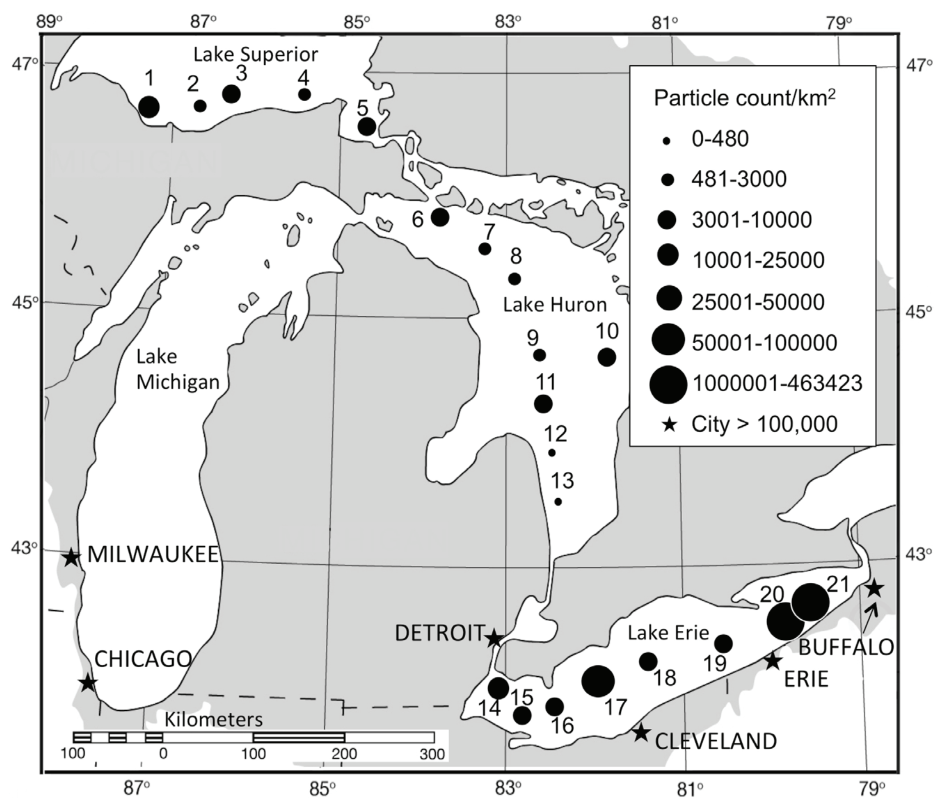


Figure 9:Distribution of surface water plastic (foam, film, and spheres) collected from 21 sites in on Lake Superior, Lake Huron and Lake Erie (Lake Michigan not sampled). The highest concentrations of microplastics were recorded on Lake Erie near population centres, and on Lake Huron, microplastic concentrations ranged between 0 and 4750 particles / km^2. Figure used with permission from Eriksen et al. (2013).

Seabins have been deployed recently in Lake Ontario in an effort to record and remove surface water plastic and other floating debris. Seabins are relatively new to the Great Lakes and have been installed in the Toronto inner and outer harbours since 2019. Preliminary data shows that 3,127 Styrofoam and foam particles have been collected in Seabins, amounting to 37% of all particles captured (Wu, 2020). In addition to removing plastic, Seabins can serve as an education tool to inform the public about sources of plastic pollution to the environment.

Wildlife

Foam studies report microplastic contamination in fish and wildlife within the Great Lakes area, and of these, three studies have shown foam ingestion[3]. Wagner et al., (2019) observed microplastics in three fish species, and PS foam (75 um) was observed in Salvelinus fontinalis (Lake Trout) from Lake Huron. Another fish study investigating fish in Lake Michigan tributaries found eleven fish species ingested microplastics, although no foam was found (McNeish et al., 2018). Multiple bird species on the Great Lakes have been shown to ingest plastic, and two of three studies have reported PS. Holland et al. (2016) recorded anthropogenic debris including plastic in Anas platyrhynchos (Mallard Duck) on Lake Ontario, although no foam was observed. Brookson et al. (2019) found poly(divinyl benzene): styrene (PS crosslinked with divinylbenzene) in Phalacrocorax auritus (Double-crested Cormorant) chicks on Lake Ontario, showing that adult birds are feeding plastic, including PS, to their young. Thaysen et al. (in review) found large pieces EPS in Larus delawarensis (Ring-billed Gull) on the St. Lawrence River. No studies to date have investigated microplastic ingestion in birds on Lake Huron.

