

Geospatial Modeling and Educational Intervention: Addressing Microfiber Pollution in
the Gulf of Mexico

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DEDICATION

To the people that never let me lose joy in the journey.

Also, for Sarah, Caroline, & Ashley, for teaching me that I'm so incredibly capable.

Thank you.

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ABSTRACT

The proliferation of cotton and polyester microfibers poses a significant risk to marine ecosystems. Understanding the environmental and societal mechanisms leading to increased microfiber ingestion by marine animal species is crucial for ecosystem preservation and human health. Previous literature suggests that the predominant factors contributing to this type of pollution are the widespread use of household washing machines and the rising consumer demand for fast fashion textiles. In addition, studies have demonstrated that ocean salinity influences the bioavailability of both cotton and polyester microfibers. Research also indicates that salinity gradients alter the adsorption of pollutants to microfiber surfaces, thereby potentially amplifying their impact. The detrimental effects of overconsumption of fast fashion in the United States are particularly evident in regions such as the Gulf of Mexico, the terminal drainage basin for the majority of rivers in the United States. However, the spatial distribution of microfiber ingestion risk and susceptible species habitats remains unclear. This study developed a geospatial model using National Oceanic and Atmospheric Administration (NOAA) salinity data and species density data from Ocean Biodiversity Information System (OBIS) in ArcGIS Pro (version 3.30) to identify high-risk areas within the Gulf of Mexico that are susceptible to elevated levels of microfiber ingestion. Seasonal salinity variations and species habitat zones were overlaid to predict pollutant adsorption trends. This analysis identifies critical habitats in the Gulf and informs targeted mitigation

strategies. Moreover, a complementary educational curriculum was developed to raise awareness about microfiber pollution to a pre-consumer audience. Pre-and-post surveys found a significant difference in both conceptual knowledge and perceived behavior change ($\alpha=0.05$). This thesis offers a two-angled approach, formally identifying habitats in the Gulf of Mexico that are most susceptible to microfiber ingestion, while further promoting sustainable textile consumption practices for the next generation of consumers.

TABLE OF CONTENTS

Chapter 1:.....	1
Geospatial Modeling of Salinity-Driven Microfiber Ingestion Risk in the Gulf of Mexico	1
1.1 Abstract.....	2
1.2 Background	2
1.2.1 Microfibers and Their Pathway to the Ocean	6
1.2.2 Aquatic Biodegradation of Cotton and Polyester Textiles.....	7
1.2.3 Impact of Textile Dyes.....	10
1.2.4 Salinity's Influence on Bioavailability	13
1.2.5 Gulf of Mexico: Area of Interest	17
1.2.6 Species of Interest.....	21
1.3 Research Objectives	24
1.4 Materials and Methods	25
1.4.1 Salinity.....	25
1.4.2 Species Habitat	26
1.4.3 Salinity by Species Habitat.....	26
1.5 Results and Discussion.....	27
1.5.1 Salinity and Seasonality.....	27
1.5.2 Salinity Trends with Depth	27

1.5.3 Species Habitat	33
1.6 Conclusion.....	46
References	48
Chapter 2 From Awareness to Action: 4-H and Sustainable Textile Consumption	66
2.1 Abstract.....	67
2.2 Background	67
2.2.1 Current Consumer Education Constraints	67
2.2.2 The Role of Youth Education and The Expectancy-Value Model in Environmental Stewardship.....	69
2.2.3 4-H Curriculum and Kinesthetic Learning	70
2.3 Study Objectives	71
2.4 Materials and Methods.....	72
2.5 Results and Discussion.....	73
2.6 Conclusion.....	75
References	78
Appendix A: Youth Lesson Plan	81
Appendix B: Assessments	94
Chapter 3	96
Overall Conclusions and Future Directions.....	96
3.1 Chapter One Key Findings.....	97

3.2 Chapter Two Key Findings.....	98
Vita.....	99

LIST OF TABLES

Table 1: Summary Statistics of <i>Lutjanidae gill</i>	34
Table 2: Summary Statistics of <i>Micropogonias undulatus</i>	36
Table 3: Summary Statistics of <i>Callinectes sapidus</i>	37
Table 4: Summary Statistics of <i>Clupeidae cuvier</i>	39
Table 5: Summary Statistics of <i>Crassostrea virginia</i>	40
Table 6: Summary Statistics of <i>Penaeidae rafinesque</i>	42
Table 7: Summary Statistics of <i>Sciaenops ocellatus</i>	43
Table 8: Summary Statistics of <i>Tursiops gervais</i>	45
Table 9: Conceptual Knowledge Summary Results.....	74
Table 10: Behavioral Expectation Summary Results.....	76

LIST OF FIGURES

Figure 1: Approximated Cotton Microfiber Composition	9
Figure 2: Polyester Manufacturing Process	10
Figure 3: Color Wheel of Natural Dyes	14
Figure 4: Adsorption of Tylosin onto Microplastic Surface Across Ranging Salinity. Data is summarized from findings reported in “Adsorption of Tylosin and Tetracycline onto Microplastics: Behavior and Effects of Adsorbents and Salinity” by Zu et al. (2023).....	20
Figure 5: Adsorption of Zinc (II) onto tire wear particles across ranging salinity. Data is summarized from findings reported in “Effects of salinity on the adsorption of cadmium and zinc to tire and road wear particles in water – Significance for river systems and road runoff treatment” by Vogel et al. (2025).	20
Figure 6: Annual mean salinity (PSU) from 2005-2017 (NOAA).....	28
Figure 7: Variation in annual mean salinity from 2005-2017 (NOAA).....	28
Figure 8: Average seasonal changes in salinity from 2005-2017 (NOAA)	29
Figure 9: Salinity Vs. Depth (0-20m)	31
Figure 10: Salinity Vs. Depth (30-50m)	31
Figure 11: Overview of seasonal salinity with depth in the Gulf of Mexico from 2005-2017 (NOAA)	32
Figure 12: Snapper Habitat vs. Salinity Fluctuation.....	34
Figure 13: Atlantic Croaker vs. Salinity Fluctuation	36

Figure 14: Blue Crab Habitat vs. Salinity Fluctuations	37
Figure 15: Tropical Sardines vs. Salinity Fluctuations	39
Figure 16: Eastern Oyster vs. Salinity fluctuations	40
Figure 17: Marine Shrimp Vs. Salinity Fluctuation.....	42
Figure 18: Salinity Fluctuation Vs. Red Drum Habitat	43
Figure 19: Bottlenose Dolphins Vs. Salinity Fluctuation	45

Chapter 1:

Geospatial Modeling of Salinity-Driven Microfiber Ingestion Risk in the Gulf of Mexico

1.1 Abstract

The rapid expansion of mass-produced textiles, which has doubled in the past two decades (EPA, 2018), has led to an influx of microfiber pollution within marine environments. Microfibers, a subset of microplastics, are known to pose direct adverse health effects upon ingestion by marine organisms, while also acting as a vector for various pollutants. Research indicates that aquatic salinity influences the bioavailability of both cotton and polyester microfibers, with the adverse effects of cotton microfiber ingestion happening at much higher salinity levels relative to polyester (Siddiqui et al., 2023). Additionally, salinity gradients affect the partitioning of organic and inorganic pollutants, however, the spatial distribution of these interactions within marine habitats remains poorly understood. The primary objective of this research is to develop a geospatial model, utilizing salinity data from the National Oceanic and Atmospheric Administration (NOAA) and species density data from the Ocean Biodiversity Information System (OBIS), to identify regions within the Gulf of Mexico susceptible to elevated microfiber ingestion and to predict the spatial patterns of pollutant adsorption onto microfibers. Using ArcGIS Pro (version 3.30), a spatial mosaic was created to represent seasonal salinity variations, which was then overlaid with species habitat zones. The analysis revealed significant salinity fluctuations ($\alpha=0.05$) across the habitats of eight selected species, suggesting that these fluctuations create optimal conditions for both the adsorption of pollutants onto microfibers and microfiber ingestion, potentially impacting species health and survival.

1.2 Background

In less than two decades, textile production has nearly doubled from the 9 million tons produced in 2000, to an estimated 17 million tons produced in 2018 (EPA, 2018). The mass

production and expansion of the textile industry has led to several negative effects, including the release of approximately 879 million tons of carbon dioxide annually (Smith, 2024).

Furthermore, the manufacturing, dyeing, and finishing processes have been linked to the release of various chemical pollutants in both freshwater and saltwater bodies (Kim et al., 2022; Kwak et al., 2022). Recently, natural and synthetic textiles have been reported to differ in their associated effects, with the material composition of the fabric often dictating the environmental outcomes.

Textiles can be categorized into three main material groupings: natural, synthetic, and blends.

Natural textiles, as the name suggests, are fibers produced from various plant and animal sources, including hemp, bamboo, flax, cotton, and wool (Dhaliwal, 2019). Alternatively, synthetic fibers are man-made, primarily consisting of polyethylene terephthalate chemicals, which are used in polyester and plastic manufacturing (Stone et al., 2020). Blended fabrics combine natural and/or synthetic materials (Behera, 2007). The fashion industry, the primary consumer of these textiles and the third largest grossing industry in the world (Zhang et al., 2021), relies heavily on cotton and polyester, which constitute 22% of 50% of the entire textile market demand, respectively (Textile Exchange, 2024).

The demand for natural and synthetic textiles remained consistent from the mid-1900s until the early 2000s (Papazolomou et al., 2022). During this time, a fundamental shift occurred within the fashion industry, captivating consumers and their desire to obtain the latest seasonal trends (Papazolomou et al., 2022). As fashion trends began to turnover rapidly, the industry increased access to new clothing materials quickly and at low prices, paving the way for a business model known today as fast fashion (Papazolomou et al., 2022). Fast fashion can be defined as the rapid production of low-quality materials sold for an inexpensive price (Joy et al.,

2015). Due to the lack of quality clothing items produced in this manner, fast fashion pieces are strongly associated with shorter product life cycles and increased purchasing frequency (Joy et al., 2015). Fast fashion pieces average approximately 7 wears before being discarded, contradictory to slow fashion which average 30 to 100 wears (Ellen MacArther Foundation, 2017). Most fast fashion pieces are made from synthetic materials (fabrics, chemical dyes, and finishes), sparking global environmental concern (Joy et al., 2015).

Research has shown that one possible reason for the continuous increase in fast fashion is the lack of consumer knowledge surrounding fast fashion textiles and their environmental impacts (Zhang et al., 2021). Additional literature has shown no generational differences in consumption behavior towards fast fashion (Niemi & Nerac, 2024). Instead, willingness to purchase from a fast fashion brand strongly coincides with the consumers educational background and other socioeconomic factors (Niemi & Nerac, 2024).

The environmental effects of textile production extend beyond manufacturing, with a primary source of textile pollution occurring in consumer households. Microfibers, a subset of microplastics that occur when synthetic components of textiles degrade (EPA, 2018), shed from textiles during domestic laundering. As the friction between the water and clothing pieces increases, tiny fabric fragments break off and are released through drainage pipes into rivers and then eventually the ocean (EPA, 2018).

It is estimated that trillions of microfibers, perhaps as many as 1.5 quadrillion (million trillion), are currently present in the ocean (Mushra, 2019). Moreover, approximately 13 million tons of synthetic fabric waste enter the ocean annually, with over 19% carried by rivers (Mushra, 2019). Once in the ocean, microfibers are often mistakenly ingested by small marine organisms.

This ingestion leads to an accumulation of the microfibers in their digestive tract where prolonged consumption has been linked to reduced hunger cues and eventual starvation (Santonicola, 2023). Furthermore, microfibers serve as a vector for the consumption of additional marine pollutants. Microfibers can adsorb pollutants such as metals, polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), and endocrine-disrupting compounds (EDCs) causing effects that can be both carcinogenic and lethal upon repeated ingestion (Singh, 2020). The accumulation of pollutants adsorbed onto microfiber surfaces—and subsequently ingested and absorbed into the tissues of marine organisms across trophic levels through bioaccumulation—represent the primary concern of microfiber pollution due to the health risks posed to aquatic life and humans who consume contaminated seafood (Singh et al., 2020).

Recent studies have highlighted key differences in the behavior of polyester and cotton microfibers within aquatic environments (Siddiqui et al., 2023). Notably, cotton microfiber degradation is highly dependent on chemical finishes and dyes. Furthermore, cotton microfibers exhibit lower primary biodegradability in water compared to terrestrial environments (Kim et al., 2022). This reduced aquatic biodegradability leads to an accumulation of cotton microfiber fragments, posing a risk of ingestion by marine life (Siddiqui et al., 2023). While cotton microfibers can biodegrade over time, polyester microfibers, made of nonbiodegradable polymers, present a different challenge. As polyester microfibers enter marine environments, they have been shown to release a range of additives that are both carcinogenic and/or lethal to some marine species upon ingestion (Kim et al., 2022). Furthermore, research indicates that the impacts of ingested microfibers vary with oceanic salinity levels: cotton microfibers tend to affect organism behavior more significantly at higher salinities, while polyester microfibers have

a greater impact at lower salinity levels (Siddiqui et al., 2023). Additionally, microfibers act as vectors for different pollutants depending on salinity conditions (Amelia et al., 2021). Therefore, it is crucial to conduct further assessments of ocean regions with salinity levels conducive to both cotton and polyester microfiber ingestion. Such studies are critical for the development of targeted, region-specific policies aimed at mitigating this pressing global issue.

1.2.1 Microfibers and Their Pathway to the Ocean

Microplastics are broadly categorized as primary or secondary. Primary microplastics are manufactured particles, ranging from 1 μ m to 5mm in length, intended for use in cosmetics, sanitary products, and industrial applications (EPA, 2018). Due to the intentionality of production, primary microplastics have a uniform shape and reduced sharp edges (Lehtiniemi et al., 2018). Secondary microplastics, conversely, originate from the fragmentation of larger plastic debris, ultimately yielding particles less than 5mm. Secondary microplastic fragments are asymmetrical and occur more often in aquatic environments due to the degradation of macroscopic plastic waste (Lehtiniemi et al., 2018). Given their ecotoxicity and abundance, microfibers are considered the dominant source of secondary microplastic pollution in marine ecosystems (Kwak et al., 2022).

Microfibers are released throughout the textile lifecycle, including through abrasion during normal wear, leaching from landfills during precipitation events, and inefficiencies in production. However, domestic laundering is recognized as the primary source of microfiber pollution (EPA, 2018; Athey & Erdle, 2021). During the laundry spin cycle, mechanical friction between clothing and water causes microfibers to detach from fabrics. These microfibers are then transported throughout riverine systems and ultimately to marine environments (EPA, 2018).

Following discharge through the drain hose, microfibers travel with additional effluent to a wastewater treatment facility (Chatterjee, 1978). Due to their small size and high abundance, current treatment methods do not achieve complete removal. With an average microfiber removal rate of 70%, the remaining 30% of unfiltered microfibers are released back into surrounding aquatic ecosystems (Sol et al., 2021). As microfibers flow through freshwater ecosystems, small portions of microfibers are consumed by local wildlife, eventually reaching the ocean (EPA, 2018). Consequently, microfibers have been identified in a wide range of aquatic environments such as lakes, rivers, deep sea, sea ice, marine sediments, bays, and even drinking water, reflecting their escalating abundance (Sol et al., 2021).

1.2.2 Aquatic Biodegradation of Cotton and Polyester Textiles

Cotton microfiber degradation varies substantially with regards to applied chemical finishes and dyes. These chemical additives can introduce various contaminants, including bisphenols, azo dyes, polyfluorinated alkyl compounds (PFAS), and formaldehyde into aquatic environments (Athey & Erdle, 2021). Cotton fibers, the fundamental component of cotton textiles, are harvested from a cotton plant and ginned to produce a clean, usable product. The primary cotton producers globally are China, the United States, Brazil, and Pakistan. Notably, cotton fibers have high absorptivity, capable of holding up to 24-27 times their weight in water. These fibers are predominantly composed of α -cellulose (88-96.5%) with cotton fibers having the highest molecular weight and structural order (degree of crystallinity determined by x-ray methods is 70-80%) compared to any other plant fiber (S. Grishanov, 2001; Clark, 2011). In addition to α -cellulose, cotton fibers contain various waxes and pectin, which help to reinforce the fiber's protective barrier (Dassanayake & Abidi, 2017).