Results from these five studies show that PS and other anthropogenic debris contaminate wildlife in Great Lakes. Still, we have a limited understanding of the extent that polystyrene foam and other plastic contaminate Great Lakes species. Research is underway to understand the effects of environmentally relevant microplastics to Great Lakes species. Many studies have investigated the effects of PS ingestion in freshwater and marine animals in habitats around the world.

3.5 Ingestion by fish and wildlife

Many observations demonstrate that PS foam is frequently found in the environment, often as one of the most common microplastic types (Derraik, 2002; Browne et al., 2007; Barnes et al., 2009). It has been shown in studies in the wild and in laboratories that PS foam is ingested by many different species and include organisms with different strategies. In the wild, PS foam has been found in the stomachs of several animals including numerous species of fish (Boerger et al., 2010), sea turtles (Jung et al., 2018; Schuyler et al., 2014), bivalves (Jang et al., 2016), and birds (Brookson et al., 2019; Thaysen et al., in review). Some animals like birds can transport PS foam between aquatic and terrestrial environments. Organisms such as zooplankton presumably consume PS passively withphytoplankton prey in non-selective feeding (K.-W. Lee et al., 2013). Scrapers and grazers such as freshwater snails likely consume PS that is on the sediment surface (Scherer et al., 2017). Selective filter feeders like copepods (Cole et al., 2015), oysters (Sussarellu et al., 2016), and mussels (Rist et al., 2019) likely ingest foam that is suspended in water.

Zooplankton and Phytoplankton

Tiny "drifters," plankton are alive, aquatic, and adrift. All plankton are essential for the stability of aquatic food webs.

Zooplankton are small (sometimes one-celled) animals.

Phytoplankton are photosynthetic organisms.

Given the ubiquity of PS in the environment, it would be desirable to be able to attribute particles that were ingested by animals in the wild with a particular source. However, a major challenge to this is that PS found in animals are often observed as small fragments (i.e. Boerger et al., 2010).

In some cases, ingested PS is in its "raw" fragment form, and could possibly originate from pellet spills or losses in manufacturing (Jung et al., 2018; Kartar et al., 1976). While many studies hypothesize potential sources of ingested PS, the specific sources can vary. Although many studies rely on best guesses, some studies are able to make very strong cases. For example, in mussels growing on PS floats, foam microplastics identified inside mussels probably originate from their substrates (Jang et al., 2016). Identifying sources in free swimming organisms can be more challenging.

[3] One study to date has investigated plastic ingestion by wildlife in Lake Huron (Wagner et al., 2019), and no studies were found that investigated plastic ingestion by wildlife in Georgian Bay

PS foam is not identified in all animals investigated. For example, a study of plastic debris and fur seals found PS and PS foam in the plastic debris, however there was no PS in the fur seals nearby (Eriksson and Burton 2003). Ingestion of different microplastics can depend on many factors, such as feeding strategy and gape size (feeding mouthpart or jaw size). While some species may avoid plastic ingestion, other species may also be drawn to plastic.

3.6 Exposure to chemicals

A wide range of toxic compounds have been identified in plastic leachates, including monomers. These compounds can leach out from PS foam over time. Under certain conditions, PS foam has been shown to leach unreacted raw materials, including styrene and benzene, ethylbenzene (Ahmad and Bajahlan, 2007; Thaysen et al., 2018). These leachates have known toxic properties (Gibbs and Mulligan, 1997). EPS foam leachate, for example, which includes ethylbenzene, can impact the survival of a freshwater zooplankton (Thaysen et al., 2018). Styrene, has been shown to have many negative effects, including disruptions to endocrine systems (Lithner et al., 2011), lung tumors (Cruzan et al., 2001), liver damage (Carlson, 2002; Vogie et al., 2004), and genotoxicity (Vodicka et al., 2006). Styrenes are widely detected in coastal waters around the world and in Canadian waters on the Great Lakes (Environment Canada & Health Canada, 1993; Kwon et al., 2015). For more information on styrene, refer to Appendix 6.3.

Monomers

A monomer is a type of molecule that can bond with other molecules into a long chain. Polystyrene is made up of a long chain of styrene monomers.

Many additives and adsorbed contaminants can also leach from PS foam. Additives including surfactants and antioxidants, flame retardants and **Phthalates** can also leach and cause toxic effects (Hermabessiere et al., 2017). Due to the long-range transport of plastics in water, this can also mean the long-range transport of environmental contaminants, such as brominated flame retardants (Heeb et al 2010). In some parts of the world, PS foam has been cited as a source of chemicals to the environment (Rani et al., 2015; Jang et al., 2017) and to wildlife (Jang et al., 2016). EPS buoys were identified as a source of flame retardants (i.e. HBCDD) to oysters (Hong et al 2013) and mussels (Jang et al., 2016). Mussels on EPS debris accumulated higher levels of HBCD than mussels attached to other substrates, such as high-density polyethylene (HDPE) buoys, metal buoys, and rocks (Jang et al., 2016). Increased HBCDD content was found in oysters in a farm where PS floats containing HBCDD were used, even when oysters were not in direct contact with the PS (Hong et al., 2013). These studies show that PS debris acts as a source of additives in the marine environment and organisms inhabiting that debris, or even in their vicinity, can be directly influenced by the additives. Certain adsorbed contaminants can also leach into terrestrial environments when plastic is beached. PS foam blocks can adsorb mercury when in water and release it into soil when PS washes up on beaches (Graca et al. 2014).

Phthalates

Phthalates are a group of chemicals used in hundreds of products, including toys, vinyl flooring, detergents, lubricating oils, food packaging, pharmaceuticals, and personal care products (nail polish, hair spray, aftershave, soap, shampoo). Often phthalates are listed as "perfume" or "fragrance" on ingredient lists in personal care products.

Over the pH range normally found in soil and surface waters (pH 5-9) PS foam can leach chemicals into the surrounding environment (Ahmad and Bajahlan, 2007; Thaysen et al., 2018). The environmental mobility of some additives is not well understood due to a lack of analytical data. Additives applied in different stages of the material production process are likely to have different physical and chemical properties. For example, lubricants added late in the production stage may be more likely to leech from PS compared to UV stabilizers and antioxidants that are incorporated into the plastic.

Due to the ingredients, additives and mobility found in PS foam and the occurrence of PS foam in the environment, PS foam poses an environmental concern.

3.7 Effects

Overall, thousands of studies have tested the effects of microplastics, and PS is one of the most widely tested polymers (Bucci et al 2019). The available data on microplastics in freshwater and marine species is dominated by investigations at the organismal and sub-organismal levels (Bucci et al 2019; Rochman et al. 2016). Increasing data is also available on the toxicity of nanoplastics (plastic particles <1um), although methods to detect particles smaller than 300um in the environment are still lacking (Covernton 2019). Laboratory studies suggest that fish as well as benthic and invertebrate taxa will ingest polystyrene microplastics if they are introduced under experimental conditions. These include fish (Jabeen et al. 2018; Qiao et al 2019; Qiang and Cheng 2019), polychaetes (Leung and Chan 2018), benthic macro invertebrates (Redondo-Hasselerharm et al. 2018), copepods (K.-W. Lee et al., 2013), zooplankton (Cole et al., 2015; Schür et al., 2020), lugworms (Besseling et al., 2013), nematodes (Lei et al. 2018b), frogs (De Felice et al. 2018), crabs (Yu et al 2018), oysters (Sussarellu et al., 2016), and algae (Mao et al. 2018).

As the size of microplastics decreases, the potential for particles to transfer outside of the gut and into other tissues is expected to increase. This transfer, also called translocation, may facilitate bioaccumulation or even biomagnification in food webs, although the size of particles that are able to translocate between tissues remains unclear. Some studies have demonstrated translocation of PS 0.5 – 9.6 um, however, a study by Sussarellu et al. (2016) using *Crassostrea gigas* (Pacific oysters) showed no evidence of PS sphere (2 and 6 μm) translocation. The highest concentrations of microplastics are often detected in the gastrointestinal tracts. Lower concentrations have been detected in other tissues such as the liver or fish tissue.

There is significant data available on the impacts of PS microplastics exposure on reproductive, developmental, and feeding processes in animals, showing mainly effects on the liver, gastrointestinal tract and on growth. The studies that have investigated effects in freshwater and marine species are outlined below.