Cotton fabric degradation during the domestic laundering process is influenced by yarn count, weave density, and weave structure (Kim et al., 2022). Kim et al. (2022) reported that fabrics with a higher yarn count and a compact weave structure showed less microfiber release throughout the spin cycle. Furthermore, fabrics treated with a water-repellent finish released fewer microfibers than untreated fabrics, while fabrics treated with peach skin finishes, designed to enhance softness, released more microfibers than untreated fabrics (Kim et al., 2022). This suggests that the optimal cotton fabric composition to reduce microfiber pollution involves a high yarn count, compact weave structure, and a water-repellent finish. See **Figure 1** for further details.

Cotton fibers exhibit lower primary degradation rates in marine ecosystems (6-12 months) as compared to terrestrial environments (1-5 months), which benefit from higher oxygen levels, diverse microbial communities, and stable, warmer temperatures (Swan & Kominosk, 2012; CottonToday, n.d.). In seawater, microbial communities inhabit and produce cellulase enzymes (Behera et al., 2016). These enzymes hydrolyze the β -1, 4-glycosidic linkages in cellulose, eventually degrading to simple glucose monomers that are metabolized by microbes (Behera et al., 2016). This degradation process, however, is highly dependent on environmental conditions and the overall chemical composition of the microfiber (Battista, 1950).

Anaerobic bacteria often struggle to fully penetrate cellulosic fibers, thereby delaying the overall degradation process (Behera et al., 2016). In addition, high levels of nitrate and phosphate in aquatic ecosystems can drastically slow cotton's degradation process, by inducing anaerobic conditions not conducive to optimal aerobic microbial function: the most efficient decomposers of organic matter (Deng et al., 2024). Furthermore, synthetic finishes and dyes

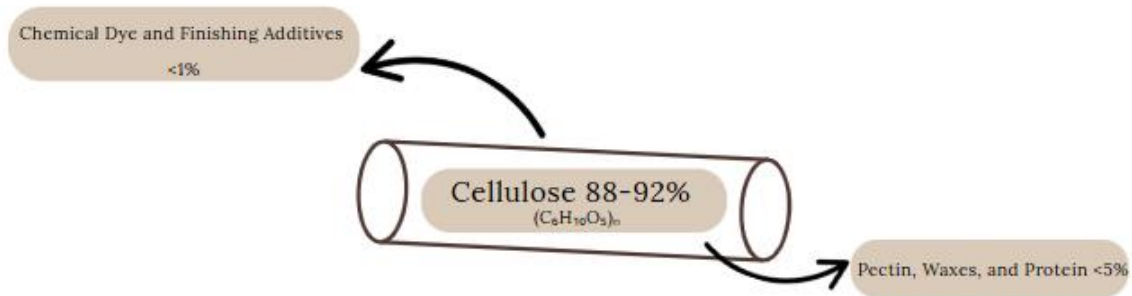


Figure 1: Approximated Cotton Microfiber Composition

applied to cotton fibers during textile production will inhibit cellulose degradation, while simultaneously releasing toxins into aquatic ecosystems (Surana et al., 2024).

Polyester, a synthetic polymer chain derived from petrochemical feedstocks (Barot et al., 2019), primarily utilizes polyethylene terephthalate (PET), which is synthesized from refined crude oil and serves as a profitable byproduct of the petroleum industry (Palacios-Mateo et al., 2021). PET is supplied to the textile industry in the form of pellets, which are then processed into fibers through extrusion and spinning techniques (Palacios-Mateo et al., 2021). These fibers are subsequently woven or knitted into fabric materials, often incorporating chemical dyes and/or additives to achieve desired material properties (Palacios-Mateo et al., 2021). Refer to **Figure 2**.

While polyester's strength, elasticity, breathability, and vibrancy, along with its low cost, have contributed to its widespread use (Brown & Reinhart, 1971), its lack of full

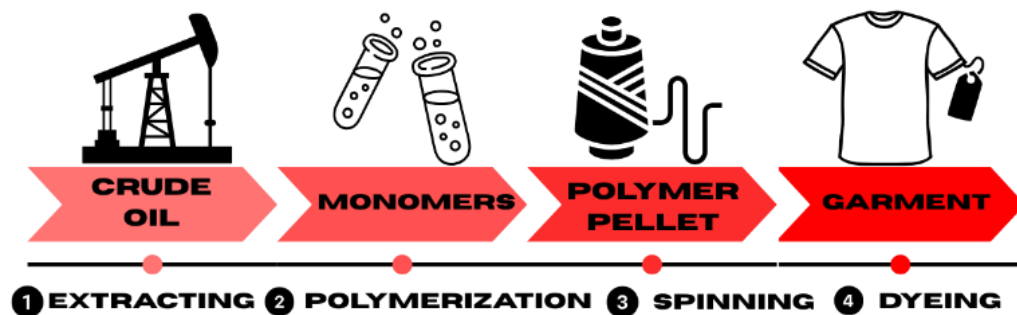


Figure 2: Polyester Manufacturing Process

biodegradability poses a significant environmental challenge (Wang, 2024). Physical weathering is the primary mechanism for polyester degradation in seawater.

As polyester fibers are repeatedly exposed to the abrasive forces of ocean currents and UV radiation, the fibers fragment into progressively smaller microfibers, dispersing across the ocean profile (Gerritse et al., 2020; Sorensen et al., 2024). While UV radiation may accelerate surface degradation (Sorensen et al., 2024), this primarily enhances physical fragmentation and has little influence on polyester's overall biodegradability. Unlike pure cotton fibers, which are susceptible to microbial metabolism, microbes on polyester form a biofilm layer that may marginally contribute to degradation. However, these microbial communities are often comprised of pathogenic strains of bacterial genera, sparking marine and human health concerns (Liddick & Reir, 2024).

1.2.3 Impact of Textile Dyes

The inherent fabric composition of microfibers represents only a fraction of their

potential environmental impact. Microfibers often comprise not only the fabric material but also synthetic or natural dyes and finishes. Natural dyes, derived from plant, mineral, and animal sources, are capable of complete biodegradation over time (Li et al., 2022). Conversely, synthetic dyes and finishes exhibit limited biodegradability, resulting in their persistence in the environment for extended periods, potentially releasing toxins into marine ecosystems (Berradi et al., 2019).

Flame retardants and water repellents are commonly applied additives during textile manufacturing, enhancing antibacterial properties and UV protection (Hesham et al., 2023). Bromide- and phosphorus-based compounds are frequently used flame retardants in textiles (Alvarez-Gonzalez et al., 2020; Sivaramakrishna & Singh, 2024). Polybrominated diphenyl ethers (PBDEs), a prevalent class of environmental pollutants, are utilized in flame retardants (Alvarez-Gonzalez et al., 2020). Octabromodiphenyl ether (OctaBDE), a derivative of PBDEs, is released during the degradation of brominated flame retardants and exhibits toxicity upon ingestion, promoting neuroendocrine disruption (Alvarez-Gonzalez et al., 2020). Tris(1,3-dichloro-2-propyl)phosphate (TDCPP), a frequently used phosphate flame retardant, is both carcinogenic (Farhat et al., 2013) and can bioaccumulate (Bekele et al., 2019). Similarly, water repellents are often formulated from fluorocarbon and siloxane compounds and contribute to the bioaccumulation of toxic compounds in marine ecosystems (Whittaker & Heine, 2018). Polydimethylsiloxane (PDMS), commonly used in silicone-based water-resistant finishes, can undergo microbial biodegradation to silica. However, this process is time-consuming, and the additives significantly impede the degradation of silicone-based water repellents (Ortiz-Ardila et al., 2023).

Textile manufacturers utilize diverse dye sources such as azo, acid, vat, and metal complex dyes, to color their materials. Azo dyes, characterized by the presence of an (-N=N-) azo group connecting to two aromatic rings (REWE, 2020), pose a significant environmental and health risk. The cleavage of the azo bond releases aromatic amines, some of which, such as benzidine and 2-naphthylamine, are carcinogenic to both marine organisms and humans (REWE, 2020). Acid dyes, synthesized from sulfonic acid groups, typically present as sodium salts (Devi, 2022). These are classified based on their structural molecules, including anthraquinone, azo, and triphenylmethane types, and are primarily used to color nylon, silk, and wool fibers (Devi, 2022). Some acid dyes are a subset of azo dyes; however not all acid dyes contain azo groups. Acid dyes, much like azo, can release aromatic amines during the degradation process (REWE, 2020). These can be classified by the three structural molecules used: anthraquinone type, azo dye type, triphenylmethane type. Vat dyes, primarily employed for dyeing cotton and rayon fibers (Rod, 2015), can be either synthetic, such as blue indanthrene RS, or natural, like indigo. Upon accumulation in aquatic environments, vat dyes impair photosynthetic efficiency by restricting oxygen circulation and overall light adsorption (Berradi et al., 2019). This poses health risks to both the aquatic flora and marine species. Metals (copper, cobalt, nickel, chromium, and lead) are incorporated into dyes to stabilize the dye and improve fabric resistance to weathering and laundering (Velusamy, 2021). Like acid dyes, metal dyes can also be classified as azo dyes, thereby inducing similar adverse effects during degradation and sparking environmental concern (Velusamy, 2021) .

Natural dyes, including indigo, pomegranate, henna, iron, and snail, are capable of complete biodegradation over time, contingent upon the chemical finishes applied to the textile

(Pizzicato et al., 2023). A primary limitation to using natural dyes opposed to synthetics is their lower fastness, or tendency to fade or bleed (Sun et al., 2024). Some natural dyes require a synthetic mordant, such as copper, to ensure fiber adherence. However, these mordants can be toxic to marine organisms (Sun et al., 2024). Additionally, natural dyeing processes are often more time-consuming, potentially resulting in uneven application (Pizzicato et al., 2023). Furthermore, natural dyes exhibit a lower affinity for synthetic fabrics, restricting their application to natural textiles (Pizzicato et al., 2023). See further details in **Figure 3**. Natural finishes are less prevalent than synthetic finishes, primarily due to their reduced durability (Pizzicato et al., 2023). As the demand for sustainable products increases, future research should focus on enhancing the durability of natural dyes, improving the efficacy of bio-based mordants, and increasing the overall sustainability of natural dyes and mordants (Sun et al., 2024).

1.2.4 Salinity's Influence on Bioavailability

Adsorption capacity (AC), the maximum amount of adsorbate that can be retained on the surface of an adsorbent (Sevim et al., 2020), is a critical factor in understanding the environmental impact of microfibers. Microfibers, a subset of microplastics, act as vectors for other marine pollutants including metals, pesticides, fertilizers, antibiotics, and polycyclic aromatic hydrocarbons, due to the adsorption of these substances onto the fibers' surface, thus increasing their overall impact on marine species (Amelia et al., 2021). Upon ingestion of microfibers by marine organisms, the adsorbed pollutants are also ingested and absorbed into the species' tissues, thereby exacerbating the observed adverse effects (Amelia et al., 2021). Though microfibers are not the sole pathway for pollutant introduction into marine species, their role as a

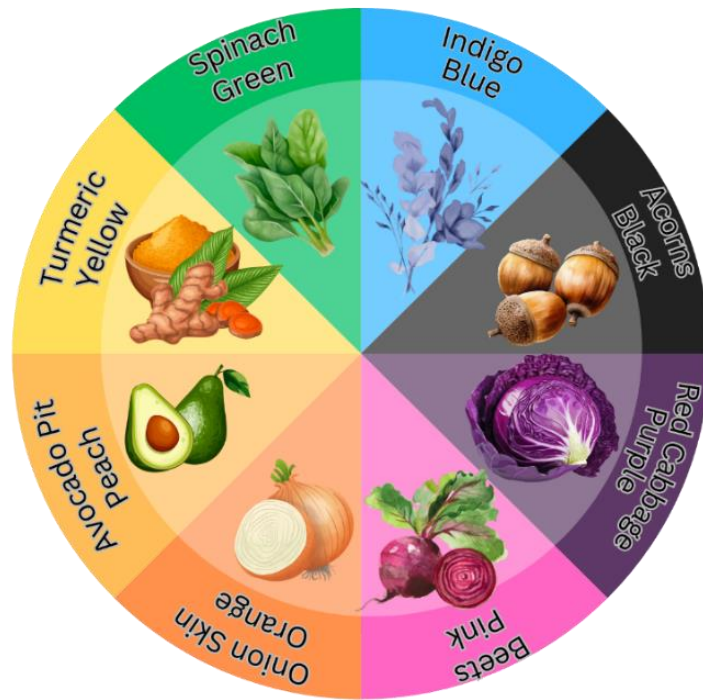


Figure 3: Color Wheel of Natural Dyes

vector for pollutant adsorption warrants significant consideration when assessing the comprehensive impacts of microfibers on marine ecosystems. Consequently, understanding the conditions that optimize the adsorption of environmental pollutants onto marine microfibers is crucial.

Salinity levels within aquatic zones influence environmental conditions favorable to the adsorption of specific pollutants. Salinity data, commonly reported in practical salinity units (PSU), can be utilized to predict which pollutants are more favorable to adsorb onto microfiber surfaces. PSU represents the quantity of dissolved salts in a solution, with one PSU equivalent to one gram of salt per thousand grams of water, or one part per thousand (Saraswat et al., 2015). Surana (2022) reported that metal adsorption (Cd(II), Zn (II), Ti(II)) onto microfiber surfaces decreased with increasing salinity. This finding aligns with results reported by Barus et al. (2021), who observed a reduction in both adsorption efficiency and the rate of metals onto polystyrene microplastics under high salinity conditions (Barus et al., 2021). Elevated salinity causes an influx of exchangeable cations, which compete for the adsorption sites on the microfibers, thus reducing metal adsorption. Sharma & Krupadam (2022) corroborated this finding in their adsorption isotherms of As(III), Cd(II), Cr(III), Pb(II), Zn(II), Ti(II), & Al(III) across brackish to oceanic salinities (3 PSU, 17 PSU, and 29 PSU), reporting a reduction in adsorption with increasing salinity (e.g., 19.44 mg g^{-1} at 29 PSU vs. 53.22 mg g^{-1} at 3 PSU). Conversely, persistent organic pollutants (POPs) exhibit increased adsorption with higher salinity. Velzeboer et al. (2014) observed enhanced Polychlorinated Biphenyls (PCBs) adsorption onto the surface of polystyrene nanoparticles and micropolyethylene, both of which are considered microplastics. Similarly, Pfeifer et al. (2005) reported that increased salinity levels (5-20 PSU) resulted in a

significant increase ($p < .001$) in enzyme dysfunction in blue mussels, attributed to the increase in absorption of organic pesticides organophosphorus and carbamate. The increased precipitation of organic pollutants out of solution is consistent with the chemical principle of “salting out” (Hyde et al., 2021). Upon the addition of salts to solution, the solubility of organic pollutants decreases, thus causing them to precipitate out of solution and onto the surface of microfibers (Hyde et al., 2021). Metals in solution are more affected by the competition for adsorption sites, thus increasing the salinity (increase of exchangeable ions) significantly hindering metal adsorption capacity.

While the estimated concentrations of both metal pollutants (e.g., Cd(II), Zn(II), Ti(II)) and organic pollutants (e.g., PCBs, tetracycline, pesticides) in aquatic ecosystems are approximated to be in $\mu\text{g/L}$ range, their potential for bioaccumulation leads to concentrations in marine species that can exceed thresholds for human consumption and induce adverse health effects in aquatic life, including neurological impairment, liver dysfunction, and reproductive dysfunction, threatening species' overall success (Annibaldi et al., 2019; Howell et al., 2008). For example, Pb(II) levels as low as $0.5 \mu\text{g g}^{-1}$ have been reported to cause adverse behavioral effects in fish species, while concentrations around $2.5 \mu\text{g g}^{-1}$ have been shown to negatively affect fish growth and development (Depew et al., 2012).

Salinity levels have been shown to influence the species-specific effects of microfiber/microplastic ingestion. Emon et al. (2024) reported a statistically significant increase in microplastic accumulation within the intestinal morphology and gills of the Nile Tilapia with increasing salinity. This finding is corroborated by Pferier et al. (2005), who observed a decrease in acetylcholinesterase activity (a biomarker for ingestion of neurotoxic compounds) in blue

mussels at elevated salinity. Conversely, Capparelli et al. (2023) documented a higher accumulation of microplastics in the gut of fiddler crabs exposed to a lower salinity river environment. However, this study's short 24-hour duration may not accurately reflect long-term exposure effects from varying salinity levels.

In addition to pollutant adsorption, salinity also influences the biological impact of polyester and cotton microfibers, with each material exhibiting varying effects. Siddiqui et al. (2023) demonstrated that polyester microfibers altered organism behavior across a broad spectrum of salinity levels, whereas cotton microfibers primarily affected behavior at higher salinities (25 PSU+). Evaluating growth in Neotropical silversides and opossum shrimps revealed that polyester microfibers inhibited growth across a broad spectrum of salinity levels. Conversely, cotton microfibers showed no growth effect on silversides but did cause reduced growth in opossum shrimps at specific salinity levels (Siddiqui et al., 2023). These findings suggest that polyester microfibers have broader bioavailability across varying salinities, while cotton microfibers had a more pronounced effect only at higher salinities (Siddiqui et al., 2023).

1.2.5 Gulf of Mexico: Area of Interest

The Gulf of Mexico provides essential ecological and economic services that are critical to the socioeconomic well-being of bordering nations. This region supports complex biological systems and a diverse array of temperate and tropical marine species (McKinney et al., 2021). The highest level of biological productivity occurs at depths less than 20 meters, which constitutes roughly 40% of the Gulf of Mexico's total area (Spies et al., 2016). Beyond its ecological significance, the Gulf of Mexico accounts for an estimated 20% of global commercial fisheries production (Spies et al., 2016), a vital resource for the United States, Cuba, and Mexico

(Spies et al., 2016). Additionally, the Gulf is a major petroleum extraction hub, producing an estimated 2.5 million barrels of oil daily (NOIA, 2020). The region's coastline is home to roughly 5% of the U.S. population (15 million people), with 800,000 individuals dependent on the coastal economy for their livelihoods (Day et al., 2024).

Beyond its regional economic and ecological importance, the Gulf of Mexico also functions as a major drainage basin for watersheds across the United States. Approximately 41% of the continental United States drains into the Gulf of Mexico (The Nature Conservancy, 2020). This hydrological input encompasses 20 major and 150 individual river systems, draining a surface area of 3.4 million square kilometers (U.S. Fish and Wildlife Service [FWS], n.d.). Notably, the Mississippi River contributes 61% of the total freshwater inflow (U.S. Fish and Wildlife Service [FWS], n.d.). Given this extensive hydrological input from diverse water bodies, maintaining the quality of riverine effluent is crucial for preserving the Gulf's environmental integrity.

Salinity in the Gulf of Mexico ranges from approximately 9 to 37 PSU, varying spatially with distance from the coastline (NOAA, n.d.). Oceanic salinity typically averages between 33 and 37 PSU, with values exceeding 37 PSU considered high (e.g., the Red Sea at 40 PSU) and values below 25 PSU classified as brackish (NOAA, n.d.). Although dissolved salt concentrations are relatively elevated compared to freshwater ecosystems, salinity within this Gulf range has been shown to influence the adsorption of different classes of marine pollutants. For example, the retention of the antibiotic tylosin by microplastics is at a maximum when the PSU is approximately 6, then retention decreases with increasing PSU. Conversely, the

adsorption of Zn by tire wear particles is at a maximum in dilute salt solutions, then continually decreases with increasing PSU.

Furthermore, previous studies have reported pH fluctuations in the Gulf, with average values of 8.00 ± 0.04 in winter, 7.86 ± 0.10 in spring, and 8.14 ± 0.16 in summer (Osborne et al., 2022). These pH variations can affect the surface charge of the adsorbent, the competition for adsorption sites, and the speciation of pollutants. The Gulf's surface water temperatures typically fluctuate between 18.3°C (65°F) and 27.8°C (82°F), generally increasing with distance from the coastline (SAS, 2015). Elevated surface temperatures, like those further offshore, have been reported to increase microbial activity and the biodegradation rate of organic materials (Sarmiento et al., 2010). Additionally, temperature can have a variable effect on the adsorption of an adsorbate onto the surface of an adsorbent, depending on whether the interaction is dominated by inner-or outer-sphere complexation (Essington, 2015).

These physicochemical characteristics of the Gulf of Mexico not only influence the biodegradation rates of microfibers but also significantly affect the adsorption efficiency of various classes of pollutants onto microfiber surfaces. Consequently, these factors play a crucial role in determining the health effects experienced by marine organisms following the ingestion and absorption of contaminated microfibers. As shown in **Figure 4** and **Figure 5**.

Terrestrial pollutants discharged into rivers significantly impact aquatic ecosystems within the Gulf of Mexico. Precipitation events, wastewater treatment facilities, and agricultural systems release a range of organic and inorganic pollutants into freshwater ecosystems (Rabalais & Turner, 2019). As water flows downstream, sediment and nutrients are continuously picked up

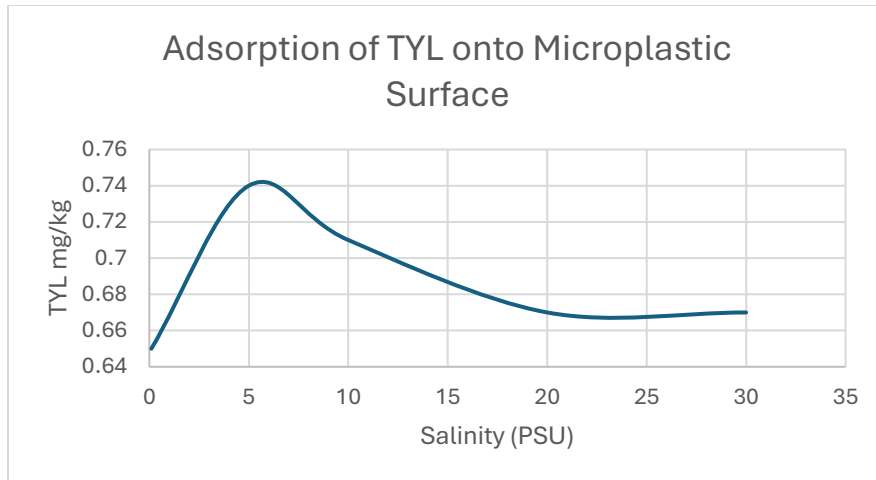


Figure 4: Adsorption of Tylosin onto Microplastic Surface Across Ranging Salinity. Data is summarized from findings reported in “Adsorption of Tylosin and Tetracycline onto Microplastics: Behavior and Effects of Adsorbents and Salinity” by Zu et al. (2023).

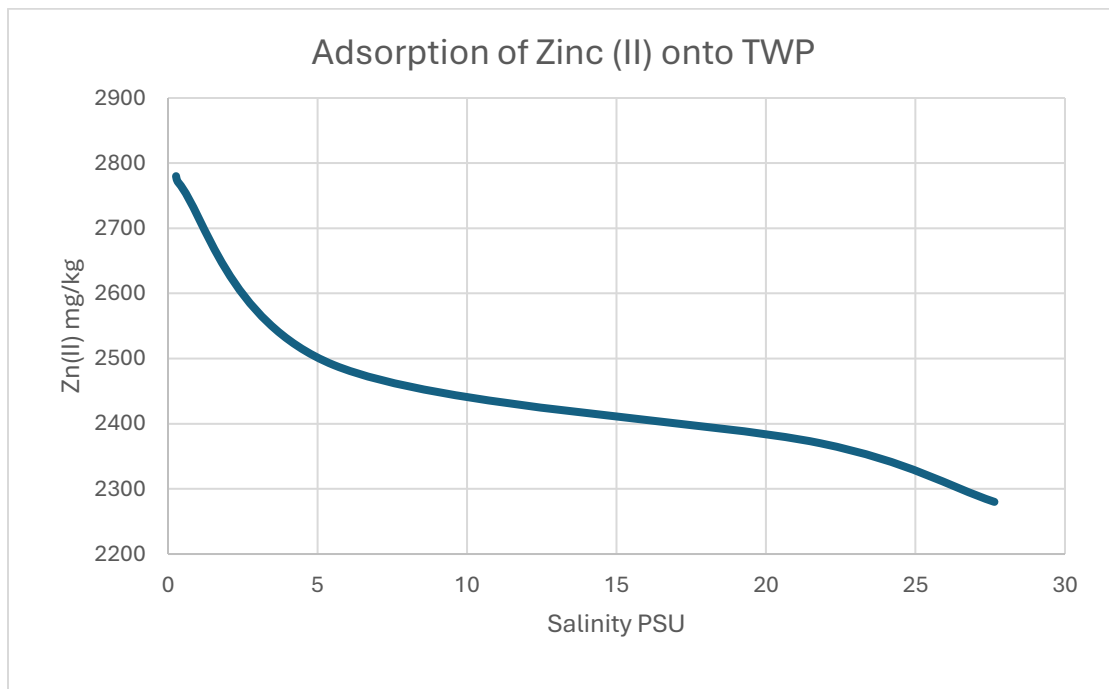


Figure 5: Adsorption of Zinc (II) onto tire wear particles across ranging salinity. Data is summarized from findings reported in “Effects of salinity on the adsorption of cadmium and zinc to tire and road wear particles in water – Significance for river systems and road runoff treatment” by Vogel et al. (2025).

and accumulated, ultimately reaching the Gulf. Any pollutants that cannot be adsorbed or settled out during this process are discharged into the Gulf's marine ecosystems. This influx has resulted in catastrophic hypoxic zones, reduced biological productivity, intensified algal blooms, and an increased risk to human health (National Oceanic and Atmospheric Administration ([NOAA], n.d.).

1.2.6 Species of Interest

The Gulf of Mexico supports a diverse range of species that provide environmental, commercial, and aesthetic value to its coastline. However, this abundant ecosystem faces persistent threats from pollutant influxes originating from adjacent coastal communities and estuaries. Without proper management, key industries, namely fishing and petroleum extraction, risk devastating losses.

Tropical sardines (Clupeidae) are a vital component of marine fisheries, sustaining livelihoods through their capture, distribution, and sale (Hunnam et al., 2021). These species typically exhibit short lifespans (approximately 1-4 years), reach maturity after the first year, and are a lower trophic level species commonly found in continental shelf waters. Depending on the particular species of Clupeidae, maximum growth and migration patterns will vary (Hunnam et al., 2021). The Gulf of Mexico supports *Clupeidae Cuvier*, a widespread and abundant species of tropical sardine (Ocean Biodiversity Information System [OBIS], 2024). *Clupeidae Cuvier* are typically observed at sea surface temperatures between 4-17 degrees Celsius and depths ranging from 20-50 meters (Ocean Biodiversity Information System [OBIS], 2024). They have been documented across a broad salinity range, with surface salinity levels between 5-10 PSU and 25-35 PSU (Ocean Biodiversity Information System [OBIS], 2024).

The family *Penaeidae* encompasses the highest-grossing commercial species of marine shrimps for the fishing industry (Hurzaid et al., 2020). While their greatest species diversity is concentrated in the Western Pacific region, *Penaeidae* shrimp are found across a broad geographic range (Hurzaid et al., 2020). *Penaeidae Rafinesque* is a species of equatorial marine shrimp that is highly prevalent in the Gulf of Mexico (Ocean Biodiversity Information System [OBIS], 2024). These shrimp are typically observed at sea surface temperatures between 20-30 degrees Celsius and depths of 0-30 meter (Ocean Biodiversity Information System [OBIS], 2024). *Penaeidae Rafinesque* prefers moderate salinity environments, with surface salinities reported between 25-35 PSU (Ocean Biodiversity Information System [OBIS], 2024).

Snappers (Lutjanidae) are highly valued in recreational fisheries and are increasingly utilized in aquaculture (Tarnecki et al., 2016). *Lutjanidae Gill* is a snapper species concentrated along equatorial regions, particularly in the Gulf of Mexico and along the Australian coastline (Ocean Biodiversity Information System [OBIS], 2024). These snappers are observed at sea surface temperatures between 25-30 degrees Celsius and salinity levels of 30-35 PSU (Ocean Biodiversity Information System [OBIS], 2024). *Lutjanidae Gill* prefers shallow waters along the continental shelf, ranging from 0-30 meters in depth (Ocean Biodiversity Information System [OBIS], 2024).

Micropogonias undulatus, more commonly known as the Atlanta croaker, is highly concentrated in the Gulf of Mexico. This species is a vital component of both local commercial and recreational fisheries (Heard, 1978). Its concentrated abundance makes it a primary contributor to regional markets (Heard, 1978). *Micropogonias undulatus* have been recorded at surface salinity levels of 25-35 PSU and temperatures between 20-25 degrees Celsius (Ocean

Biodiversity Information System [OBIS], 2024). The Atlanta croaker occupies a shallow depth range of 0-10 meters, making it extremely sensitive to anthropogenic impacts along the coastline (Ocean Biodiversity Information System [OBIS], 2024).

The Eastern Oyster, *Crassostrea virginica*, is the second most economically valuable bivalve fish in the U.S. and provides numerous environmental benefits (Gobler & Talmage, 2014). Eastern oysters contribute to water filtration, removing pollutants from riverine and coastal inputs (Gobler & Talmage, 2014). They also aid in the formation of coral reefs, which support high levels of marine biodiversity (Gobler & Talmage, 2014). *Crassostrea virginica* is primarily found along the Eastern U.S. coastline and the Gulf of Mexico (Ocean Biodiversity Information System [OBIS], 2024). This species has been observed across a wide range of sea surface temperatures (5-30 degrees Celsius) and is concentrated in salinity levels between 25-35 PSU (Ocean Biodiversity Information System [OBIS], 2024).

Callinectes sapidus, more commonly known as blue crabs, are a valuable protein (14-30% body composition) and omega fatty acid source for human consumption (Arena et al., 2024). Additionally, blue crabs contribute significantly to commercial fisheries (Arena et al., 2024). *Callinectes sapidus* Rathbun is concentrated along the southeastern U.S. coastline, the northern African coastline, and the Gulf of Mexico (Ocean Biodiversity Information System [OBIS], 2024). Blue crabs prefer higher salinity levels of 30-35 PSU and are often observed in sea surface temperatures between 20-30 degrees Celsius (Ocean Biodiversity Information System [OBIS], 2024). Like most crab species, blue crabs are found in shallow coastal waters at depths of 0-10 meters.

Sciaenops ocellatus (Red Drum) is a vital species in the aquaculture industry. Red drum aquaculture is highly sought after, contributing significantly to markets in 11 countries (Xiao et al., 2023). Wild *Sciaenops ocellatus* populations are primarily concentrated along the Gulf Coast, with sparse populations observed in East Africa (Ocean Biodiversity Information System [OBIS], 2024). This shallow-water species (0-10 meters) prefers salinity levels of 30-35 PSU (Ocean Biodiversity Information System [OBIS], 2024). Recorded sea surface temperatures for this species range between 20-25 degrees Celsius (Ocean Biodiversity Information System [OBIS], 2024).

Bottlenose dolphins, *Tursiops* Gervais, serve as ecosystem indicators, their presence and abundance signaling the overall health of their environment (Wells et al., 2004). *Tursiops* Gervais tolerate a wide range of surface temperatures, with typical observations occurring between 10-35 degrees Celsius (Ocean Biodiversity Information System [OBIS], 2024). However, bottlenose dolphins are primarily found in salinity levels of 25-35 PSU and at depths of up to 10 meters (Ocean Biodiversity Information System [OBIS], 2024).

Collectively, these species illustrate the Gulf of Mexico's rich biodiversity, which provides substantial economic and ecological benefits. Consequently, there is a compelling rationale for safeguarding the Gulf's environmental integrity and effectively managing pollutant inputs that jeopardize these vital biological resources.

1.3 Research Objectives

The comprehensive objective of this research is to create a spatially explicit model that delineates ocean regions with salinity levels conducive to microfiber adsorption and identifies

high-density zones of vulnerable species within these areas. This will be accomplished through the following methodological steps:

1. Synthesize a comprehensive literature review to characterize fundamental compositional differences between cotton and polyester microfibers and how these differences are manipulated at ranging salinity levels.
2. Construct a geospatial salinity layer using historic salinity data collected by NOAA to map oceanic salinity distribution and identify areas with salinity parameters favorable to both pollutant adsorption and microfiber ingestion.
3. Perform a spatial overlay analysis by integrating species density layers of susceptible marine organisms with the geospatial salinity layer to pinpoint high-risk zones.

1.4 Materials and Methods

1.4.1 Salinity

Seasonal salinity data (1/10° NetCDF) for the years 2005-2017 were acquired from the NOAA database ([climatology.tar.gz](https://climate.geog.udel.edu/climate/html/ncdc)) and imported into ArcGIS Pro (version 3.30). Seasonal salinity variation from 0 to -5500 meters was graphically represented in 10-meter increments to visualize the impact of seasonality on salinity within the upper 100 meters of the Gulf's water column. Temporal spread statistics (range, mean, standard deviation, maximum, & minimum) were calculated using the multidimensional analysis tools in ArcGIS, to assess salinity variation across seasons. Using the Catalog tool, two mosaic datasets were created for each season: one representing the average salinity (PSU) at each coordinate and depth and the corresponding standard deviation at each location.