3.7.1 Freshwater species

Due to the prevalence of PS foam in the Great Lakes St. Lawrence River Basin, a literature search was done to investigate the known toxicity of PS microplastics on freshwater species. Examples of effects demonstrated include reduced feeding behaviour and growth, mortality, changes to lipid composition, oxidative stress, changes to swimming behaviour, and reduced reproductive output (Table 3).

In these studies, exposure to PS microplastics is most likely via ingestion. Limited data are available on other paths of exposure, such as PS foam leachates, such as work by Thaysen et al., (2018). The significance of these pathways in the environment is unclear, as leachates may only occur under certain conditions and PS foam can contain different chemicals used as ingredients or adsorbed from the environment. However, due to the known toxicity of additives and the potential to leach, leachates are additionally a source of exposure for potential effects.

Table 3: Summary findings in studies that investigate the effects of PS microplastics to freshwater species.

STUDY	DESCRIPTION	CITATION	FINDINGS & SUPPORTING FILES
Acute (4-hour) and chronic (21-day) toxicity studies	Study in *Daphnia magna* (Water flea) comparing short- and long-term toxicity of PS (2 μm)	Aljaibachi and Callaghan 2018	Findings: • Impacts on feeding behaviour, mortality • No impact on reproduction Supporting files: • Peer reviewed study
Acute (developmental stages 36-46) toxicity study	An evaluation of blue PS microplastic (2.75 μm) in *Xenopus laevis* (African clawed frog) tadpoles	De Felice et al. 2018	Findings: • PS observed in digestive tracts • No impact on mortality, body growth, or swimming activity Supporting files: • Peer reviewed study

STUDY	DESCRIPTION	CITATION	FINDINGS & SUPPORTING FILES
Acute	Exposure of PS microplastics (70 µm) on *Chlorella sorokiniana* (freshwater green algae)	Guschina et al. 2020	Findings: • PS disrupted lipid composition in algae, including two essential fatty acids, linoleic and linolinic • PS impacted galactolipids, lipids involved in photosynthesis Supporting files: • Peer reviewed study
Chronic (6-week) toxicity study	Comparison of sublethal effects between PS fragments (2.5-3mm), ethylene vinyl acetate fibers (0.7-5mm) and polyethylene acrylate pellets (4.9-5mm) in *Carassius auratus* (goldfish)	Jabeen et al. 2018	Findings: • Impaired growth (all particle types) • Fragments and pellets changed the upper and lower jaws of fish • Hepatic stress (sinusoid dilation in livers) observed in 13.1% and damage to oral cavity seen in 80% of fish exposed to PS fragments • No impact on mortality (all particle types) Supporting files: • Peer reviewed study
Acute (2-day) toxicity study	2-d study in *Caenorhabditis elegans* (nematode) comparing effects from different PS sizes (0.1, 1.0, and 5.0 µm)	Lei et al. 2018b	Findings: • 1.0 µm particles caused the highest mortality • PS accumulated in the intestines and caused intestinal damage Supporting files: • Peer reviewed study (also includes results from 10-d study in Danio rerio (zebrafish) with virgin PA, PE, PP, and PVC
Long-term (30-day) toxicity study	Evaluation in *Chlorella pyrenoidosa* (freshwater green algae) growth with PS microbeads (1.0 µm)	Mao et al. 2018	Findings: • Impaired growth, reduced photosynthesis, and changes to cell morphology Supporting files: • Peer reviewed study
Acute (20-hour) toxicity study	Study in *Danio rerio* (Zebrafish) evaluating PS effects (1 µm) on larvae development and swimming performance	Qiang and Cheng 2019	Findings: • No significant impact on hatching rate • PS found to adhere on embryo chorion (outer membrane) • Significant decreases in swimming distance and larvae speed in low-light levels, no effects observed in light conditions Supporting files: • Peer reviewed study
Chronic (21-day) toxicity study	Study in *Danio rerio* (Zebrafish) evaluating effects of PS microbeads (5 µm) on intestinal stress	Qiao et al. 2019	Findings: • Impacts on intestinal damage, oxidative stress, and increased permeability • Significant alterations in gut microbiome Supporting files: • Peer reviewed study