1.4.2 Species Habitat

Species distribution records for eight ecologically and economically significant species (*Clupeidae* Cuvier, *Penaeidae* Rafinesque, *Lutjanidae* Gill, *Micropogonias undulatus*, *Crassostrea virginica*, *Sciaenops ocellatus*, *Callinectes sapidus* Rathbun, and *Tursiops* Gervais) were obtained from the Ocean Biodiversity Information System (OBIS) database. OBIS facilitates the collection of global species distribution data through collaborative partnerships with research institutions, government agencies, and citizen scientists (Ocean Biodiversity Information System, 2024). Diverse field collection techniques and autonomous instruments are employed to ensure representative data capture. All observations undergo taxonomic verification, geospatial accuracy checks, and consistency cross-referencing with existing records. The public availability of extensive point and distribution data enables distribution modeling for this research to occur for a wide range of ecological and economically valuable species along the Gulf Coast. The species distribution records were imported into ArcGIS Pro (version 3.30). The Clip tool was used to constrain species coordinates to the extent of the seasonal salinity dataset. The Aggregate Points tool was then employed to summarize species point features within a polygonal radius of 0.36 decimal degrees (approximately 25 miles) to capture the general habitat distribution along the Gulf of Mexico.

1.4.3 Salinity by Species Habitat

Zonal statistics for range, maximum, and minimum salinity levels were calculated through multidimensional analysis, accounting for variations in ocean depth (0-50 meters), which represents the depth range inhabited by the species. These zonal statistics were used to

assess significant differences in salinity variation within species habitats, allowing for the evaluation of pollutant bioavailability and microfiber ingestion in these areas.

1.5 Results and Discussion

1.5.1 Salinity and Seasonality

Estuarine regions, where rivers discharge freshwater into the Gulf of Mexico, exhibit the lowest annual salinity levels (González-Ramírez & Parés-Sierra, 2020). These areas also experience the greatest salinity fluctuations, with fluctuations ranging between 8 to 12 PSU. Conversely, the highest salinity levels and lowest fluctuations are located farther offshore. Overall, salinity levels within the Gulf of Mexico vary anywhere from 0-12 PSU. This range has been shown to significantly influence species' physiological responses and competition for pollutant adsorption (Pfeifer et al., 2005; Sharma & Krupadam, 2021). Refer to **Figure 6** and **Figure 7** for further details.

Seasonal salinity variations are shown in Figure 8. Over the course of the calendar year, salinity fluctuations are most pronounced along the coastline, as indicated by the blue regions in **Figure 8**. The lowest average salinity occurs during spring, while the highest salinity is observed in autumn.

This pattern is likely due to seasonal differences in climate and precipitation, as increased precipitation leads to elevated river inflow into the Gulf (Khadim et al., 2024).

1.5.2 Salinity Trends with Depth

NOAA salinity data reveal distinct seasonal patterns across varying depths in the Gulf of Mexico (**Figure 9**). At the surface (0 meters; **Figure 9a**), salinity fluctuations are most pronounced during spring and summer, coinciding with peak precipitation and evaporation,

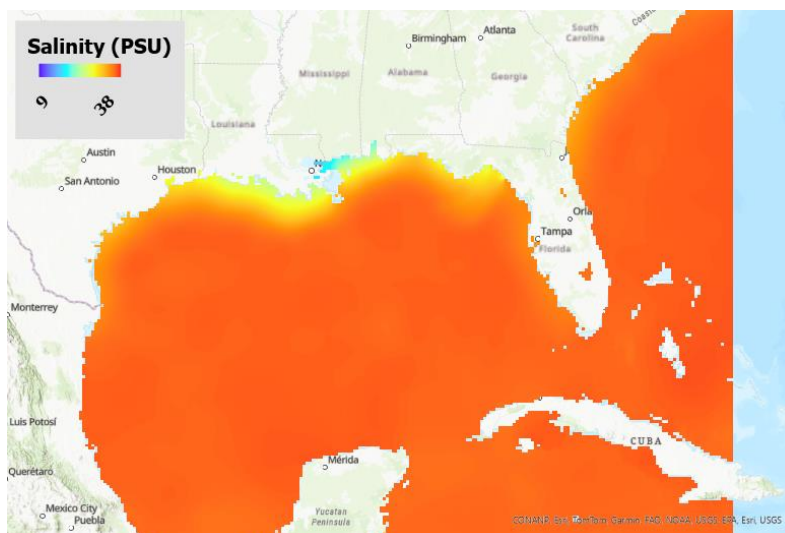


Figure 6: Annual mean salinity (PSU) from 2005-2017 (NOAA)

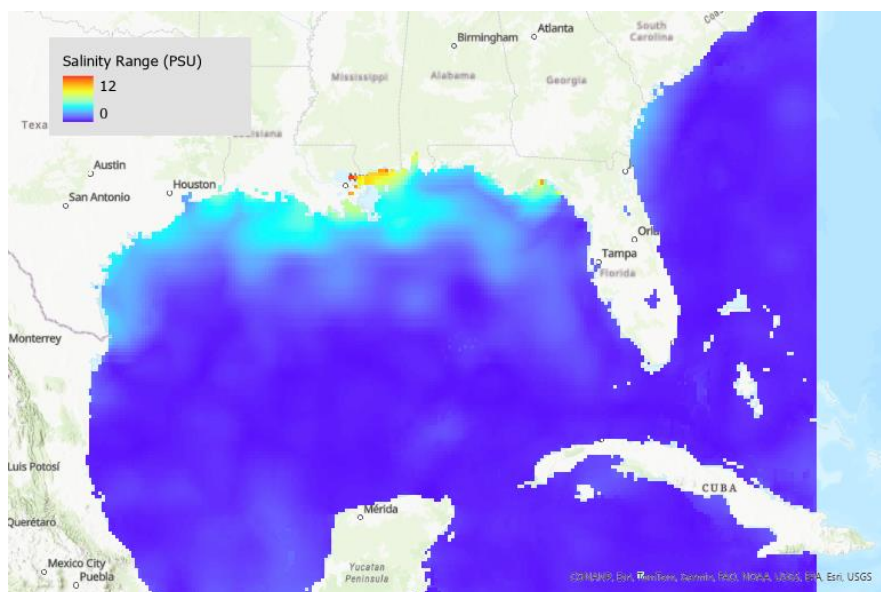


Figure 7: Variation in annual mean salinity from 2005-2017 (NOAA)

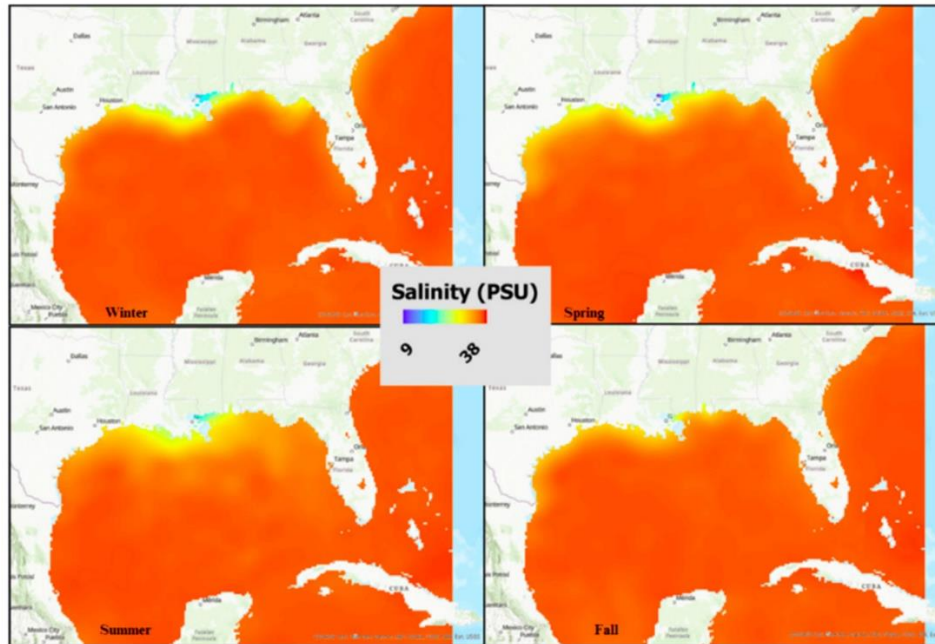


Figure 8: Average seasonal changes in salinity from 2005-2017 (NOAA)

while autumn exhibits the least variation. The minimum recorded salinity at this depth is approximately 31 PSU, and the maximum is 37 PSU. Moving to 10 meters (**Figure 9b**), significant salinity fluctuations are again observed during summer, aligning with increased evaporation and precipitation. The minimum salinity at this depth is 33 PSU in summer, while the maximum is 36.7 PSU in spring. Autumn shows the least fluctuation.

At 20 meters (**Figure 9c**), spring and summer continue to exhibit the greatest salinity fluctuations, with corresponding minimum and maximum levels. Notably, winter, rather than autumn, displays the smallest range. A shift occurs at 30 meters (**Figure 9a**), where the greatest salinity fluctuations are observed during autumn, and the smallest during summer. Spring maintains the highest recorded salinity.

This pattern continues at 40 and 50 meters (**Figure 9b-9c**), with autumn consistently showing the greatest salinity fluctuations. Spring remains the season with the highest recorded salinity, while autumn consistently shows the lowest salinity. Overall, surface fluctuations are highly influenced by precipitation and evaporation, while deeper levels have a more consistent pattern of autumn being the most variable. Refer to **Figure 9** and **Figure 10** for further information.

NOAA salinity data indicated a clear seasonal stratification pattern, with surface waters (0-20 meters) exhibiting higher salinity variability compared to the more consistent salinity measurements in deeper layers (30-50 meters); as demonstrated in **Figure 11**). This distinction is ecologically significant, as the typical habitat range for the studied species lies within the upper 50 meters of the water column. The observed seasonal salinity pattern with depth has been previously attributed to the patterns of surface heat flux, primarily solar radiation. Additionally,

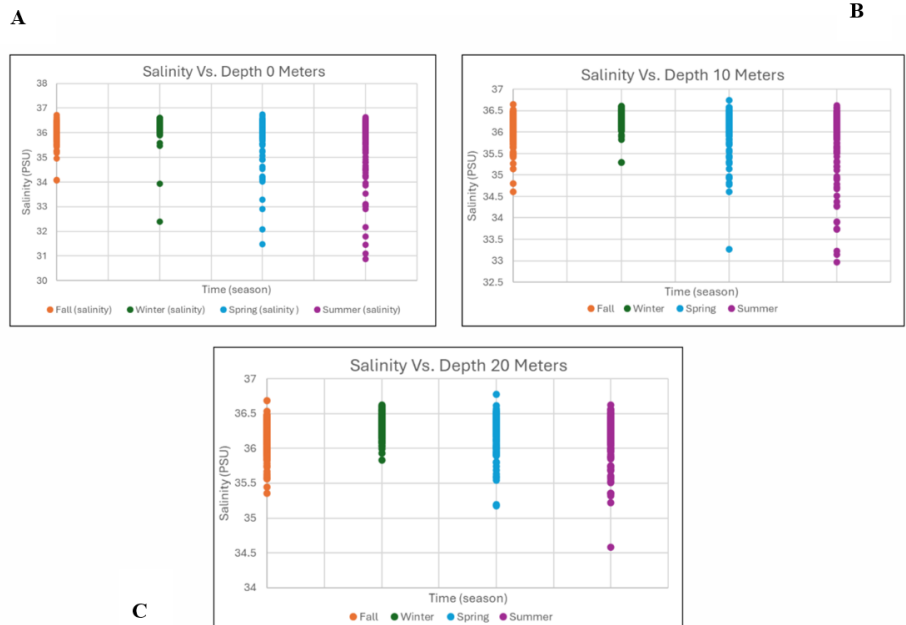


Figure 9: Salinity Vs. Depth (0-20m)

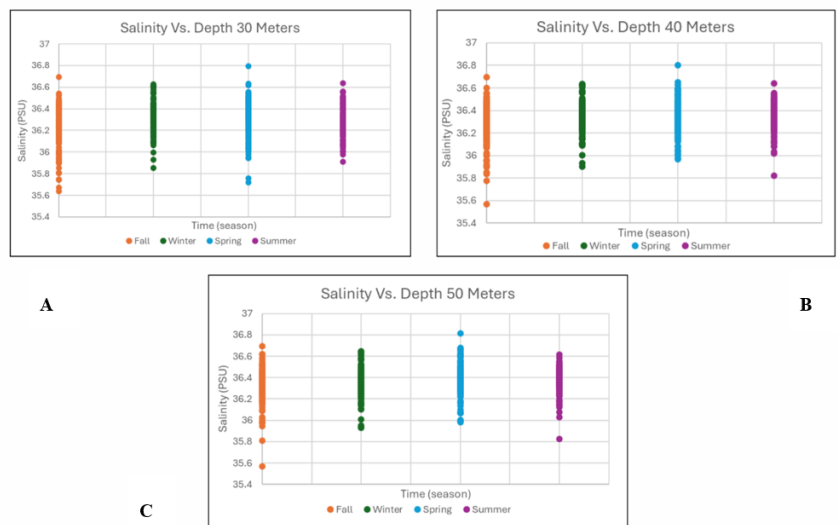


Figure 10: Salinity Vs. Depth (30-50m)

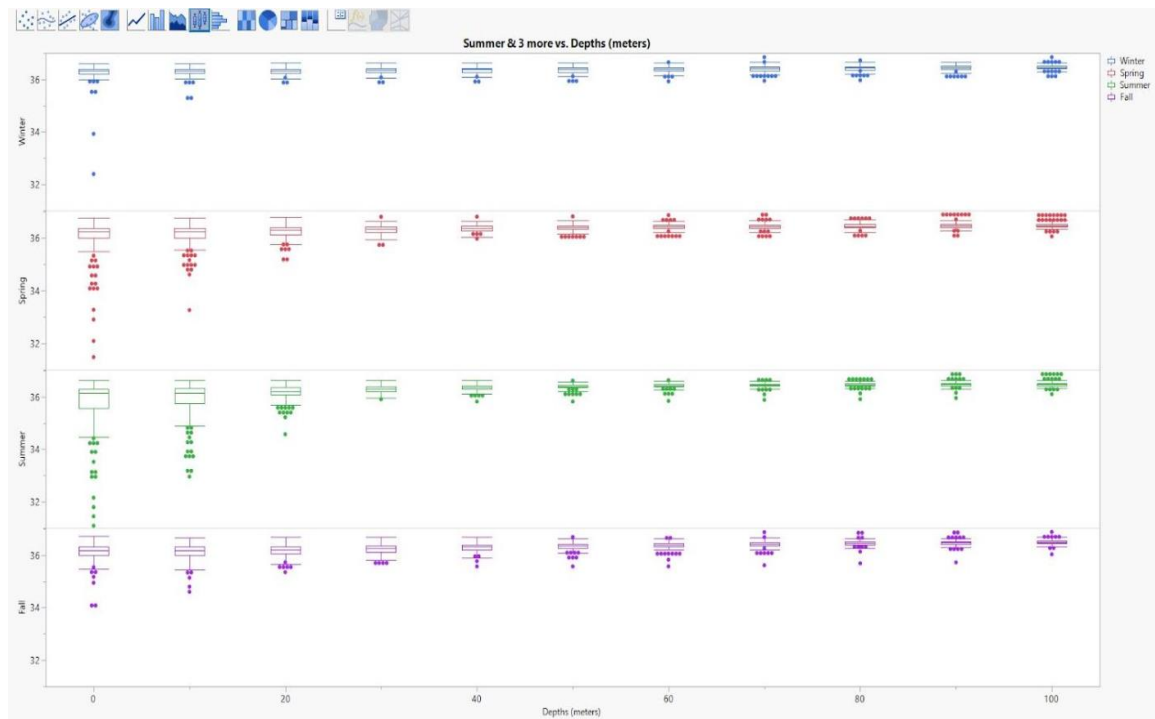


Figure 11: Overview of seasonal salinity with depth in the Gulf of Mexico from 2005-2017 (NOAA)

the higher solar energy transfer at the surface leads to increased evaporation, drastically impacting surface salinity conditions (Stewart, 2024).

These findings suggest that the detrimental effects of cotton microfibers on animal behavior are most likely to manifest during the spring, when elevated salinity levels exacerbate their impact. Furthermore, surface-dwelling species are at an increased risk of microfibers acting as a vector for both inorganic and organic pollutants during the summer.

Conversely, species inhabiting depths of 30-50 meters are more vulnerable during autumn. If these seasonal salinity fluctuations correlate with trends reported in previous literature, they suggest a wide spectrum of potential impacts on marine species, including adverse health effects from both cotton and polyester microfibers, as well as the role of microfibers in transporting inorganic and organic pollutants via ingestion.

1.5.3 Species Habitat

OBIS data indicate that snappers (*Lutjanidae gill*) are widespread along the coastline of the Gulf of Mexico, regions characterized by significant salinity fluctuation ($\alpha=0.05$, **Figure 12**). This species is observed at a wide salinity range, from 25.15 PSU to 36.88 PSU, spanning from near-freshwater conditions to the upper limit of typical ocean salinity (**Table 1**). Furthermore, the average localized range of salinity levels within this habitat fluctuates by 1.14 PSU but can reach as high as 6.33 PSU near the mouth of the Mississippi River (NOAA, 2023). Given this wide salinity tolerance, *Lutjanidae gill* are particularly vulnerable to microfiber ingestion (Klangnurak et al., 2025). In addition, recent literature has specifically mentioned acute mercury toxicity and Polycyclic Aromatic Hydrocarbons (PAHs) ingestion being a primary concern amongst snapper populations (The Fish Site, 2008; Nicholson et al., 2023). The pollutants, exacerbated by

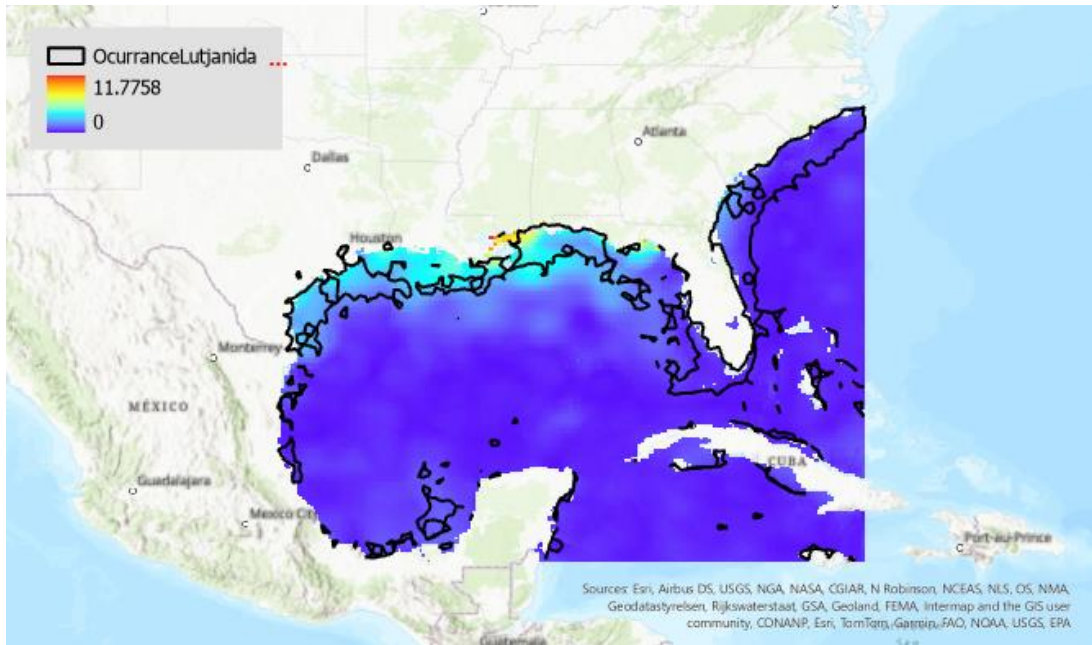


Figure 12: Snapper Habitat vs. Salinity Fluctuation

Table 1: Summary Statistics of Lutjanidae gill (LG)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	34.786	1.137	35.923
	Minimum	25.154	0.058	30.041
	Maximum	36.535	6.334	36.880
	Standard Deviation	2.271	1.264	1.117

fluctuating salinity, can negatively impact snapper feeding patterns, liver function, and reproductive success (Klangnurak et al., 2025; The Fish Site, 2008; Nicholson et al., 2023).

The Atlantic croaker (*Micropogonias undulatus*) occupies a more restricted habitat region compared to *Lutjanidae gill* yet still exhibits significant salinity fluctuation ($\alpha=0.05$). This species experiences salinities ranging from approximately 25 PSU to 37 PSU, spanning from near-freshwater to high oceanic conditions. As shown in **Figure 13**, the distribution of *M. undulatus* aligns with regions of notable salinity variation. Summary statistics presented in **Table 2** reveal a mean salinity of 32.95 PSU within this species' habitat, with an average range of 2.09 PSU. However, the maximum recorded range reaches 5.66 PSU, indicating localized areas of substantial salinity variability. Pollutants such as metals can accumulate in croaker tissues, causing neurological damage, kidney and liver damage, and reproductive impairment (Thomas & Rahman, 2011).

OBIS data demonstrates a spatially concentrated habitat of blue crab, or *Callinectes sapidus* (Rathbun), along the northern coastline of the Gulf. Despite the limited geographic extent, there is still a significant fluctuation in the salinity levels of the blue crab habitat ($\alpha=0.05$) ranging from 20.64 PSU (freshwater) to 36.42 (moderate) (**Table 3**). **Figure 14** illustrates the relationship between *C. sapidus* habitat and salinity variability. *C. sapidus* are particularly vulnerable to pollutants due to their estuarine habitat, which often experiences fluctuating salinities and high levels of anthropogenic influence. Since most of their habitat lies along the coastline in low-salinity areas, metal contamination poses significant concern for blue crabs. Multu et al. (2011) reported metals such as cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), aluminum (Al), and zinc (Zn) commonly found in blue crab

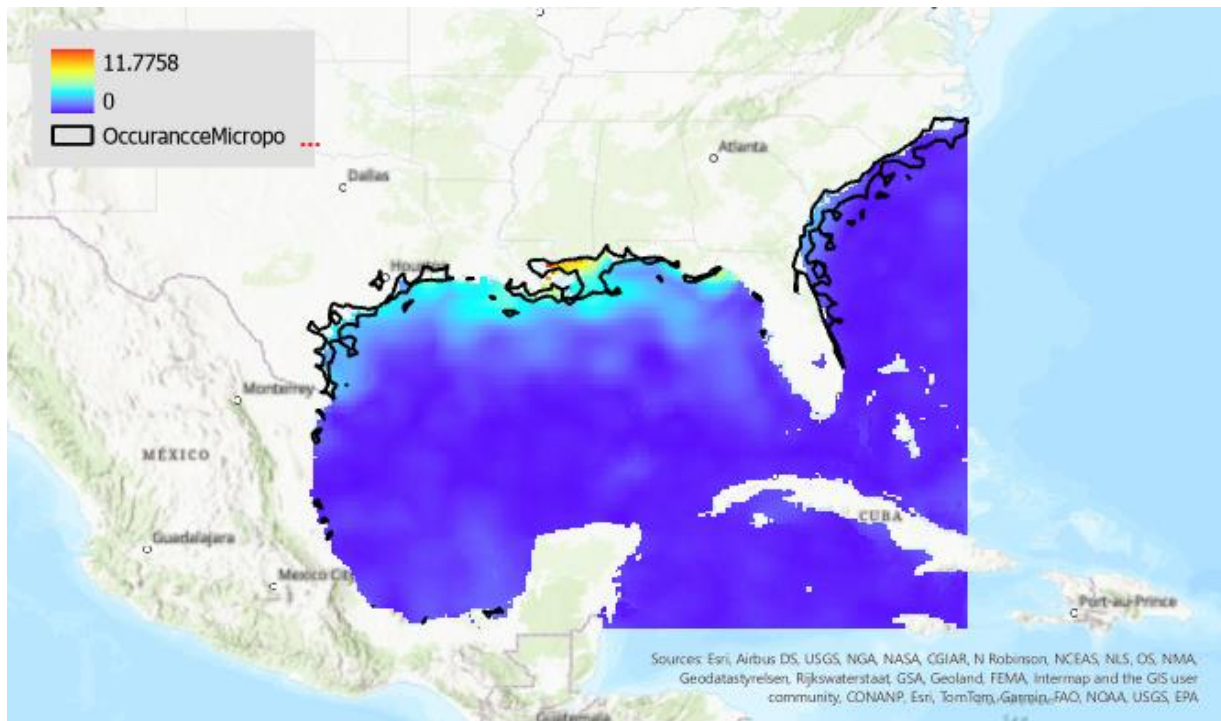


Figure 13: Atlantic Croaker vs. Salinity Fluctuation

Table 2: Summary Statistics of *Micropogonias undulatus* (MU)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	32.954	2.086	35.040
	Minimum	24.962	0.053	29.491
	Maximum	36.064	5.660	36.906
	Standard Deviation	3.339	1.727	1.836

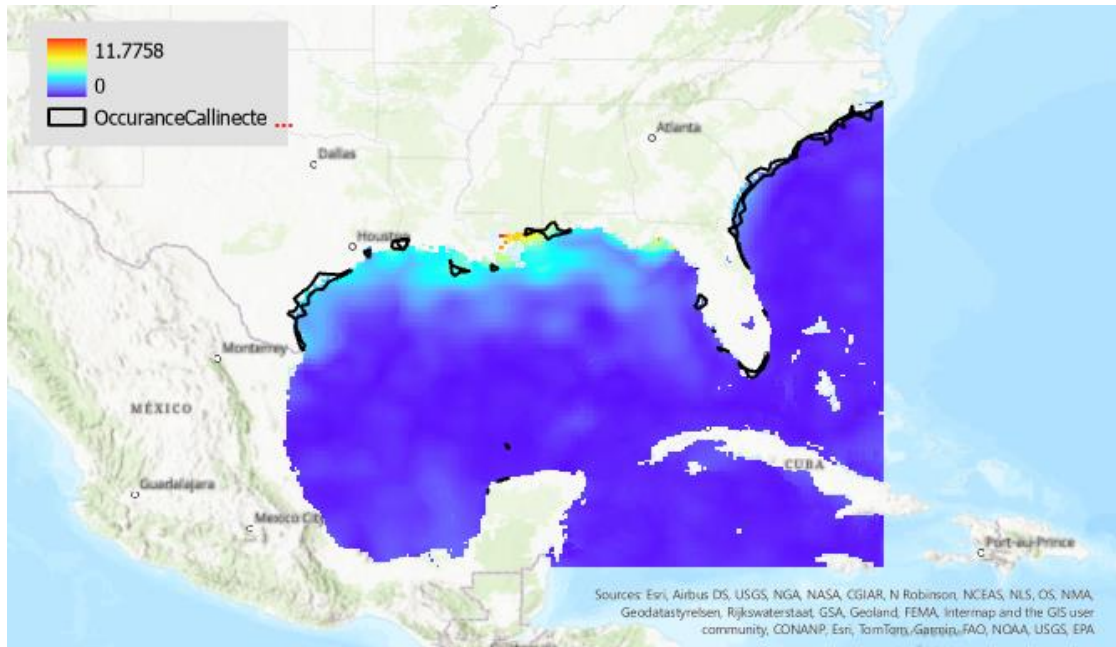


Figure 14: Blue Crab Habitat vs. Salinity Fluctuations

Table 3: Summary Statistics of *Callinectes sapidus* (CR)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	30.905	2.872	33.776
	Minimum	20.648	0.129	30.042
	Maximum	36.289	9.907	36.418
	Standard Deviation	4.657	2.466	2.439

populations can lead to metabolic dysfunction, genotoxic effects, and respiratory impairment (Waqas & Shafiq, 2024).

Tropical sardines (*Clupeidae cuvier*) inhabit regions characterized by relatively stable salinity regimes compared to the other species, however, there was a statistically significant difference ($\alpha=0.05$) in the overall range of salinity values within their habitat (**Figure 15; Table 4**).

Given the concentration of their population in areas of minimal salinity fluctuation and higher salinity (as indicated by the polygons on the eastern US coast), it is hypothesized that the primary concern for this species is the increased adsorption of organic pollutants onto the surface of microfibers. Furthermore, behavioral effects induced by cotton microfibers have been documented in fish species with anatomical similarities to Tropical sardines, suggesting potential ecological implications. Further Owatari et al. (2023) found that survival of tropical sardines increased with higher salinity levels. Thus, large fluctuations in salinity levels, as shown below, are threatening the survival rate of *Clupeidae cuvier*.

OBIS data indicate a concentrated distribution of the Eastern Oyster (*Crassostrea virginia*) along the Gulf of Mexico coastline (**Figure 16**). Significant salinity fluctuations are observed in this region ($\alpha=0.05$). *C. virginica* persists across a broad salinity range, from approximately 20 PSU to 36.27 PSU (**Table 5**). Eastern oysters are filter feeders, making them highly susceptible to pollutants in their habitats. Fluctuating salinities add another layer of complexity, as higher levels of salinity have been shown to enhance the adsorption of PAHs, a pollutant that can impair immune responses, lower reproductive output, and can bioaccumulate in humans upon consumption (Wang et al., 2014; Gan et al., 2021).

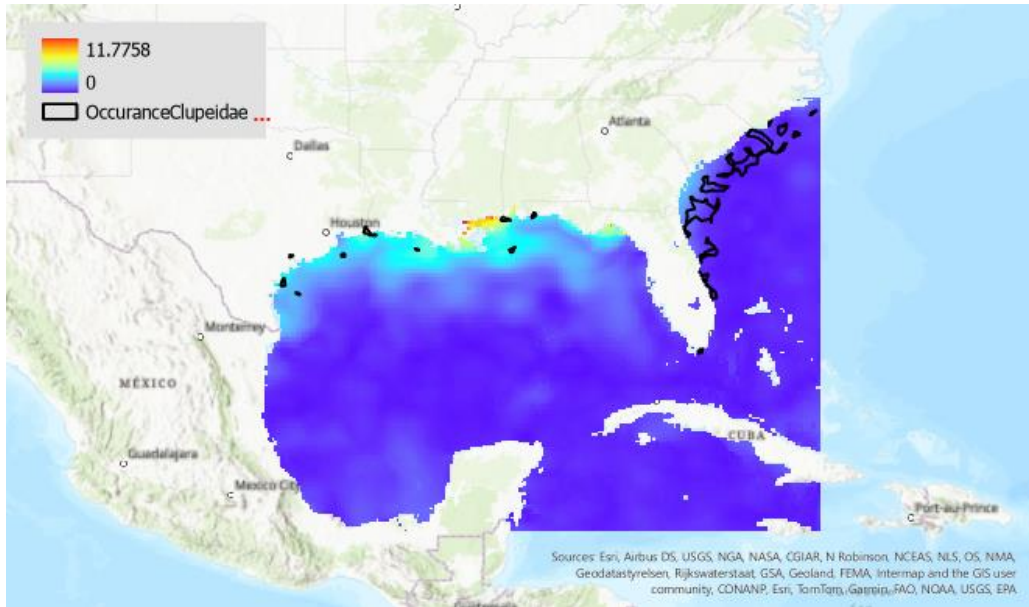


Figure 15: Tropical Sardines vs. Salinity Fluctuations

Table 4: Summary Statistics of *Clupeidae cuvier* (CC)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	33.503	1.700	35.203
	Minimum	25.553	0.210	30.641
	Maximum	35.950	6.321	36.389
	Standard Deviation	3.419	1.832	1.725

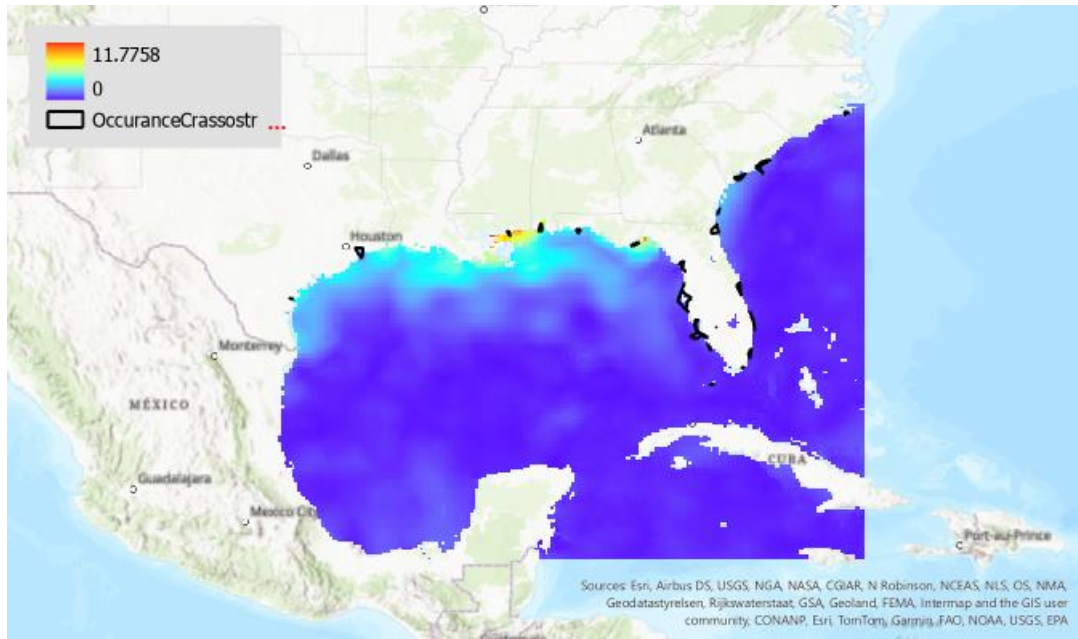


Figure 16: Eastern Oyster vs. Salinity fluctuations

Table 5: Summary Statistics of *Crassostrea virginica* (CV)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	30.949	2.891	33.840
	Minimum	19.986	0.399	28.640
	Maximum	35.815	8.972	36.276
	Standard Deviation	5.051	2.561	2.787

Penaeidae rafinesque (marine shrimp) exhibit a broad habitat range throughout the Gulf of Mexico, characterized by significant salinity fluctuations ($\alpha=0.05$). This species extends to considerable distances offshore, allowing it to experience a vast salinity range from 10 to 37 PSU. Metal and pesticide exposure are significant concerns due to the wide fluctuation in salinity across their habitat. Hossain et al. (2022), reported that metal pollutants, specifically lead (Pb), (Cr), nickel (Ni), copper (Cu), and zinc (Zn) are commonly found in marine shrimp and often surpasses the threshold for bioaccumulation in human upon consumption. Additionally, exposure to sublethal levels of pesticides have been linked to restlessness, tremors, and irregular swimming patterns in marine shrimp (Tu et al., 2010). Detailed salinity fluctuation data and summary statistics are presented in **Figure 17** and **Table 6**.