STUDY	DESCRIPTION	CITATION	FINDINGS & SUPPORTING FILES
Chronic (28-day) bioassays	Single species experiments with benthic freshwater macroinvertebrates, including *Gammarus pulex* and *Hyalella azteca* (amphipods), *Asellus aquaticus* (isopod), *Sphaerium corneum* (bivalve), and *Lumbriculus variegatus* and *Tubifex spp* (worms) using environmentally-relevant concentrations of PS microplastics (20—500 µm)	Redondo-Hasselerharm et al. 2018	Findings: • No effects on the survival of G. pulex, H. azteca, A. aquaticus, S. corneum and Tubifex spp • No effects found on the reproduction of L.variegatus • No significant differences in growth were found for H. azteca, A. aquaticus, S. corneum, L. variegatus, and Tubifex spp • Significant reduction in growth in G. pulex (amphipod) Supporting files: • Peer reviewed study
Multigenerational (4 generations) toxicity study	Study on *Daphnia magna* (Water flea) evaluating effects of irregular PS (<63 µm) and natural reference particle	Schür et al. 2020	Findings: • High PS concentrations reduced survival, resulting in extinctions within the experiment • PS impacted reproduction and growth • Exposure to natural reference particle (kaolin) at similar concentrations did not show negative effects Supporting files: • Peer reviewed study
Chronic (10-day) toxicity studies	*Daphnia magna* (Water flea) study evaluating toxicity of uncoated PS (1.25 µm)	Tang et al. 2019	Findings: • Impact on body growth rate • No impact on mortality. Supporting files: • Peer reviewed study
10-day uptake experiment and chronic (21-day) toxicity study	Study in *Eriocheir sinensis* (Chinese mitten crab) evaluating toxicity PS microspheres (5 µm)	Yu et al. 2018	Findings: • Weight gain, specific growth rate, and hepatosomatic index (HSI) generally decreased with increasing PS concentrations • PS exposure led to oxidative stress in the liver Supporting files: • Peer reviewed study

3.7.2 Marine species

Many studies have also looked at the effects of PS microplastics in marine species, and the effects across a range of organisms includes reductions in fecundity (Cole et al., 2015), reductions in survival (Leung and Chan 2018), increased oxidative stress (Lu et al 2016), increased hepatic stress (Jabeen et al. 2018; Yu et al. 2018), reduced feeding activities (Cole et al., 2015), reduced energy reserves and balance (Besseling et al., 2013), decreased swimming ability (Qiang and Cheng 2019), and altered reproduction (Lithner et al. 2011; Sussarellu et al 2016). The results of these studies are not yet conclusive, but the sum of existing laboratory experiments, many of which use PS beads and not expanded or extruded PS, highlight the detrimental effects of PS in a broad range of taxa.

3.7.3 Human health

Little is known about effects on PS microplastics on human health. Human health studies show mainly effects from PS leachates from food and beverage containers or impacts from chemicals via occupational exposure. Human health studies show impacts from styrene monomers as possibly carcinogenic (see Appendix 6.3).

4. Discussion and Conclusions

4.1 Uncertainties and data gaps

Data gaps for PS foam remain, especially since methods are limited to attribute environmental PS foam to sources. For example, when PS foam is small, it can be difficult to say whether these fragments originated from docks or other sources. This is also a challenge for all plastic types found in the environment. However, new methods have been proposed to help attribute plastic found in the environment to link them to sources. Identifying chemical additives in PS foam may present an opportunity to link foam in the environment to possible sources. For example, flame retardants added in high concentrations could link foam to construction material as a source. In addition, future work should identify whether effects to organisms are from the physical particle, chemical additives, or both.

4.2 Conclusions

The known effects of PS and the ubiquity of PS foam as a pollutant in Georgian Bay, the Great Lakes, and globally is cause for concern. There are known solutions to limit PS foam that can move towards eliminating this type of plastic pollution from the environment. Alternatives exist to PS foam in floating docks, and there is currently a call to action to demand more sustainable materials.

4.3 Next steps

There are actions that can be taken to prevent additional PS foam pollution from building up in the environment. Producers, sellers, buyers, and governments can work together to prevent future unencapsulated foam use for docks or other uses in freshwater; additionally existing unencapsulated foam docks can be replaced with alternative materials while ensuring owners of discarded PS foam docks have access to proper disposal, thereby discouraging abandonment in the aquatic environment. Currently, PS docks and floats can be replaced by alternatives, for example wood and metal. These materials are considered to be less toxic and less persistent in the environment. Durable plastic could also be an option since certain polymers are less likely to fragment into microplastics, although concerns over leachates also exist for other plastic materials.