OBIS data indicate that the habitat of the red drum (*Sciaenops ocellatus*) is primarily coastal. Though their habitat does not extend far from shore, this species does experience a significant difference in salinity ($\alpha=0.05$). Red drums typically encounter salinity levels of 33 PSU (lower moderate range), with observed values ranging from approximately 25 PSU to 36 PSU. The highest salinity variability is observed at the Mississippi River outflow (**Figure 18; Table 7**).

Red drum, compared to other anatomically similar fish species, accumulate more environmental pollutants in their tissues (James et al., 2025). This is especially concerning, as significant salinity fluctuation in their habitat creates optimal conditions for both inorganic and organic pollutant adsorption onto the surface of microfibers, which are readily ingested.

Bottlenose dolphins (*Tursiops gervais*) occupy a broad spatial range within the Gulf of Mexico, experiencing significant salinity fluctuations ($\alpha=0.05$). However, compared to other species

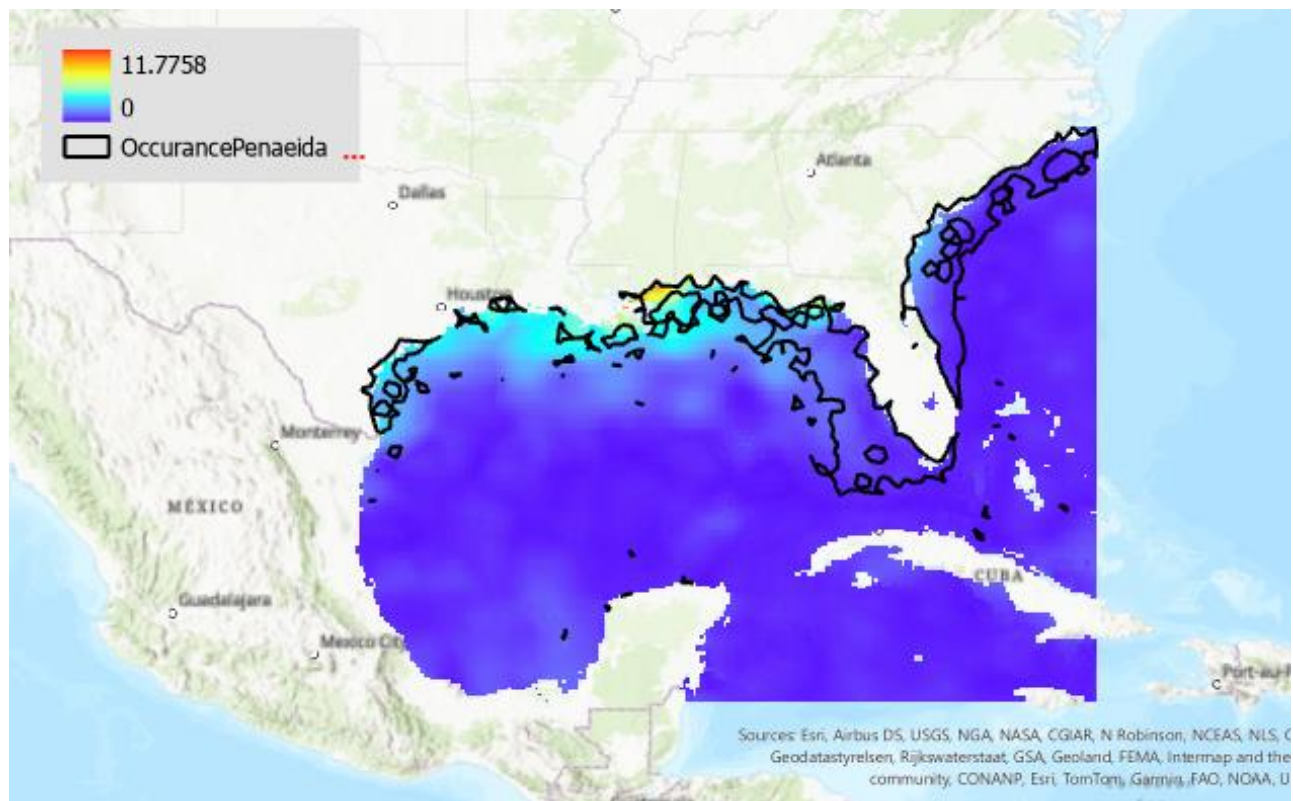


Figure 17: Marine Shrimp Vs. Salinity Fluctuation

Table 6: Summary Statistics of *Penaeidae Rafinesque* (PD)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	32.233	2.473	34.706
	Minimum	10.058	0.106	21.830
	Maximum	36.658	11.772	36.799
	Standard Deviation	5.219	2.352	3.039

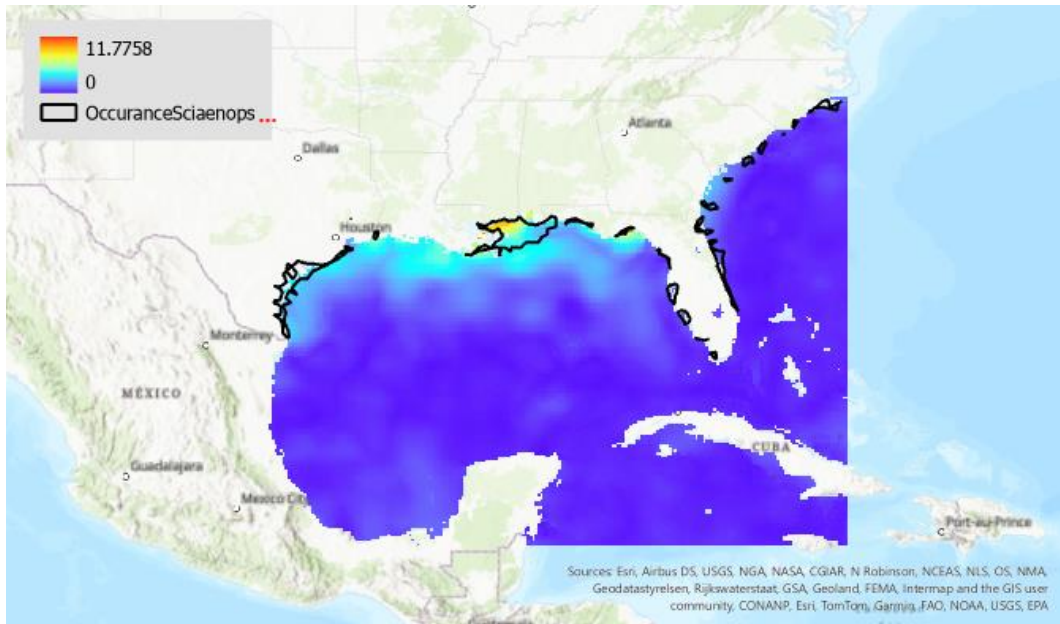


Figure 18: Salinity Fluctuation Vs. Red Drum Habitat

Table 7: Summary Statistics of *Sciaenops ocellatus* (SO)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	32.665	2.2890	34.954
	Minimum	25.154	0.199	30.041
	Maximum	35.918	7.089	36.145
	Standard Deviation	3.260	1.944	1.562

examined, *Tursiops gervais* inhabit a narrower salinity range, with minimum and maximum values of approximately 30 PSU and 37 PSU, respectively. This limited salinity variation may suggest reduced competition between inorganic and organic pollutants for adsorption sites on microfibers, potentially influencing the perceived adverse effects in this species. Furthermore, the relatively high salinity level increases the likelihood of bottlenose dolphins experiencing adverse effects from both cotton and polyester microfiber ingestion throughout their habitat range (Siddiqui et al., 2023). Previous literature, similar to marine shrimps, has warned of the devastating effects that both metal and halogenated organic compounds (HOCs) pose to bottlenose dolphins. HOC exposure is shown to reduce testosterone production in male dolphins, affecting both mating patterns and reproductive success (Trego et al., 2019) and increased mercury concentrations can lead to acute neurotoxicity, reduced reproductive output, and increased oxidative stress (Griffen et al., 2024). The significant salinity fluctuation in this region facilitates conditions in which microfibers act as vectors for these pollutants, threatening species success. See **Figure 19** and **Table 8**.

Significant salinity fluctuations ($\alpha=0.05$) were observed within the habitat of each of the eight species examined. These fluctuations have been reported to increase the adsorption of diverse pollutants, including organic compounds (e.g., antibiotics) and inorganic substances (e.g., pesticides, metals) onto microfiber surfaces. Consequently, ingestion of microfibers is expected to increase physiological stress across these species. Repeated exposure to multiple pollutants within a single timeframe is likely to impair the organisms' overall ability to maintain homeostasis and normal physiological functions. Furthermore, the salinity conditions within each species' habitat are conducive to the adverse health effects associated with natural and synthetic

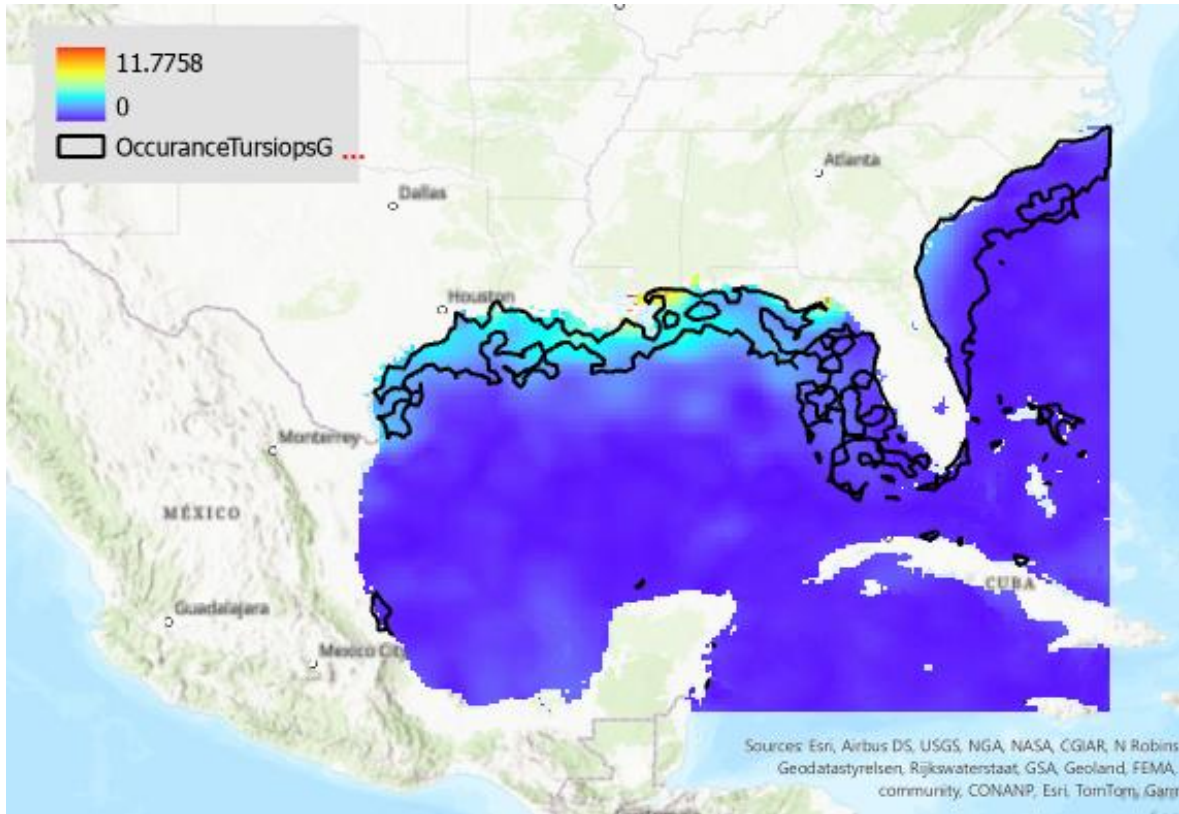


Figure 19: Bottlenose Dolphins Vs. Salinity Fluctuation

Table 8: Summary Statistics of *Tursiops Gervais* (TG)

		Entire Gulf of Mexico (2005-2017)		
Summary Statistics (PSU)		Minimum	Range	Maximum
Within Gulf of Mexico	Mean	35.421	0.762	36.184
	Minimum	31.005	0.090	34.336
	Maximum	36.328	3.330	36.536
	Standard Deviation	1.121	0.791	0.422

microfiber ingestion. Therefore, behavioral abnormalities (e.g., breeding, feeding, activity patterns) reported by Siddiqui et al. (2023) following cotton microfiber ingestion are anticipated within this environment. These findings underscore the substantial threat posed by microfiber pollution to marine ecosystems, given the microfibers' capacity to interact with a broad spectrum of environmental pollutants. Given the persistent compatibility of salinity conditions for both cotton and polyester microfiber ingestion, urgent research is needed to mitigate consumer-generated microfiber pollution.

1.6 Conclusion

The persistent growth of fast fashion in the global market continues to exacerbate concerns regarding the environmental impacts of microfibers (Periyasamy, 2023). The increased consumption of limited-use textiles has led to a rapid accumulation of landfill waste and escalated microfiber production. Microfibers, both natural and synthetic, serve as a vector for organic and inorganic environmental pollutants, resulting in detrimental effects on marine species upon ingestion. Beyond the pollutants adsorbed onto their surfaces, microfibers themselves pose significant health risks. Previous literature indicates that cotton microfibers exhibit increased health effects at higher salinities, inducing behavioral abnormalities in fish species, whereas polyester microfibers have shown increased health effects at lower salinities, affecting both physical growth and behavior (Siddiqui et al., 2023). Given the established relationship between salinity and microfiber bioavailability, this study aimed to investigate the influence of current salinity conditions on pollutant availability and observed effects in eight ecologically and economically critical species within the Gulf of Mexico ecosystem. Salinity data from NOAA demonstrated that surface salinity levels exhibit the greatest

fluctuations during spring and summer, likely due to increased precipitation and evaporation, while fluctuations at depths of 30-50 meters occur predominantly in autumn. Nonetheless, the habitats of all eight species, as reported by OBIS data (0–50 meters), are consistently exposed to conditions that promote the simultaneous adsorption of diverse pollutants.