There are local ordinances, state regulations, or entity requirements for ***encapsulating foam in docks.*** *Examples include: Oregon, Washington State, Arkansas, Miami-Dade, the Lower River Colorado Authority, the Lake of the Ozarks, the United States Army Corps of Engineers, and the Lower River Colorado Authority.*[1]

[1] Enclosed dock foam rules sources: Oregon (https://www.oregon.gov/osmb/forms-library/Documents/Environmental/FoamEncapsulationRules_2019.pdf), Washington State (https://apps.leg.wa.gov/wac/default.aspx?cite=220-660-140), Arkansas (https://drive.google.com/file/d/1VXuxUYnNDmHOw-A9i3uWCZzexX8zRuAD/view), Miami-Dade (http://www.miamidade.gov/govaction/matter.asp?matter=172438&file=true&yearFolder=Y2017), Lake of the Ozarks (https://dnr.mo.gov/pubs/pub2041.pdf), Unites States Army Corps of Engineers policy 1130-2-406, Appendix C, Page 3, Paragraph 14 USACE 2008c from: https://apps.dtic.mil/dtic/tr/fulltext/u2/a508398.pdf.

Restrictions on certain EPS products like packaging or containers have emerged or are proposed. Examples include: New York City, Maine, Maryland, San Francisco, and the City of Vancouver.

EPS regulation sources: New York City (https://www1.nyc.gov/assets/dsny/site/resources/recycling-and-garbage-laws/collection-set-out-laws-for-business/foam-ban), San Francisco (https://sfenvironment.org/zero-waste-legislation), Maine (https://legislature.maine.gov/LawMakerWeb/summary.asp?ID=280071044), Maryland (http://mgaleg.maryland.gov/2020rs/bills_noln/sb/fsb0840.pdf), City of Vancouver (https://vancouver.ca/green-vancouver/foam-ban.aspx?)

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4.3 Next steps

Steps to reduce dock foam pollution at source by the partnership of Georgian Bay Forever (GBF), the "Say No" to Dock Foam Committee, and the Township of The Archipelago

- Released the results of 9 shoreline clean-ups in Georgian Bay. The most prevalent litter was dock foam (Report: https://bit.ly/2019GBcleanups).
- Formed the "Say No" to Dock Foam Committee with objectives to: commission known scientific proof of harm to the environment (this report), research dock alternatives, educate consumers, sellers, and municipalities on environmental impacts and alternatives, and work to remove PS unencapsulated foam docks from the future marketplace.
- Support the Township of The Archipelago to bring recommendations on this issue to a future Great Lakes St. Lawrence Cities Mayors' Conference and to the Ontario government at a conference of the Association of Municipalities of Ontario.
- Work in partnership with community associations, the Georgian Bay Association and the Township of The Archipelago to help facilitate the disposal of old and abandoned docks.
- Find and work with new partners to expand the reach and effectiveness of these steps.
- Expand Seabin use. Work in partnership with stakeholders like municipalities and marinas to deploy seabins, and help collect litter data. As of April 2020, there is an agreement with the Town of Collingwood .The Town will install two bins and GBF has committed to purchase and install one. GBF is also hopeful that we will be able to install five gutter bins as a test. GBF learned that Desmasdon's and Beacon marine are installing Seabins this summer (2020), and they have offered to assist GBF in quantifying and classifying bin contents (litter collected) as much as possible.

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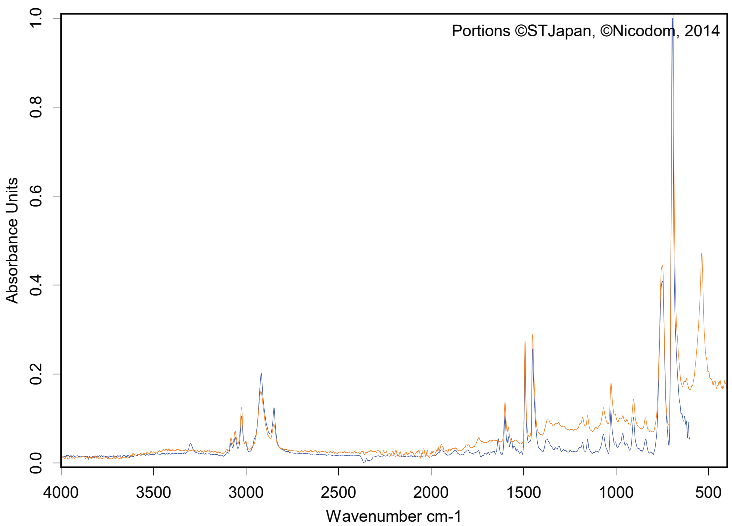
6. Annexes

Appendix 6.1 White Foam

Search Library **2019-09-30 12:16:34 PM**



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Molecular Weight	
CAS Registry Number	
Sample Preparation	ATR single bounce
Comment	polystyrene
Reference	320/ MP0209
Copyright	(c) 2014 Nicodom
Entry No.	638
Library name	ATR-LIB-POLYMERS-2-472-2.S01

Color	Hit Quality	Compound name	CAS Number	Molecular formula	Molecular weight
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Color	File	Path	Spectrum Type
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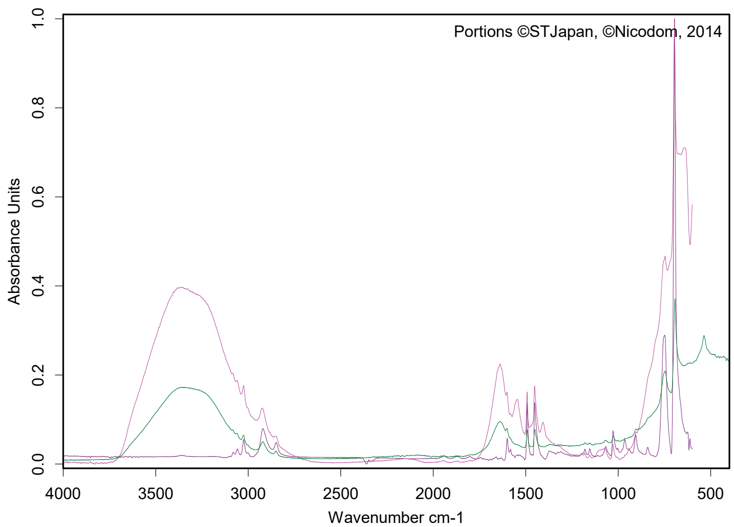
Appendix 6.2 Blue Foam

Search Library **2019-09-30 12:12:18 PM**



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Molecular Formula	(C8H8)n
Molecular Weight	
CAS Registry Number	
Sample Preparation	ATR single bounce
Comment	polystyrene
Reference	489/ MP0204
Copyright	(c) 2014 Nicodom
Entry No.	633
Library name	ATR-LIB-POLYMERS-2-472-2.S01

Color	Hit Quality	Compound name	CAS Number	Molecular formula	Molecular weight
	842	NEOCRYL A-1091			
	717	POLYSTYRENE HIGH IMPACT		(C8H8)n	

Color	File	Path	Spectrum Type
	Bluefoam_GBF.0	C:\Users\RochmanLab\Documents\Bruker\OPUS_7.8.44\DATA\MEAS	Query Spectrum

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Note: The blue foam had a two-component match, PS and NeoCryl-A-1091. NeoCryl-A-1091is a chemical made from a styrene acrylic polymer. There are many NeoCryl chemicals that are commercially available for water-dispersible resin emulsions; examples include the NeoCryl product line which have many acrylic styrene copolymer emulsions acrylic copolymer emulsions (Markies et al., 2013). NeoCryl-A-1091is listed under the Toxic Substances Control Act (TSCA), and regulated under the Canadian Domestic substances list (DSL) (Ash and Ash, 2004). However, due to the uncertainties in FTIR analysis, it cannot be said with any certainty that this is the exact chemical that is in the PS. At most, we can say that a PS copolymer was present. A copolymer is a polymer derived from more than one species of monomer, and many different commercial copolymers are common.