A primary limitation of this research is its reliance on existing literature, rather than independent data collection. Future studies, contingent upon funding availability, should prioritize the collection of microfiber samples across a range of salinity conditions. These samples should be analyzed to quantify the adsorption of environmental pollutants onto individual microfiber surfaces. In addition, salinity is not the only factor that can change adsorption dynamics in this system. Research should additionally seek to measure how manipulations of pH and temperature affect the adsorption dynamics of different pollutants onto the surfaces of microfibers and whether these factors are a more dominant mechanism for adsorption within this system. Furthermore, additional research is warranted to elucidate the ecological differences in threats posed by natural and synthetic microfiber pollution. Specifically, the influence of natural and synthetic dyes and finishes on the adsorption of various environmental pollutants requires further investigation.

In summary, microfibers pose a significant and ongoing threat to coastal ecosystems. The capacity of microfibers to serve as vectors for environmental pollutants, coupled with their direct physical effects on marine species, necessitates immediate attention and further research. Addressing this issue is crucial for ensuring a sustainable and biodiverse ocean, benefiting both human populations and the diverse species that inhabit these ecosystems.

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Chapter 2

From Awareness to Action: 4-H and Sustainable Textile Consumption

2.1 Abstract

Consumer behavior plays a critical role in limiting microfiber pollution, as the majority of microfiber pollution occurs with domestic laundering (Hazlehurst et al., 2023). The current educational curricula surrounding sustainable consumption is minimal and fails to address the attitude-behavior gap, a prevalent phenomenon in consumer-driven environmental issues (Wiederhold & Martinez, 2018). The primary objective of this study is to close this gap by developing a comprehensive lesson plan and four hands-on activities designed to impart sustainable textile consumption practices. Pre- and post-intervention surveys were administered to 4-H in-service training workshops in East, Middle, and West Tennessee to assess changes in conceptual knowledge and self-reported consumer behavior is impacted at the conclusion of the lesson. Paired t-test results revealed statistically significant improvements ($\alpha=0.05$) in both domains, suggesting that cultivating engaging, activity-based educational interventions is a viable solution in preventing microfiber pollution amongst a pre-consumer audience.

2.2 Background

2.2.1 Current Consumer Education Constraints

Consumer behavior is a recognized critical factor in mitigating microfiber pollution. The rise of fast fashion, driven by social media marketing, has resulted in a market shift in consumer demand towards the production of inexpensive, rapidly manufactured synthetic textiles with limited usage lifespans (Papazolomou et al., 2022). After purchase, these textiles are typically utilized for approximately seven years, during which repeated domestic laundering contributes significantly to the release of microfibers into aquatic environments (Hazlehurst et al., 2023).

Furthermore, the cyclical nature of microtrends often precipitates the premature disposal of these garments (Papazolomou et al., 2022).

Consumer education regarding the complete lifecycle of clothing is crucial in mitigating the environmental impact of microfiber pollution. However, current sustainable textile curricula are often rudimentary, with substantial gaps regarding production, material sourcing, labor practices, and the comprehensive environmental footprint across the materials' lifecycle (Garbagnoli & Garlaschi, 2023). These informational gaps, compounded by the dissemination of contradictory information, contribute to consumer skepticism and exacerbate the attitude-behavior gap. This phenomenon occurs when consumers appear informed and empathetic toward the environmental impact of their products, yet this awareness does not translate into their purchasing behavior (Wiederhold & Martinez, 2018).

Conversely, targeted and effective consumer education has demonstrated the potential to enhance consumer willingness to purchase sustainable products by developing their environmental consciousness (Senooane et al., 2025). Furthermore, Meyer (2015) suggests that education increases awareness of the anthropogenic causes of environmental issues, thereby promoting a sense of personal responsibility among consumers. A survey of over 600 participants by Ma & Chen (2024) observed a positive correlation between sustainability knowledge and the prioritization of environmental impact in consumption decisions.

Collectively, the existing literature suggests that education can play a pivotal role in transitioning consumer behavior toward a model that prioritizes the sustainability of the textile market. However, the lack of consistent and reputable information available through online and social media platforms contributes to consumer confusion and frustration, potentially leading to

feelings of disempowerment regarding everyday consumption patterns (Wiederhold & Martinez, 2018). Consequently, the development and implementation of a consistent, credible, and effective educational curriculum is imperative to gain consumer support in mitigating microfiber pollution.

2.2.2 The Role of Youth Education and The Expectancy-Value Model in Environmental Stewardship

Environmental education is critical for fostering connection, stewardship, and accountability, particularly within industrial manufacturing contexts (UNESCO, 1979). Consistent and effective environmental education has been shown to create lasting effects in consumers' lives, cultivating the integration of sustainable actions into their personal identities (Chawla, 2009). Furthermore, the introduction of sustainability curricula during early childhood development can establish a foundational framework for lifelong environmental engagement, influencing the entirety of an individual's consumption patterns (Chawla, 2009).

The Expectancy-Value model (Eccles & Wigfield, 2002) posits that individuals, particularly children, gravitate their interests towards goals they perceive as attainable, enjoyable, and valuable. The consistent engagement in goal-oriented activities contributes to the development of self-identity (Chawla, 2009; Eccles & Wigfield, 2002). Applying these principles to environmental education necessitates designing educational curricula that are perceived as relevant and attainable within children's daily lives (Chawla, 2009). By facilitating the development of sustainable behaviors aligned with clear sustainability goals, educators can reinforce children's confidence and interest in environmental stewardship (Eccles & Wigfield, 2002). The iterative process of goal setting and achievement within the sustainability domain

promotes the internalization of sustainable actions as core components of their personal identities (Chawla, 2009; Eccles & Wigfield, 2002).

For instance, didactic lectures on recycling may have limited effectiveness in applying the Expectancy-Value model due to the absence of a tangible goal and lack of real-world application outside of the classroom. Conversely, a lecture that emphasizes the value of recycling, followed by a practical activity such as a plastic waste collection drive (e.g., each child collects 10 plastic items), empowers children to develop personalized strategies for waste reduction and collection, thereby fostering a sense of accomplishment and engagement. The continuous reinforcement of sustainability-related goals facilitates the internalization of environmental stewardship as an integral aspect of their individual identities (Chawla, 2009). Implementing these educational strategies early in life provides a prolonged period of identity formation around sustainable behaviors (Chawla, 2009).

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2.2.3 4-H Curriculum and Kinesthetic Learning

The 4-H youth development organization employs hands-on learning activities to facilitate skill development in advocacy, leadership, and collaboration among youth aged 5-18

(Lerner et al., 2018). Serving nearly six million students across diverse subjects, including science, mathematics, agriculture, arts, and technology, 4-H distinguishes itself through its emphasis on kinesthetic, or hands-on, learning methodologies (Grant et al., 2020; Lerner et al., 2018). These activities encompass a range of modalities, including puzzles, model building, and interactive cognitive games (4-H, 2024).

Kinesthetic learning has been associated with enhanced material retention, increased student engagement, improved comprehension of abstract concepts, and the development of problem-solving skills (Hernandez et al., 2020; Nosek & Goldman, 2022). Furthermore, kinesthetic activities closely align with the principles of the Eccles & Wigfield (2002) Expectancy-Value model, providing students with achievable in-class activities that reinforce their confidence in that subject area.

Hernandez et al. (2020) reported that the use of 3-D visual croquet models significantly improved the performance of kinesthetic learners by amplifying their spatial visualization. Similarly, Nosek & Goldman (2022) observed that hands-on activities increased material retention and fostered a more positive perception of the subject matter.

Contemporary educational research, notably from Stanford University, characterizes kinesthetic learning as “active” learning, which empowers students to assume responsibility for their learning by being an active participant in discussions, projects, and the attainment of learning objectives, thereby enhancing cognitive and academic outcomes (Yannier et al., 2021).

2.3 Study Objectives

While existing literature underscores the importance of increasing environmental and sustainability education among youth, there is limited academic curriculum specifically

addressing sustainable textile consumption. Furthermore, a significant knowledge gap exists regarding the lifecycle of synthetic textiles and the environmental impact of microfiber pollution. Consequently, the primary objective of this research is to develop a comprehensive lesson plan and cultivate engaging activities to educate a pre-consumer audience on sustainable textile consumption practices and the enduring effects of microfibers.

2.4 Materials and Methods

A lesson plan, designed in accordance with the Institutional Review Board (IRB) guidelines, was developed to address microfiber pollution and promote sustainable textile consumption among a youth audience (approximately 9-10 years old). The lesson plan comprises four in-class activities, each lasting 5-7 minutes, designed to enhance awareness of the entire lifecycle of clothing materials (Appendix A). This study utilized “Train-the-Trainer” methodologies to cultivate effective educational training techniques for instructing students on this issue (Marks et al., 2013). Subsequently, a presentation and accompanying script were created to facilitate the efficient delivery of foundational principles of microfibers to elementary teachers and 4-H agents. Pre- and post-examinations were developed to assess conceptual knowledge of microfibers and evaluate consumer purchasing behaviors (Appendix B).

The developed presentation and class activities were presented at three 4-H In-service Trainings events across Tennessee (East, Middle, and West regions). A total of 50 extension agents participated in the study: 15 from the East region, 15 from the Middle region, and 20 from the West region. At each in-service training event, extension agents completed pre- and post-examinations to evaluate changes in their knowledge of microfibers and perceived consumption

behavior following the lesson. Paired t-tests were performed using R-Studio (version 4.4) to determine if a significant difference ($\alpha=0.05$) existed between pre- and post-examination scores.

2.5 Results and Discussion

Analysis of the conceptual knowledge survey revealed a statistically significant increase ($\alpha=0.05$) in mean post-lesson scores compared to pre-lesson scores across all three testing locations (**Table 9**). Furthermore, no significant differences ($\alpha=0.05$) were observed in post-lesson scores among the three different testing locations. This finding suggests that the developed lesson plan demonstrated consistent educational value, regardless of regional cotton production prevalence.

Despite the observed increase in overall mean scores, analysis of individual question performance revealed no statistically significant differences ($\alpha=0.05$) between pre- and post-survey responses. This outcome may be attributed, in part, to the relatively small sample size ($n=50$) used in this study. Additionally, the complexity of the survey questions, designed for a target demographic of children ages 9-10, may have resulted in a ceiling effect for the extension agent participants, who likely possess a higher baseline knowledge of sustainable consumption practices.

Despite the lack of significant changes in individual question scores, the significant improvement in overall average scores confirms that the curated lesson plan effectively increased the participants' general knowledge of microfiber-related impacts. See **Table 9** for further details.

The behavioral survey revealed a statistically significant increase ($\alpha=0.05$) in mean scores from pre-to-post-lesson administration. Furthermore, no significant differences ($\alpha=0.05$) were observed in behavioral survey scores across the three designated regions.

Table 9: Conceptual Knowledge Summary Results

Question	Mean (Pre)	Mean (Post)	P-Value
What is a microfiber?	48%	78%	0.118
Which accurately describes differences in natural and synthetic microfibers?	90%	98%	0.182
How does microfiber pollution occur?	94%	100%	0.083
Select the <u>best</u> scenario to prevent microfiber pollution	56%	72%	0.376
Select the best scenario to prevent microfiber pollution	92%	98%	0.322
Overall Score	79%	87%	2.678*10 ⁻¹¹ **

A notable distinction between the behavioral and conceptual surveys was the observed significant improvement ($\alpha=0.05$) in individual question performance on the behavioral survey. This finding contradicts previous research that suggests that increased consumer knowledge of environmental issues does not consistently translate into changes in consumer behavior (Xiao et al., 2025).

In summary, the behavioral survey results provide compelling evidence that the pedagogical approach employed in this lesson plan, specifically the inclusion of active learning activities, can effectively promote sustainable consumption behaviors among pre-consumers (**Table 10**).

2.6 Conclusion

Consumer behavior plays a pivotal role in mitigating microfiber pollution. However, current sustainability curricula often oversimplify the issue and fail to address the attitude-behavior gap, a common challenge in consumer-mediated environmental issues (Wiederhold & Martinez, 2018). This study aimed to develop hands-on activities that foster confidence and perceived attainability in addressing environmental challenges related to microfiber pollution. Pre- and post-lesson surveys suggest that the developed lesson plan, incorporating kinesthetic learning methodologies, effectively increases awareness of microfiber pollution and promotes sustainable consumption behaviors among participants ($\alpha=0.05$).

Nevertheless, several limitations to this study should be acknowledged. Primarily, the lesson plan was not implemented directly with its intended youth audience (ages 9-10) within the study's timeframe. While significant improvements were observed in the knowledge and behavioral expectations of educators, extrapolating these findings to a younger audience requires

Table 10: Behavioral Expectation Summary Results

Question	Average (Pre) (1-5)	Average (Post) (1-5)	P Value
How often do you look at the material tag when you're shopping for clothes?	2.91	3.32	0.028
How confident are you in understanding differences in natural and synthetic material?	3.33	4.28	2.27×10^{-6}
How confident are you in defining a microfiber when talking to a friend or family member?	2.49	4.25	1.58×10^{-11}
How aware are you of the environmental impacts of synthetic and natural microfibers?	2.33	4.21	1.26×10^{-14}
How confident are you in identifying sources of microfiber pollution?	2.15	4.19	2.2×10^{-16}
Would you be willing to change your purchasing habits to reduce microfiber pollution?	3.65	3.96	0.046
Overall	16.81/30	24.21/30	0.024

caution. Future research should implement the lesson plan with youth (ages 9-10 years) and conduct the same analysis to assess its effectiveness within the targeted demographic.

Furthermore, the behavioral survey assessed self-reported behavioral intentions rather than actual long-term consumer habits. To gain a more comprehensive understanding, a longitudinal follow-up study, conducted approximately five years post-intervention, would be beneficial to assess the sustainability of reported behavioral shifts.

From a broader perspective, strengthening environmental education with a focus on sustainable consumerism is essential for addressing microfiber pollution. Accessible and engaging educational initiatives can play a pivotal role in reducing microfiber pollution by targeting the issue at its source and fostering trust and engagement among the next generation of consumers.

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Appendix

Appendix A: Youth Lesson Plan

W XXXX

Marine Microfibers

How Naturally and Synthetically Dyed Microfibers impact Marine Species

Skill Level

Beginner (4th/ 5th grade)

Learner Outcomes

The learner will be able to:

- Define the word “microfiber”
- Compare Cotton and Polyester
- Describe differences between natural and synthetic dyes
- Rationalize how synthetic textile components effect marine species

Educational Standard(s) Supported

List TN educational standard numbers. Can search documents online for key words.

Success Indicator

Time Needed

Activity – 15 minutes

Presentation – 15 minutes

Assessment – 10 minutes

Materials List

- Two white barbie t-shirts
- One mini electric washing machine toy
- Double A Batteries
- 2 Clear water cups
- Red food coloring
- Clothing items with material tag intact

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Introduction to Content

Microfibers are a subset of microplastics that occur when synthetic components of textiles degrade. As machine washing occurs, friction between the clothing pieces increases, causing tiny fabric fragments to break off and become released into our oceans. Microfiber pollution can occur under a wide range of textile materials including both natural and synthetic fibers, however, the effects that these have on marine wildlife vary based on material, dye, and chemical finish applied. This lesson will introduce how microfiber pollution occurs, and the harmful effects synthetically dyed microfibers pose on marine wildlife. Students will examine how synthetic dyed microfibers affect marine species, by modeling a washing machine cycle for a synthetically dyed t-shirt. Additionally, students will compare how nature interacts with natural and synthetic microfibers as they travel from washing machine to ocean.

Terms and Concepts

Microfiber – synthetic material with a diameter less than 1.3 denier
Denier- grams per 9000 meters of fabric
Natural – existing or caused by nature
Synthetic- made by the combination of chemicals
Cotton – white fluffy subtropic plant used to produce fabric
Polyester – synthetic fabric made from gasoline

Introduction to Methodology

Students will simulate a washing machine cycle to visualize how textile dyes persist in ocean bodies. This activity can be done in groups of 4-6 students depending on classroom size. For this experiment classrooms will need to purchase one mini washing machine toy per group. Other materials are common household items such as: white doll shirts, food coloring, clothing items, clear glasses, and double AA batteries.



Setting the Stage/ Opening Questions

Say “The laundry is far more than our least favorite chore! Each time we put our dirty clothes into the washing machine and press start we create friction. This friction between clothing items causes tiny pieces of fabric to break off; these pieces are known as microfibers. Microfibers then travel via pipe eventually flowing into our rivers and oceans. Due to their near invisible size, fish often mistake these little microfibers for dinner, leading to dangerous side effects.”

Say “Now, what microfiber is made of will control what effects marine species will experience. If the microfiber is made from natural fabrics and dyes the microfiber is fully biodegradable. This means that nature can recycle those materials into something new! The same way a cardboard box can be recycled to make a magnificent birthday Piñata! Synthetic fabrics and dyes are not biodegradable and can persist in our waterways for 1000s of years. Since animals don’t understand the microfibers are synthetic, they mistake microfibers for a midnight snack. Unfortunately, this causes them to get stuck in the animal’s belly, making them sick!” The activities that follow will explore how microfiber pollution occurs. In addition, students will analyze how natural and synthetic dyes impact the side effects felt by marine species.

1. What is friction?

Students are expected to mention that friction is what slows objects down. They may mention that it happens when an object interacts with another object.

To encourage further understanding, have the students rub their hands together as if it was cold outside. Have the students note that heat created from this is a result of friction. The friction created by their hands rubbing together caused an increase in energy. Now, ask the students to rub two pieces of clothing material together. This is expected to cause lint to become visible in the air. Explain to the students that this too is increasing energy causing tiny pieces of these clothes to break off. Say “Unfortunately, when clothes rub against each other, we don’t get to see the fabric materials breaking off until they end up in the belly of a fish!”

2. What are some examples of natural fabrics?

Natural fabrics are made from materials grown in nature. Cotton is the most popular, with this making up 22% of all fabrics purchased. That’s over a million tons of cotton fabric produced each year! Natural fabrics can also be made from wool from sheep, hemp seeds, bamboo, & silk. A general rule of thumb is it can be grown on a farm or produced by an animal it is a natural fabric!

Strategies to Increase Student Engagement

- Bring clothing items from home with the tag still intact. Students can read tags and decipher which fabrics are natural or synthetic
- Students can watch this video overiewing how friction in the washing machine causes clothing to breakdown, releasing microfibers into our waterways:

[The Story of Microfibers](#)



Figure 1: Natural Fabric Sources

3. What are some examples of synthetic fabrics?

Synthetic fabrics are made from different manufactured chemical combinations. Chemicals are made from tiny molecules mixed to form another substance. Ask the students to reflect on what water is made of. Explain to them that water is made of Oxygen and Hydrogen combining. Continue to state, “the difference between water and synthetic chemicals is water is made in nature, and synthetic chemicals are made in a laboratory.” Encourage students to read the tags of the clothing items distributed and ask them to call out any words they don’t recognize. Students are expected to call out nylon, polyester, and spandex. Elaborate to the students that these are examples of synthetic fabrics.

Since synthetic fabrics are not created by nature, they aren’t able to interact with animals and plants in a positive way. Nature simply does not recognize these materials so they accumulate in spaces they shouldn’t. Synthetic fabrics result in large quantities of water pollution and greenhouse gases emitted

during the production stage. These materials also can't be broken down over time, so they last in landfills or waterways long after our lifetimes.



Figure 2: Polyester Factory

4. Using what we have previously discussed about natural and synthetic fabrics, what do you think the difference is between natural and synthetic dyes?
Natural and synthetic dyes follow the same rules we previously discussed. Natural dyes are made from plant and animal materials while synthetic dyes are made from chemicals. Beets, Indigo, and Black walnuts are some examples of plants that can make natural dyes. Can you think of any others? (Berries! Fun fact Cleopatra used to use berries to make her cheeks rosy, red)

Experience

Part I. Exploring Friction

Allow the students to rub clothing materials, creating friction. Have the students notice that small pieces are breaking off into the air. Then ask students what causes friction to occur in the washing machine. Explain to students that the spinning motion of the washing machine causes clothes to rub against each other, similar to the activity they just performed. This friction created in the washing machine causes small pieces of clothing, of all colors, to break and travel towards the ocean.

Part II. Do you know where your clothes come from?

Have the students locate the material tags in their T-shirts. They can use a buddy's help locating the tags. Have the students raise their hand if more than 50% of their shirt is made from natural fabrics. Tally the students. Following this, have the students who have t-

Notes

shirts made from synthetic fabrics raise their hand. Tally the students. Ask what students think the differences are between natural and synthetic fabrics. Additionally, have the students reflect on what consequences their natural and synthetic “ratio” may have in the real world.

Part III. Laundry Activity

1. Prepare Barbie shirts by dyeing them red with food coloring.
2. Split students into groups of 6 each receiving 1 washing machine gadget, 1 clear cup, 1 red doll shirt, and 2 fish figurines.
3. Explain to students that the red shirt will demonstrate how dyed fabric interacts with the washing machine.
4. Add water and the red doll shirt to the washing machine and press start.
5. Once the cycle ends, remove the barbie shirt and dump the leftover water into a clear cup.
6. Once finished, have students record their observations, noting color difference prior to adding the effluent.

Part VI. Home to Ocean Pathways

Using the Trace Downstream Application in Arc-GIS, show the path dyed microfiber pollutants take from washing machine to ocean. Have the students note that organisms in the river along the way can breakdown and use naturally dyed microfibers. However, with synthetically dyed microfibers, they persist in the environment for a long time and are unable to break down. This allows them to travel straight from washing machine to our ocean!

Share

Ask students, knowing that dyes travel from our washing machine to our ocean, which microfiber do you think would have a greater effect on wildlife. One dyed with natural dyes (beets), or one dyed with synthetic dyes (like azo). Why?

Process

To generate further understanding ask students why they think synthetic dye causes more harm to ocean environments? After student participation, re-emphasize those synthetic materials, including dyes that are not found in nature leaving animals confused on whether these materials are friend or foe. Synthetic components cannot be digested in animals, so they stay inside the animal’s belly causing harmful effects over time.

Generalize

You get home from school and your mom asks you to bring your dirty clothes to the laundry room. You walk into your room and see your clothes all over your bedroom. Should you throw all the clothes into the dirty hamper and bring them to your mom to put in the washing machine, or should you sort your clothes and only add the truly dirty clothes into your laundry basket? What kind of impact do you hypothesize each choice would have on marine species, why or why not?

Apply

Five years have passed since this lesson and you, and your best friend, want new outfits for your sweet sixteen! You guys could go to the mall and pick a new trendy outfit made from synthetic materials, you could purchase secondhand items from a local thrift store, or you could purchase from a small local business that uses natural materials and dyes. Remembering this lesson, you try to advise your friend to pick which option? When she asks why, what could be a possible response?

Based on this lesson what ideas do you think could help reduce marine pollution?

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Supplemental Information
Educational Standards Met

TIPPS
Life Skills

- Critical thinking
- Cause and Effect relationships
- Consumption

Student Worksheet

A. Experiment Questions

What causes friction to occur in the washing machine?

How does nature interact with natural dyes. How is this different than how nature interacts with synthetic dyes?

Where did your clothes today truly come from? Was it a farm or a factory?

B. Sorting Activity

Draw a line from the material name into the corresponding natural and synthetic bins.

Natural

Wool

Nylon

Spandex

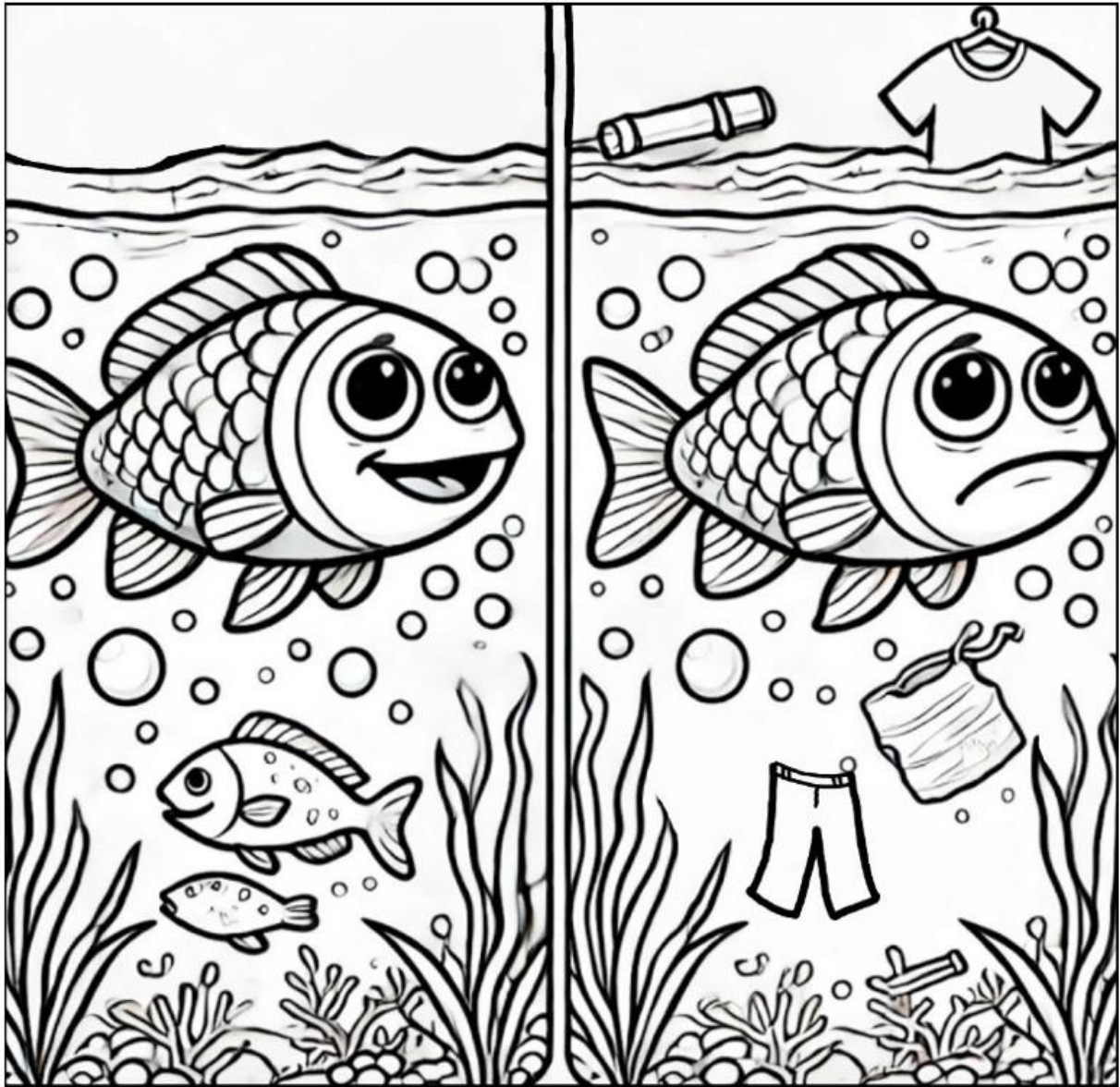
Beets

Indigo

Synthetic

C. Fish Coloring Activity

Color each ocean scene to your liking, what are some clear differences between each ocean environment? How do you think this impacts marine species?



Appendix B: Assessments

Quiz

1. What is a microfiber?
 - A. A natural piece clothing material with a diameter <1.3 denier
 - B. A synthetic piece clothing material with a diameter < 1.3 denier
 - C. A synthetic piece clothing material with a diameter > 1.3 denier
 - D. A natural piece clothing material with a diameter >1.3 denier
2. Which accurately describes differences in natural and synthetic microfibers?
 - A. Natural microfibers occur in nature, synthetic microfibers are produced by chemicals
 - B. Natural microfibers are produced by chemicals, synthetic microfibers occur in nature
 - C. Natural and synthetic microfibers are the exact same thing
 - D. Natural microfibers hurt marine ecosystems, synthetic microfibers do not
3. How does microfiber pollution occur?
 - A. From the washing machine
 - B. From friction between the clothes
 - C. From buying clothes with synthetic dyes
 - D. All of the above
4. Select the best scenario to prevent microfiber pollution: Five years have passed since this lesson and you, and your best friend, want new outfits for your sweet sixteen! You go to the mall and pick out a new trendy outfit made from synthetic material, purchase secondhand items from a local thrift store, or purchase from a small local business that uses natural materials. Remembering this lesson, you try to advise your friend to pick which option?
 - A. New outfits from the mall
 - B. Thrifted outfits from a local thrift store
 - C. Local business that uses natural materials
 - D. None of these would be a sustainable option
5. Select the best scenario to prevent microfiber pollution: You arrive home from school and your mom asks you to bring your dirty clothes to the laundry room. You walk into your room and see clothes all over your bedroom. Should you throw all the clothes into the dirty hamper and bring them to your mom to put in the washing machine, or should you sort your clothes and only add the truly dirty clothes into your laundry basket?
 - A. Throw all clothes into your laundry basket
 - B. Throw only the dirty clothes into the laundry basket
 - C. Don't bring your mom the laundry at all
 - D. Throw the clothes in the floor in the trash

For the questions below, you will answer with a number from 1-5, with 1 meaning nothing or not at all and 5 meaning greatly or all the time.

On a scale of 1-5, how often do you look at the material tag when you're shopping for clothes?

1 2 3 4 5

On a scale of 1-5, how confident are you in understanding differences in natural and synthetic material?

1 2 3 4 5

On a scale of 1-5, how confident are you in defining a microfiber when talking to a friend or family member?

1 2 3 4 5

On a scale of 1-5, how aware are you of the environmental impacts of synthetic and natural microfibers?

1 2 3 4 5

On a scale of 1-5, how confident are you in identifying sources of microfiber pollution?

1 2 3 4 5

On a scale from 1-5, would you be willing to change your purchasing habits to reduce microfiber pollution?

1 2 3 4 5

On a scale of 1-5, how much has your knowledge of microfiber changed from this presentation?

1 2 3 4 5

Chapter 3

Overall Conclusions and Future Directions

3.1 Chapter One Key Findings

Microfiber pollution, driven by the rapid growth in consumer textile demand, is an emerging issue that necessitates immediate attention and remediation due to its health effects for both marine species and the human population that consumes them. Microfibers serve as a threat through two primary mechanisms. First, through accumulation in the organism's digestive tract, leading to reduced hunger cues, ineffective prey drive, and reproduction impairment (Santonicola, 2023). In addition, microfibers serve as one of the many vectors for both organic and inorganic pollutants which are then absorbed into organisms' tissues upon ingestion, leading to increased and additional health effects (Singh, 2020). Previous literature has noted that differences in salinity not only affect the observed side effects in both cotton and polyester microfiber ingestion, but also in the adsorption of different pollutants onto the surface of the microfiber (Siddiqui et al., 2023; Surana, 2022).

This thesis used geospatial modeling of oceanic salinity levels in the Gulf of Mexico to assess the implications of these phenomena on eight ecologically and environmentally important species. This study revealed significant salinity fluctuations ($\alpha=0.05$) within the habitats of all eight species examined, creating conditions favorable for a diverse range of pollutant adsorption in addition to the predicted health effects from both cotton and polyester microfiber ingestion. Furthermore, estuarine areas experience the greatest salinity fluctuations, ranging between 8 to 12 PSU, and are likely to have increased physiological stress in high species density zones near the coastline due to a wider range of bioavailable pollutants as compared to further offshore. The primary limitation for this study is its reliance on existing literature and the inability to evaluate material properties independent of chemical dye and finish. Further research should be

conducted to validate model predictions, and to assess the dominant mechanism for pollutant adsorption onto the microfibers' surface. Current technologies are being utilized to address microfiber pollution at its source, through filtration systems installed onto the back of domestic laundering units. However, legislation mandating the use of filtration systems in consumer households remains at a stalemate (Great Lakes Protection Fund, 2025). In summary, the impact of microfiber pollution, especially in areas with high salinity fluctuations, warrants further evaluation to mitigate potential health effects on marine species and human health.

3.2 Chapter Two Key Findings

Effective consumer education serves an important role in mitigating microfiber pollution through the promotion of sustainable purchasing behaviors. Current consumer education, however, fails to establish consumer trust and confidence in individual consumer dynamics. To address this, a lesson plan and four hands-on activities were developed to facilitate sustainable purchasing behaviors amongst a pre-consumer audience. In addition, both a conceptual knowledge and behavioral survey were employed to analyze lesson efficacy. Both surveys revealed a significant increase in consumer knowledge and predicted behavioral change at $\alpha=0.05$, indicating that educational initiatives can play a pivotal role in reducing microfiber pollution by targeting the issue at its source and fostering trust and engagement among the next generation of consumers.

Vita

Kali Butler was born in Dayton, Ohio, on December 28, 2001. She graduated from Olentangy Orange High School in May 2020, determined to pursue her passion for Environmental Science at the University of Tennessee, Knoxville. She followed that path and earned a Bachelor of Science in Environmental and Soil Sciences in December 2023. Following graduation, Kali chose to continue her studies at the University of Tennessee, where she is currently pursuing a Master's degree in Environmental and Soil Sciences. She plans to begin her professional career in the environmental science field upon completion of her graduate studies.