Appendix 6.3 Styrene

Styrene, also known as vinylbenzene, ethenylbenzene, cinnamene, or phenylethylene, is the monomer used to produce PS. In addition to PS, styrene is also used in the production of other plastics and resins, including fiberglass in boat hulls, copolymers used in piping, automotive components, refrigerator liners, and car battery enclosures (i.e. styrene-acrylonitrile and acrylonitrile-butadiene-styrene), styrene-butadiene rubber used in car tires, industrial hoses, and shoes, styrene-butadiene latex in carpet, paper coatings, and latex paints, and other styrene copolymer used in liquid toner for photocopiers and printers (IARC, 2002; Luderer et al., 2006; NTP, 2016).

Styrene has been detected in surface water, drinking water and fish in the Great Lakes area (Environment Canada & Health Canada, 1993). Styrene in water could be due to leachates, or from air. A study collecting air samples from 1988 to 1990 found styrene concentrations were highest in industrial areas in cities across Canada, with concentrations up to 34.20 ug/m3 (Dann, 1990). Styrene has also been detected in sewage, indoor air in single family homes, cigarettes, combustion from spark-ignition engines, waste incineration, and natural sources, including by-products from fungus and microbes (Concord Environmental, 1992; Environment Canada & Health Canada, 1993). Styrene volatizes rapidly from surface waters and typically has a half-life in water ranging from 1 to 60 hours (Min and Martin, 1992; Santodonato et al., 1980; Zoeteman et al., 1980). Volatilization depends on depth of the water body and degree of turbulence (Environment Canada & Health Canada, 1993; Zoeteman et al., 1980), and deep water can prolong styrene half-life values (Zoeteman et al., 1980; Alexander, 1990). In surveys of Canadian water supplies, elevated levels of styrene have been detected in raw and treated drinking water from the Great Lakes (Environment Canada & Health Canada, 1993). The maximum concentration measured in raw water during that study was 1.7 mg/L, in Cornwall (Environment Canada and Health Canada). A study of Great Lakes fish found styrene ranging between 15 and 100 mg/kg in walleye and splake caught in the St. Clair River (Bonner and Meresz, 1981)(Bonner and Meresz, 1981).

According to the International Agency for Research on Cancer (IARC), there is evidence of styrene carcinogenicity from studies in experimental animals (NTP 2016). Styrene caused lung tumors (Cruzan et al., 2001), liver damage (Carlson, 2002; Vogie et al., 2004), and genotoxicity (genetic damage such as coding errors) (Vodicka et al., 2006). In vitro studies have observed mutagenic effects in cell cultures (Bastlova and Podlutsky, 1996).

For human health, evidence on exposure to styrene is from epidemiological studies of workers exposed to styrene in the plastics and rubber industries (NTP 2016). These studies show increased mortality from cancer in the lymphohematopoietic system and increased damage in lymphocytes and with increased levels of DNA adducts (Kogevinas et al., 1994; Kolstad et al., 1995, 1994). Occupational exposure to styrene in the reinforced-plastics industry in Europe experienced increased cancer risks, including malignant lymphoma and leukemia when exposed to higher levels of styrene, or longer exposures (Kogevinas et al., 1994; Kolstad et al., 1995, 1994). Two studies from workers exposed to styrene from plastics manufacturing in the USA did not find significant associations between exposure to styrene and lymphohematopoietic cancer (Ruder et al., 2004; Wong et al., 1994), however, these studies have been criticized as having low statistical power to detect an association (IARC, 2002; NTP, 2016). A slightly increased risk of miscarriage was reported in Canadian women employed in the processing of PS, however, this observation was based on small sample size with poorly characterized exposure levels (McDonald et al., 1988).

Styrene, styrene polymers, and styrene copolymers are often approved for use in food packaging (FDA, 2018), although small amounts may migrate to food from styrene-based plastic food packaging (ATSDR, 2010; Environment Canada & Health Canada, 1993; FDA, 2018). Since 2018, styrene is no longer permitted in food additives (i.e. chewing gum base) (FDA, 2018). Styrene concentrations in bottled water have a limit of 0.1 mg/L in the USA (FDA, 2019). No set limits could be found for Canada, although the presence of styrene has been reported in food and drink from containers made of PS (Environment Canada & Health Canada, 1993).

For more information and references, see the National Toxicology Program (NTP) Report on Carcinogens, Fourteenth Edition, Styrene: https://ntp.niehs.nih.gov/ntp/roc/content/profiles/styrene.pdf